Application of PWSCC Crack Initiation Laboratory Test Data

Screening Process for Laboratory PWSCC Crack Growth Data

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Application of PWSCC Crack Initiation Laboratory Test Data

Application of PWSCC Initiation Test Data

Benefit of Crack Initiation Test Data

- Main design criterion (GDC 4) is extremely low probability of rupture
  - Therefore, calculation of probability of rupture (i.e., risk-based approach) is key for pressure boundary components
  - Hence, modeling of crack initiation and crack growth are desirable
- Consideration of crack growth alone by assuming that initiation has occurred is an unnecessary overconservatism
- Appropriate timing of first inspection of Alloy 690/52/152 components should consider time to initiation
- "The perfect is the enemy of the good."
  - Building on existing knowledge for Alloy 600/82/182/132 (and MRP-111 and EPRI Alloy 690/52/152 white paper), a reasonable set of initiation tests with Alloy 690/52/152 can be used to derive much benefit

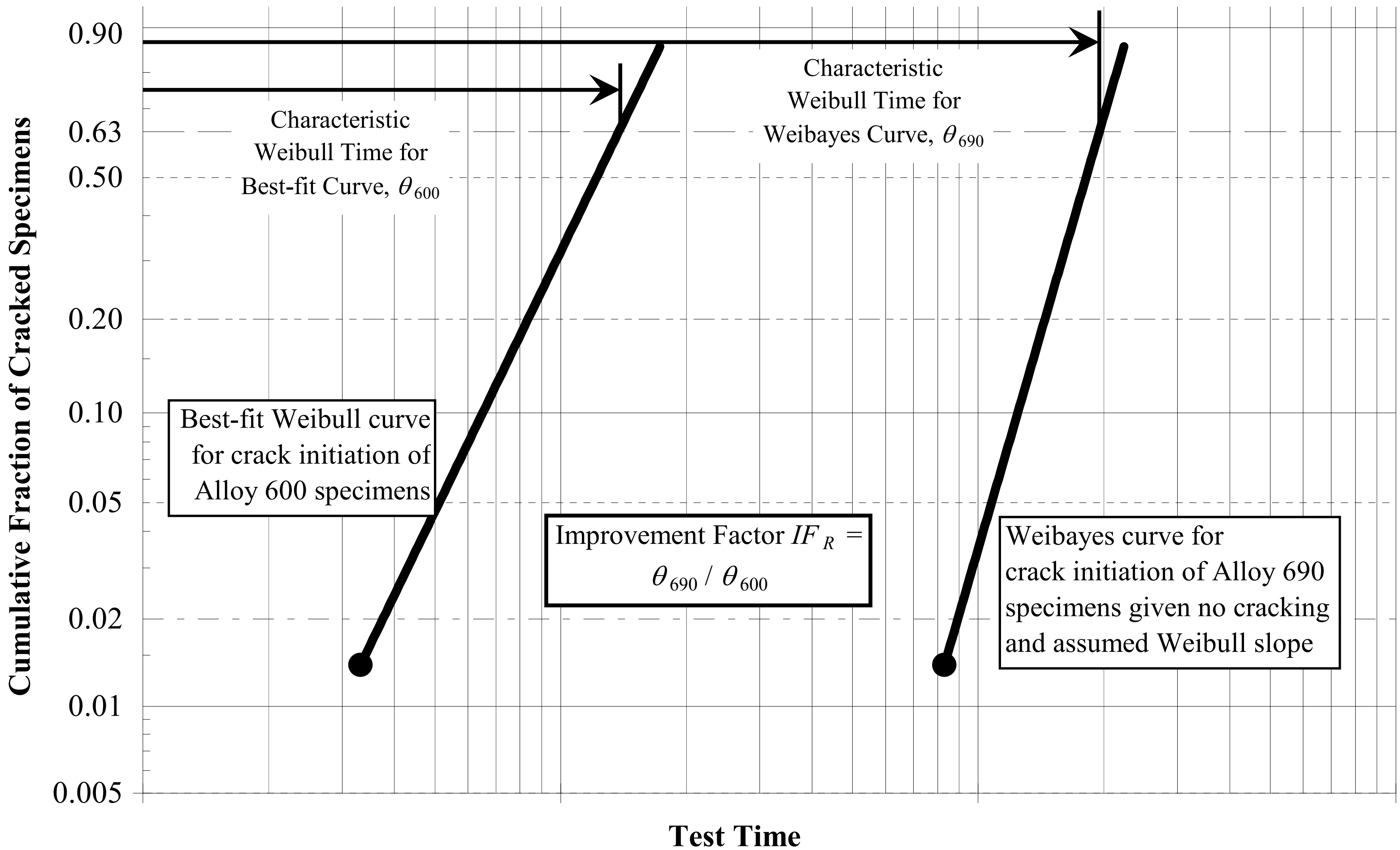
Application of PWSCC Initiation Test Data

Approach

- Laboratory testing is applied to develop crack initiation material improvement factors for Alloy 690/52/152 vs. 600/82/182
  - Next two slides show approaches to improvement factor when no crack initiation is observed in a lab test
- The goal of crack initiation testing is understanding of any material or environmental conditions (surface condition, off water chemistry, fabrication defects, etc.) that lead to significantly reduced material improvement factors
- Lab initiation testing is used to determine the <u>relative</u> effects of various factors including Cr content (e.g., 690 vs 600), stress level, temperature, etc.

Application of PWSCC Initiation Test Data

Calculation of Improvement Factor When No Initiation is Observed (MRP-111 Method 1)



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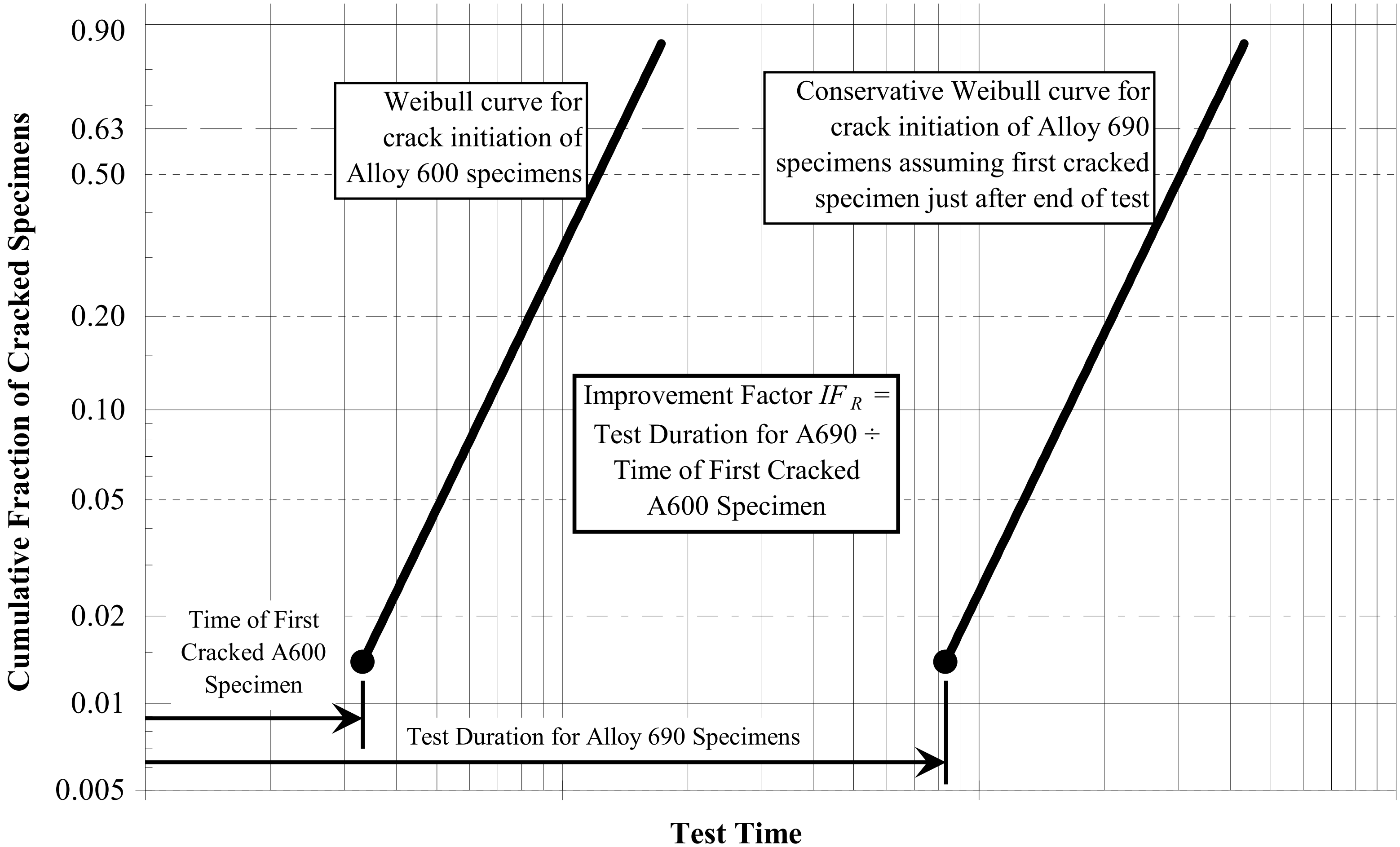
Calculation of Improvement Factor When No Initiation is Observed (MRP-111 Method 2)



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Application of PWSCC Initiation Test Data

Definition of Initiation

- In plants, initiation is typically defined as the presence of a flaw detectable via NDE
- From an engineering reliability viewpoint, this simplification is appropriate, especially given that we do not have good crack growth rate models for short cracks (less than say 0.025 inches deep) for which the stress intensity factor approach is not strictly applicable
- The situation for lab initiation testing is generally different, but initiation testing is used to investigate factors causing a <u>relative</u> difference in time to initiation
  - not for fundamental modeling of the detailed initiation and short crack growth process

Application of PWSCC Initiation Test Data

Approach (cont'd)

- Then a base reference curve for predicting crack initiation can be fit to actual plant data (preferably with adjustment for crack growth beyond the engineering "initiation" depth) by correcting for these various relative factors
- Finally, the reference curve is applied to a subject set of plant components by again adjusting to the subject set of conditions
- So, initiation lab testing is key to making effective use of plant experience
- Also, an approach avoiding definition of an initiation depth can be taken:
  - D. O. Harris, D. D. Dedhia, and E. D. Eason, "Probabilistic Analysis of Initiation and Early Growth of Stress Corrosion Cracks in BWR Piping," *1986 ASME PVP Conference*, 86-PVP-11.

Application of PWSCC Initiation Test Data

Relative Susceptibility Factor Approach to Crack Initiation Modeling

- Corrections for Differences in
  - Material Cracking Susceptibility
  - Operating Temperature
  - Surface Stresses
  - Fabrication Methods
  - Plant Water Chemistry

$$F(t) = 1 - e^{-\left(\frac{t}{\theta}\right)^b} \qquad \theta = \frac{\theta_{ref}}{RSF}$$

$$RSF = \left(\frac{f_{chem}}{f_{chem,ref}}\right)\left(\frac{f_{fab}}{f_{fab,ref}}\right)\left(\frac{f_{mat}}{f_{mat,ref}}\right)\left(\frac{s_{sur}}{s_{sur,ref}}\right)^x \exp\left[-\frac{Q_i}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right]$$

RSF	=	relative susceptibility factor for scaling θ or equivalently operating time t
f_{chem}	=	water chemistry factor
f_{fab}	=	fabrication factor
f_{mat}	=	material factor
s_{sur}	=	maximum surface stress including residual and operating stresses
x	=	stress exponent
Q_i	=	apparent activation energy for crack initiation (kJ/mole)
R	=	gas constant = 8.314×10^{-3} kJ/mole-K
T	=	absolute operating temperature (K)

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Screening Process for Laboratory PWSCC Crack Growth Data

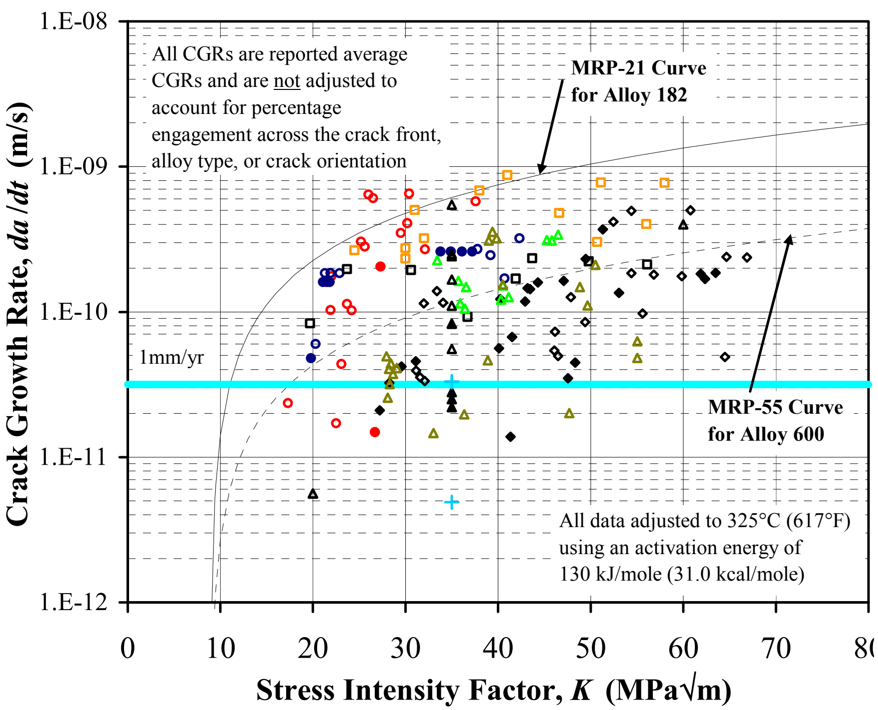
Screening for Lab Crack Growth Data

Introduction

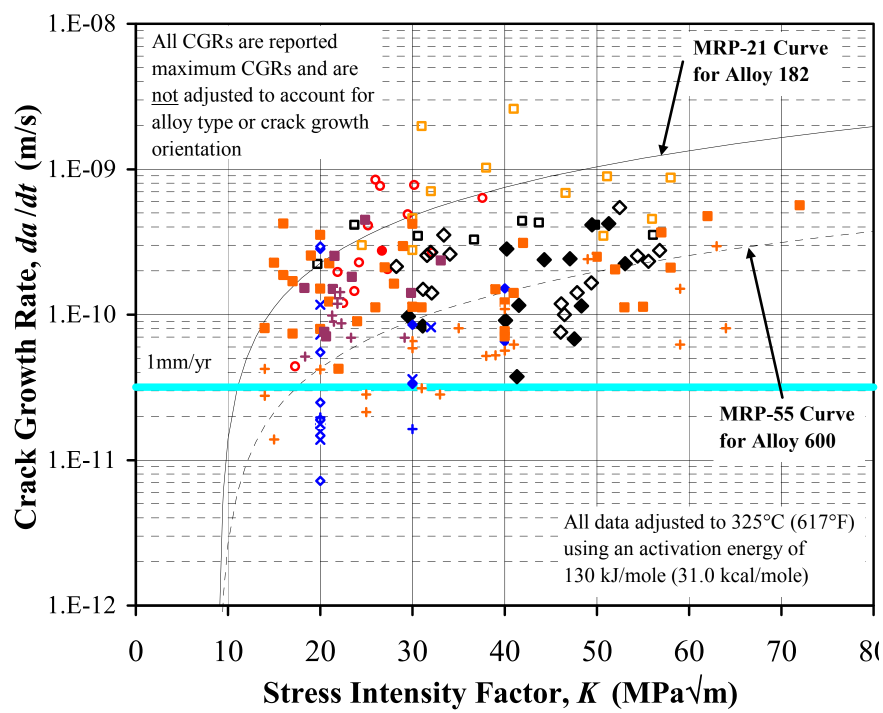
- Greater standardization of PWSC crack growth rate testing practices would have two key benefits:
  - Reduce scatter in test data from different labs
  - Reduce the amount of lab data screened out from statistical evaluations used to develop disposition curves
- As a case study, the following slides describe the screening process applied to worldwide laboratory PWSCC crack growth data for Alloy 82/182/132 to develop the MRP-115 disposition equation

Screening for Lab Crack Growth Data

Unscreened CGR Data for Alloys 82/182/132



Complete worldwide results for AVERAGE CGR (144 points)



Complete worldwide results for MAXIMUM CGR (158 points)

Decision was made to use average CGR data (as in MRP-55)

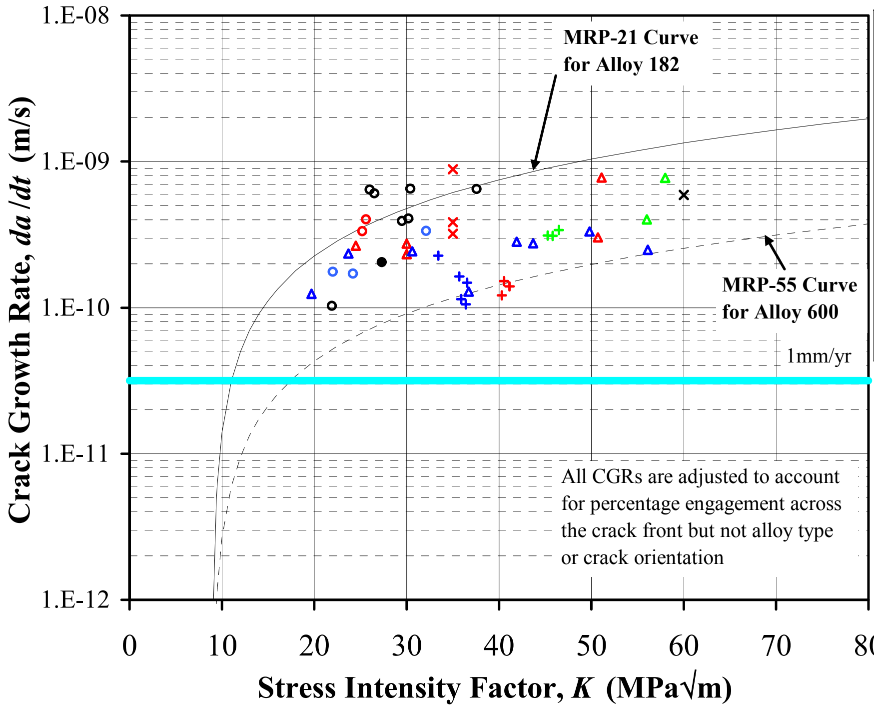
Screening for Lab Crack Growth Data

Key Data Screening Issues

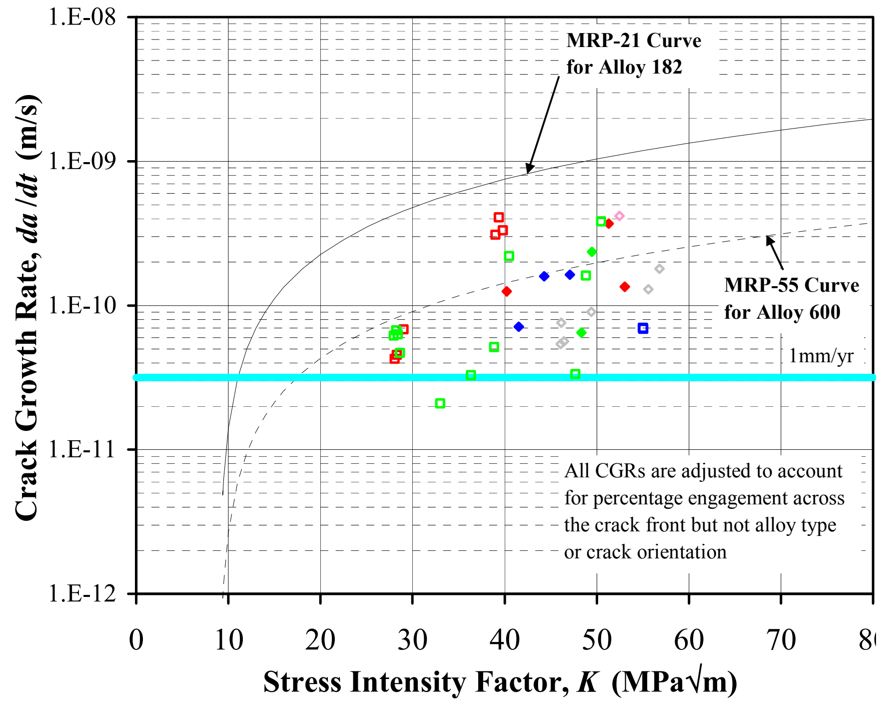
- Material within specifications including composition/condition/heat treatment
- Mechanical strength properties
- ASTM specimen size criteria and degree of plastic constraint
- Pre-cracking technique (inc. straightness criteria, plastic zone size, crack morphology)
- Special requirements for testing welds (e.g. pre-crack location, residual stresses/strains)
- Environment (chemistry, temperature, electrochemical potential (ECP), flow rate at specimen, neutron/gamma flux)
- Loop configuration (e.g., once-through, refreshed, static autoclave)
- Water chemistry confirmation by analysis (e.g., Cl, SO_4, O_2, Cr, total organic carbon (TOC), conductivity)
- Active constant or cyclic loading vs. constant displacement loading (e.g., using wedge)
- On-line measurement of crack length versus time during test (including precision)
- Actual crack length confirmed by destructive examination (assessment method/mapping)
- Appropriateness of crack characteristics (fraction SCC along crack front, uniformity, adequate SCC increment, transgranular portions within IGSCC fracture surface, etc.)
- Possible effects of changes in loading or chemistry conditions during a test (including heat up and cool down)
- Calculation and reporting of K or ΔK values
- Reporting of raw a vs. t data and derivation of da/dt values
- Reproducibility of data under nominally identical test conditions

Screening for Lab Crack Growth Data

Screened CGR Data for Alloys 82/182/132



Average CGR data for Alloys 182/132 after screening (43 points)



Average CGR data for Alloy 82 after screening (34 points)

Note the absence of results at K-values < 20 (A182) & < 28 MPa√m (A82)

Screening for Lab Crack Growth Data

Reasons for Data Exclusion for MRP-115 Study for Alloy 82/182/132

- Original set of worldwide laboratory CGR data comprised 261 individual data points.
- 184 data points were excluded from the statistical evaluation for the following objective reasons:
  - reported CGR based only on the maximum crack increment along the crack front because the MRP data reduction was based on the average crack extension (95 points),
  - no measurable crack growth (24 points),
  - less than 0.5 mm of crack extension averaged along the crack front (23 points),
  - hold time less than 1 hour for periodic unloading tests (18 points),
  - complex loading changes during the test (16 points),
  - hydrogen concentration outside standard plant range (12 points with 150 cc/kg),
  - loading exceeding the nominal linear elastic fracture mechanics (LEFM) limit (9 points),
  - engagement to intergranular (i.e., stress corrosion) cracking along less than 50% of the crack front (4 points),
  - flutter loading (2 points), and
  - temperature change during the test (1 point)
- For 20 of the excluded data points, two of the above reasons applied. However, the data excluded because only maximum CGRs were available were not evaluated for compliance with the screening criteria regarding minimum average crack extension and minimum engagement to intergranular cracking.

Screening for Lab Crack Growth Data

Lessons Learned

- Greater standardization of PWSC crack growth rate testing practices (test methods, test parameter control, data reduction, and data reporting) will have the benefit of reducing the extent of data exclusion from statistical evaluations used to apply laboratory data to plant analyses
  - Larger screened database will result in more reliable statistics
- Agreement on data reduction methods is not necessary as long as sufficient data are available for a common data reduction method to be applied later
- A test standard or guidelines document would be valuable for further defining key data screening issues
- In some cases, data exclusion is due to purposeful investigation of conditions outside normal range
  - E.g., environmental fatigue testing, K outside LEFM, off water chemistry conditions

Screening for Lab Crack Growth Data

Published Reports and Papers

- Thick-Section Alloy 600 Wrought Material
  - MRP-55 (EPRI 1006695) was published in proprietary and non-proprietary forms in 2002.
  - G. A. White, J. Hickling, and L. K. Mathews, "Crack Growth Rates for Evaluating PWSCC of Thick-Wall Alloy 600 Material," *11th International Symposium on Environmental Degradation of Materials in Nuclear Power Systems—Water Reactors* (Stevenson, WA, August 11–14, 2003), ANS, La Grange Park, Illinois, 2003.
- Alloy 82/182/132 Weldments
  - MRP-115 (EPRI 1006696) was published in proprietary and non-proprietary forms form in 2004/2005.
  - G. A. White, N. S. Nordmann, J. Hickling, and C. D. Harrington, "Development of Crack Growth Rate Disposition Curves for Primary Water Stress Corrosion Cracking (PWSCC) of Alloy 82, 182, and 132 Weldments," *12th International Symposium on Environmental Degradation of Materials in Nuclear Power Systems* (Salt Lake City in August 2005), TMS, 2005.