Update of NUREG/CR-6909 Methodology for Environmentally Assisted Fatigue (EAF) - Revised F_{en} Expressions

Omesh Chopra and Yogen Garud (ANL)
Gary Stevens (NRC/RES)

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Section III Subgroup on Fatigue Strength
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Objectives

- The objective of this presentation is to summarize all issues identified and discussed to-date by the NRC and ANL that are being addressed as a part of NRC's EAF research activities, and to provide a status of those issues and the related activities.

- NRC/ANL will be wrapping up all EAF research activities later this year; final comments and input from interested stakeholders is welcomed prior to September 2012.

Outline

- Background Information
- Fatigue Life – Definition
- Revised F_{en} Expressions
- Strain Amplitude Threshold
- F_{en} Validation Calculations
- Possible Mechanisms of Fatigue Crack Initiation
- Responses to Comments Received on F_{en} Validation Calculation Spreadsheet
- NRC Positions on EAF Code Cases
- Summary
- Next Steps

- Backup Slides – Detailed Comments Received on NRC Spreadsheet Calculations

Background Information

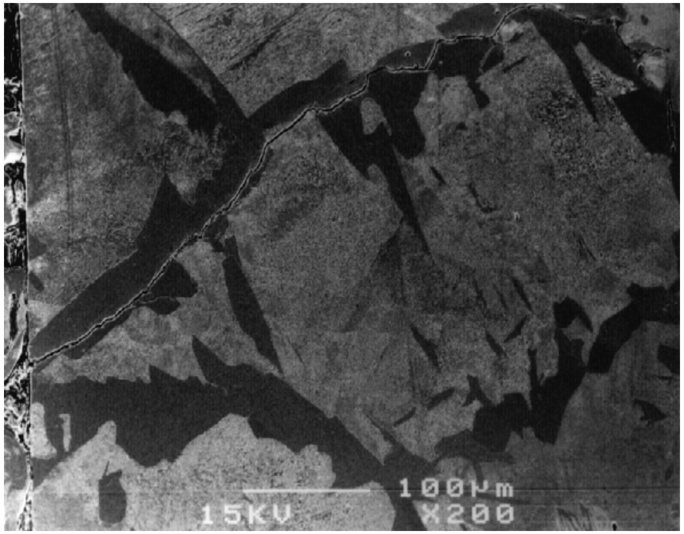
Issue – Environmental Effects on Fatigue Life or Environmentally Assistant Fatigue (EAF)

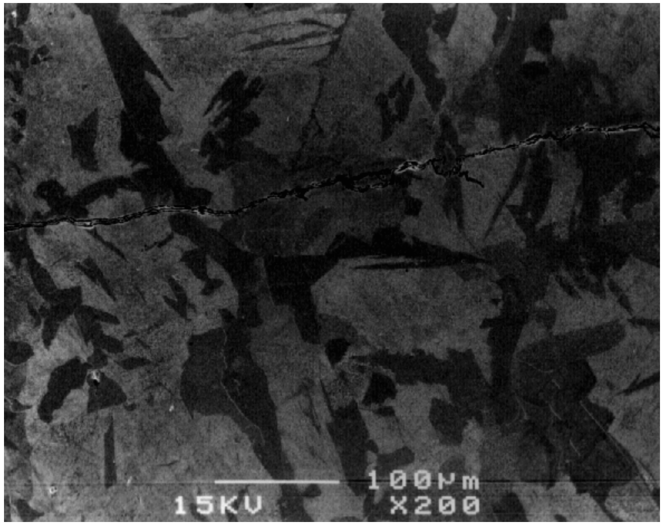
- Fatigue data indicate significant effects of LWR environment
- Data are consistent with each other and with much larger database for fatigue crack growth rates (CGRs or da/dN):
  - In LWR environments, effects of material, loading, and environmental parameters are similar for fatigue ε-N and CGR data
- Fatigue ε-N (S-N) data have been evaluated to:
  - identify key parameters that influence fatigue life
  - define ranges for these parameters where environmental effects are significant, i.e., establish threshold and saturation values
- If these conditions exist during reactor operation, environmental effects will be significant and must be addressed
  - Paragraph NB-3121, "Corrosion," recognizes that the data used to develop the fatigue design curves did not include "environmental effects" that might accelerate fatigue failure and requires that provisions be made for these effects

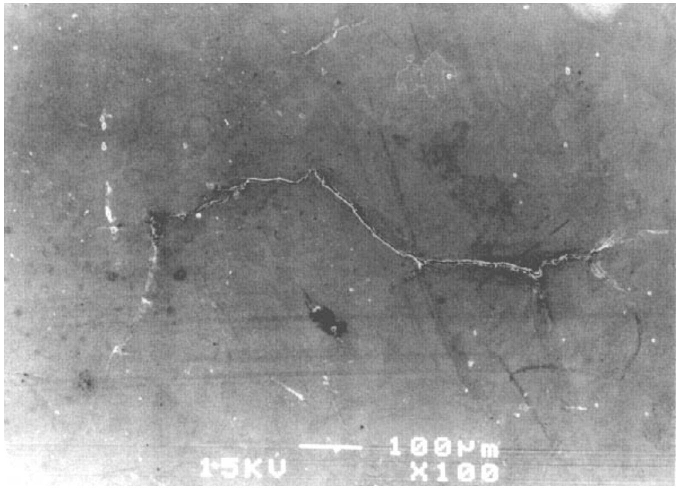
Fracture Behavior in Air and Water Environments

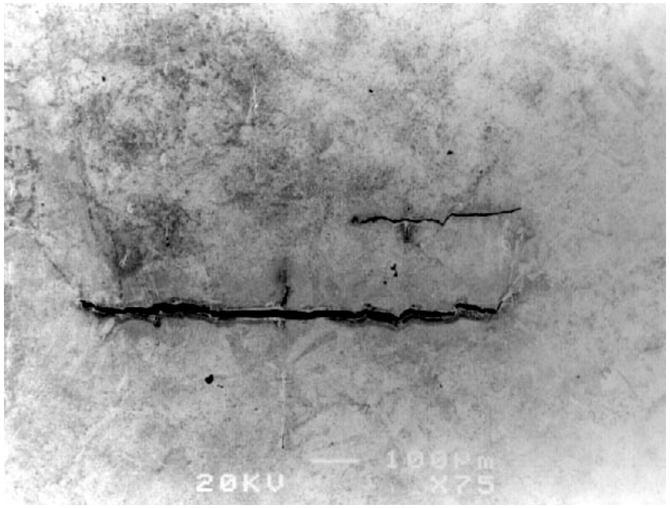
Air

High-DO Water









EAF – Historical Perspective

- Since the late 1980s, NRC staff have been involved in discussions with ASME Code committees, PVRC, and others in the technical community to address issues related to environmental effects on fatigue
- 1991, ASME BNCS requested the PVRC to examine worldwide fatigue strain vs. life data and develop recommendations
- 1995, resolution of GSI-166 established that:
  - Risk to core damage from fatigue failure of RCS very small; no action required for current plant design life of 40 years
  - NRC staff concluded that fatigue issues should be evaluated for extended period of operation for license renewal (under GSI-190)
- 1999, GSI-190, Fatigue Evaluation of Metal Components for 60-Yr Plant Life
  - 10 CFR 54.21, Aging Management Programs for license renewal should address component fatigue including the effects of coolant environment

EAF – Historical Perspective (Contd.)

- December 1, 1999, by letter to the Chairman of the ASME BNCS, the NRC requested ASME to revise the Code to include environmental effects in the fatigue design of components
- ASME initiated the PVRC Steering Committee on Cyclic Life and Environmental Effects
- PVRC recommended revising Code design fatigue curves (WRC Bulletin 487)
- Multiple ASME Task Groups on Environmental Fatigue could not reach consensus after years of deliberation concerning the recommended methods and approaches to resolve concerns regarding EAF under LWR conditions
- 2005, NRR requested RES to develop an NRC position on EAF:
  - Develop guidance for determining the acceptable fatigue life of ASME pressure boundary components, with consideration of the LWR environment
  - For use in supporting reviews of applications that the agency expects to receive for <u>new reactors</u> (i.e., NRC Regulatory Guide RG 1.207)

EAF – Historical Perspective (Contd.)

- ~2008, Section III Subcommittee on Design developed a plan for addressing EAF in Section III; to-date has published 2 Code Cases (N-761 and N-792) with two others (strain rate and flaw tolerance) under development
- 2010, NRR requested RES to perform additional research:
  - Review Code Cases
  - Revise F_{en} equations considering new available data and issues raised by industry
  - Address issues that arise in reviews of applications that the agency receives for license renewal applications and new reactors
  - Revise NUREG/CR-6909 and Regulatory Guide RG 1.207, as appropriate

Methodology for Incorporating Environmental Effects

- Initially, the NRC reviewed two methods for incorporating LWR effects; the second method was adopted :
  - 1. Develop new environmental fatigue curves
  - 2. Use of an environmental correction factor, F_{en}
- F_{en} is defined as the ratio of fatigue life in air at room temperature to the fatigue life in water under service conditions:

$$F_{en} = N_{air}/N_{water}$$

- F_{en} is multiplicative to the calculated fatigue usage in air:

$$U_{en} = U_1 F_{en,1} + U_2 F_{en,2} ..... U_n F_{en,n}$$

Fatigue Life - Definition

Fatigue Life – Definition

- In ASME Section III Appendix I, fatigue life N_f is defined as cycles to failure; ASTM Designation E 1823-09 "Standard Terminology," N_f is defined as: "the number of cycles that a specimen sustains before failure."
- ASTM Designation E 606-04, Section 8.9 "Determination of Failure," determination of failure may vary with the use:
  - Separation: total separation or fracture of the specimen
  - Modulus method: ratio of unloading modulus to loading modulus is 0.5
  - Force drop: decrease in max. force or elastic modulus by approximately 50%
- Current test practice defines N_f of test specimens by 25% load drop; typically, this corresponds to a ≈3 mm ("engineering") crack
- The Code design fatigue curves were obtained by first adjusting the best-fit of strain-cycling test data for mean stress effects, and then shifting the adjusted curves by factors of 20 on cycles and 2 on stress
- The factors of 2 and 20 are <u>not</u> factors of safety; rather, they are intended to adjust small, polished test specimen data to make it applicable to actual components

Fatigue Life – Definition (Contd.)

- In other words, these factors were used to account for the effects of variables that can influence fatigue life but were not investigated in the tests that provided the data for developing the ASME Code design curves
- These variables are broadly classified into the following groups (see WRC Bulletin 487 and Section III Criterion Document):
  - Material variability and data scatter (heat-to-heat variation and data scatter)
  - Size effect (component size relative to a small test specimen)
  - Surface finish (industrial-grade surface finish compared to polished specimen)
  - Loading history (constant strain tests compared to variable strain loading)
- Factors on life applied to best-fit of test data to account for these variables:

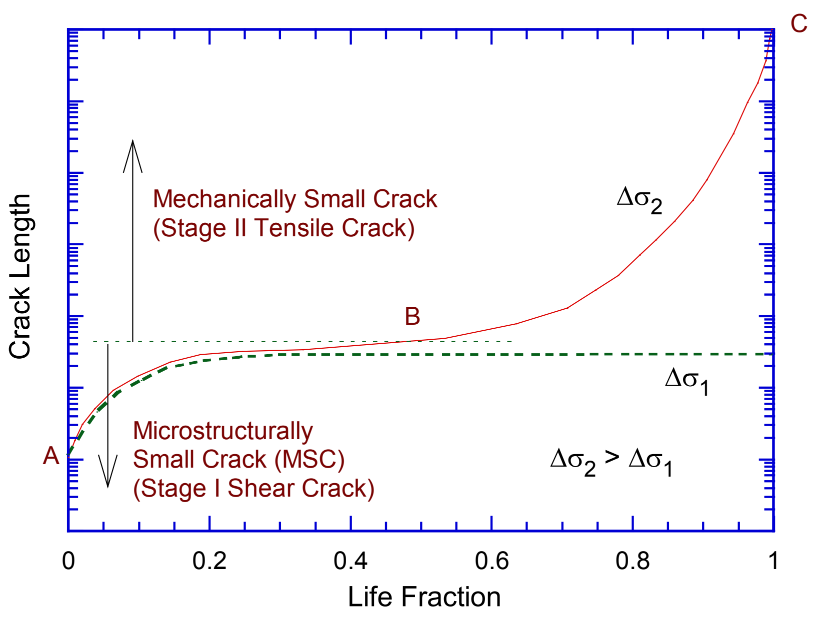
	Criterion Doc.	NUREG/CR-6909
– Material variability and scatter	2.0	2.1 – 2.8
– Size effect	2.5	1.2 – 1.4
– Surface finish	4.0	2.0 – 3.5
– Loading history	-	1.2 – 2.0
– Total	20	6.0 – 27.4

Fatigue Life – Definition (Contd.)

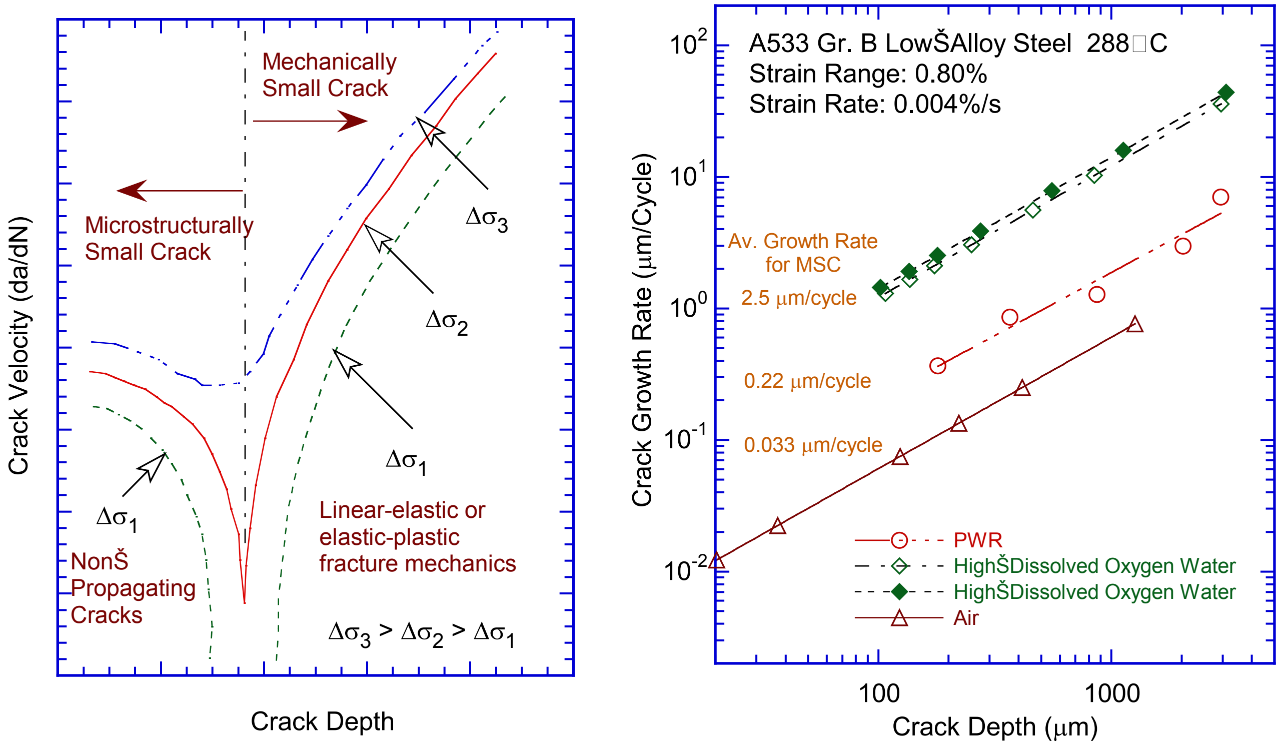
- From W. E. Cooper's document:
  - failure in test data represents a 3/16" (4.8 mm) visual crack or about 1.5-mm deep
  - *"The available test data (7.1) indicate that the actual factor of safety on cycles probably ranges between one and five, with a mean value of about three. Since these data defined failure as the appearance of about 3/16" visual crack, this should be considered a factor of safety on initiation - not on failure."*
- Cooper's "factor of safety" is often used to account for environmental effects
- In NUREG/CR-6909, this "factor of safety" was determined to be 1.7 (= 20/12), and was incorporated in the development of the revised fatigue air curves.
- NUREG/CR-6909 air design curves (Figs. A.1, A.2, & A.3) were obtained by applying a factor of 2 on strain & factor of 12 on life (instead of 20)
  - from NUREG/CR-6909, a factor of 12 on life bounds 95% of the data
  - selection of a 95^{th} percentile bound is based on engineering judgment; it is made with the understanding that design curve controls fatigue initiation, not failure

Fatigue Life – Definition (Contd.)

- Regardless of whether fatigue life is defined as "initiation" or "failure," it consists of two stages:
  - Initiation: growth of micro-structurally small cracks, < 300 μm
  - Propagation: growth of mechanically small cracks, 300-3,000 μm (EPFM)
- Surface cracks ≈10 μm deep form very early during fatigue loading
- Most of the fatigue life (including high-cycle fatigue) is associated with growth of cracks; 10 to 3,000 μm (or the final crack size that is believed to represent fatigue life)

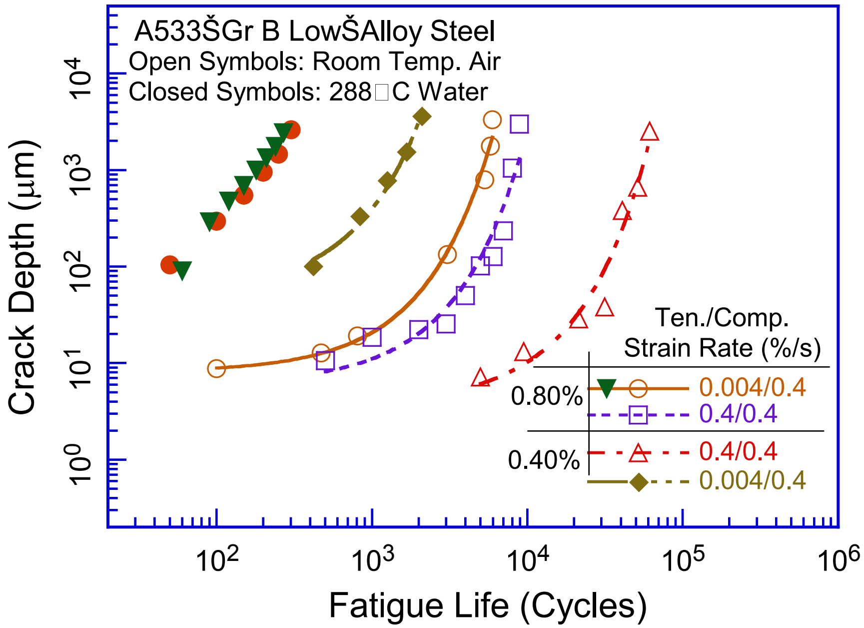


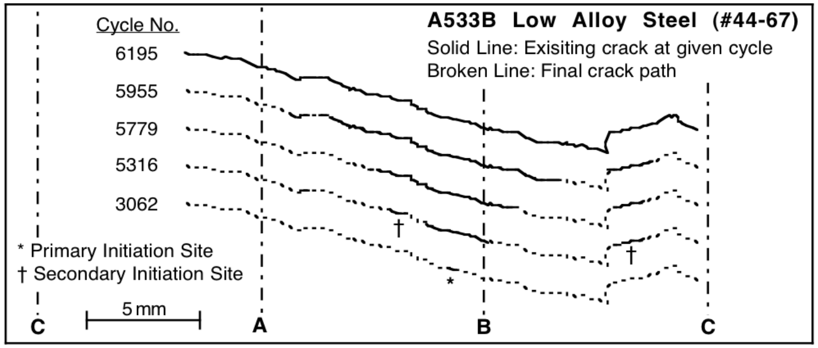
Fatigue Life – Definition (Contd.)

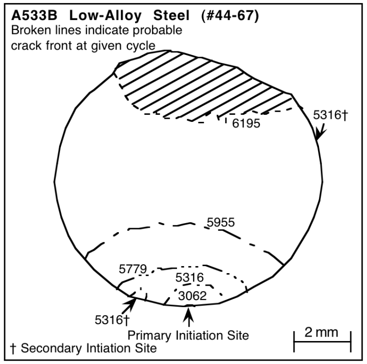


- Environment affects both stages: initiation and propagation
- Environmental effects on fracture mechanics controlled-growth are widely recognized
- ε-N data indicate effects on growth of micro-structurally small cracks may be even greater

Crack Initiation & Growth Characteristics



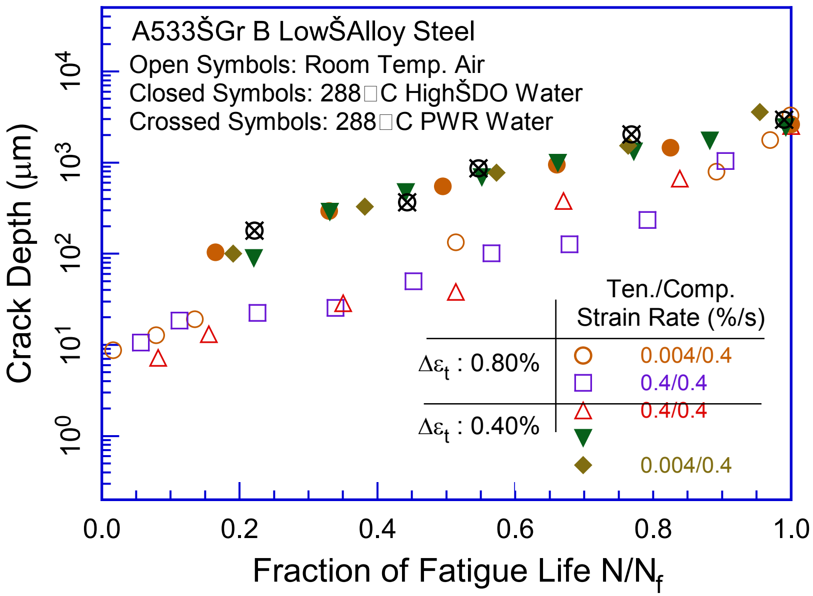


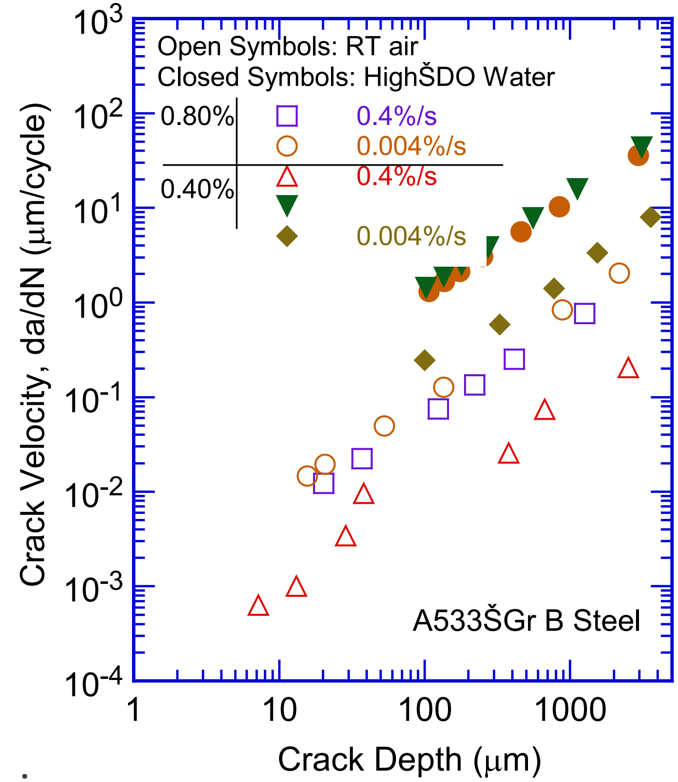


- Experimental data have been obtained on effect of LWR environments on growth of micro-structurally-short cracks & mechanically-short cracks
- Both the growth of micro-structurally & mechanically small cracks are influenced by water environment
- Effects on growth of micro-structurally small cracks are greater

Data from Gavenda et al., Fatigue & Fracture 1, Vol. 350, ASME 1997

Crack Initiation & Growth Characteristics (Contd.)





- Crack growth rates in high–DO water are nearly two orders of magnitude higher than in air for crack sizes <100 mm, & one order of magnitude higher for crack sizes >100 mm
- In high–DO water, surface cracks grow entirely as tensile cracks normal to stress axis
- In air & low–DO water, growth of surface cracks occurs initially as shear cracks ≈45° to the stress axis, and then as tensile cracks normal to the stress axis

Data from Gavenda et al., Fatigue & Fracture 1, Vol. 350, ASME 1997

Revised F_{en} Expressions

Updated Experimental Fatigue S-N Database

- Carbon Steels: EAF data total 625 data points (increase of 269 points over that used for RG 1.207)
  - 6 types of steels (A106-B, A106-C, A333-6, A226, A516, A508-1)
  - 18 different heats
- Low-Alloy Steels: EAF data total 585 data points (increase of 223 points over that used for RG 1.207)
  - 6 types of steels (A302-B, A533-B, A508-2, A508-3, 15MnNi63, 17MnMoV63)
  - 16 different heats
- Austenitic Stainless Steels: EAF data total 597 data points (increase of 255 points over that used for RG 1.207)
  - 6 types of wrought and cast SSs (Type 304, 304L, 316, 316NG, CF-8, and CF-8M)
  - 26 different heats
- Nickel Alloys: EAF data total 162 data points (increase of 58 points over that used for RG 1.207)
  - 6 types of alloys (A600 and A690, and A182, A82, A132, and A152 weld metals)
  - 13 different heats

Applicable ASTM Standards for Fatigue S-N Data

- E 606: Practice for Strain-Controlled Fatigue Testing
- E 466: Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials
- E 468: Practice for Presentation of Constant Amplitude Fatigue Test Results for Metallic Materials
- E 739: Practice for Statistical Analysis of Linear or Linearized Stress-Life (S-N) of Stain-Life (ε-N) Fatigue Data
- E 1012: Practice for Verification of Specimen Alignment Under Tensile Loading
- E 1823: Terminology Relating to Fatigue and Fracture Testing
- Richard C. Rice, "*Fatigue Data Analysis*," Metals Handbook, Vol. 8, ASM 1985 pp. 695-720

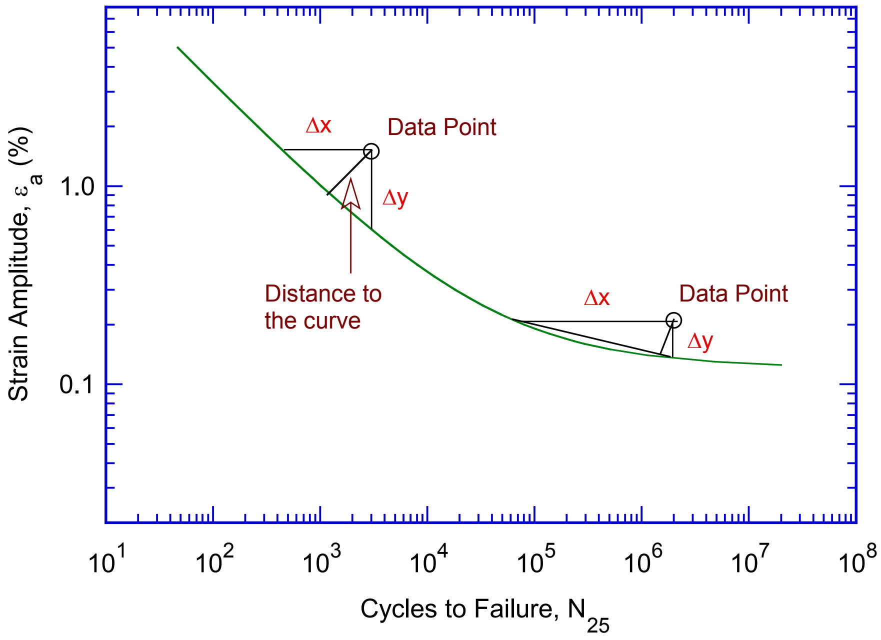
Method for Best Fit of Experimental Data

- Fatigue strain amplitude (ε_a) vs. life (N_{25}) data are expressed as:

  $$\ln(N_{25}) = A - B \ln(\varepsilon_a - C)$$

- Constants determined from a best-fit of the fatigue S-N data

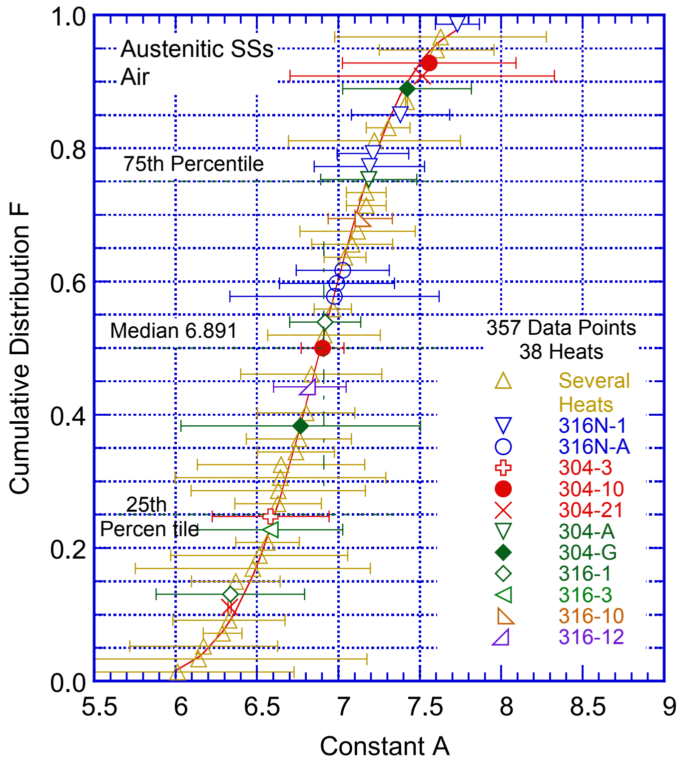
NUREG/CR-6335 (1995) gives rigorous statistical analysis to estimate probability of initiating a fatigue crack



- Ideally, a best-fit of the experimental data should be determined for:
  - low-cycle fatigue by minimizing the error in life
  - high-cycle fatigue by minimizing the error in strain
- In the present study, a best-fit of the experimental S-N data is determined by minimizing the error in the distance between the data point and the curve
- However, both of these analyses may be biased depending on the heats of material used in obtaining the fatigue S-N data

Estimated Cumulative Distribution of Constant A for Various Types of Stainless Steels and Heats

- In NUREG/CR-6909, the constant A in the best-fit curve of fatigue S-N data was determined from the cumulative distribution curve of constant A
- As mentioned earlier, a best-fit of the fatigue S-N data may yield biased results depending on the heats of material used in the analysis
- Estimated fatigue lives will be longer if a majority of the data are for Heats 304-10 and 304-G, and will be shorter if a majority of the data are for Heats 304-21 and 316-1
- For accurate estimates of environmental effects on fatigue life, the data used in developing the F_{en} expressions should be representative of the materials, loading, and environmental conditions observed in service



NUREG/CR-6909 F_{en} Expressions - Carbon and Low-Alloy Steels

- Carbon steel: $F_{en} = \exp[0.632 - 0.101\ S^*T^*O^*R^*]$
- Low-alloy steels: $F_{en} = \exp[0.702 - 0.101\ S^*T^*O^*R^*]$
  - $S^* = 0.001$ $(S \leq 0.001$ wt.%)
    $S^* = S$ $(S \leq 0.015$ wt.%)
    $S^* = 0.015$ $(S > 0.015$ wt.%)
  - $T^* = 0$ $(T < 150^\circ C)$
    $T^* = (T - 150)$ $(150 < T \leq 350^\circ C)$
  - $O^* = 0$ (DO $\leq$ 0.04 ppm)
    $O^* = \ln(DO/0.04)$ (0.04 < DO , 0.5 ppm)
    $O^* = \ln(12.5)$ (DO > 0.5 ppm)
  - $R^* = 0$ (R > 1%/s)
    $R^* = \ln(R)$ $(0.001 \leq R \leq 1\%/s)$
    $R^* = \ln(0.001)$ (R < 0.001%/s)
- Input received from stakeholders has focused on the constants in these expressions, which results in an F_{en} of ≈2 even at temperatures below 150° C and very high strain rates; this seems inconsistent with any mechanism proposed for environmental fatigue
- The maximum temperature limit should be 300° C (not 350° C), as there are no data above 300° C

NUREG/CR-6909 F_{en} Expressions - Austenitic Stainless Steels

- Wrought and cast SSs: $F_{en} = \exp[0.734 - T' O' R']$
  - $T' = 0$ $(T < 150^{\circ}\text{C})$
    $T' = (T - 150)/175$ $(150 < T \leq 325^{\circ}\text{C})$
    $T' = 1$ $(T \geq 325^{\circ}\text{C})$
  - $O' = 0.281$ (all DO levels)
  - $R' = 0$ $(R > 0.4\%/s)$
    $R' = \ln(R/0.4)$ $(0.0004 \leq R \leq 0.4\%/s)$
    $R' = \ln(0.001)$ $(R < 0.0004\%/s)$

- Once again, input from stakeholders has focused on the constant in the F_{en} expression
- A F_{en} of ≈ 2 even at temperatures below 150°C and very high strain rates seems inconsistent with any mechanism proposed for environmental fatigue
- Also, the above expression yields conservative estimates of F_{en} for some materials in high-DO environments, e.g., for low-C wrought SSs or non-sensitized high-C wrought SSs

Best-Fit Curves for Test Specimen S-N Data

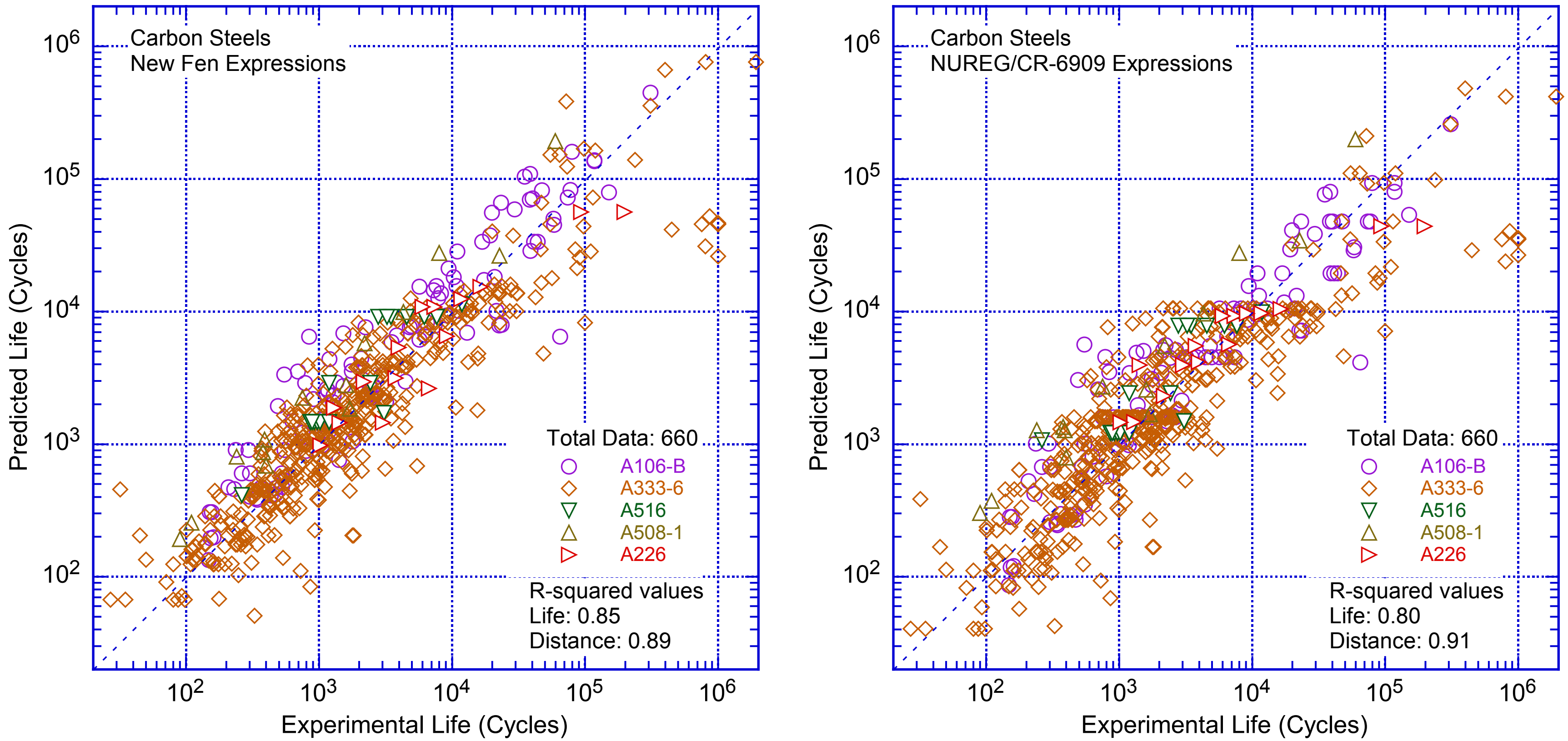
- NUREG/CR-6909:
  - Carbon Steels: 6.583 -1.975 ln(ε_a – 0.113)
  - Low-Alloy Steels: 6.449 -1.808 ln(ε_a – 0.151)
  - Stainless Steels: 6.891 -1.920 ln(ε_a – 0.112)
- ASME Code:
  - Carbon Steels: 6.726 -2.000 ln(ε_a – 0.072)
  - Low-Alloy Steels: 6.339 -2.000 ln(ε_a – 0.128)
  - Stainless Steels: 6.954 -2.000 ln(ε_a – 0.167) (2008 and earlier editions)
- JNES*:
  - Carbon Steels: 6.626 -2.041 ln(ε_a – 0.113)
  - Low-Alloy Steels: 6.493 -1.779 ln(ε_a – 0.155)
  - Stainless Steels: 6.861 -2.188 ln(ε_a – 0.110)
  - Ni-Cr-Fe Alloys: 6.543 -2.222 ln(ε_a – 0.118)

* JNES Report No. JNES-SS-1005, "Nuclear Power Generation Facilities Environmental Fatigue Evaluation Method for Nuclear Power Plants," March 2011, available at http://www.jnes.go.jp/gijyutsu/seika/ss_genshi.html.

Revised F_{en} Expressions - Carbon and Low-Alloy Steels

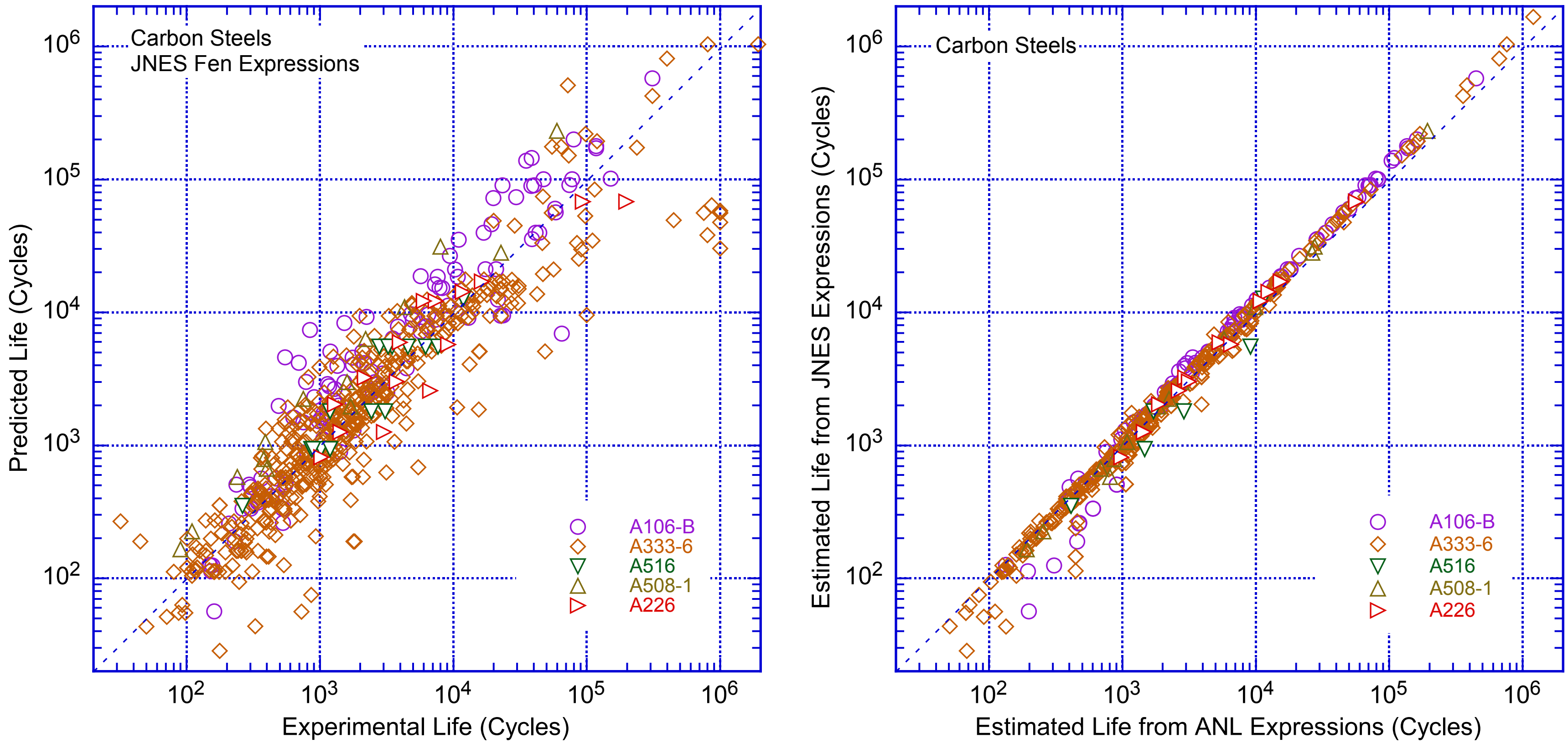
- CSs and LASs: $F_{en} = \exp[(0.003 - 0.031R^*) S^*T^*O^*]$
  - $S^* = 2.0 + 98\,S$ $(S \le 0.015\ \text{wt.\%})$
    $S^* = 3.47$ $(S > 0.015\ \text{wt.\%})$
  - $T^* = 0.395$ $(T < 150^\circ\ \text{C})$
    $T^* = (T - 75)/190$ $(150 < T \le 325^\circ\ \text{C})$
    $T^* = 1.316$ $(T \ge 325^\circ\ \text{C})$
  - $O^* = 1.49$ $(DO < 0.04\ \text{ppm})$
    $O^* = \ln(DO/0.009)$ $(0.04 \le DO \le 0.5\ \text{ppm})$
    $O^* = 4.02$ $(DO > 0.5\ \text{ppm})$
  - $R^* = 0$ $(R > 2.2\%/\text{s})$
    $R^* = \ln(R/2.2)$ $(0.001 \le R \le 2.2\%/\text{s})$
    $R' = \ln(0.001/2.2)$ $(R < 0.001\%/\text{s})$
- CSs and LASs: $F_{en} = 1$ (strain amplitudes $\le 0.07\%$)
- There is a single expression for both carbon steels and low-alloy steels and parameters S*, T*, O*, and R* have been modified
- A strain rate threshold is included at 2.2%/s above which F_{en} is 1.0; this eliminates the issue with the constants in the previous expressions
- Maximum temperature limit set to 325° C (vs. 300° C) as a reasonable extension to cover all operating conditions

Measured and Predicted Fatigue Life - CSs



- The new expression yields a comparable or slightly better fit of the data compared to the NUREG/CR-6909 expressions
- For A106-B carbon steel in low-DO environments, NUREG/CR-6909 and the new expressions both predict greater fatigue lives than the measured values

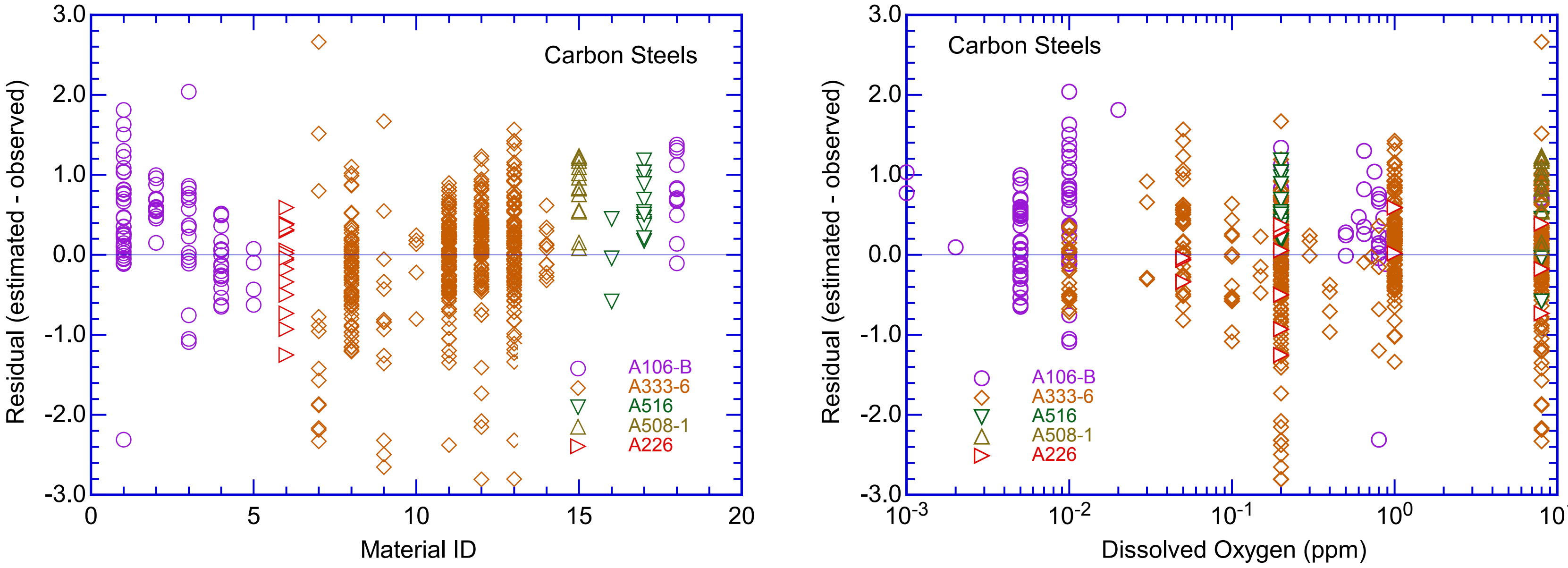
Measured and Predicted Fatigue Life - CSs



- Relative to JNES estimates*, fatigue lives from the new expression are comparable in the low-cycle regime and are marginally smaller in the high-cycle regime
- Few data with poor fit represent conditions typically not observed in service; $F_{en} > 25$

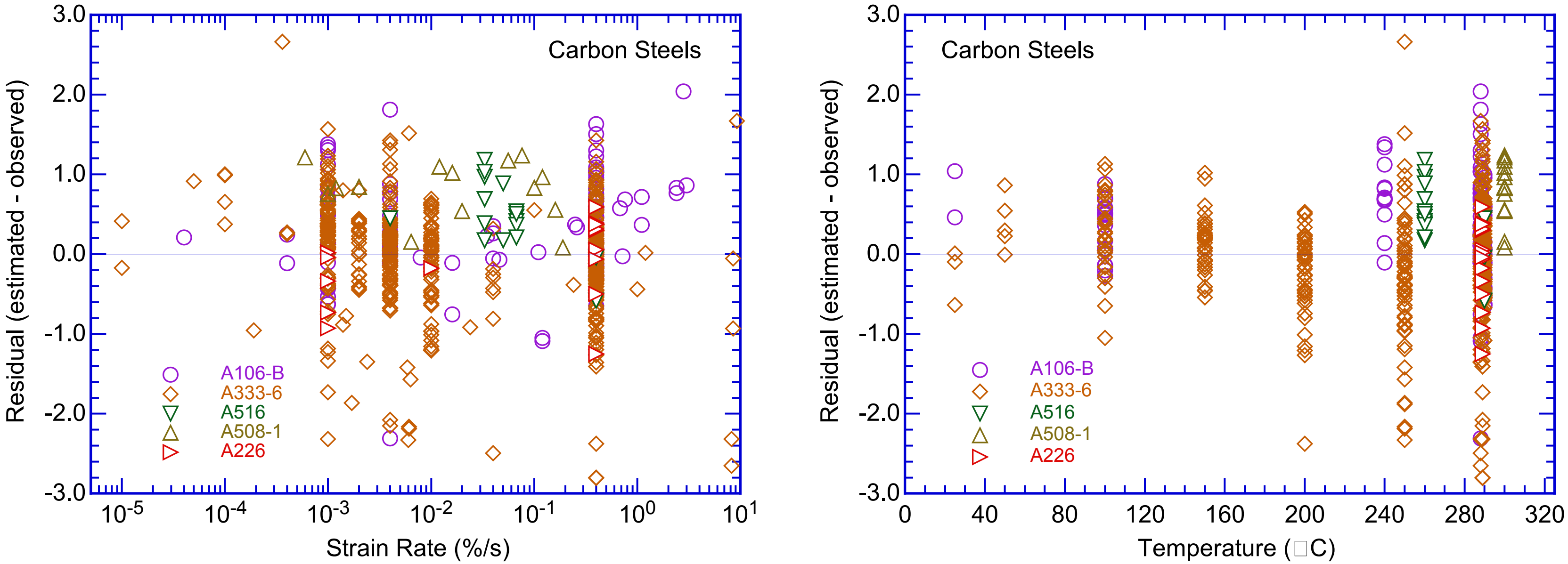
* Using expressions from JNES Report No. JNES-SS-1005.

Residuals vs. Material ID and Dissolved Oxygen - CSs



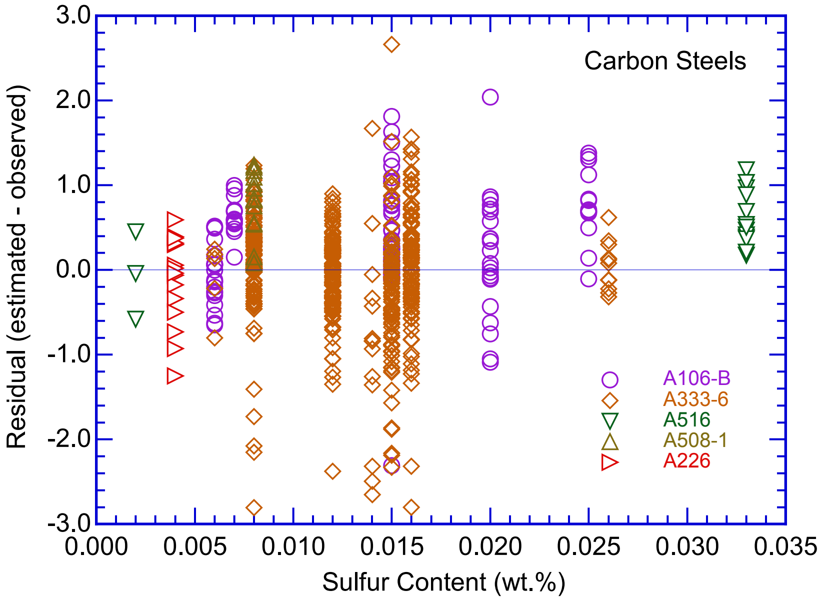
- "Positive residuals" means estimated fatigue life is greater than observed fatigue life (i.e., non-conservative estimate, maybe under predicting environment effects); "negative residuals" means conservative estimates of life
- Residuals for a few heats (e.g., IDs #1, 2, 15, 17 and 18) are mostly positive
- Data evenly distributed for all DO levels

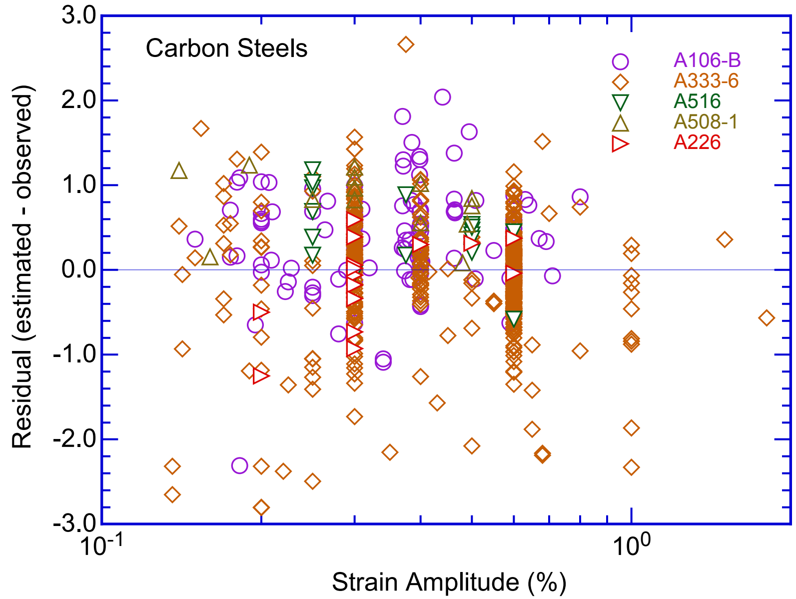
Residuals vs. Strain Rate and Temperature - CSs



- Most of the data are evenly distributed about the mean
- Few exceptions are very low strain rates (<10^{-4} %/s) and temperatures (25 & 50° C)

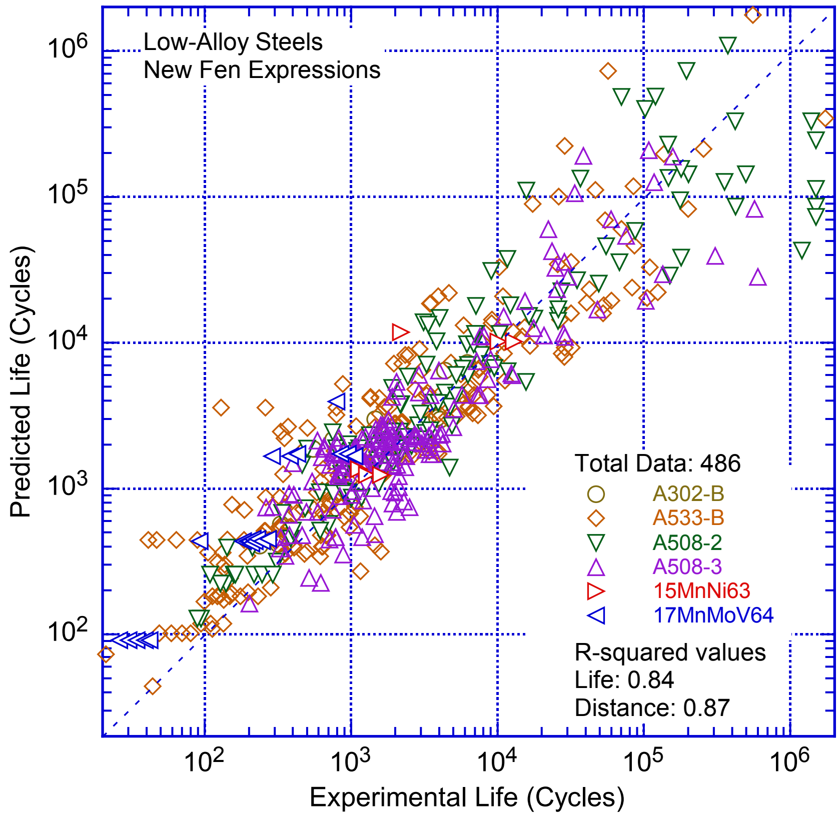
Residuals vs. Sulfur and Strain Amplitude - CSs

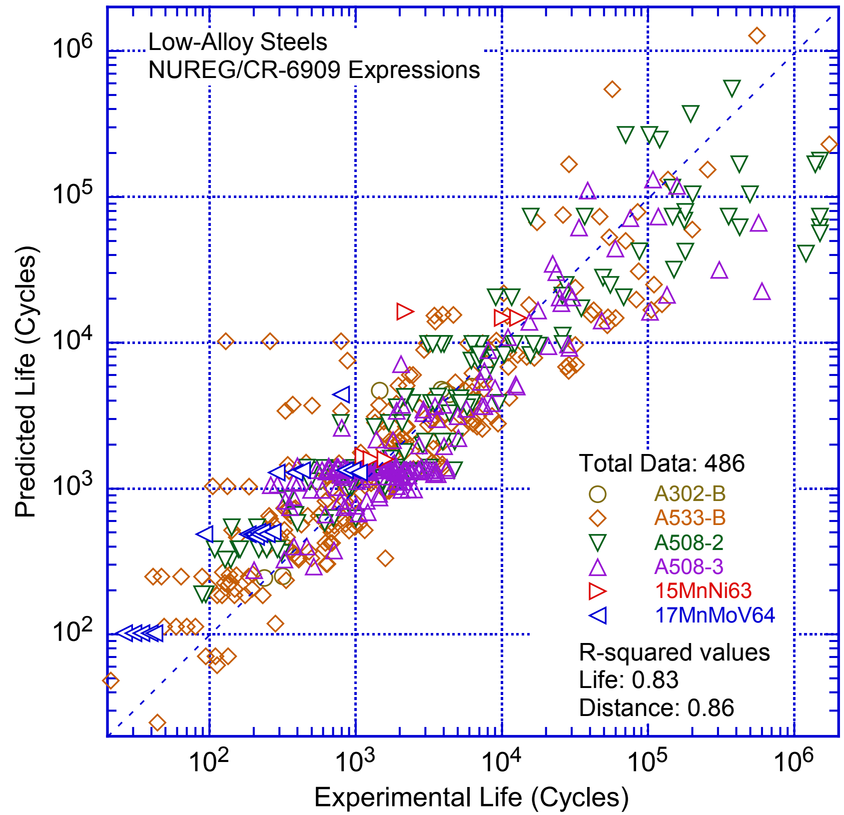




- Most of the data are evenly distributed about the mean
- The few materials with non-conservative estimates include:
  A516 with 0.033 wt.% S; A508-1 in 8 ppm DO; and A106-B with 0.025 wt.% S

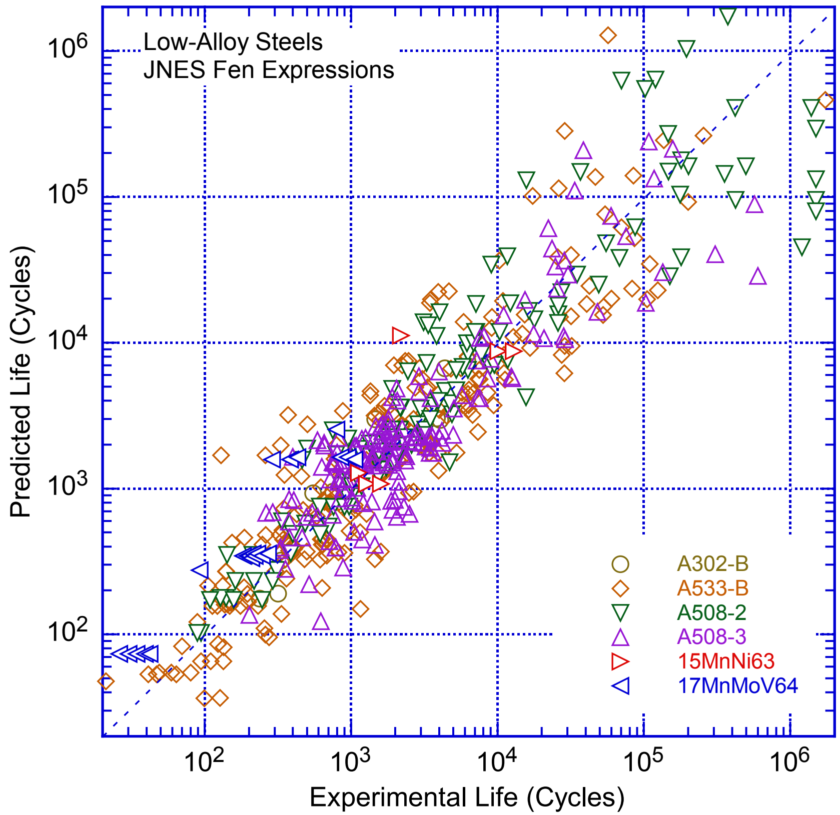
Measured and Predicted Fatigue Life - LASs

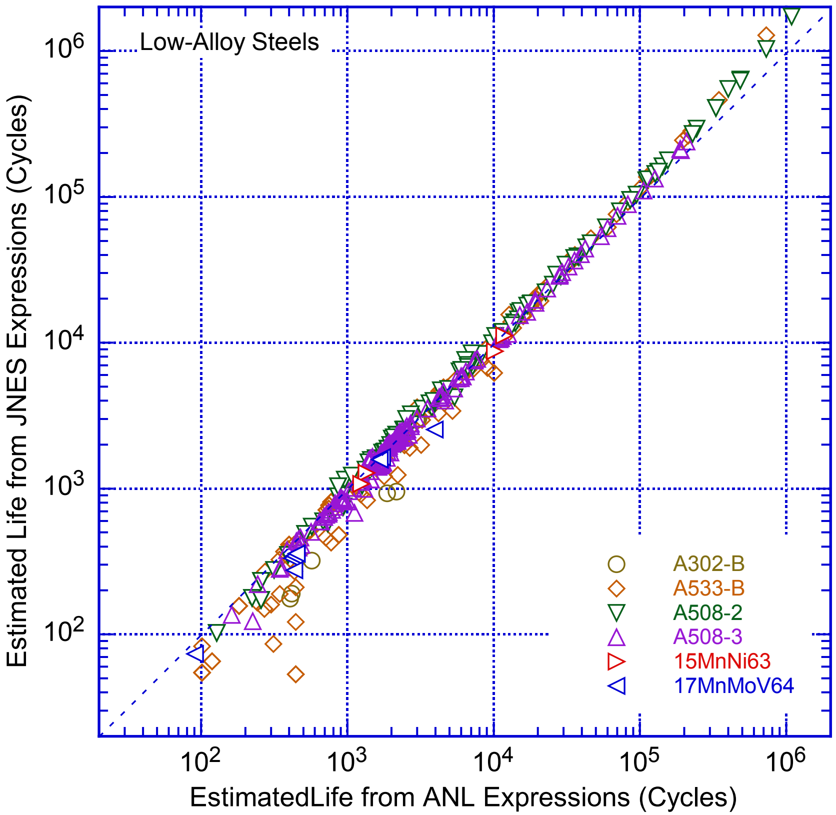




- Although the data scatter is somewhat larger for low-alloy steels, the overall fit is better with the new expressions

Measured and Predicted Fatigue Life - LASs

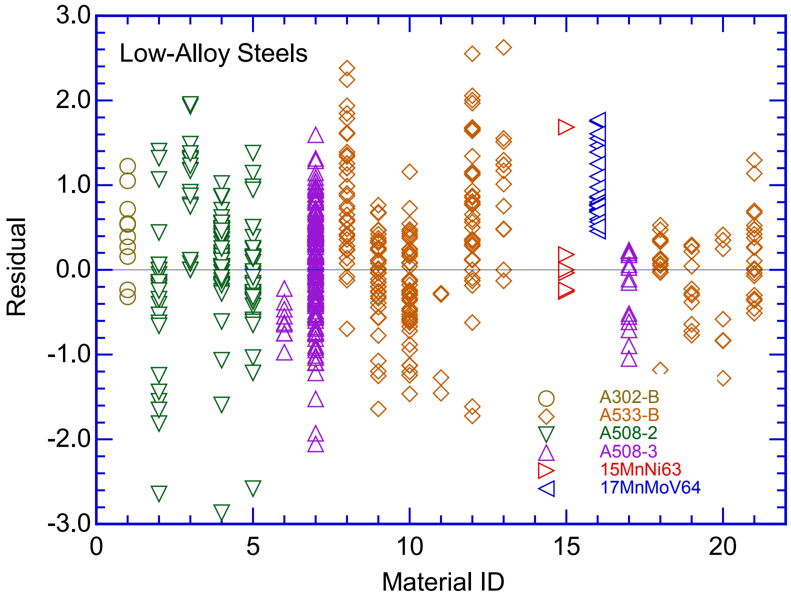


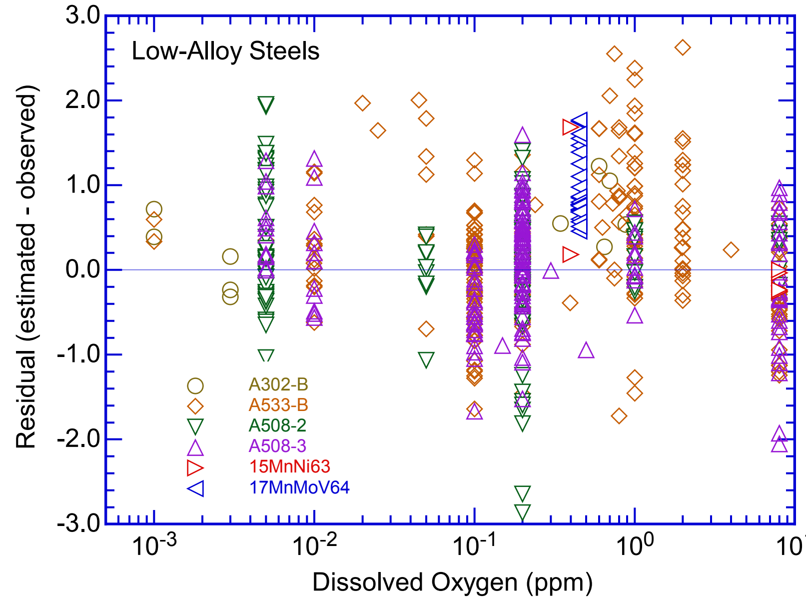


- In general, fatigue lives estimated from the new expression are comparable to those from JNES expressions*; slightly longer lives in the low cycle regime and slightly shorter lives in the high cycle regime
- Few data with poor fit represent conditions typically not observed in service; $F_{en} > 25$

* Using expressions from JNES Report No. JNES-SS-1005.

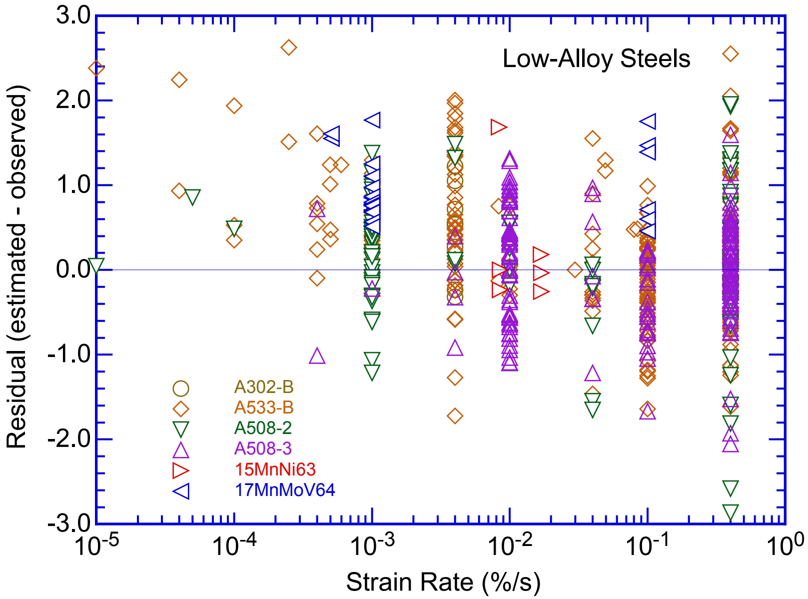
Residuals vs. Material ID and Dissolved Oxygen - LASs

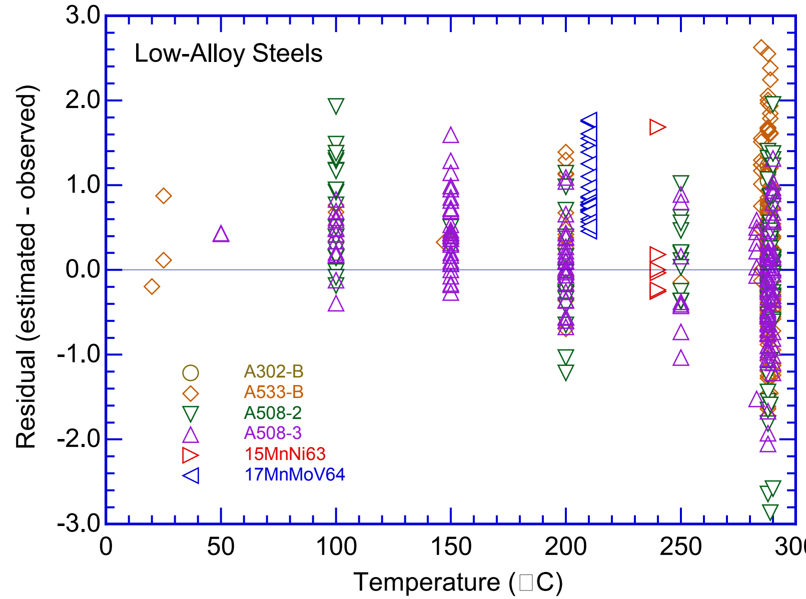




- Residuals for a few heats (e.g., IDs #3, 8, 12, 13 and 16) are mostly positive (non-conservative)
- Except for Heat #3, all other heats with non-conservative estimates were tested in high DO water (≥ 0.5 ppm DO)

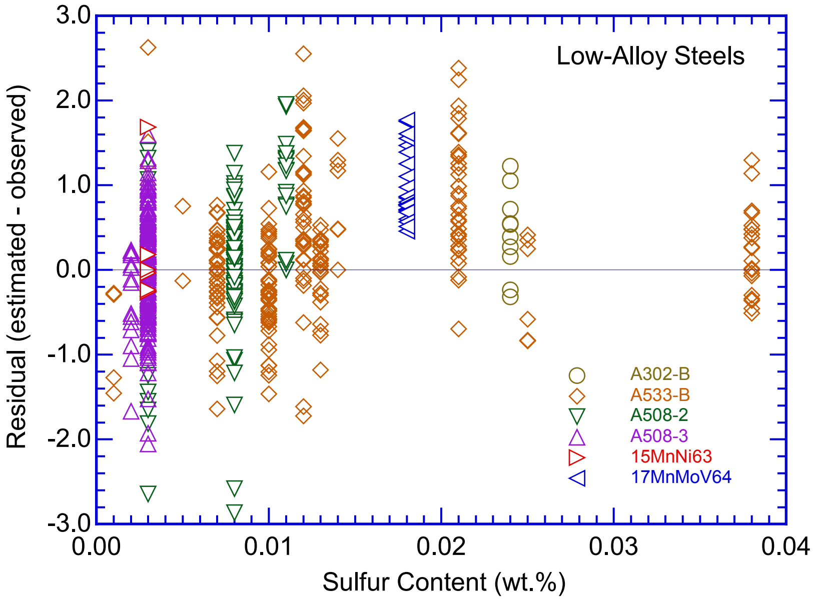
Residuals vs. Strain Rate and Temperature - LASs

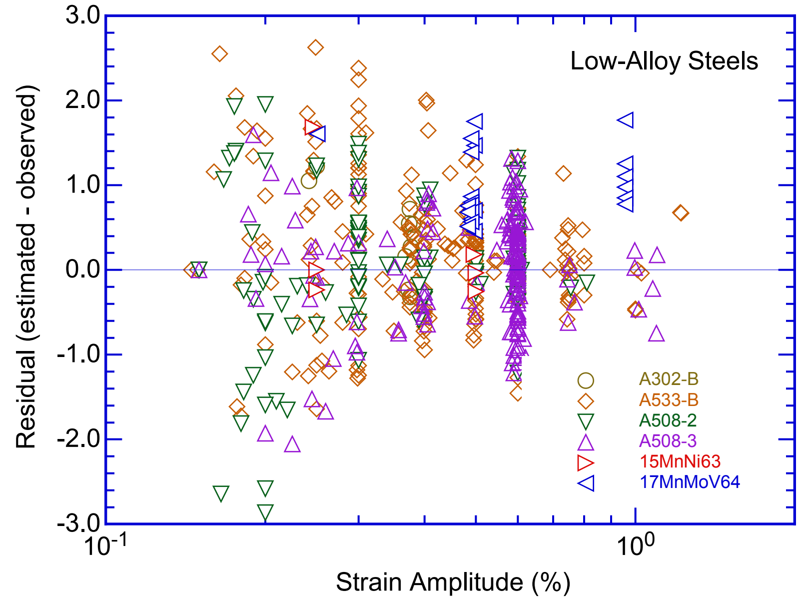




- Most of the data are evenly distributed about the mean
- A few exceptions are the data for very low strain rates (< 10^{-3} %/s) and low temperatures (≤ 150° C)

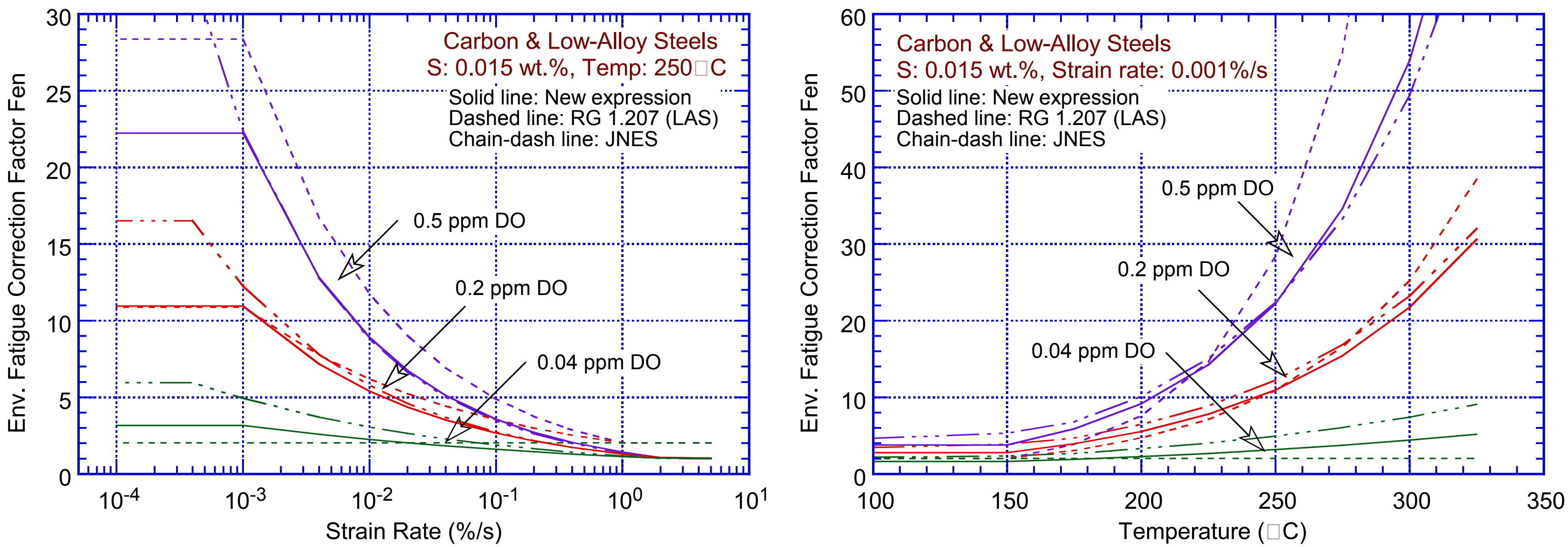
Residuals vs. Sulfur and Strain Amplitude - LASs





- The data are evenly distributed about the mean
- The results for high-S steels (≥ 0.018 wt.% S) show positive residuals (non-conservative)

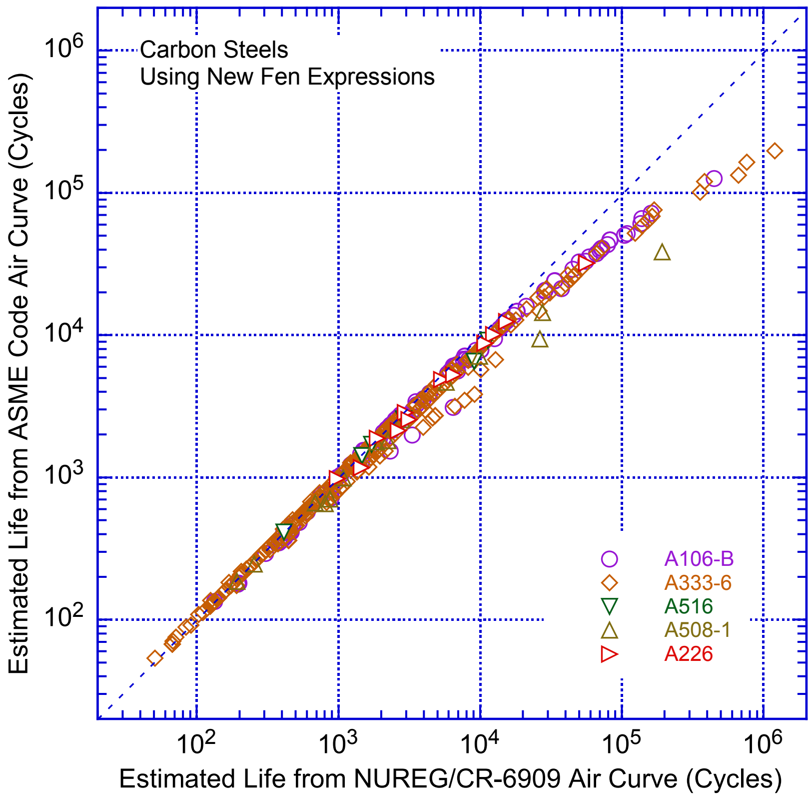
New Expressions vs. NUREG/CR-6909 – Comparison Carbon and Low-Alloy Steels

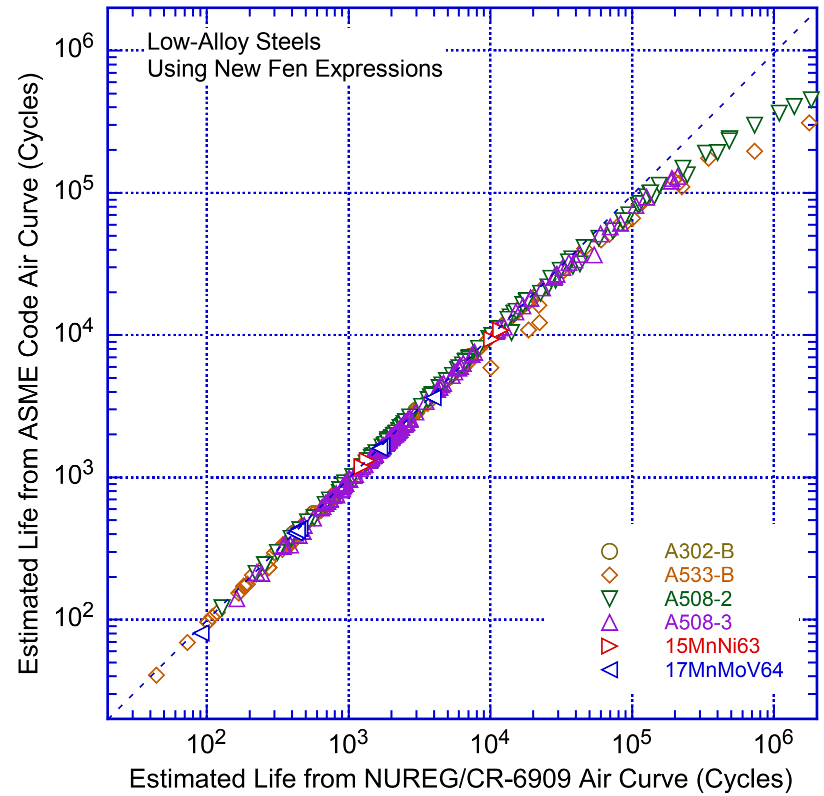


- Under typical operating conditions, the new expressions yield comparable F_{en} values to those estimated from NUREG/CR-6909; estimates at very high DO are lower
- Estimates of fatigue lives based on the new expressions and the JNES expressions* are comparable

* Using expressions from JNES Report No. JNES-SS-1005.

RG 1.207 vs. Code Case N-792 Methodologies





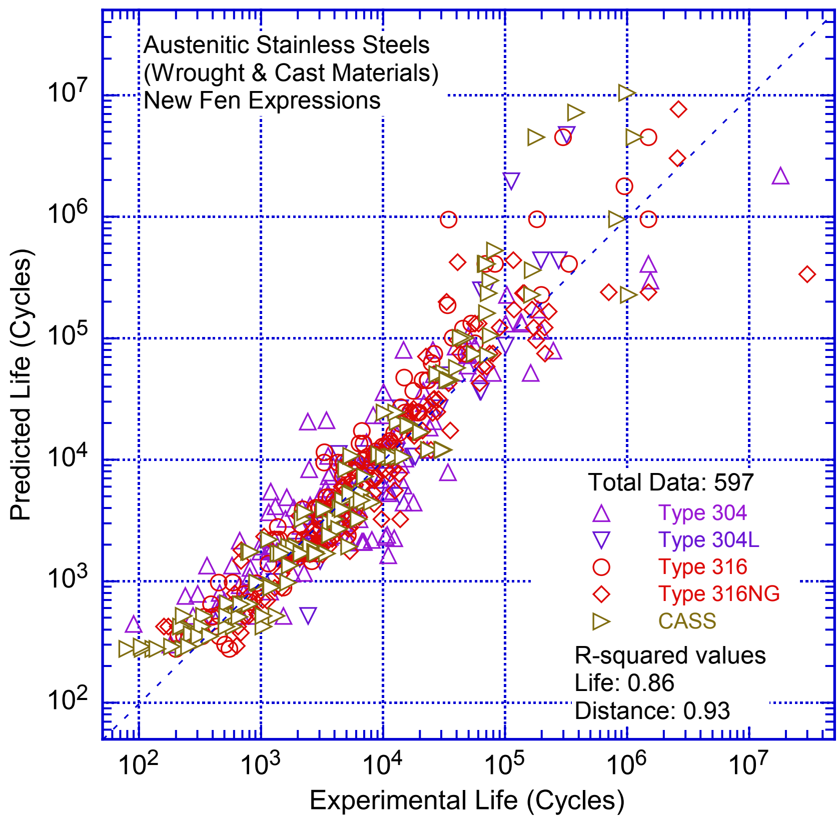
- In RG 1.207, for carbon and low-alloy steels, CUF values in air maybe determined using NUREG/CR-6909 air curves, whereas Code Case (CC) N-792 recommends using the ASME Code design curves
- As a result, estimates of fatigue life based on CC N-792 will be lower in the high cycle regime

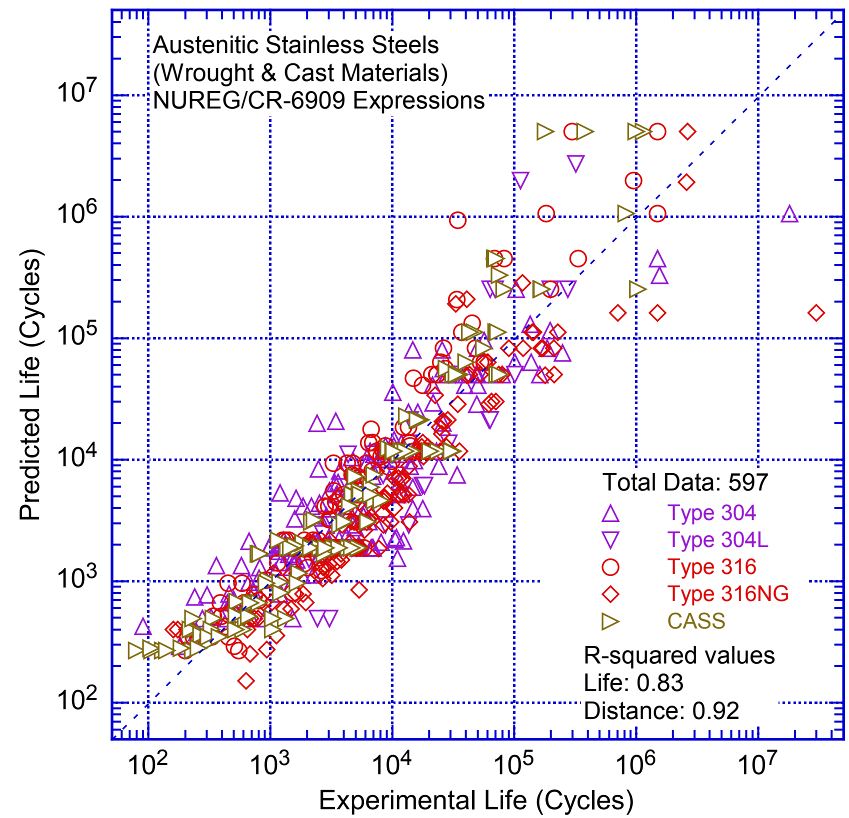
Revised F_{en} Expressions - Austenitic Stainless Steels

- Wrought and cast SSs: $F_{en} = \exp[-T' O' R']$
  - $T' = 0$ $(T < 100^\circ C)$
    $T' = (T - 100)/250$ $(100 < T \leq 325^\circ C)$
    $T' = 0.90$ $(T \geq 325^\circ C)$
  - $O' = 0.29$ (<0.1 ppm DO) all wrought and cast SSs and heat treatments
    $O' = 0.29$ (>0.1 ppm DO) sensitized Hi-C wrought SSs and cast SSs
    $O' = 0.14$ (>0.1 ppm DO) all wrought SSs and treatments except sensitized Hi-C
  - $R' = 0$ $(R > 10\%/s)$
    $R' = \ln(R/10)$ $(0.0004 \leq R \leq 10\%/s)$
    $R' = \ln(0.0004/10)$ $(R < 0.0004\%/s)$
- Wrought and cast SSs: $F_{en} = 1$ (strain amplitudes $\leq 0.1\%$)

- The expressions for T', O' and R' have been modified
- A strain rate threshold is included at 10%/s above which F_{en} is 1.0; this eliminates the issue with the constants in the previous expressions
- Dependence of temperature has been modified to be consistent with JNES expressions
- For low-C SSs (not sensitized), F_{en} is lower in high-DO environment (NWC BWR) than in low-DO environment (PWR and HWC BWR)

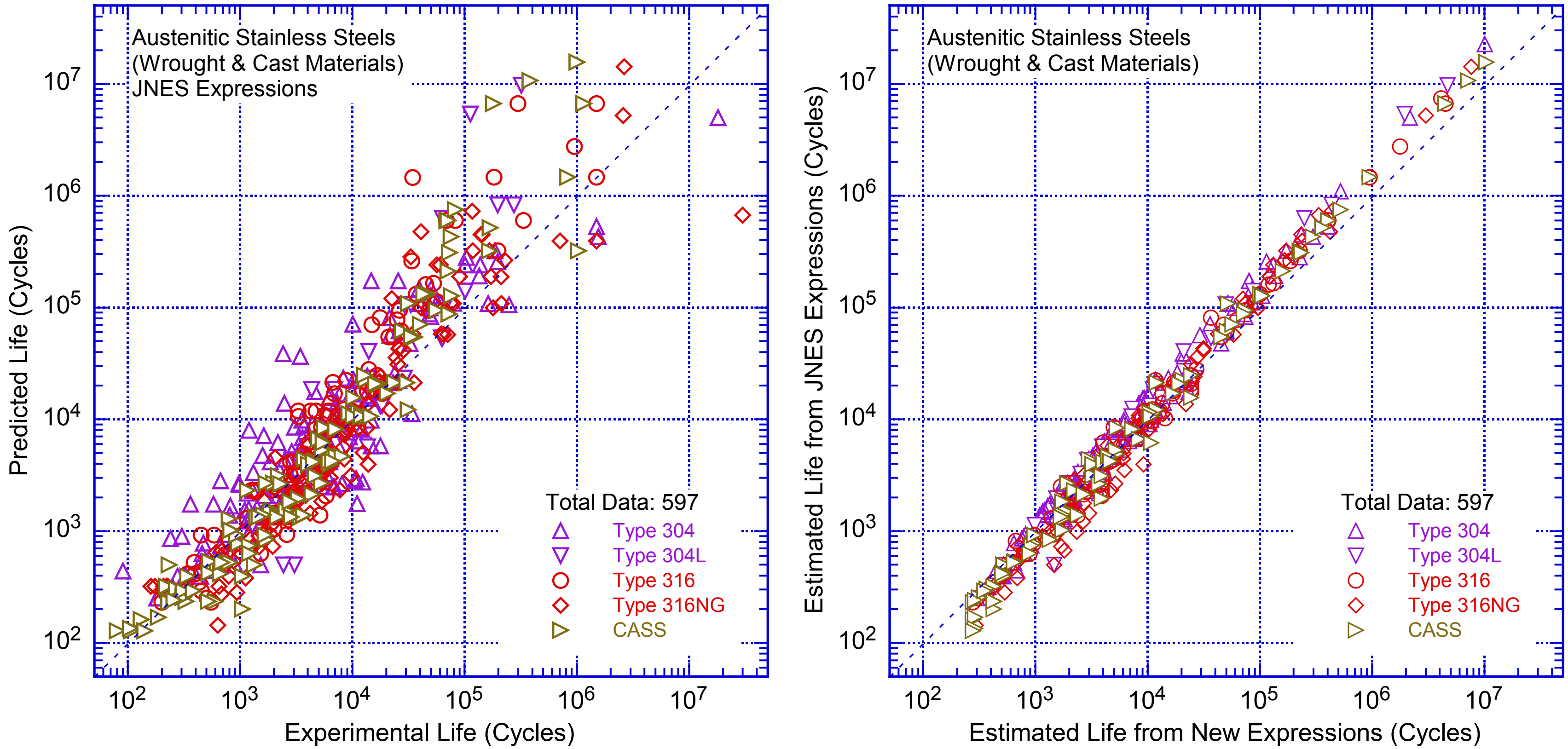
Measured and Predicted Fatigue Life - Austenitic SSs





- The new expressions yield a slightly better fit of the data
- Type 316NG data exhibit a steeper slope, i.e., observed life is longer than predicted values at high strain amplitudes and shorter at low strain amplitudes

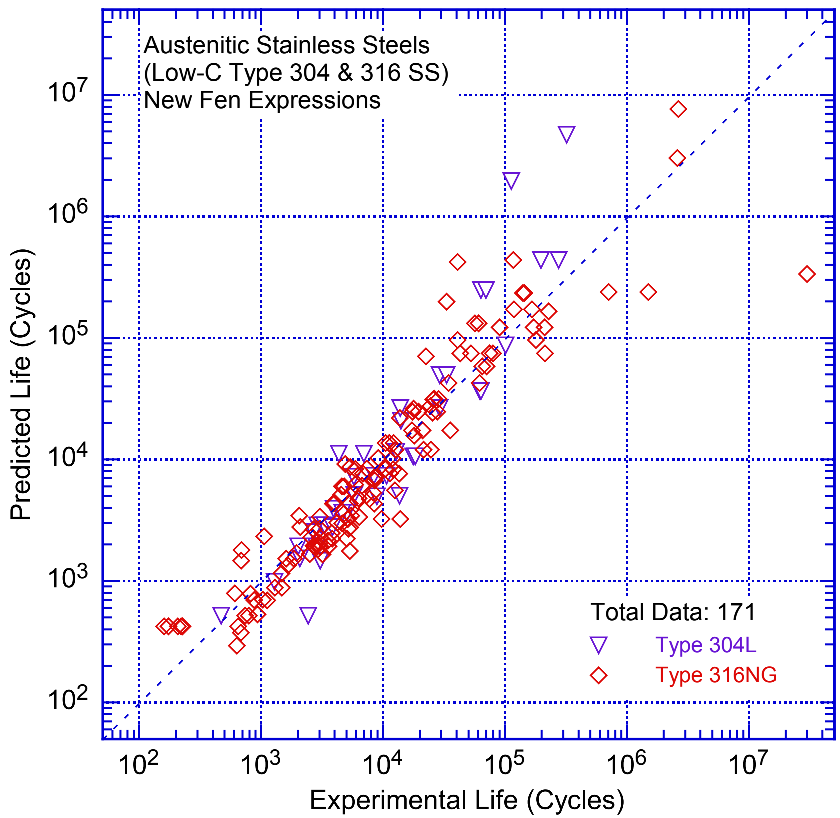
Measured and Predicted Fatigue Life - Austenitic SSs

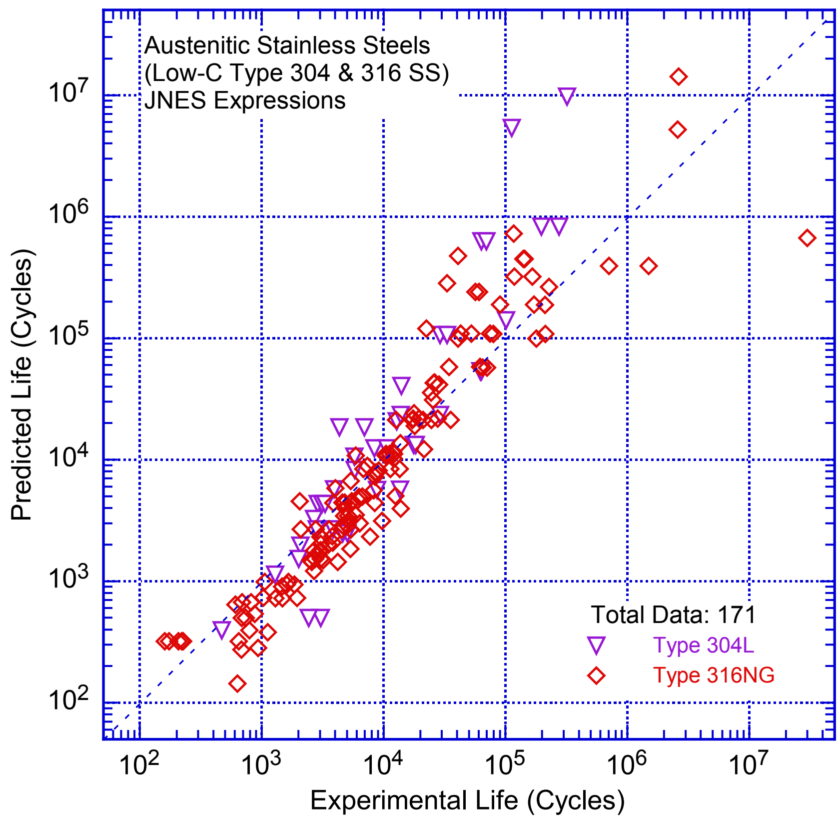


- In general, fatigue lives estimated from the new expression are comparable to those from JNES expressions* in the low cycle regime and slightly shorter in the high cycle regime

* Using expressions from JNES Report No. JNES-SS-1005.

Measured and Predicted Fatigue Life - Low-C SSs

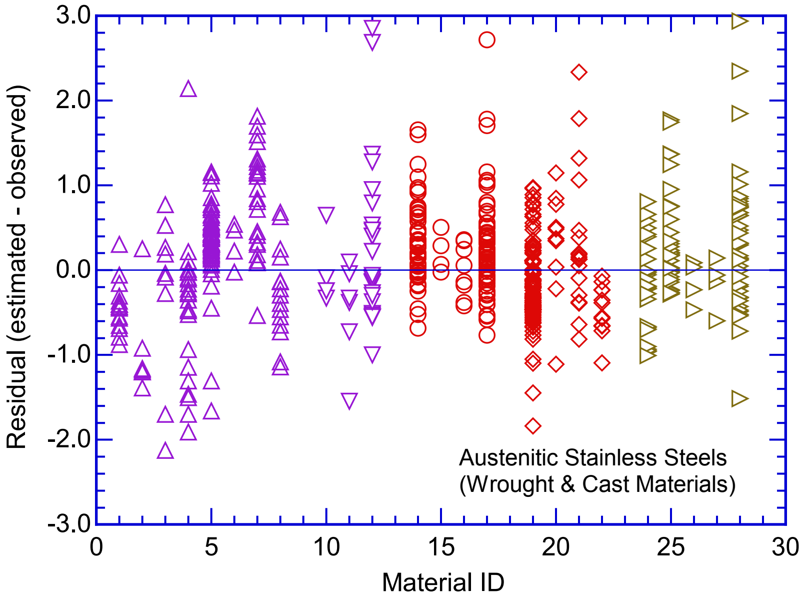


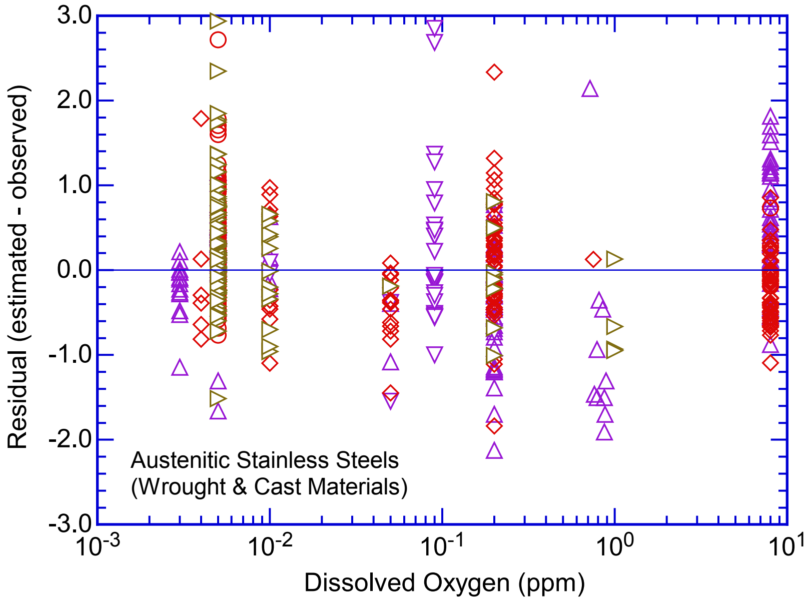


- Estimated fatigue lives for low-C SSs (not sensitized) show good agreement with the observed values
- The majority of the data for 316NG was obtained in high-DO water (i.e. > 0.1 ppm)

JNES expressions from JNES Report No. JNES-SS-1005.

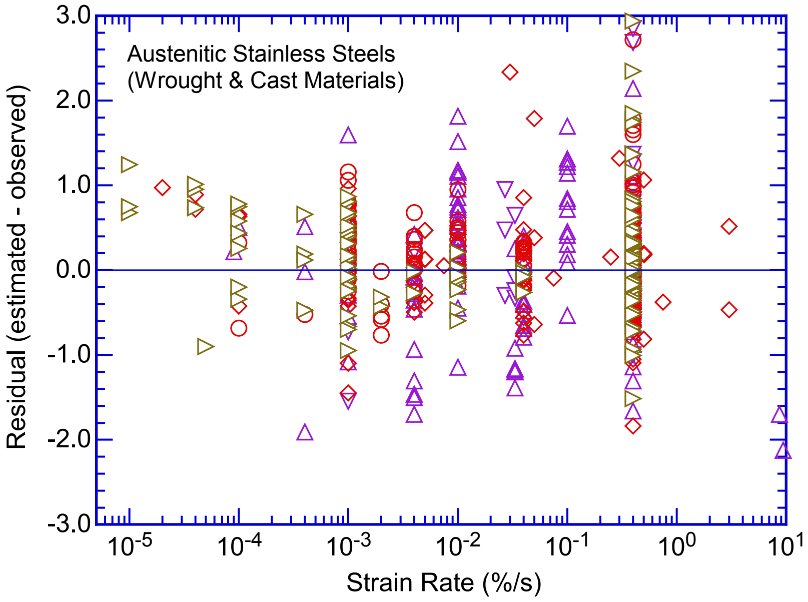
Residuals vs. Material ID and Dissolved Oxygen - SSs

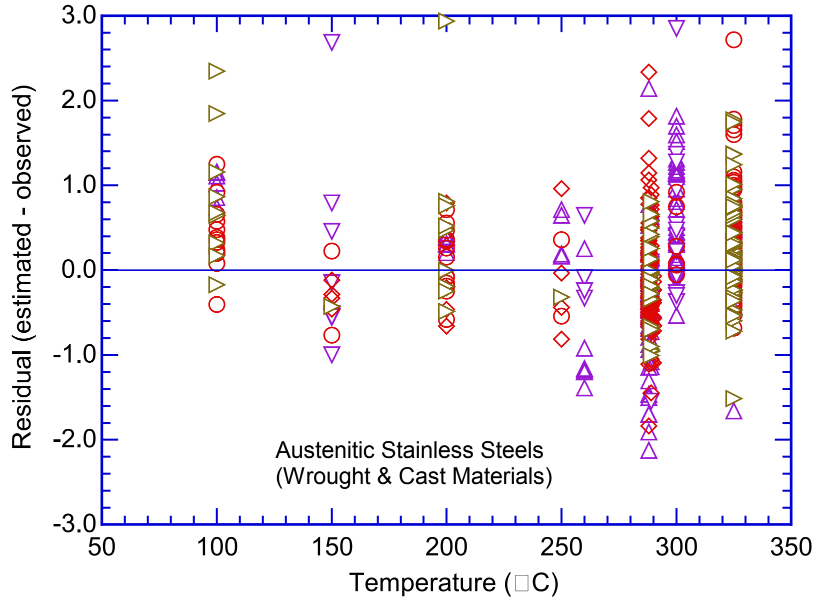




- For residuals, most of the data are evenly distributed about the mean

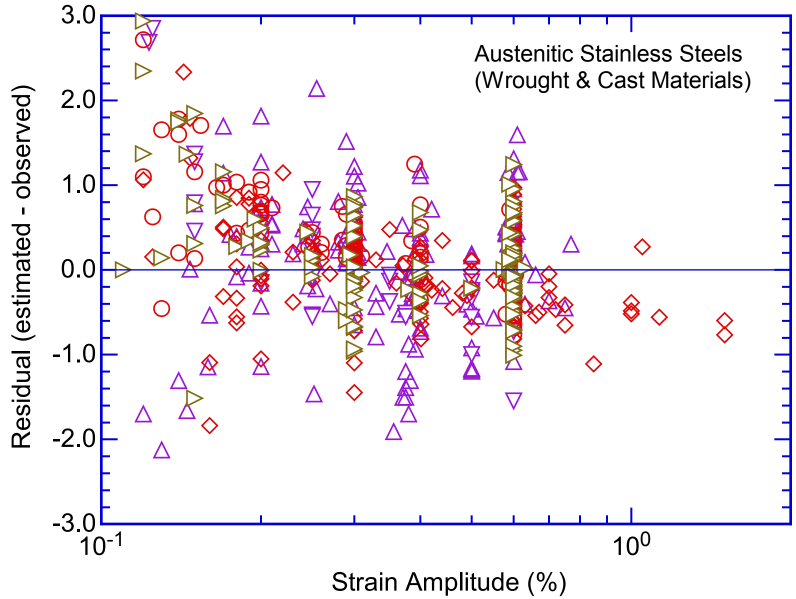
Residuals vs. Strain Rate and Temperature - SSs





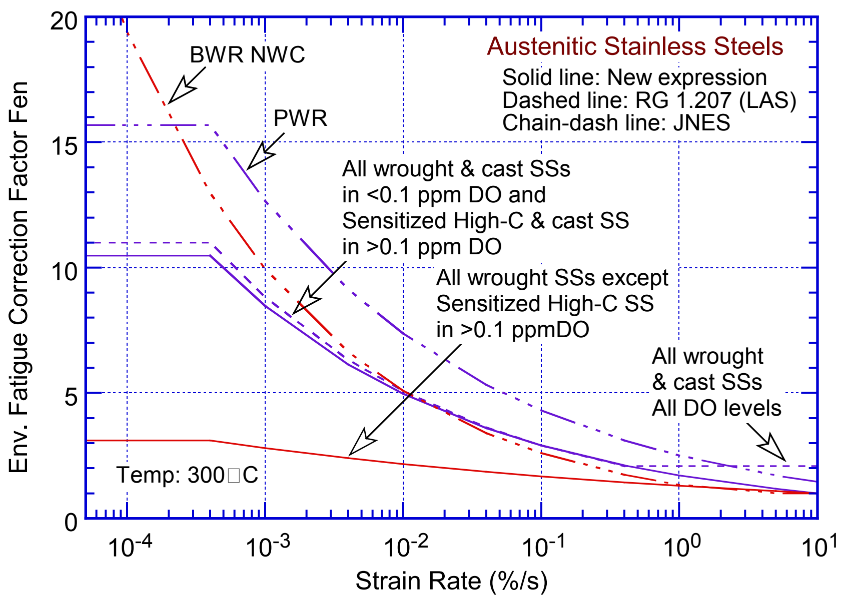
- For residuals, most of the data are evenly distributed about the mean

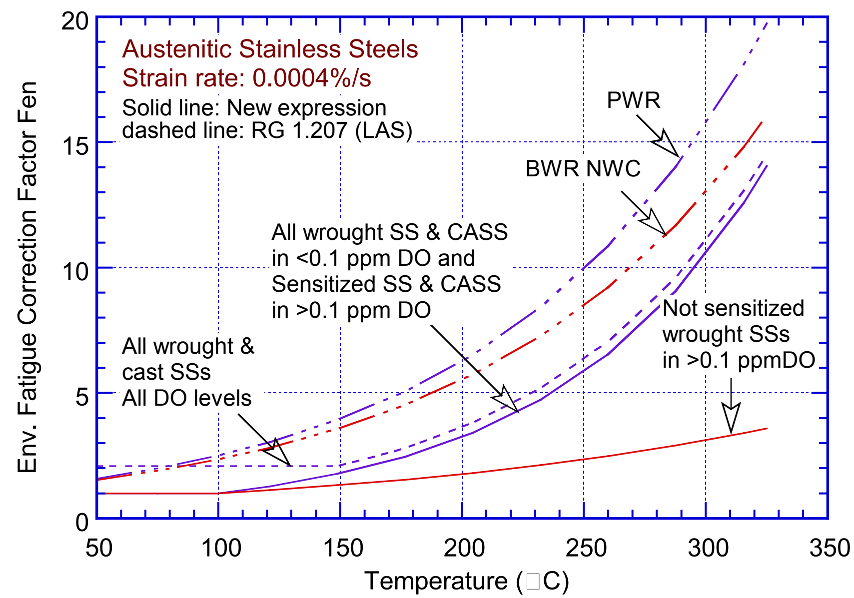
Residuals vs. Strain Amplitude - SSs



- For residuals, the data are evenly distributed about the mean except at very low strain amplitudes (< 0.15 %)

New Expressions vs. NUREG/CR-6909 - Comparison Austenitic Stainless Steels





- Under typical operating conditions, the new expression yields comparable or lower F_{en} values to those estimated from NUREG/CR-6909
- F_{en} values estimated from the new expression are lower than those from the JNES expressions*, particularly in high DO water (> 0.1 ppm DO) – we are investigating with JNES

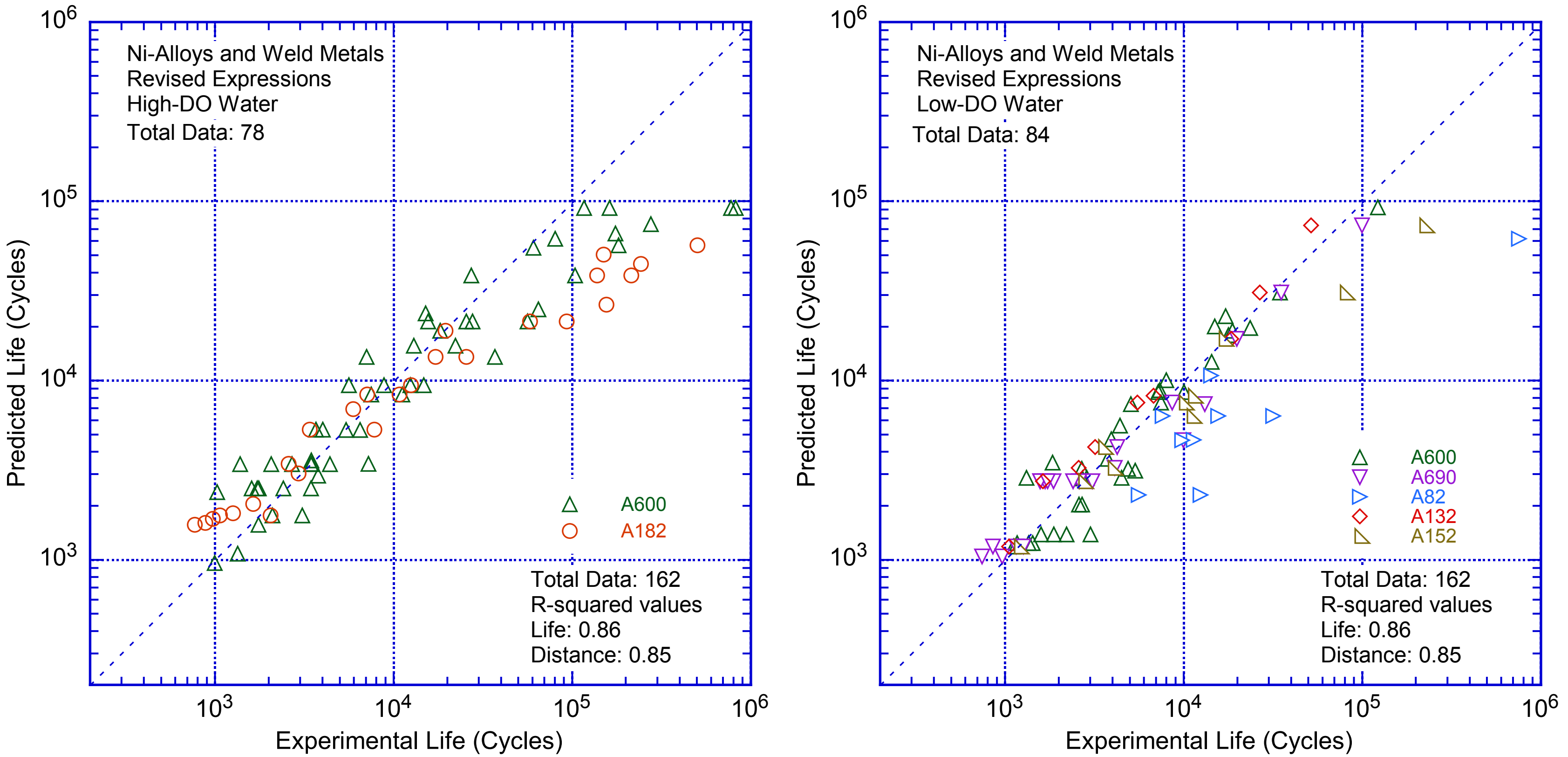
* Using expressions from JNES Report No. JNES-SS-1005.

Revised F_{en} Expressions - Ni-Cr-Fe Alloys

- Ni-Cr-Fe alloys & welds: $F_{en} = \exp[-T' O' R']$
  - $T' = 0$ ($T < 50^{\circ}$ C)
    $T' = (T-50)/275$ (50° C $\leq T < 325^{\circ}$ C)
    $T' = 1.0$ ($T \geq 325^{\circ}$ C)
  - $O' = 0.06$ (NWC BWR water)
    $O' = 0.14$ (PWR or HWC BWR water
  - $R' = 0$ ($R > 5.0\%/s$)
    $R' = \ln(R/5.0)$ ($0.0004 \leq R \leq 5.0\%/s$)
    $R' = \ln(0.0004/5.0)$ ($R < 0.0004\%/s$)
- All alloys & welds: $F_{en} = 1$ (strain amplitudes $\leq 0.1\%$)

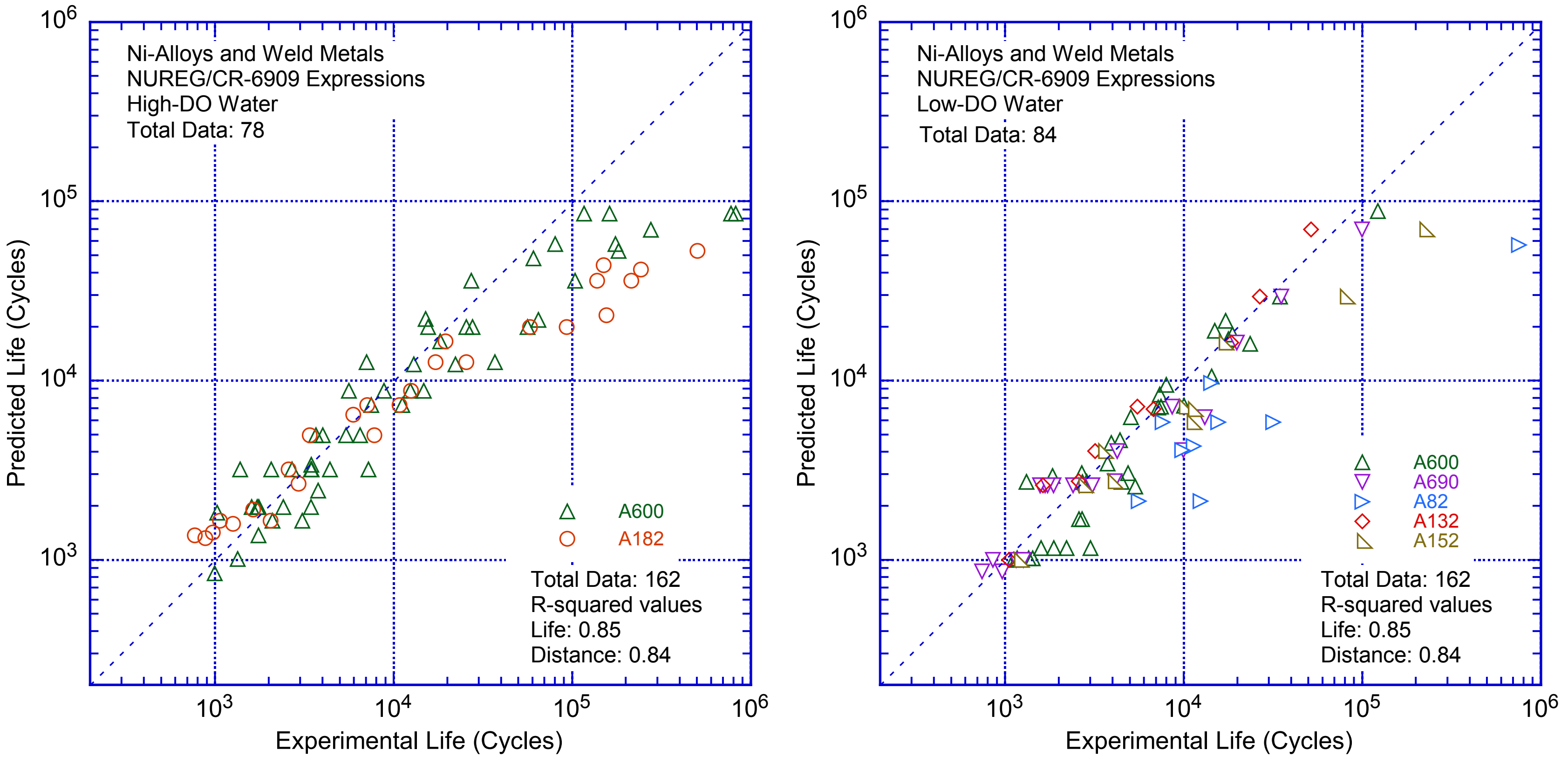
- The temperature dependence has been modified so that $F_{en} = 1$ below 50° C
- F_{en} expressions have been reevaluated using a larger database; values of O' have been revised
- Available fatigue S-N data indicate that both A152 and A82 weld metals show superior fatigue resistance in LWR environments than other Ni-Cr-Fe alloys or weld metals; the data for these weld metals were excluded from the analysis to update F_{en} expressions

Measured and Predicted Fatigue Life - Ni-Cr-Fe Alloys



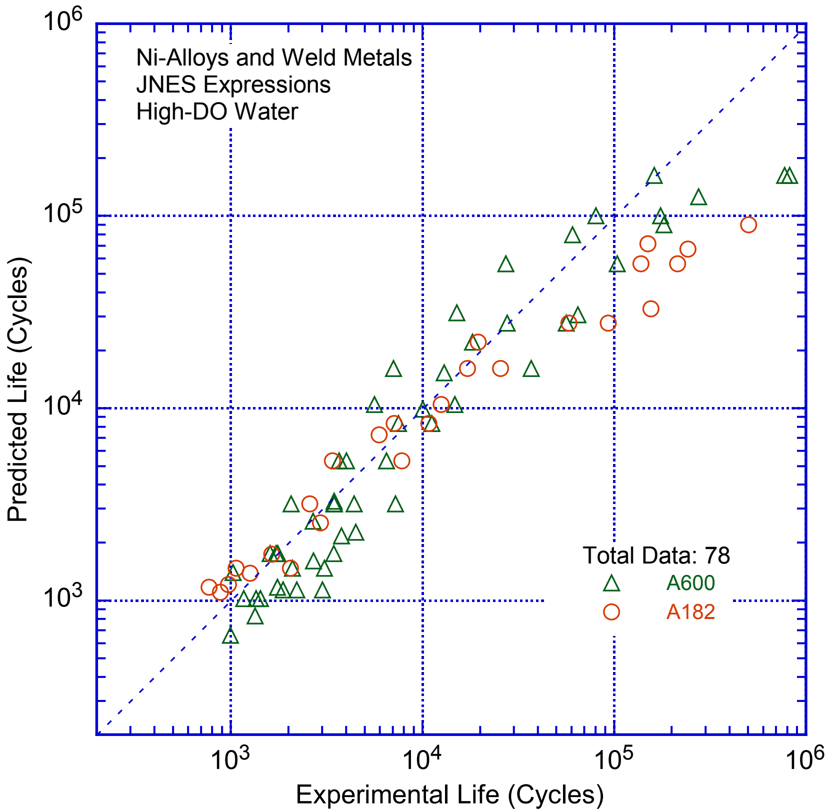
- Predicted lives show good agreement with observed values, except in HCF regime
- Observed fatigue lives of A152 and A82 weld metal are longer than predicted values; most likely because of better fatigue resistance of these alloys

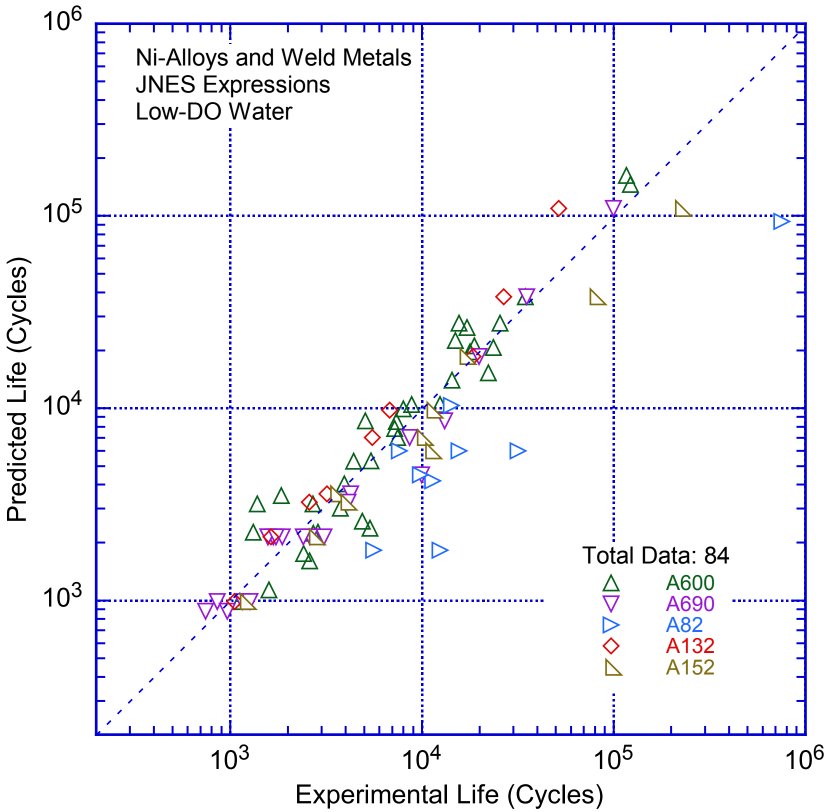
Measured and Predicted Fatigue Life - Ni-Cr-Fe Alloys



- Predicted lives are slightly lower than those estimated from the revised expressions
- Behavior of A152 & A82 is consistent with fatigue crack growth & SCC behavior

Measured and Predicted Fatigue Life - Ni-Cr-Fe Alloys

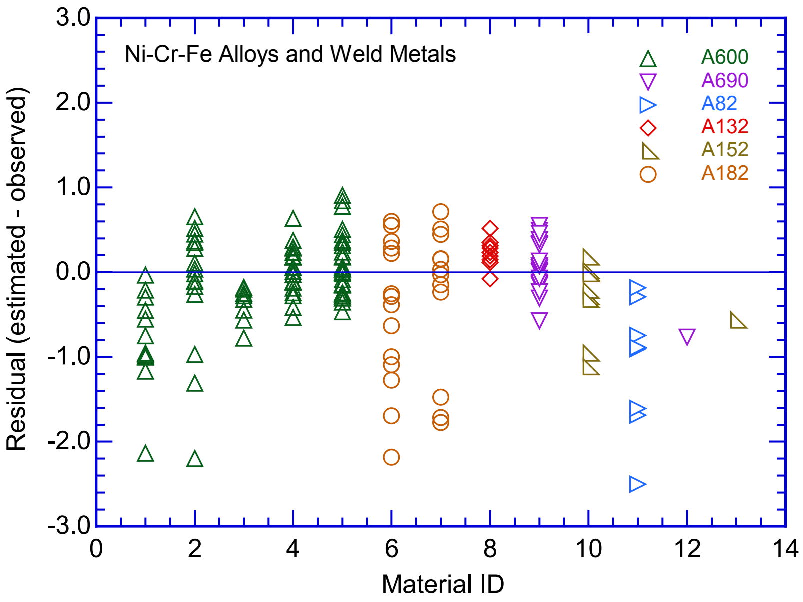


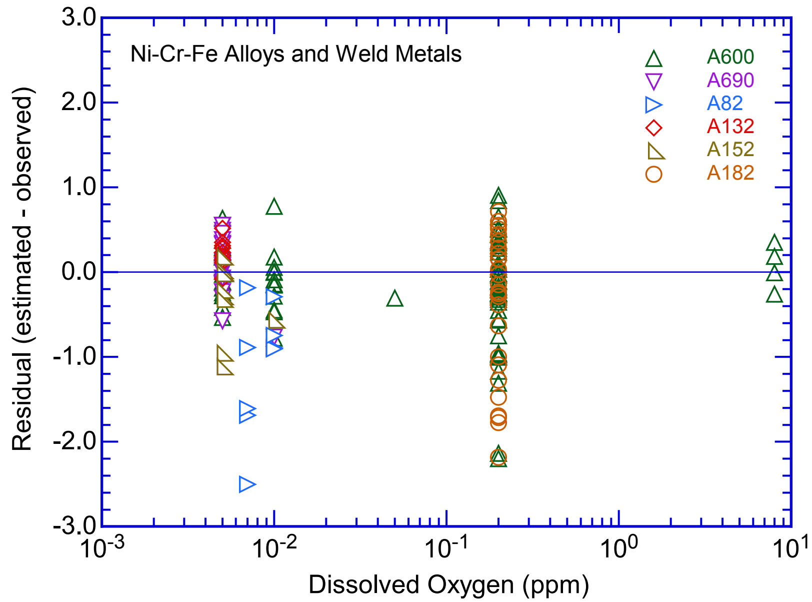


- Estimates of fatigue life in the high-cycle regime are somewhat better than those from revised expressions, because a different air curve is used for Ni-Cr-Fe alloys (with a steeper slope)

JNES expressions from JNES Report No. JNES-SS-1005.

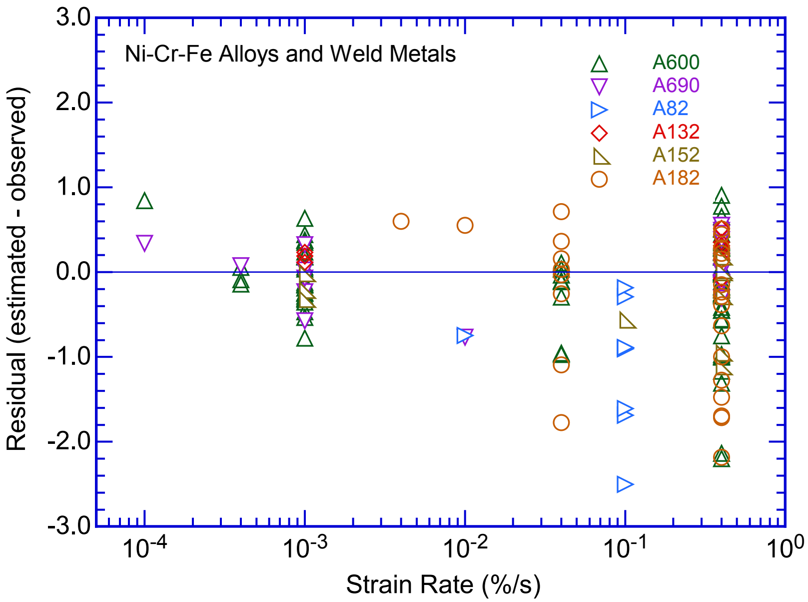
Residuals vs. Material ID and Dissolved Oxygen - Ni-Cr-Fe Alloys

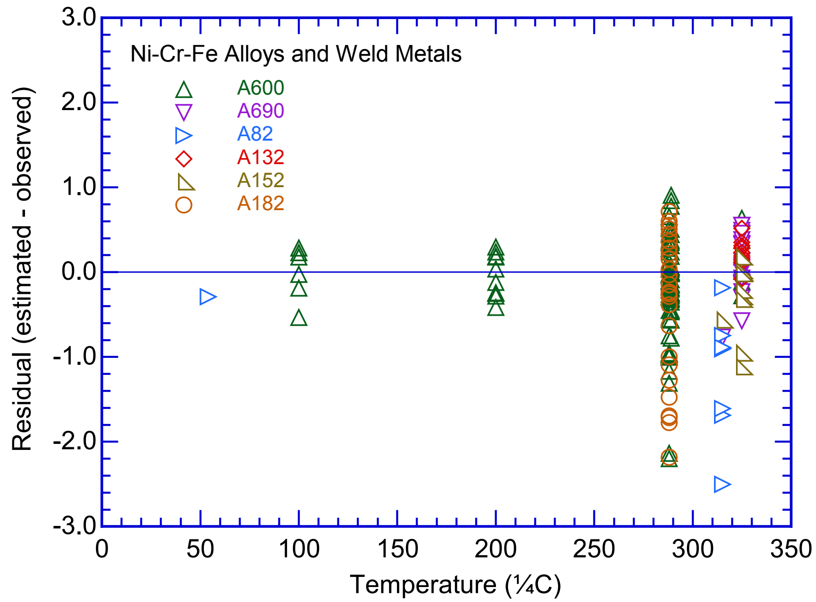




- For residuals, most of the data are evenly distributed about the mean

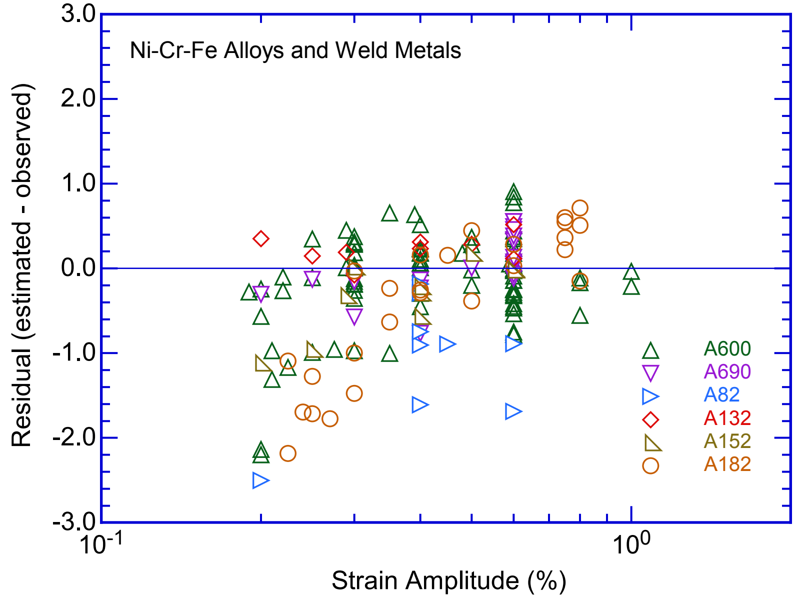
Residuals vs. Strain Rate and Temperature - Ni-Cr-Fe Alloys





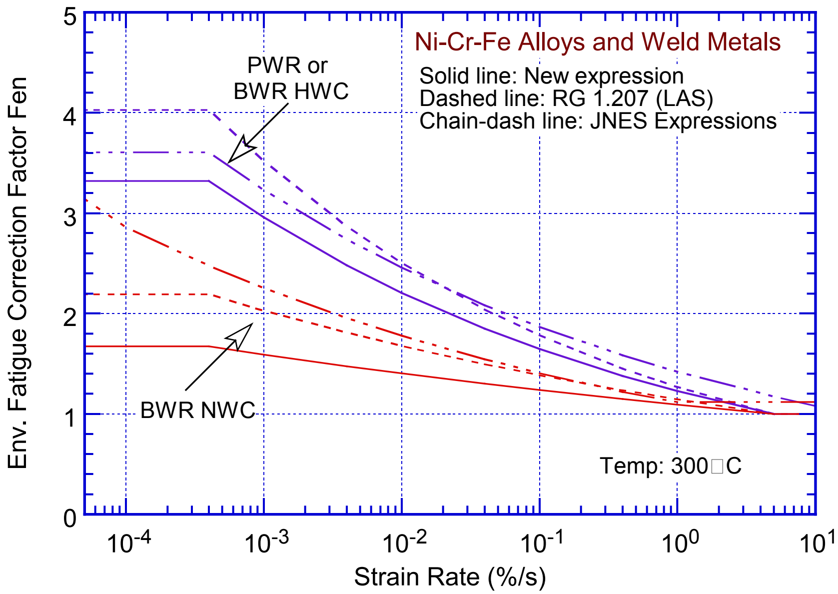
- For residuals, most of the data are evenly distributed about the mean

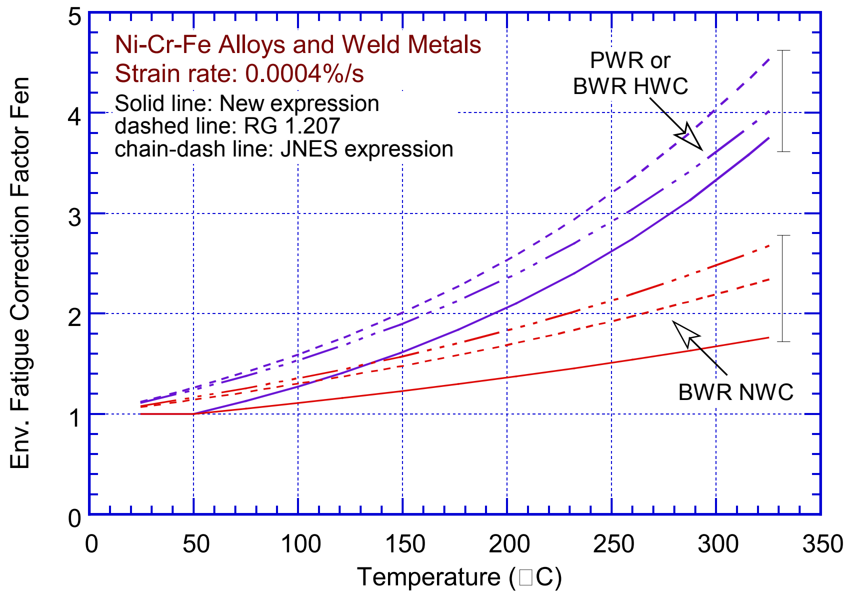
Residuals vs. Strain Amplitude – Ni-Cr-Fe Alloys



- For residuals, the data are evenly distributed about the mean, except at very low strain amplitudes (< 0.15 %)

New Expressions vs. NUREG/CR-6909 - Comparison Ni-Cr-Fe Alloys



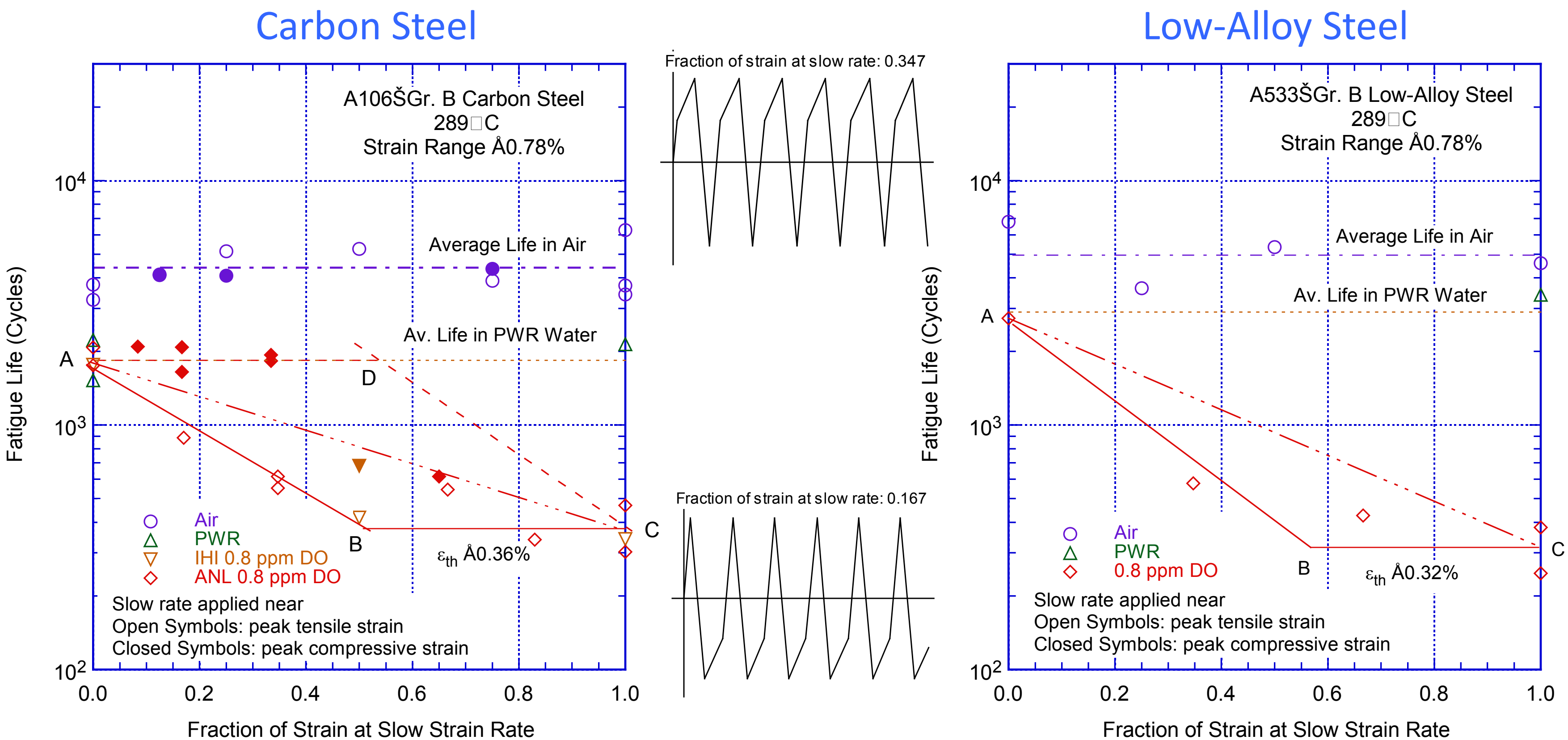


- Under typical operating conditions, the new expression yields lower F_{en} values to those estimated from NUREG/CR-6909
- F_{en} values estimated from the new expression are lower than those from the JNES expressions*, particularly in high DO water (> 0.1 ppm DO) – we are investigating with JNES

* Using expressions from JNES Report No. JNES-SS-1005.

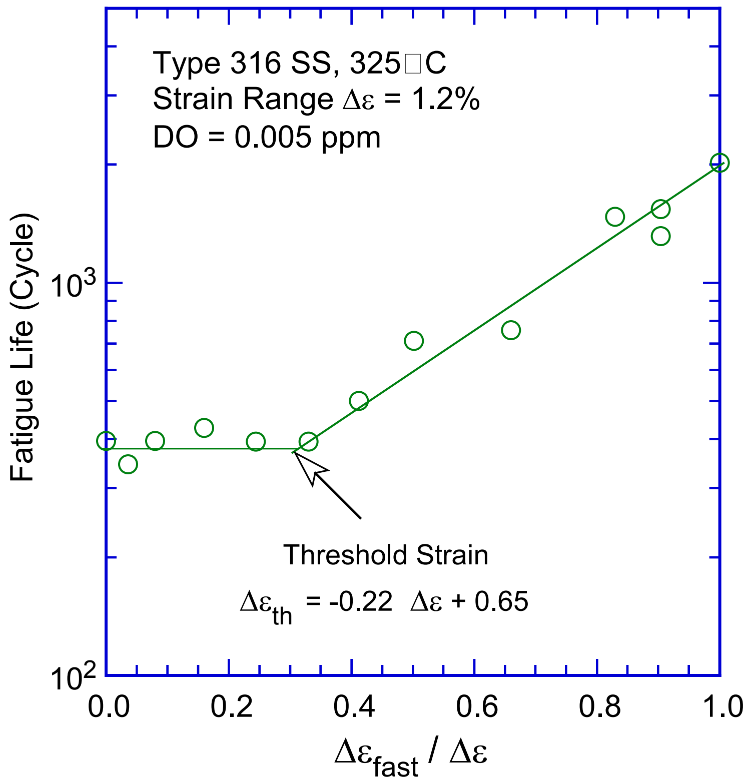
Strain Amplitude Threshold

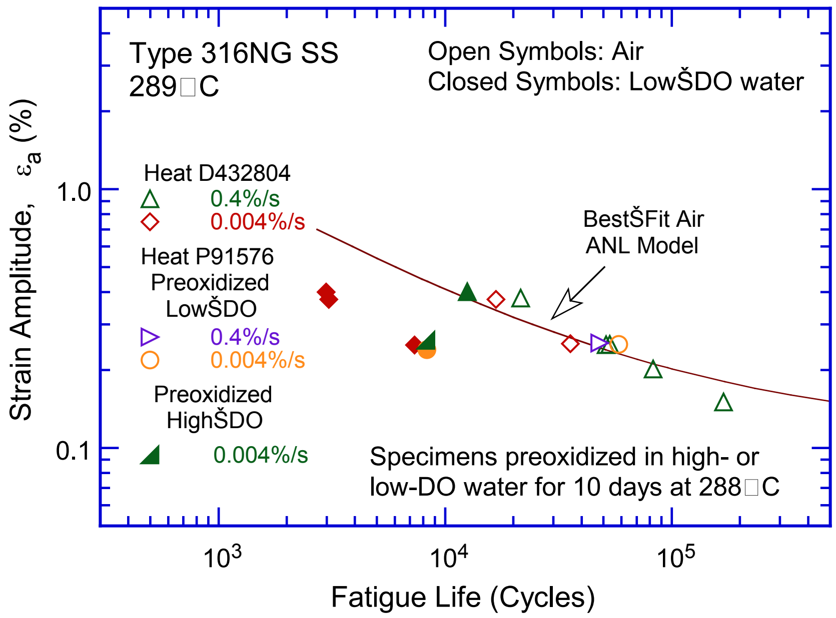
Minimum Threshold Strain for Environmental Effects



- Data indicate that during a strain cycle, the relative damage due to slow strain rate occurs only after the strain exceeds a threshold value
- If the relative damage was the same at all strain levels, fatigue life should decrease linearly from A to C along the chain-dot line
- For carbon & low-alloy steels threshold strain range is between 0.28 & 0.37%

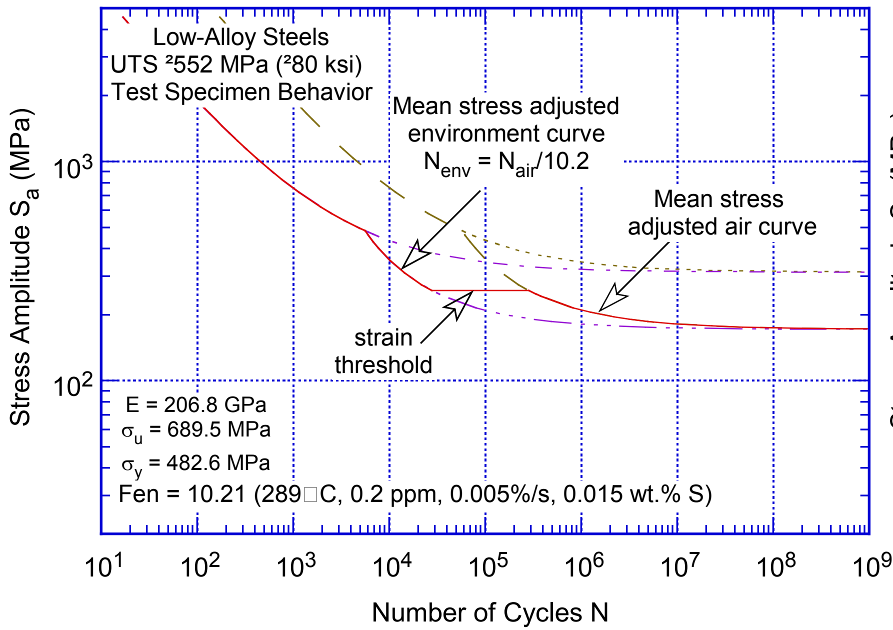
Threshold Strain & Effects of Surface Oxide - SSs

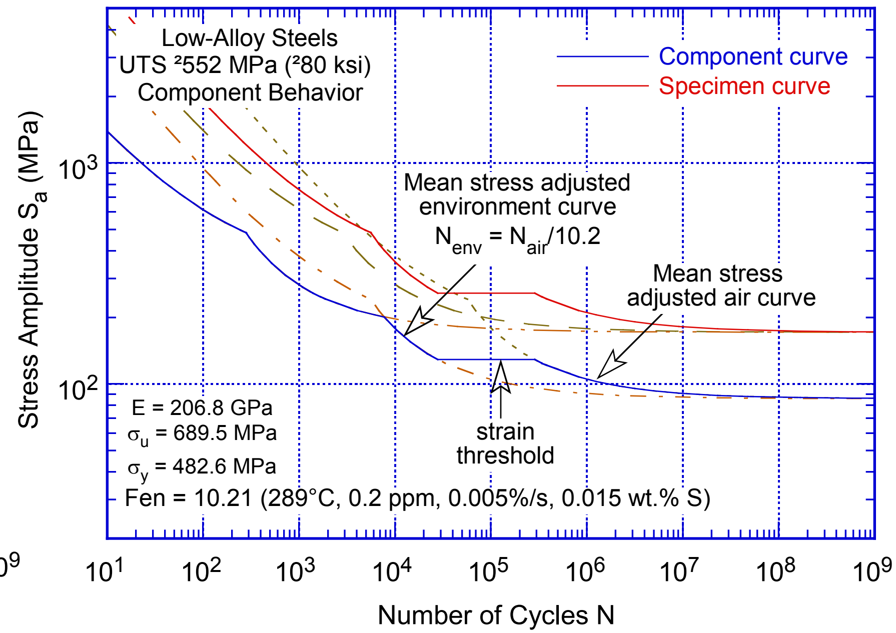




- For SSs, threshold strain seems to be independent of material type (weld or base metal) & temperature between 250-325° C, but decreases with strain range
- No effect of preoxidation of test specimens; N_f same as that of unoxidized specimens
- If micropits were responsible for reduction in life, preoxidized specimens should show lower life in air & fatigue limit should be lower; data show no effect

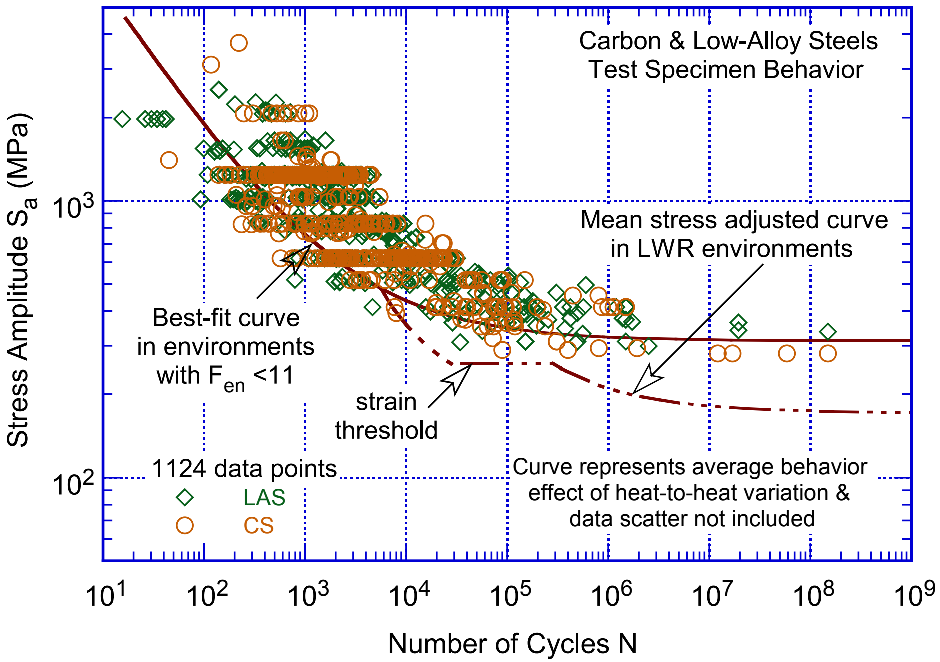
Strain Threshold - Specimen & Component Behavior





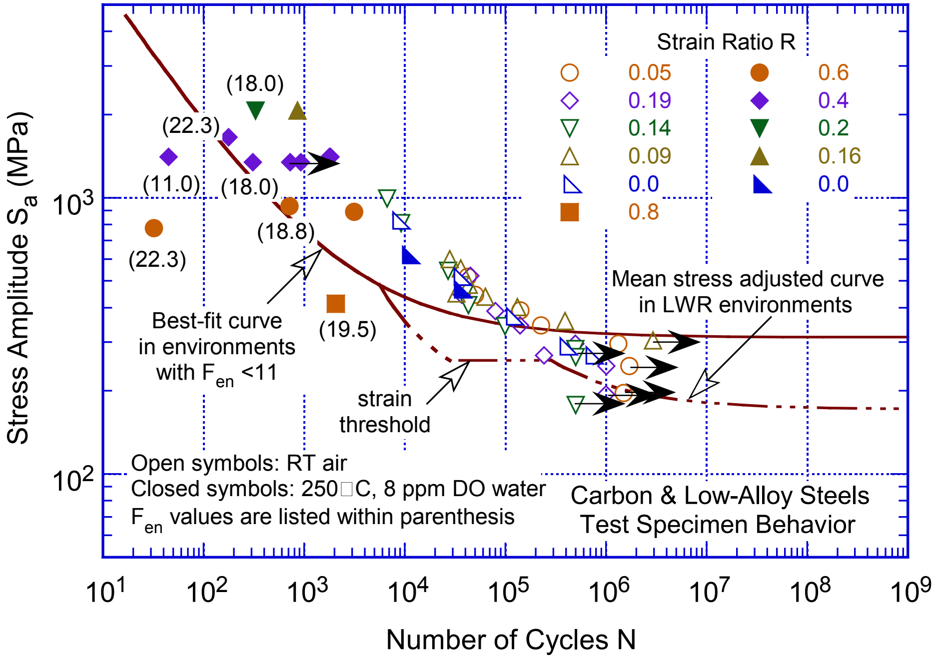
- Concern that strain amplitude compromises the margin of 2 on strain (presentation by Chuck Bruny Feb. 2012)
- The mean-stress adjusted environmental curve for test specimens (in red) and the environmental curve for components (in blue) above clearly show that the margins of 20 on life and 2 on stress (or strain) are not compromised

Strain Threshold - Specimen Behavior



- Since solid line represents average behavior of carbon & low-alloy steels in LWR environments that yield a F_{en} of 11, some of the data fall below the solid line
- As discussed in NUREG/CR-6909, a factor of 2.8 on life can account for the effects of heat-to-heat & data scatter – only 4 or 5 data points are more than 2.8 lower
- A factor of 1.2 on strain is enough to account for the data in high-cycle regime

Strain Threshold - Tests at R Values other than -1



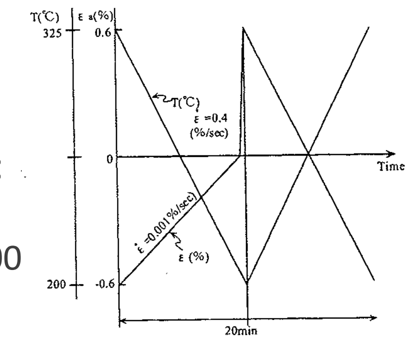
- Data* in room temperature air are bounded by mean stress adjusted best-fit curve
- For the data in high-DO water at 250° C, F_{en} values range from 10.8 to 22.3
- Since the best-fit curve in environment represents F_{en} values less than 11, some of the test data in high-DO water fall below the environmental curve
- Data in LWR environments at strain amplitudes of 0.3% or lower are not available

* Data from JNUFAD database, compiled by PVRC.

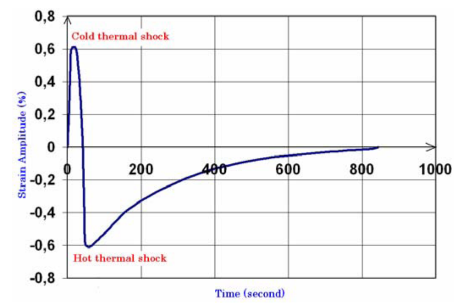
F_{en} Validation Calculations

F_{en} Validation Calculations

- The results of following experimental data sets were compared with estimates of fatigue life based on the F_{en} methodology to validate the revised F_{en} expressions.
  - Tests with changing strain rate within a strain cycle:
    Higuchi, Iida, & Asada, ASTM STP 1298, 1997
    Higuchi, Iida, & Sakaguchi, ASME PVP-419, 2001
    Higuchi, Sakaguchi, & Nomura, ASME PVP2007-26101, 2007
  - Tests with changing strain rate & temperature within a strain cycle:
    Nomura, Higuchi, Asada, & Sakaguchi, ASME PVP-480, PVP2004-2679, 2004
    Sakaguchi, Nomura, Suzuki, & Kanasaki, ASME PVP2006-ICPVT-11-93220, 200



  - Tests with spectrum loading (random strain amplitudes):
    Solin, ASME PVP2006-ICPVT-93833, 2006
  - Tests with complex loading (actual PWR transient – cold & hot thermal shock):
    Le Duff, Lefrancois, & Vernot, ASME PVP2009-78129, 2009
  - EPRI U-bend tests in inert & PWR environment:
    Hickling, Kilian, Spain, & Carey, ASME PVP2006-ICPVT-11-93318, 2006
  - Thermal fatigue test of a stepped pipe:
    Jones, Holliday, Leax, & Gordon, ASME PVP-482, PVP2004-2748, 2004



- Since the experimental data sets were tested to failure (i.e., CUF = 1.0+), the goal of these evaluations is to benchmark the F_{en} methodology vs. the predictions of failures & make adjustments, if warranted.

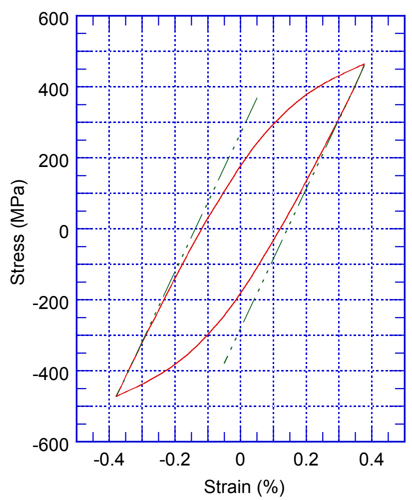
Different Methods Used to Calculate F_{en}

- The following three F_{en} methods are used to calculate environmental correction factor F_{en} that is applied to the fatigue CUF in air to determine CUF in the environment.
- Strain-Integrated Method:
  - $F_{en,i}$ is computed using the revised F_{en} expressions or NUREG/CR-6909 expressions at each time interval, i, using T_i. The summation applies when the strain increment is positive.

Overall integrated $$F_{en} = \frac{\sum F_{en,i}\left(\varepsilon_i - \varepsilon_{i-1}\right)}{\left(\varepsilon_{max} - \varepsilon_{min}\right)}$$

A threshold strain ε_{th} may be considered

- Simplified Method:
  - F_{en} is computed using the revised F_{en} expressions or NUREG/CR-6909 expressions for the entire interval where strain rate is greater than zero using an average T for the interval. Also, average strain rate is used (straight line from valley to peak).



Different Methods Used to Calculate F_{en} (Contd.)

- Multi-Linear Strain-Based Method:
  - Depending on the test case, loading consists of 2 or more ramps (with strain rate >0), and $F_{en,i}$ is computed using the revised F_{en} expressions or NUREG/CR-6909 expressions for each ramp using average T for the ramp.

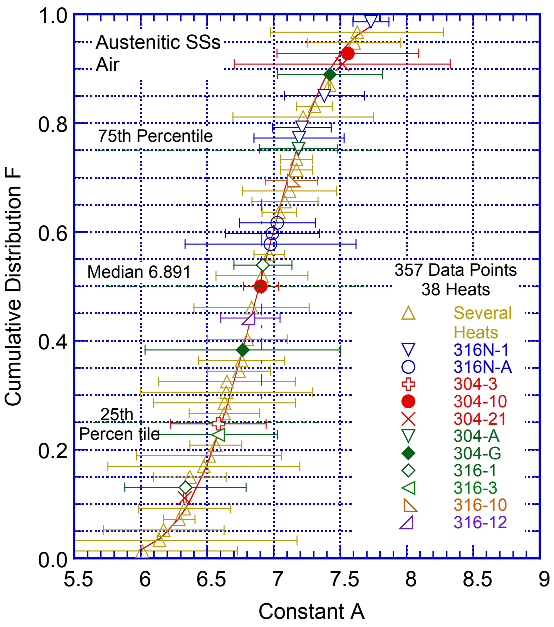
    For a 2-ramp case:

    Overall $$F_{en} = \frac{F_{en,1}\Delta\varepsilon_1 + F_{en,2}\Delta\varepsilon_2}{\left(\Delta\varepsilon_1 + \Delta\varepsilon_2\right)}$$

  Similar calculations are performed for the 3- or 4-ramp case.

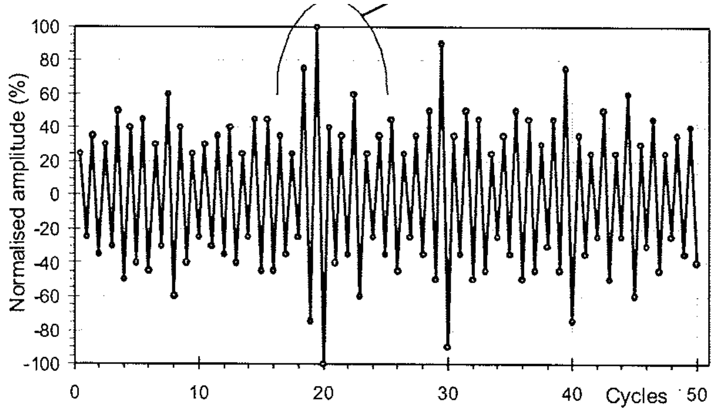
Comparison of Estimated & Measured Fatigue Lives

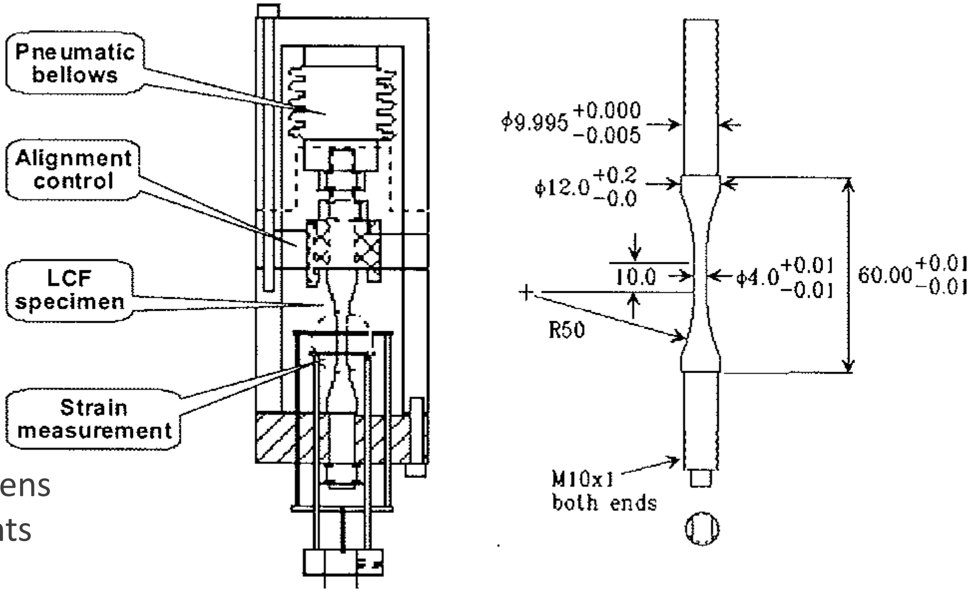
- Purpose of these calculations is to validate the F_{en} expressions, i.e., by using best estimates of applied strain in the test specimens, and not those determined from ASME Code procedures
- Fatigue life of test specimen is determined by multiplying the life estimated from the best-fit (or mean) air curve for the material by F_{en}
- Since the best-fit air curve represents data obtained on small, smooth test specimens, estimated lives need to be adjusted to compare with results from component tests
  - Heat-to variability (2.1 – 2.8)
  - Size effect (1.2 – 1.4)
  - Surface roughness (2.0 – 3.5)
  - Random loading vs. constant loading (1.2 – 2.)



Spectrum Straining of Type 316NG & Ti-Mod. 316

(ASME PVP2006-ICPVT-93833 & PVP2011-57943)



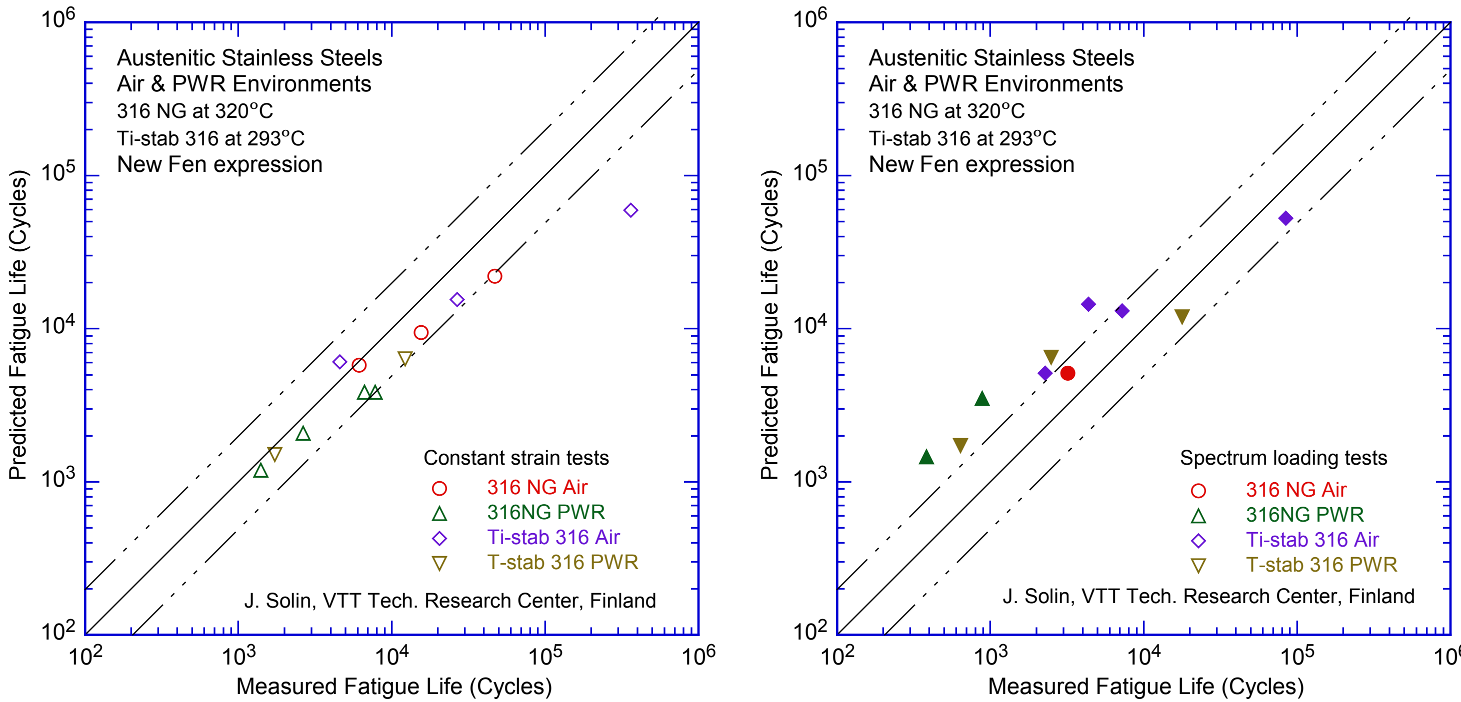


Cylindrical 12-mm diameter smooth, test specimens
Tested in air & simulated PWR/VVER environments
316NG: YS = 250 MPa & UTS = 570 MPa
T-Mod: YS = 330 MPa & UTS = 595 MPa

- Rigid pneumatic bellows loading unit used to perform strain-controlled tests on smooth cylindrical specimens in PWR or VVER environments with constant or spectrum loading
- For both heats of materials, baseline data indicate comparable fatigue life at strain amplitudes of 0.3% or higher, and slightly superior fatigue life at lower strain amplitudes
- Since only two tests on T-modified 316 were conducted at strain amplitudes less than 0.3%, the experimental data does not need to be adjusted for heat-to-heat variation

Spectrum Straining (Contd.)

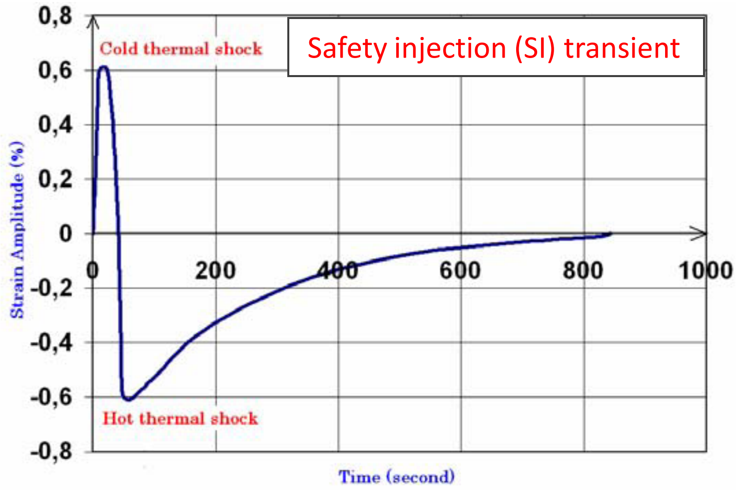
(ASME PVP2006-ICPVT-93833 & PVP2011-57943)

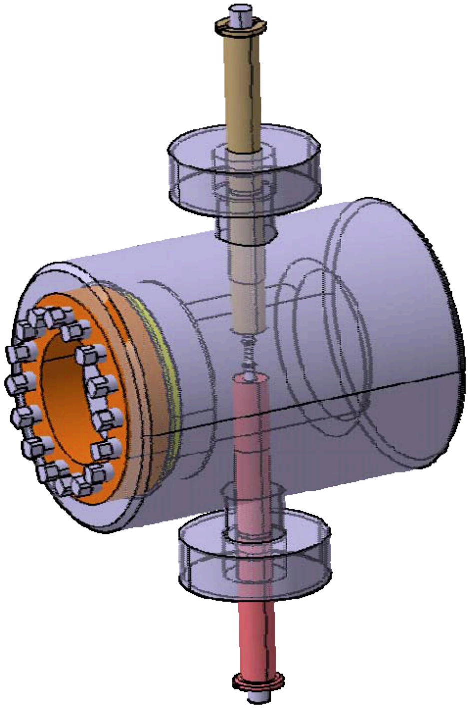


- For constant loading, estimates of fatigue life show good agreement with measured values; estimated lives are slightly lower than measured values
- As expected, fatigue life in air and water under spectrum loading is a factor of 2-3 lower; i.e., these results validate that the effect of loading history must be included in the factors of 2 & 20 to obtain the design curves

Complex Loading Tests on 304L SS Specimens

(ASME PVP2009-78129)



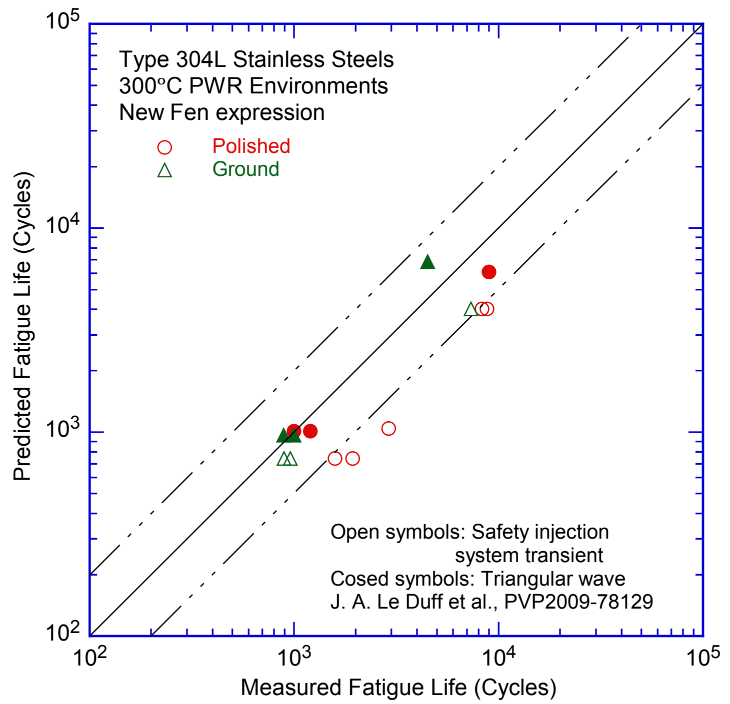


- 12-mm dia. test specimens in PWR environment
- Strain-controlled with triangular or complex signal to simulate safety injection transient
- RT YS = 255 MPa & UTS = 573 MPa
- Surface finish: polished or ground

- Baseline data indicate no heat-to-heat variation, fatigue S-N data for the material fall on the mean best-fit curve for smooth test specimens
- Since tests were conducted on small test specimens under constant loading conditions and the effects of surface finish are being investigated in this study, no adjustments are needed and test results should be within data scatter

Complex Loading Tests on 304L SS Specimens

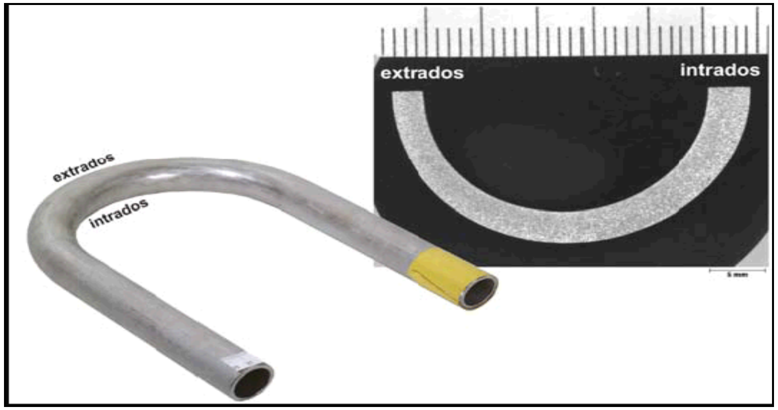
(ASME PVP2009-78129)



- Estimated fatigue lives using strain-integrated method show good agreement with measured values for triangular wave tests whereas those for SI transients are somewhat conservative
- For SI transient, multi-linear method is comparable & simplified method more conservative
- For both triangular & complex loading, surface grinding decreased life by a factor of up to 2
- May consider a threshold strain ε_{th} in computing F_{en}

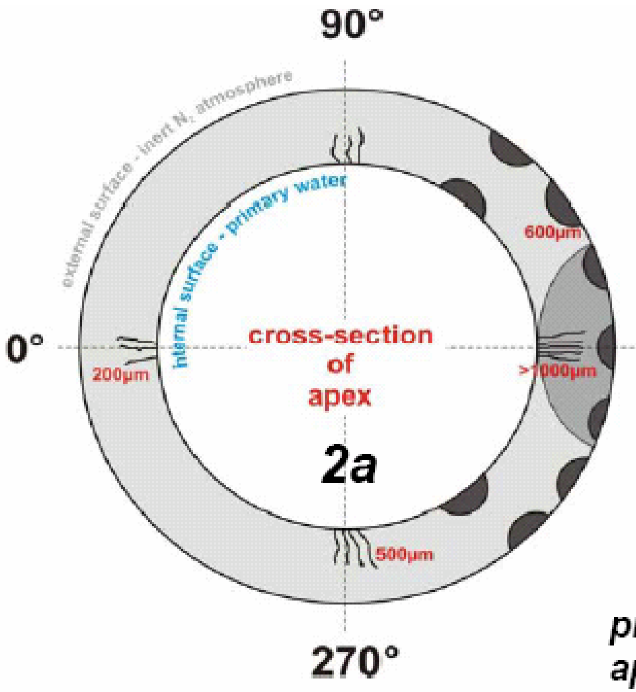
Type 304L U-Bends in Inert & PWR Water at 240°C

(ASME PVP2006-ICPVT-11-93318)



- Cold bending of nominal 33.4 mm OD 3.38 mm wall; resulting U-bends exhibit nonuniform wall thickness
- Surface finish: as pickled or mechanical polish
- RT YS = 275 MPa & UTS = 605 MPa
- Loading: axial strain controlled at OD surface of U-bend specimen intrados (180° position)
- OD cracks are circumferential & ID cracks typically are axial

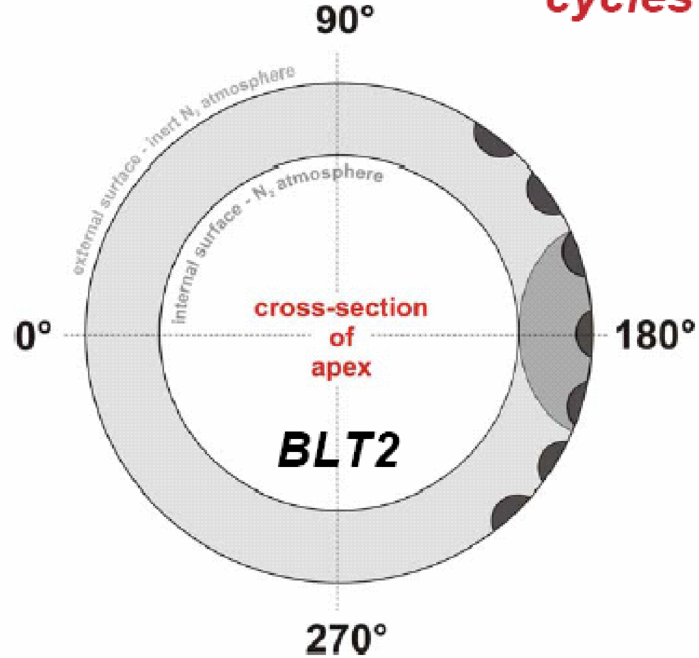
1520 cycles



0.6% strain amplitude

pickled/ as bent apex

1705 cycles

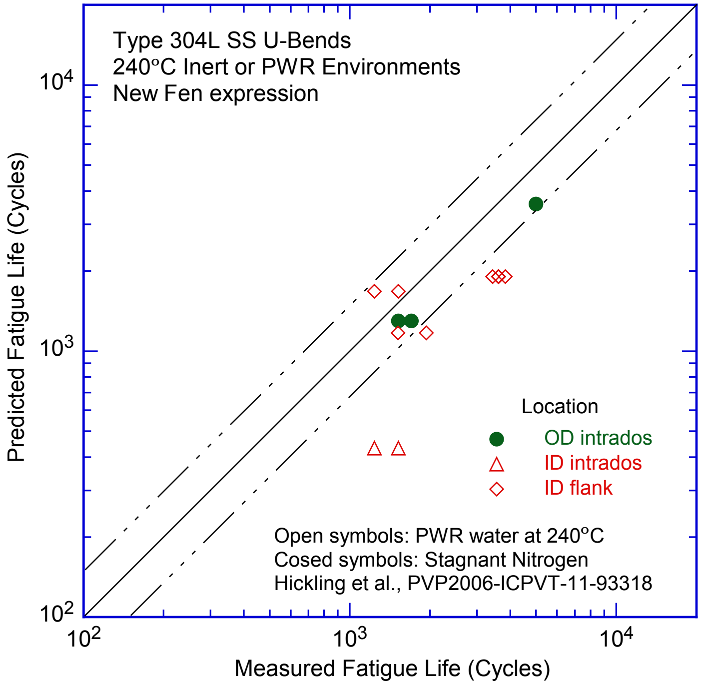


pickled/ as bent apex

Type 304L U-Bends in Inert or PWR Water at 240˚C

(ASME PVP2006-ICPVT-11-93318)

- The most significant result from this study is that for a given strain-controlled (at OD surface) test, relative to an inert environment, cracking in PWR environments occurred much earlier at the ID surface & at lower strain amplitudes
- In PWR environment, at 0.4% strain amplitude, through-wall failure was due to ID axial cracks at the flank location
- In inert environment, failure was due to OD circumferential cracks

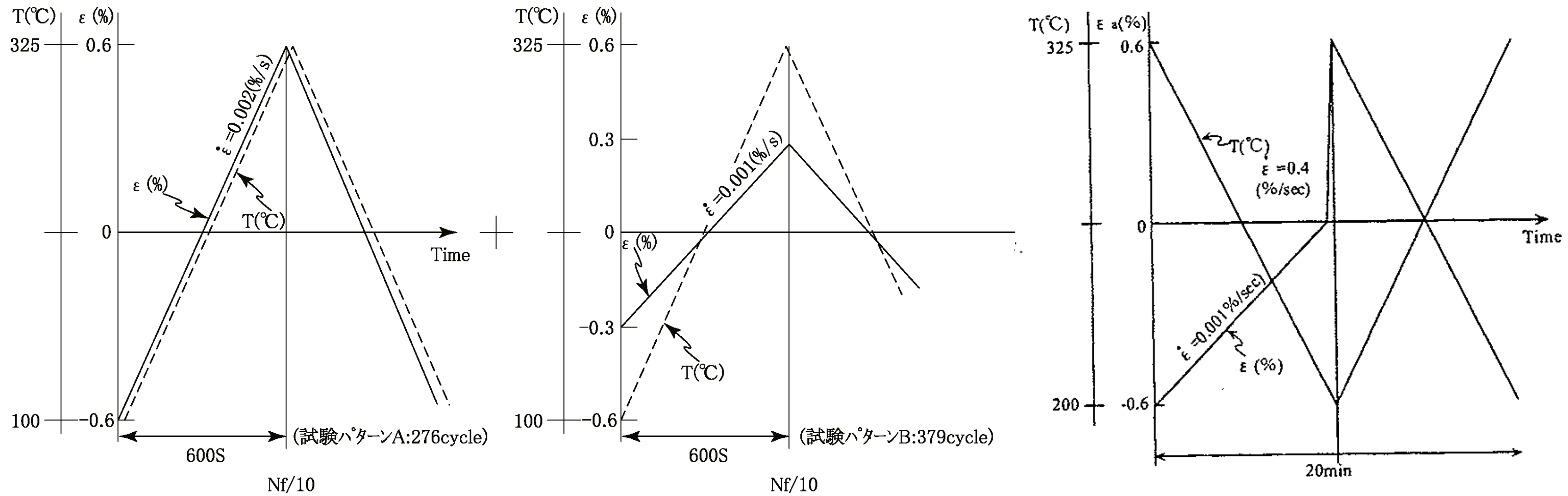


- To compare with results from a component test, predicted life was adjusted by a factor of 2.5 for surface finish & 1.2 for size, i.e., total of 3.0
- Since, heat-to-heat variation is also not known, including the effect of data scatter, estimated values of fatigue life may vary within ±2.8
- Estimated life in inert and PWR environments shows good agreement with measured values
- The lack of agreement for axial cracking at ID intrados is most likely related to the concurrent, dominant mechanical cracking (from OD) at the same location

Simulation of Actual Plant Conditions

(ASME PVP2006-ICPVT-11-93220)

- Each test included two or more blocks of different strain & temperature range with changing strain rate and/or temperature
- Transient waveforms selected to simulate the following 7 design transients:
  normal operation – plant heat-up & cooling, unit loading & unloading
  off-normal operation – reactor trip, inadvertent RCS depressurization, loss of load, & inadvertent ECCS actuation
- Tests performed on cylindrical hollow specimens of Type 316 SS, having 12 mm diameter & 3 mm wall in simulated PWR environment

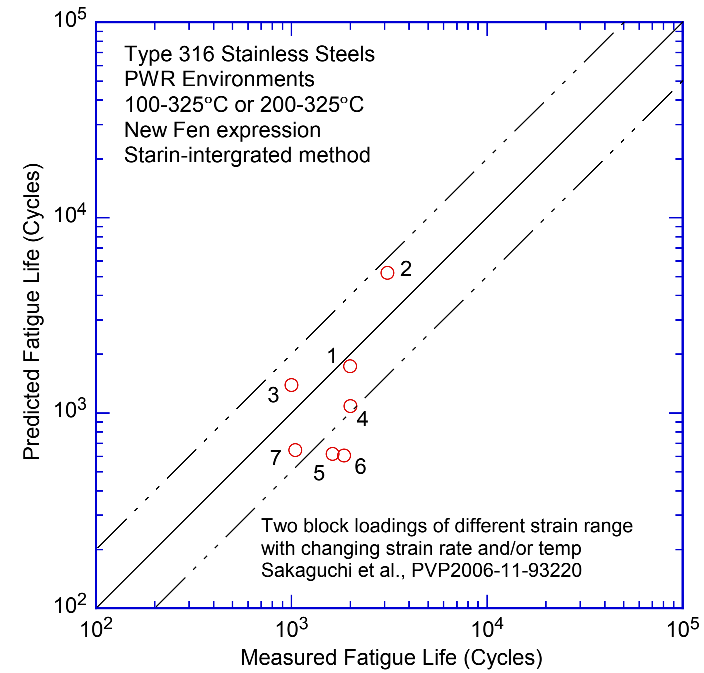


Simulation of Actual Plant Conditions (Contd.)

(ASME PVP2006-ICPVT-11-93220)

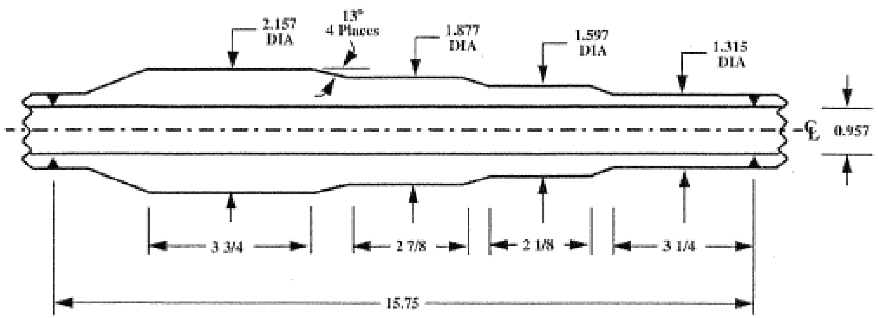
Test No	Block 1					Block 2					
	ε_a %	Pattern	Temp °C	Strain Rate %/s	Cycles /Block	ε_a %	Pattern	Temp °C	Strain Rate %/s	Cycles /Block	CUF Env.
1	0.6	In phase	100-325	0.002	275	0.3	In phase	100-325	0.001	379	1.20
2	0.6	In phase	100-325	0.002	27	0.3	In phase	100-325	0.001	379	0.70
3	0.6	Out of phase	100-325	0.002	311	0.6	In phase	200-325	0.002	152	0.74
4	0.6	Out of phase	100-325	0.002	311	0.6	In phase	200-325	0.002	15	1.84
5	0.6	In phase	200-325	0.4-0.001	77	0.6	In phase	200-325	0.001-0.4	70	2.82
6	0.6	Out of phase	200-325	0.4-0.001	70	0.6	Out of phase	200-325	0.001-0.4	77	2.48
7	0.6	In phase	200-325	0.4-0.001	77	0.6	Out of phase	200-325	0.001-0.4	77	1.51

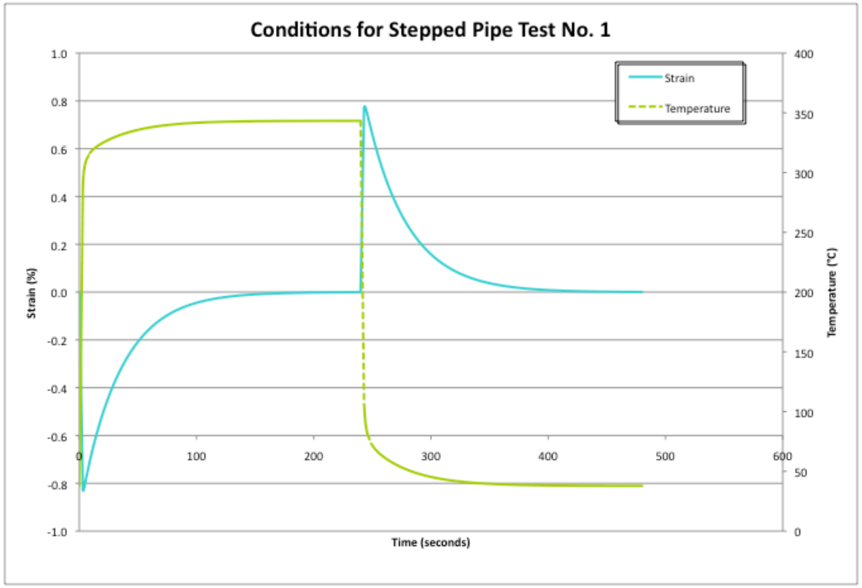
- Last column gives CUF for the tests expressed as $N_{observed}/N_{predict}$
- Data for heat-to-heat variation not known
- Predicted lives are either in good agreement with the observed values or are conservative
- Since, heat-to-heat variation is not known, including data scatter, estimated fatigue life may vary ±2.8



Thermal Fatigue Test of Stepped Type 304 SS Pipe

(ASME PVP-482, PVP2004-2748)





- Thickness: 15.2, 11.7, 8.12, & 4.55 mm
- Surface finish: production run piping
- RT YS = 207 MPa & UTS = 517 MPa
- Pipe pressurized to 17.2 MPa (2500 psi) & cycled between 38 and 343˚C

- Baseline fatigue data for this heat in air are comparable or slightly lower than the best-fit-curve (for the new Code design curve); i.e., minor heat-to-heat variation. *Note that the ASME best-fit air curve shown in Fig. 8 of the paper is the old curve*
- Fatigue life is defined as number of cycles to initiate a 0.254 mm (0.01 in.) crack because although many cracks initiated early they did not grow once they grew beyond the very steep stress gradient at the specimen surface.
- In the stepped pipe test crack growth rates decrease with crack advance, whereas in a strain-controlled test crack growth rates increase
- *NOTE: actual stress gradients are not expected to be steep because of plastic yielding*

Thermal Fatigue Test of Stepped Pipe (Contd.)

(ASME PVP-482, PVP2004-2748)

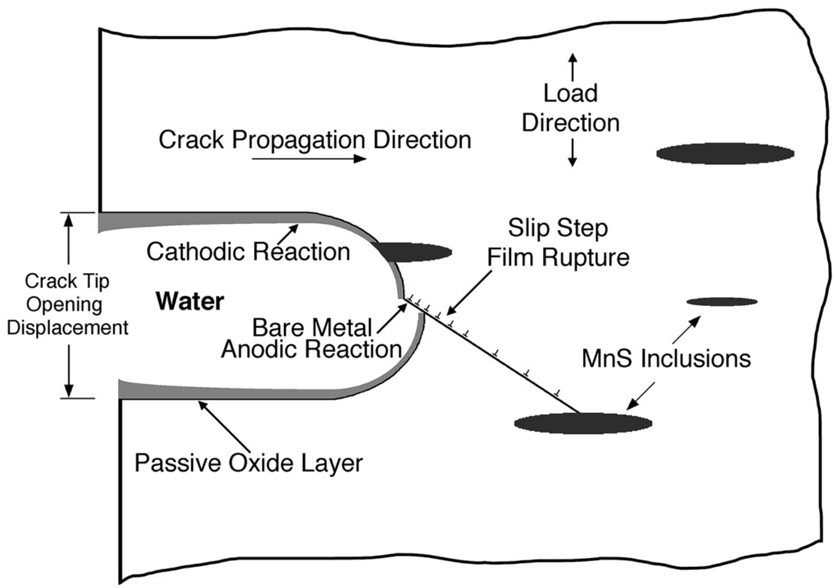
- Two pipe sections were examined for cracks after 708 and 2008 cycles:
  - Extensive cracking was observed in 15.2- & 11.7-mm thick sections of both specimens
  - Most cracks were 2.54 mm deep or deeper when tests were terminated; Fig. 7 shows several cracks in the 15.2-mm thick section that are 7 - 8 mm deep
  - Crack initiation was determined for selected defects by metallographic examination & counting fatigue striations back from the final crack size
  - Note that the reported values of crack initiation may not represent the minimum value

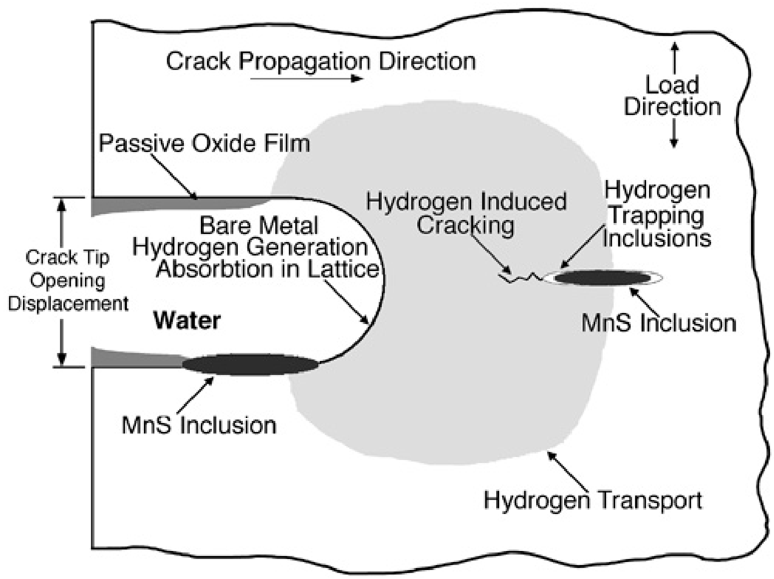
- For 15.2-mm section: N_{env} = 365-1408 cycles; N_{av} = 957 & N_{min} = 365 cycles; if these values represent 5-10% load drop N_{25} (at 25% load drop) = 380 cycles
- Estimated N_{air} = 1995 for specimen; using factors of 2 for surface finish & 1.3 for size N_{air} = 767 cycles for component (pipe); $N_{env} = N_{air} / F_{en}$ = 767/3.74 = 205
- Estimates of fatigue life based on strain-integrated & 4 ramp methods are comparable (205 and 184) & simplified method yields longer lives (e.g., 340)
- Predicted life is within the data scatter (i.e., a factor of slightly less than 2 lower)

Possible Mechanisms of Fatigue Crack Initiation

Possible Mechanisms for Fatigue Crack Initiation

- *Film Rupture/Slip Dissolution*: A strain increment ruptures the protective surface oxide film, crack extension occurs by dissolution/oxidation of the freshly exposed surface. Critical concentration of sulfide / hydrosulfide ions is required at crack tip
- *Hydrogen-induced Cracking*: hydrogen & vacancies produced by corrosion reaction enter the steel, hydrogen diffuses to strong trapping sites (MnS inclusions) ahead of the crack tip, which act as initiation sites for local quasi-cleavage cracking as well as void formation, & crack advances by linking of these microcracks with the main crack



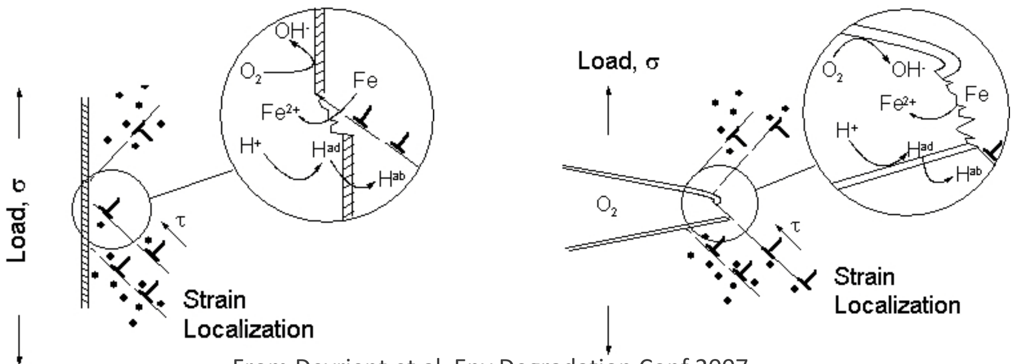


Fatigue Crack Initiation - Significant Results

- Fatigue data show very strong strain-rate dependence of life in LWR environments
- For low-alloy steels, fatigue data suggest that cracking occurs by hydrogen-induced cracking at high strain rates and by film rupture/slip dissolution at slow strain rates
  - at high strain rates, surface cracks are inclined to the stress axis and grow in a tortuous manner; fracture surface exhibits the typical fan-like or quasi-cleavage cracking
  - at slow strain rates, surface cracks are absolutely straight perpendicular to stress axis; & fracture surface is flat with evidence of crack arrest
- Fatigue crack initiation & crack growth may be enhanced in LWR environments by a combination of the two mechanisms
  - Hydrogen produced by the oxidation reaction diffuses into the steel ahead of the crack tip thereby changing the stacking fault energy, which results in more localized deformation
  - Strain localization leads to increased film rupture frequency, and crack extension occurs by dissolution/oxidation of the freshly exposed surface
- Dynamic strain aging may play an important role in the cyclic deformation process
  - DSA occurs in alloys containing solutes that segregate strongly to dislocations resulting in strong elastic interactions between the solute & dislocation stress-strain field
  - Depends on temperature and strain rate

Effect of Dynamic Strain Aging

- In high-temp water, the synergistic interactions between EAC and DSA during fatigue environment may be rationalized as follows:
  - Hydrogen and vacancies produced by the corrosion reaction at the crack tip enter the steel and hydrogen diffuses to strong trapping sites inside the crack tip maximum hydrostatic stress region (e.g., MnS inclusion) ahead of the crack tip
  - According to hydrogen-induced cracking, these sites act as initiation sites for local quasi-cleavage cracking and void formation, and these microcracks link with the main crack
  - According to an alternative mechanism, at a given macroscopic strain, the microscopic strain in a steel that is susceptible to DSA is higher because of strain localization to small areas, which leads to higher rates and larger steps of oxide film rupture. Therefore, the film rupture/slip dissolution process would enhance crack initiation or crack growth rates
  - Such processes occur under certain conditions of temperature, strain rate, and DO level, & may enhance EAC and increase fatigue crack initiation and crack growth rates



From Devrient et al. Env Degradation Conf 2007

Responses to Comments Received on F_{en} Validation Calculation Spreadsheet

NRC's Spreadsheet Calculations for Stepped Pipe Thermal Fatigue Test

- NRC performed spreadsheet calculations to evaluate a set of fatigue S-N data to validate the F_{en} methodology
- As discussed earlier, the results of seven experimental data sets were compared with calculations of fatigue life based on the NUREG/CR-6909 methodology and the revised F_{en} expressions for incorporating the effects of LWR coolant environments into fatigue CUF analyses
- The spreadsheet calculations for the stepped pipe test were provided to EPRI's Advisory Panel on EAF for review and comment on 01/11/2012 -- comments were requested by 01/31/2012
- On 02/14/2012, the NRC extended the comment period to 02/27/2012 at EPRI's request
- Four sets of comments were received (detailed comments at end of presentation):
  - Chuck Bruny (ASME Section III) – 01/18/2012
  - Robert Gurdal (AREVA) – 02/27/2012
  - Mark Gray and Matt Verlinich (Westinghouse) – 02/22/2012
  - Shannon Chu and Jean Smith (EPRI) – 02/28/2012
- *Paraphrased comments in purple italics;* NRC/ANL responses in black

Spreadsheet for Stepped Pipe Thermal Fatigue Test - Comments by Chuck Bruny (paraphrased)

- *This test does not validate F_{en} expressions; based on the following comments:*
  - *Comparing worst case crack initiation result with average air data is VERY conservative.*
  - *In Fig. 8 of the PVP paper, this heat appears to be below the best-fit curve, no adjustment for heat-to-heat variation & data scatter is conservative.*
  - *Test used crack initiation for the determination of cycles to failure; cracks initiated early but did not grow beyond the influence of the thermal skin stress.*
- Maybe this is a poor example for validating F_{en} because applied stress intensity decreases as cracks advance, whereas it increases in test specimens. However:
  - Even the test specimen data represent the worst case crack. Although several cracks initiate in a test specimen, the "fatigue life" whether defined by 25 or 50% load drop, separation, or 50% modulus change, is based on the longest crack.
  - As discussed in slide 75, the ASME best---fit air curve shown in Fig. 8 of the PVP paper represents the old curve. The spreadsheet calculations are based on the new Code curve; the heat used in these tests is marginally below the new best-fit curve.
  - Estimated values were adjusted by a factor of 2 for surface finish and 1.3 for size for a total of 3, difference between predicted and measured life should be within data scatter.
  - Since fatigue life is defined as a 0.254-mm crack, the effect of skin stress is unlikely to be significant; if this represents a 5-10% load drop for a test specimen, N_{25} will be 5% larger.

Spreadsheet for Stepped Pipe Thermal Fatigue Test

Comments by Robert Gurdal (paraphrased)

- *Comments 1 and 2 provided comparisons between AREVA's F_{en} calculations and NRC/ANL's F_{en} calculations. The comparisons showed very close agreement. It was noted that the new F_{en} expressions are improved (lower), but the improvements is not enough.*
- NRC/ANL appreciates the results of AREVA's efforts and considers these differences to be very small, as they are all within 10%. This difference is within the accuracy of the analysis.
- NRC/ANL have improved the F_{en} methodology to the extent possible based on incorporation of all fatigue test data that is currently available. In addition, we are adjusting the methodology to remove unnecessary conservatisms (i.e., the constant terms that lead to a jump in CUF even when EAF conditions are not present).
- The NRC has encouraged the industry to perform additional testing of actual components to test the ASME Code Section III CUF calculation methodology to allow for possible future reductions in conservatism.

Spreadsheet for Stepped Pipe Thermal Fatigue Test

Comments by Robert Gurdal (paraphrased) (cont'd)

- *Comments 3, 4, 5, 6, 7, 8, 10, 11, and 14 provided several comments on the selection of N_{air} and N_{leak} for the Bettis stepped pipe test and the use of those values to determine F_{en}.*
- The basis for the NRC's/ANL's selection of values is detailed on Slides 75 and 76 of this presentation.
- As mentioned on Slide 76, if 0.01" is considered to represent only 5% load drop, based on the actual measurements on test data on strain-controlled tests, the difference between 5% and 25% load drop is only 4 or 5% larger life (365 cycles vs. 380 cycles).

Spreadsheet for Stepped Pipe Thermal Fatigue Test

Comments by Robert Gurdal (paraphrased) (cont'd)

- *Comment 9: Those percentage differences reported in the Spreadsheet are very difficult to judge… The correct factor to look at is the severity factor, which is how severe the ASME-Code Design Methodology is vs. the test results.*
- NRC/ANL have eliminated the percentage differences – e.g., refer to the plot on Slide 74 which shows Calculated Fatigue Life vs. Measured Fatigue Life with factor of 2 variance lines.

Spreadsheet for Stepped Pipe Thermal Fatigue Test

Comments by Robert Gurdal (paraphrased) (cont'd)

- *Comment 13: Conclusion: The stepped pipe fatigue tests have shown us how severe the ASME-Code Fatigue Methodology is, EVEN before applying the F(en) factors and EVEN when using a crack depth of 0.25 mm, instead of through-wall cracking from the ASME-Code.*
- NRC/ANL agree with the comment.

Spreadsheet for Stepped Pipe Thermal Fatigue Test

Comments by Robert Gurdal (paraphrased) (concluded)

- *Comment 15: From an AREVA colleague from another Division, the idea is – for ASME-Code Piping Design – to use an exaggerated (conservatively) high F(en) factor of 15 together with performing the piping stress analysis only based on the internal pressure ranges and moment ranges (and without any peak stresses). I can very well see how the Nuclear Power Industry here in the U.S. has to find a simplified conservative methodology such as that one. This new idea has a lot of merit as the fatigue tests that are the basis for the ASME-Code Curves and for the F(en) equations only consider membrane-types of stresses and not at all the fact that the peak stresses ("skin stresses") do not grow cracks through the thickness (see also item 14 above).*
- NRC/ANL agree with the comment and note that most calculations we have seen use only ASME Section III NB-3200 methods. Very little work has been done using NB-3600 piping equations (because of the reduced conservatism needed).

Spreadsheet for Stepped Pipe Thermal Fatigue Test

Comments by Westinghouse (paraphrased)

- *Method #1 & #4: Strain Integrated Methods:*
  - *No comment can be made about the calculation of ε_i because the verifier did not have access to the input stress time history.*
  - *There is a difference in the F_{en} equations used by NRC/ANL and Westinghouse -- the difference in equations did not impact this comparison, but there is potential for other circumstances. This problem does not test the potential difference.*
  - *There is a difference in the T* equations reported in November in St. Louis to those used in the spreadsheet. This difference impacts both the ANL and 6909 sections, but again, this difference does not impact results for this particular problem.*
- The NRC can provide the input stress time history, if desired.
- The NRC's calculations used the Modified Rate Approach for F_{en} integration, as described in Section 4.2.14 of NUREG/CR-6909. It was not the intent to test methods from ASME Code Case N-792, which differ from those used in NUREG/CR-6909.
- There is no difference in the T* (or T') expressions shown in Westinghouse's comments.

Spreadsheet for Stepped Pipe Thermal Fatigue Test

Comments by Westinghouse (paraphrased) (cont'd)

- *Method #2 & #5: Simplified (Average) Methods:*
  - *These methods contained the same discrepancy described above in the boundaries of the inequalities for transformed temperature.*
  - *Different results are produced depending on how average temperature is calculated. For example average temperature could be interpreted as the average of the maximum and minimum temperature over the strain history (MV-Method), or the average of the temperatures at the time when strain is at its maximum or minimum value (Omesh). No precise guidance is present in NUREG-6909 or N-792 for this situation.*
  - *Noted that these methods, #2 and #5, have the potential to be un-conservative, as can be seen here by comparing N_{leak} to N_{water} for Method #2.*
- Refer to the responses to the comments above.
- Additional guidance will be provided on the appropriate temperature to use as a part of the planned revision to NUREG/CR-6909.
- Whereas N_{leak} is lower than N_{water}, the calculated results are within the factor of two scatter that is inherent to the test data. The intent of the calculations is to validate the F_{en} methodology by showing that the result is within the accuracy of the data used to develop the methodology.

Spreadsheet for Stepped Pipe Thermal Fatigue Test

Comments by Westinghouse (paraphrased) (cont'd)

- *Method #3 & #6: Multi-Linear Strain (Modified Rate) Methods:*
  - *These methods contained the same discrepancy described above in the boundaries of the inequalities for transformed temperature.*
  - *There is no guidance for segmentation of strain history in NUREG-6909 or N-792, so it is understandable that results from this method could potentially vary significantly from analyst to analyst.*
  - *The strain history was split into 4 segments to be consistent with resolution chosen by Omesh; however, verifier chose his own segments independently. The Westinghouse independent results more closely approximate the integrated method for both ANL and 6909 equations but are still in good agreement with Omesh's results for this problem. Westinghouse was able to duplicate Omesh's results exactly when using his time points; no errors with his calculations were discovered.*
- Refer to the responses to the comments above.
- Generally, the use of fewer segments is conservative with respect to F_{en}. The NRC feels that the trade-off of conservatism vs. accuracy is best left to the analyst.
- The results show that the selection of segments caused a minor impact on results. The NRC judges these differences to be small and well within the accuracy of the analysis.

Spreadsheet for Stepped Pipe Thermal Fatigue Test

Comments by Westinghouse (paraphrased) (concluded)

- *It is assumed the objective of Omesh's calculation was to compare various F_{en} expressions to experimental results of the "stepped pipe" model... This is an excellent start for such a comparison, but there must be further work before conclusions can be drawn. Some issues encountered while solving Sample Problem 2 should be considered… If conclusions were to be drawn from only this data, it appears that any of the methods/equations are conservative with respect to the test, with the exception of "Method #2: Simplified", and that the ANL equations yield smaller F_{en} factors than NUREG 6909; however, further development is required before definite conclusions can be drawn.*
- The primary comparison is to validate how well the F_{en} expressions predict failure of test data. As a secondary part of performing this validation, we investigated the various strain rate calculation methods that have typically been used by licensees in their calculations. The NRC agrees that the Sample Problem issues listed in the comment are important, but there is a lack of test data. Absent test data for actual components with complex loading, the F_{en} methods have been established to predict within the data scatter -- the NRC believes other observed conservatisms are likely due to conservatisms in the CUF calculational process.

Spreadsheet for Stepped Pipe Thermal Fatigue Test

Comments by EPRI (paraphrased)

- *EPRI also reviewed the spreadsheet, and had no comments and agreed with the methodology applied.*
- Thank you!

NRC Position on EAF Code Cases

ASME EAF Code Cases

- Fatigue Curve Code Case (ASME Approval Date: September 20, 2010):
  - N-761, "Fatigue Design Curves for Light Water Reactor (LWR) Environments"
- F_{en} Code Case (ASME Approval Date: September 20, 2010):
  - N-792, "Fatigue Evaluations Including Environmental Effects"

    (Revision 1 is currently under development)
- Strain Rate Code Case (still under development):
  - Action #10-293, "Procedure to Determine Strain Rate and F_{en} for use in an Environmental Fatigue Evaluation"
- Flaw Tolerance Code Case (still under development):
  - Action 09-274, "Fatigue Evaluations Using Flaw Tolerance Methods to Consider Environmental Effects"

Code Case N-761

Fatigue Design Curves for Light Water Reactor (LWR) Environments

- This Code Case was included in Supplement 3 to the 2010 Edition of Section III
- The NRC does not approve this Code Case:
  - The proposed curves for carbon and low alloy steels and the curves for austenitic stainless steels are not acceptable as sufficient technical basis has not been provided.
  - These curves are developed based on a factor of 10 on cycles and a factor of 2 on stress, which are not in agreement with the factor of 12 on cycles and a factor of 2 on stress as established in NUREG/CR-6909. The use of a different set of factors for the consideration of the LWR coolant environmental effects is inconsistent from both a technical and regulatory perspective.
  - The technical basis document does not describe the process step-by-step from beginning to end as to how final design curves for LWR environment were obtained.
  - The environmental curves included in this Code Case are not consistent with the experimental data. The strain rate dependence for the first three curves is much lower than that observed in experimental data on smooth cylindrical or tube specimens or even the recent EPRI-sponsored component tests in Germany.

Code Case N-761 (cont'd)

Fatigue Design Curves for Light Water Reactor (LWR) Environments

- The NRC does not approve this Code Case (cont'd):
  - There is no information provided in the basis document about the operating conditions that were used to represent the worst case environmental curve. Also, no information is provided in the basis document regarding the equation for the best-fit curve of the experimental data.
  - The technical basis document for the code case should address the effect of strain threshold and tensile hold time in fatigue evaluations.
- The NRC review will be included in a future revision to Regulatory Guide 1.193, "ASME Code Cases Not Approved for Use"

Code Case N-792

Fatigue Evaluations Including Environmental Effects

- This Code Case was included in Supplement 3 to the 2010 Edition of Section III
- The NRC does not approve this Code Case:
  - Based on industry comments that the F_{en} expressions give F_{en} values greater than 1.0 for situations when environmental effects have no impact, there are ongoing activities at NRC to modify F_{en} expressions. The Office of Research (RES), with the assistance of ANL experts, is pursuing this effort.
- The NRC review will be included in a future revision to Regulatory Guide 1.193, "ASME Code Cases Not Approved for Use"
- The NRC does not support revision of this Code Case at this time due to NRC's ongoing research activities

ASME Action Item #10-293 (no Code Case # yet)

Procedure to Determine Strain Rate and F_{en} for use in an Environmental Fatigue Evaluation

- This Code Case is still under development
- The NRC is evaluating this Code Case as a part of their current research activities, and will provide input on this Code Case after those activities are completed (currently scheduled for December 2012)

ASME Action Item #09-274 (no Code Case # yet)

Fatigue Evaluations Using Flaw Tolerance Methods to Consider Environmental Effects

- This Code Case is still under development
- The NRC does not support this Code Case:
  - In the design of Class 1 components, it is the NRC's expectation that the designer will ensure that the design limits specified by the Code in Section III are met.
  - As much as a designer is expected to meet the allowable stress limits specified for certain load levels, the same is also expected for the fatigue (CUF) limit of 1.0.
  - If the component is configured in such a way that the Code limits cannot be met, a designer must change the component configuration in such a way to ensure that all applicable limits are met.
  - This Code Case is developed to enable bypassing such design expectation for a new component.

Summary

Summary

What You Should Take Away From This Presentation

- Background Information
  - The debate should be over -- fatigue data indicate significant effects of LWR environment
  - NRC is completing additional research:
    - Review ASME EAF Code Cases
    - Revise F_{en} equations considering new available data and issues raised by industry
    - Address issues that arise in reviews of applications that the agency receives for license renewal applications and new reactors
    - Revise NUREG/CR-6909 and Regulatory Guide RG 1.207
- Fatigue Life – Definition
  - ASME Section III defines fatigue life as cycles to failure
  - ASME Section III used factors of 2 on stress and 20 on life to adjust small, polished test specimen data to make it applicable to actual components; they are not factors of safety
  - NUREG/CR-6909 used factors of 2 on stress and 12 on life to bound 95% of the data

Summary (cont'd)

What You Should Take Away From This Presentation

- Revised F_{en} Expressions
  - The F_{en} expressions presented in NUREG/CR-6909 have been revised/updated to address concerns related to:
    - The constants in the F_{en} expressions that results in a F_{en} of about 2 even at temperatures below 150 °C and very high strain rates
    - For carbon and low alloy steels, the temperature dependence of F_{en}; the NUREG/CR-6909 expressions extended up to 350 °C, which was beyond the range of the experimental data
    - For austenitic stainless steels, the dependence of F_{en} on water chemistry (i.e., BWR NWC vs. BWR HWC or PWR environments)
  - Under typical operating conditions, the new expressions yield comparable, and in some conditions slightly lower, F_{en} values to those estimated from NUREG/CR-6909
  - The new expressions yield comparable F_{en} values to those estimated from the JNES expressions*

* Using expressions from JNES Report No. JNES-SS-1005.

Summary (cont'd)

What You Should Take Away From This Presentation

- Strain Amplitude Threshold
  - Data indicate that during a strain cycle, the relative damage due to slow strain rate occurs only after the strain exceeds a threshold value
  - The mean-stress adjusted environmental curve for test specimens and the environmental curve for components show that the margins of 20 on life and 2 on stress (or strain) are not compromised
- F_{en} Validation Calculations
  - The results of 6 experimental data sets were compared with estimates of fatigue life based on the F_{en} methodology to validate the revised F_{en} expressions
  - The purpose of these calculations is to adjust and validate the F_{en} expressions, i.e., by using best estimates of applied strain in the test specimens, and not those determined from ASME Code procedures
  - The predicted life for all data sets was within the data scatter (i.e., a factor of slightly less than 2 lower) – therefore, there was no need to further adjust the revised F_{en} expressions

Summary (cont'd)

What You Should Take Away From This Presentation

- Possible Mechanisms of Fatigue Crack Initiation
  - Film Rupture/Slip Dissolution and Hydrogen-induced Cracking are two possible mechanisms that explain fatigue crack initiation
    - Fatigue data show very strong strain-rate dependence of life in LWR environments
    - For low-alloy steels, fatigue data suggest that cracking occurs by hydrogen-induced cracking at high strain rates and by film rupture/slip dissolution at slow strain rates
    - Fatigue crack initiation & crack growth may be enhanced in LWR environments by a combination of these two mechanisms
  - Dynamic strain aging may play an important role in the cyclic deformation process
- Responses to Comments Received on F_{en} Validation Calculation Spreadsheet
  - NRC solicited review of F_{en} calculations for the Bettis stepped pipe test
  - Four sets of comments were received from interested stakeholders
  - NRC has provided brief responses in this presentation. Detailed responses are being prepared. Both will be posted in ADAMS for public access (by ~6/30/12)

Summary (concluded)

What You Should Take Away From This Presentation

- NRC Positions on the EAF Code Cases
  - The NRC does not endorse any of the four ASME Section III EAF Code Cases
    - Fatigue Curve Code Case, N-761
    - F_{en} Code Case, N-792
    - Strain Rate Code Case (still under development), Action #10-293
    - Flaw Tolerance Code Case (still under development), Action #09-274

Next Steps

Next Steps

- NRC will post this presentation and responses to comments posted in ADAMS by ~06/30/12
- Interested stakeholders should provide their input to the NRC before September 2012 (firm)
- NRC will attend EPRI's EAF Panel Meeting at ASME Code Meetings in Washington, DC in August and will request time on agenda to hear stakeholder feedback
- NRC will finalize all research activities in September 2012
- NRC will revise NUREG/CR-6909 to incorporate results of research activities (October-December 2012)
  - New contents to be added: Hold Time Effects, Strain Threshold, Summary of JNES Data, Revised F_{en} Expressions, F_{en} Validation Calculations, Practical issues with F_{en} Methodology
- NRC will begin revising Reg. Guide 1.207 in 2013 – current estimate is for it to be out for public comment in ~Fall 2013

Questions?

Backup Slides – Detailed Comments Received on NRC Spreadsheet Calculations

Spreadsheet for Stepped Pipe Thermal Fatigue Test - Detailed Comments by Chuck Bruny

1. *I have several reservations about using this test as a benchmark for evaluating F_{en}. The Code basis for the air fatigue curves and application of F_{en} is to prevent leakage or through wall failure, not crack initiation. This test used crack initiation for the determination of cycles to failure. PVP2004-2748 states that many of the cracks were initiated early but did not grow once they grew beyond the influence of the thermal skin stress. It is not clear which test specimen contained which test result other than cycles to initiation greater than 708 had to be from the second specimen. The assumption appears to be that the cracks evaluated were still growing when the test was stopped. If he evaluated cracks had arrested prior to stopping the test, the cycles to crack initiation would be over estimated. The report also stated most of the cracks (I assume this means most of the cracks reported in Table 4 Test Results) were 0.1 inch (2.5 mm) deep or deeper. However I assume the growth rate was decreasing if not arrested as the crack moved out of the high stress area. I believe this is a better benchmark to evaluate the fracture mechanics crack growth evaluation to see how the crack growth and crack depth at arrest predictions compare to the test results.*

Spreadsheet for Stepped Pipe Thermal Fatigue Test - Detailed Comments by Chuck Bruny (concluded)

2. *I offer the following comments to the spreadsheet. Based on the figure in the PVP paper, the performance of this heat appears to be below the best fit curve. Considering no adjustment for heat-to-heat variation may be generous. Adjusting the best fit air curve for only surface effects results in 1995/2 = 998 cycles to failure (or at least a 3 mm crack) compared to an average of 957 cycles for crack initiation (0.25 mm) in the water environment. This would suggest that the F_{en} for this test is less than 1.0 ignoring size effect and even lower if size effect is considered. The use of the worst case crack initiation result and comparing it to in-air average results with no adjustment for heat-to-heat variation or data scatter is VERY conservative.*
3. *In my opinion this does not validate F_{en}. However, considering my comments above, I would not expect it to validate F_{en}. It does appear to validate that high thermal skin stress cycles will not drive a crack through the thickness. Additional cyclic loads would be required to propagate the cracks initiated by the local thermal stress.*

Spreadsheet for Stepped Pipe Thermal Fatigue Test - Detailed Comments by Robert Gurdal

1. *The Spreadsheet F(en) values versus my F(en) values:*

Method No.	Description	NRC/ANL F(en)	F(en) From Robert	Spreadsheet F(en), compared with Robert's Calcs	Notes
1	Nov. 2011 F(en) Equations / Integral of F(en) values	3.86	3.89	-1 %	Negligible difference
2	Nov. 2011 F(en) Equations / Average temp. and aver. Strain rate	1.67	1.57	+ 7 %	Relatively small difference
4	March 2007 NUREG/CR-6909 / Integral of F(en) values	4.19	4.23	-1 %	Negligible difference
5	March 2007 NUREG/CR-6909 / Average temp. and aver. Strain rate	2.82	2.72	+ 4 %	Relatively small difference

Conclusion of the Table above: the F(en) calculations performed in the Spreadsheet have been QA'ed for the Methods 1, 2, 4 and 5, but have not been verified for the Methods 3 and 6.

Spreadsheet for Stepped Pipe Thermal Fatigue Test - Detailed Comments by Robert Gurdal (cont'd)

2. *November 2011 F(en) values versus NUREG/CR 6909:*

   - *NRC/ANL F(en) + Using average temperature and average strain rate: 1.67 / 2.82 = 0.59   Inverse = 1.69*
   - *F(en) from Robert + Using average temperature and average strain rate: 1.57 / 2.72 = 0.58   Inverse = 1.73*
   - *NRC/ANL F(en) + Integral of F(en) values: 3.86 / 4.19 = 0.92   Inverse = 1.09*
   - *F(en) from Robert + Integral of F(en) values: 3.89 / 4.23 = 0.92   Inverse = 1.09*

   Therefore, the latest November 2011 F(en) equations show the trend that is needed for the future: find methods that give a relief to the U.S. Nuclear Industry. What is being done here is however not enough (between a 9 % and a 73 % improvement).

Spreadsheet for Stepped Pipe Thermal Fatigue Test - Detailed Comments by Robert Gurdal (cont'd)

3. *The NRC/ANL Spreadsheet states that N(leak) from the test is equal to 365, ALTHOUGH N(0.01" crack) is equal to 365. Therefore, it is impossible for N(leak) to be equal to 365. N(leak) would be 1,000 as a minimum, and probably more.*

   On this topic of the number of cycles for the stepped pipe fatigue tests, on page 16 of the Attachment 3 of the November 2011 ASME-Code SGFS Meeting Minutes, it is mentioned that the number of cycles to produce a 3 mm crack depth would be 450. This is an extremely low number that hopefully will not be used by anybody, when compared with the MINIMUM number of cycles of 365 to produce a 0.254 mm crack (12 times less than 3 mm).

Spreadsheet for Stepped Pipe Thermal Fatigue Test - Detailed Comments by Robert Gurdal (cont'd)

4. *Changing the value of N(leak) = 365 in the Spreadsheet to a higher value (see item 3 above) would change completely the values of the Differences (-45.53 %, 25.61 %, etc ....) reported in the Spreadsheet, as N(leak) (which needs to be considered in the ASME-Code methodology) is probably here a very high number, much higher than 365.*

Spreadsheet for Stepped Pipe Thermal Fatigue Test - Detailed Comments by Robert Gurdal (cont'd)

5. *Concerning the Adjusted N(air) value of 767 in the Spreadsheet, this is here 1,995 / (2 * 1.3), where 1.3 is the correct size effect factor, but the surface finish effect should be approx. 2.65, instead of 2.0. The main thing here is that the data scatter factor has not been considered at all, although the smallest number of cycles to generate the 0.01" crack depth has been used as the comparison number. All these discussions happened already in 2007 and 2008, and - in general - the conclusion of those discussions was that the ASME-Code or NUREG/CR-6909 Design number of cycles needed to be compared with the number of cycles to produce a leak, and not a higher number of cycles, such as done here (1,995 / (2 * 1.3), for example). This makes a lot of sense, because the Nuclear Industry is designing for fatigue based on the final Design fatigue curve, and not based on the equations analyzed to develop those Design Fatigue Curves. I am almost sure that everybody will agree with me about that, as it is what makes sense and as it was agreed upon in the 2007/2008 time frame.*

Spreadsheet for Stepped Pipe Thermal Fatigue Test - Detailed Comments by Robert Gurdal (cont'd)

5. *(cont'd)*
   Another way to express this is that - if we do not divide by the data scatter effect (2.42, according to NUREG/CR-6909) - then the number of cycles to produce a 0.01" crack depth is NOT at all 365, but 957, where this number of cycles of 957 is the AVERAGE number of cycles to produce a 0.01" crack depth, and these two numbers of cycles of 365 and 957 are still very low, as what counts for the ASME-Code methodology is the number of cycles corresponding to through-wall cracking (as told to us so many times by Dr. O'Donnell and as mentioned in the ASME-Code), and not at all the number of cycles to produce a 0.01" crack depth.
   *In summary: the value of 767 needs here to be changed to 1,995 / (2.65 * 1.3 * 2.42), where 2.65 is the correct value for the surface finish effect from the NUREG/CR-6909 Report, and 2.42 is the data scatter effect, also from the NUREG/CR-6909 Report, and that is if we do not consider the sequence effect, which - in the Nuclear Industry - does not need to be considered, as the thermal transients are distributed quite evenly during the life of the nuclear power plant, in addition to the ASME-Code requiring a severe pairing of the Peaks and Valleys for the ASME-Code fatigue calculations.*

Spreadsheet for Stepped Pipe Thermal Fatigue Test - Detailed Comments by Robert Gurdal (cont'd)

6. *As I do not know enough how to predict the numbers of cycles to generate a 3 mm crack or to reach through-wall cracking, the number of 365 (0.25 mm crack) should be retained with the understanding that this is not the number of cycles corresponding to the ASME-Code fatigue methodology. This last point is very important, as the number of cycles corresponding to the ASME-Code fatigue methodology (through-wall cracking) would be a very high number.*

Spreadsheet for Stepped Pipe Thermal Fatigue Test - Detailed Comments by Robert Gurdal (cont'd)

7. *In that big Spreadsheet on the stepped Pipe fatigue Tests, I found the following statement:*

   - *Fig 7 of the Bettis paper PVP2004-2748 shows no heat-to-heat variability for the heat of material used for stepped pipe test. Smooth specimen data at 24° C and 357° C fall on the best-fit-curve for test specimens. So, not need to apply any factor for heat-to-heat variability.*

   If there is no heat-to-heat variability to be considered (which I did not verify), there is anyway - in Design - still a scatter effects factor of 2.0 to be considered when calculating the allowable number of cycles. As a result, if we want to compare with the Minimum number of cycles of 365 (to produce a 0.01" crack depth, which is a very small crack depth), the analytical number of in-air Adjusted allowable cycles needs to be 767 (which in itself is already a big number, compared to what it should be) divided by 2.0, and not just 767. This factor of 2.0 has been completely forgotten in that Spreadsheet.

Spreadsheet for Stepped Pipe Thermal Fatigue Test - Detailed Comments by Robert Gurdal (cont'd)

8. *It is very unclear how the Adjusted N(air) value can be 767. I am not sure how it got Adjusted ? The correct N(air) value is either 144 (pre-2009) or 168 (2009 and beyond), a lot less than 767. Therefore, this number of cycles of 767 needs to be canceled as soon as possible from the Spreadsheet.*

Spreadsheet for Stepped Pipe Thermal Fatigue Test - Detailed Comments by Robert Gurdal (cont'd)

9. *Those percentage differences reported in the Spreadsheet are very difficult to judge, because it is not clear for example what the denominator should be and what a positive or negative number really means ? The correct factor to look at is the severity factor, which is how severe the ASME-Code Design Methodology is vs. the test results. Therefore, it is very simple.*

Spreadsheet for Stepped Pipe Thermal Fatigue Test - Detailed Comments by Robert Gurdal (cont'd)

10. *Based on item 9 above, WITHOUT any consideration of F(en) factors, the severity factor resulting from these tests is simply 365 / 168 = 2.2, which is a severity factor that has been pushed down to the lowest possible value as it is based on the number of cycles to produce a 0.25 mm crack (much too small) and as I did not impact the 168 cycles from Design by any F(en) factor.*

Spreadsheet for Stepped Pipe Thermal Fatigue Test - Detailed Comments by Robert Gurdal (cont'd)

11. *We need to remember here that the factor of 1.55 for sequence effects should not be in the factor of 12 when developing the Section III, Div. 1 ASME-Code Fatigue Curve, as Section III, Div. 1 of the ASME-Code is for the Nuclear Power Plants. Therefore, trying to push this Severity Factor from item 10 above as low as possible, it is recognized that the severity factor is 2.2 / 1.55 = 1.4, which is still higher than 1.0 and therefore completely unacceptable for a reasonable Design, as this 1.4 is based on that very low number of cycles of 365 (0.25 mm crack depth, instead of through-wall cracking).*

Spreadsheet for Stepped Pipe Thermal Fatigue Test - Detailed Comments by Robert Gurdal (cont'd)

12. *Based on the F(en) factors calculated in the NRC/ANL Spreadsheet, the Severity factor of 1.4 would increase to:*

- *5.9 (Method 4; NUREG/CR-6909, Integrated F(en))*
- *5.4 (Method 1; Nov. 2011 F(en) equations, Integrated F(en))*
- *4.0 (Method 5; NUREG/CR-6909, average T and average strain rate)*
- *2.3 (Method 2; Nov. 2011 F(en) equations, average T and average strain rate)*

All these severity factors are just not acceptable at all for a reasonable ASME-Code fatigue design for the nuclear power plants, and to minimize this severity factor as much as possible, note that the combination of taking the Nov. 2011 F(en) equations and the average T and average strain rate methodology would have to be adopted, ALTHOUGH still extremely severe, as this is still based on the number of cycles of 365 from the tests.

Spreadsheet for Stepped Pipe Thermal Fatigue Test - Detailed Comments by Robert Gurdal (cont'd)

13. *Conclusion: The stepped pipe fatigue tests have shown us how severe the ASME-Code Fatigue Methodology is, EVEN before applying the F(en) factors and EVEN when using a crack depth of 0.25 mm, instead of through-wall cracking from the ASME-Code.*

Spreadsheet for Stepped Pipe Thermal Fatigue Test - Detailed Comments by Robert Gurdal (cont'd)

14. *For these stepped pipe fatigue tests, there is a reason why the crack cannot grow through the thickness and that was very well mentioned in the 9th slide of Tim Gilman's presentation from January 22nd 2009 (in Charlotte, N.C.; I was not there) : "0.01" crack size criterion was used, because, although cracks initiated, they simply would not grow past the influence of thermal skin stresses with subsequent cycles". Although it is not known for sure, there is a possibility that the crack - in this case - would never have reached a depth of 3.0 mm (0.118").*

Spreadsheet for Stepped Pipe Thermal Fatigue Test - Detailed Comments by Robert Gurdal (concluded)

15. *From an AREVA colleague from another Division, the idea is – for ASME-Code Piping Design – to use an exaggerated (conservatively) high F(en) factor of 15 together with performing the piping stress analysis only based on the internal pressure ranges and moment ranges (and without any peak stresses). I can very well see how the Nuclear Power Industry here in the U.S. has to find a simplified conservative methodology such as that one. This new idea has a lot of merit as the fatigue tests that are the basis for the ASME-Code Curves and for the F(en) equations only consider membrane-types of stresses and not at all the fact that the peak stresses ("skin stresses") do not grow cracks through the thickness (see also item 14 above).*

Spreadsheet for Stepped Pipe Thermal Fatigue Test - Detailed Comments by Westinghouse

1. *Comments on Application of Methods:*

   Method #1 & #4: Strain Integrated Methods

   - *No comment can be made about the calculation of ε_i because the verifier did not have access to the input stress time history.*
   - *[There is a difference in the F_{en} equations used by NRC/ANL and Westinghouse] -- the difference in equations did not impact this comparison, but there is potential for other circumstances. This problem does not test the potential difference.*
   - *[There is a difference in the T* equations reported in November in St. Louis to those used in the spreadsheet.] This difference impacts both the ANL and 6909 sections, but again, this difference does not impact results for this particular problem.*

   Method #2 & #5: Simplified (Average) Method

   - *These methods contained the same discrepancy described above in the boundaries of the inequalities for transformed temperature.*
   - *Different results are produced depending on how average temperature is calculated. For example average temperature could be interpreted as the average of the maximum and minimum temperature over the strain history (MV-Method), or the average of the temperatures at the time when strain is at its maximum or minimum value (Omesh). No precise guidance is present in NUREG 6909 or N-792 for this situation.*

Spreadsheet for Stepped Pipe Thermal Fatigue Test - Detailed Comments by Westinghouse (cont'd)

1. *Comments on Application of Methods (cont'd):*
   - *Noted that these methods, #2 and #5, have the potential to be un-conservative, as can be seen here by comparing N_{leak} to N_{water} for Method #2.*

   Method #3 & #6: Multi-Linear Strain (Modified Rate) Method
   - *These methods contained the same discrepancy described above in the boundaries of the inequalities for transformed temperature.*
   - *There is no guidance for segmentation of strain history in NUREG 6909 or N-792, so it is understandable that results from this method could potentially vary significantly from analyst to analyst.*
   - *The strain history was split into 4 segments to be consistent with resolution chosen by Omesh; however, verifier chose his own segments independently. The Westinghouse independent results more closely approximate the integrated method for both ANL and 6909 equations but are still in good agreement with Omesh's results for this problem. Westinghouse was able to duplicate Omesh's results exactly when using his time points; no errors with his calculations were discovered.*

Spreadsheet for Stepped Pipe Thermal Fatigue Test - Detailed Comments by Westinghouse (concluded)

2. *Comments on Objective of Calculation:*
   - *It is assumed the objective of Omesh's calculation was to compare various F_{en} expressions to experimental results of the "stepped pipe" model.*
   - *It seems the primary comparison is between the experimental results and the increasingly detailed F_{en} methods (Simplified, Multi-Linear, and Strain Integrated).*
   - *Thus the secondary comparison was between the 6909 equations for the aforementioned three methods and the ANL-modified equations for the same methods.*
   - *This is an excellent start for such a comparison, but there must be further work before conclusions can be drawn. Some issues encountered while solving Sample Problem 2 are: pairing and selection of "tensile producing" portions of complex stress histories, overlapping strain ranges for transient pairs, calculation and use of signed stress intensity, irregular stress time histories, etc.*
   - *If conclusions were to be drawn from only this data, it appears that any of the methods/equations are conservative with respect to the test, with the exception of "Method #2: Simplified", and that the ANL equations yield smaller Fen factors than NUREG 6909; however, further development is required before definite conclusions can be drawn.*

Spreadsheet for Stepped Pipe Thermal Fatigue Test - Detailed Comments by EPRI

1. *Thank you again for allowing extra time. I saw that you were copied on the additional comments from Westinghouse and Areva. Jean Smith here at EPRI also reviewed the spreadsheet, she had no comments and agreed with the methodology applied.*

The End