

Fatigue Limit of Stainless Steel for Use in Vibration Evaluation

June 30, 2016

NRC Public Meeting on Fatigue Research and Related ASME Activities

Rockville, MD



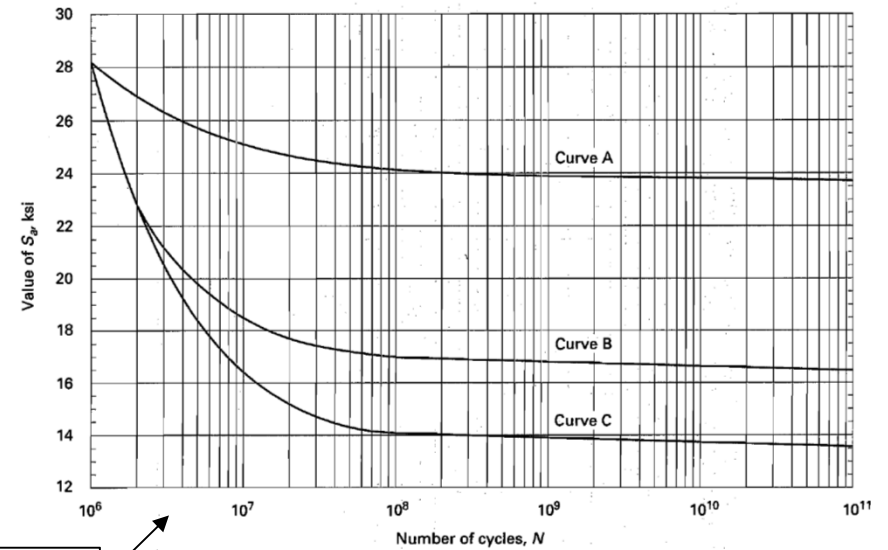
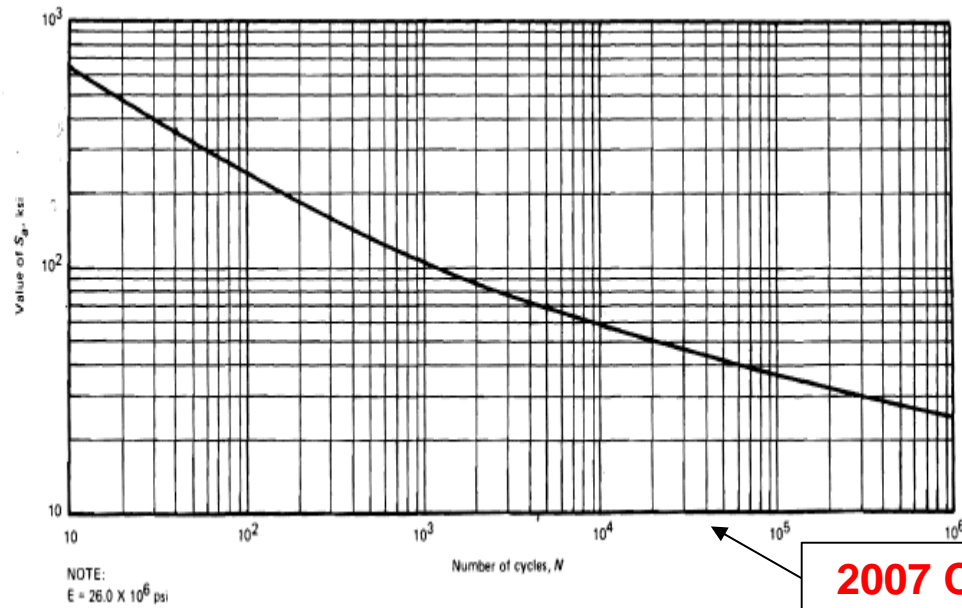
Outline

- Background
- Differences in the Fatigue Curve in the 2007 and 2010 Code
- Jaske –O'Donnell Curves
- Kanazawa work on Stainless Steel High Cycle Fatigue
- Work of Manjoine and Tome on Curves A/B/C
- NUREG/CR 6909 work that resulted in the 2010 Code Curve
- Relationship of Fatigue limit to Ultimate Strength
- Fatigue Limit based on Load Controlled Data
- Mean Stress Correction based on S_y and S_u at Temperature
- Conclusions and Recommendations
- Proposed Code case

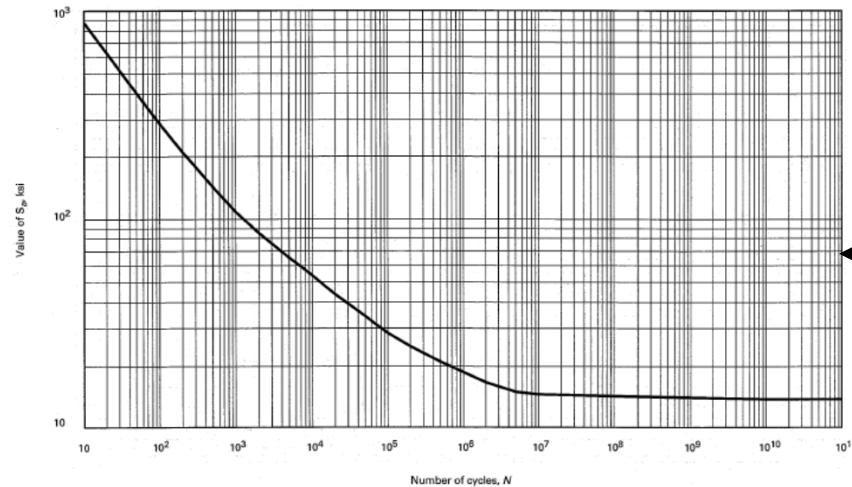
Background

- Reactor internals are subjected to fatigue cycling from stress cycles due to operating transients and vibrations
 - ASME Code design fatigue curves are largely based on low cycle fatigue tests with strain cycling. The strains are converted into pseudo-elastic stress by multiplying by the elastic modulus
 - High cycle fatigue associated with vibrations is load controlled, not dependent on the elastic modulus, E , and involves stress amplitudes below S_y
 - Since the stress under high cycle fatigue is independent of E (stress was either P/A for axial loading or Mc/I for bending), the question of whether a correction for E is required for high cycle fatigue becomes relevant
- Earlier versions of the Code (up to 2007 Edition) fatigue curves for stainless steels had recognized the difference between cycle fatigue and low cycle fatigue from the point of view of the correction for E
 - The first curve from 10 to 10^6 cycles specified an E value
 - The second sets of curves from 10^6 to 10^{11} cycles didn't provide a specific E value
- Later versions of the Code (2010 and later) combined the two sets of curves into a single curve with a cyclic range of 10 to 10^{11} cycles with E value specified at room temperature

Comparison of the Fatigue Curve in the 2007 and 2010 Codes



2007 Code



2010 Code

GENERAL NOTES:
 (a) $E = 28.3 \times 10^6$ psi
 (b) Table I-9.2 contains tabulated values and an equation for an accurate interpolation of this curve.

Background (cont.)

- As a result of combining the low and high cycle parts into a single curve, the requirement for E correction applies to the high cycle end also
 - Correction for E can reduce the fatigue limit by up to 8%. This could be problem for some reactor internals
- An important question is how strain controlled test data can be used to evaluate vibratory loading specifically as it applies to correction for E. Alternatively, are other ways available to establish the fatigue limit for stainless steel?
- Initial discussions with the ASME WG on Fatigue Strength led to the requests for reviewing the technical basis documents for the change in the 2010 Code
- Objective of this project is to develop the technical basis for the fatigue limit of stainless steel for use in vibration evaluation

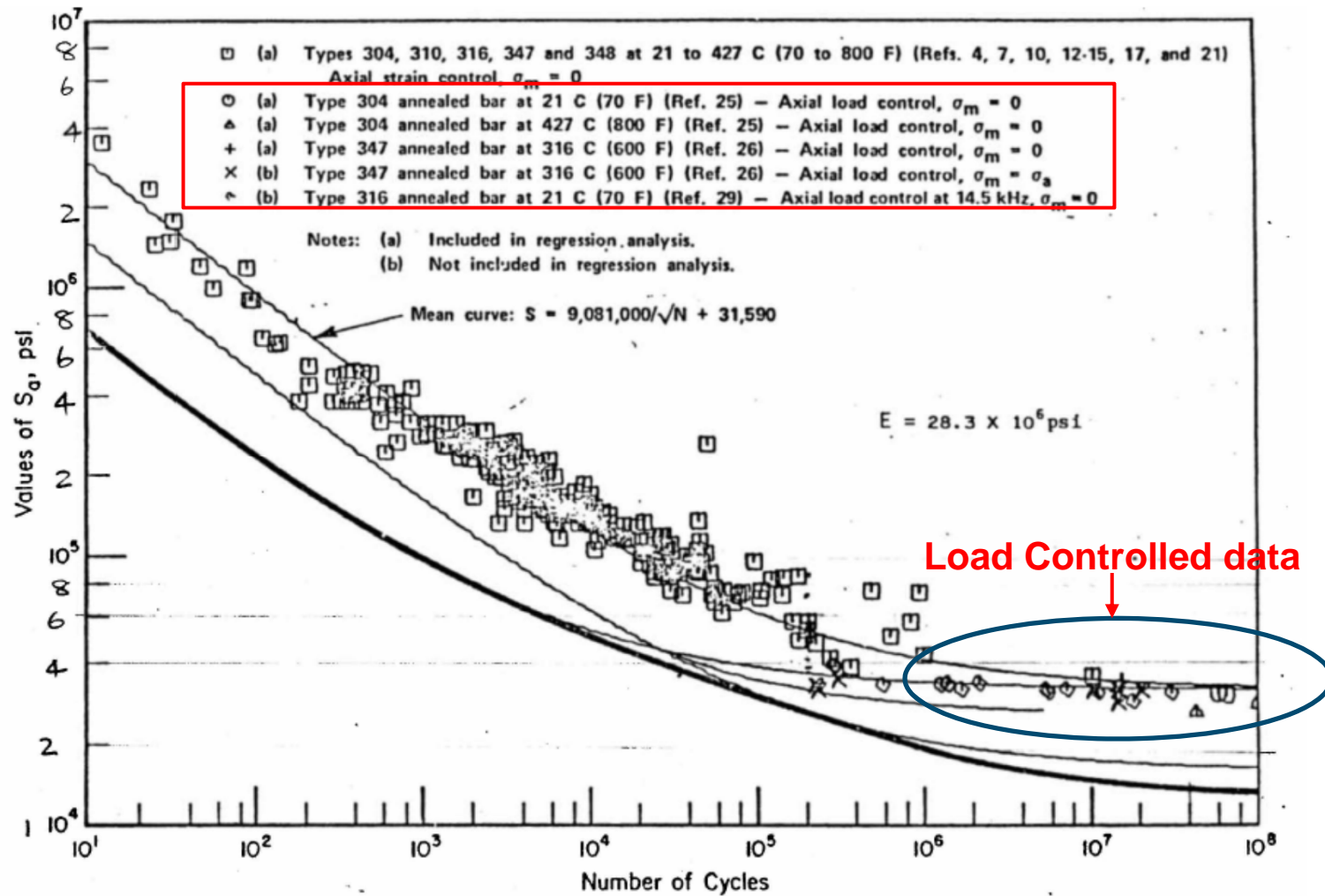
Review of Background Documents

- Several technical basis documents of the WG on Fatigue Strength (WGFS) used in the development of the ASME Code fatigue design curve were reviewed.
- Much of the work by WGFS was directed to methods for considering environmental effects in the fatigue design
 - High cycle fatigue or the E-correction issue was not explicitly addressed.
- In the end they accepted the NUREG/CR-6909 suggested curve for stainless steels
 - Differences between Curves A/B/C and new method not explicitly addressed
 - In particular, the documentation suggests that the differences between load control data and strain control data and the issue of E-correction for load control were not explicitly addressed
 - Other papers were reviewed to resolve the Fatigue Limit issue. The review of the literature on stainless steel fatigue is described here.

Jaske-O'Donnell Paper on Stainless Steel Fatigue

- The original Langer fatigue curve was limited to 10^6 cycles. Data beyond 10^6 cycles are needed for vibration assessment.
- Work of Jaske-O'Donnell added new data for a variety of stainless steels and for Ni-based alloys (up to 10^8 cycles)
- Data covered temperatures up to 800°F and included both strain and load-controlled data up to 10^8 cycles
- Using the best fit curve for the low and high cycle fatigue data, the fatigue limit was 31.6 ksi. This was based on combining low cycle strain control data and high cycle load control data
- With the 2 and 20 margin and mean stress correction, the fatigue limit was determined to be 13.6 ksi
- While the paper added new data, the approach of combining the strain controlled low cycle data and load controlled high cycle fatigue data to determine a new curve fit brings up questions

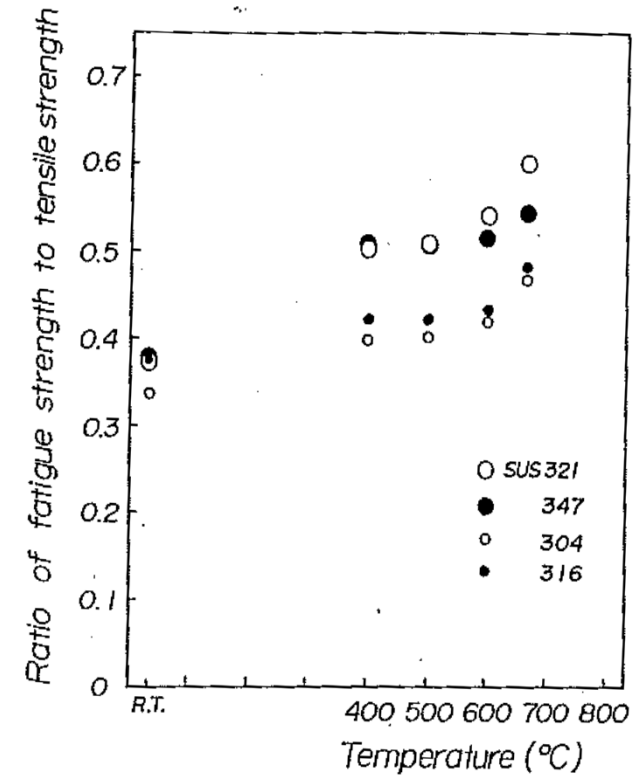
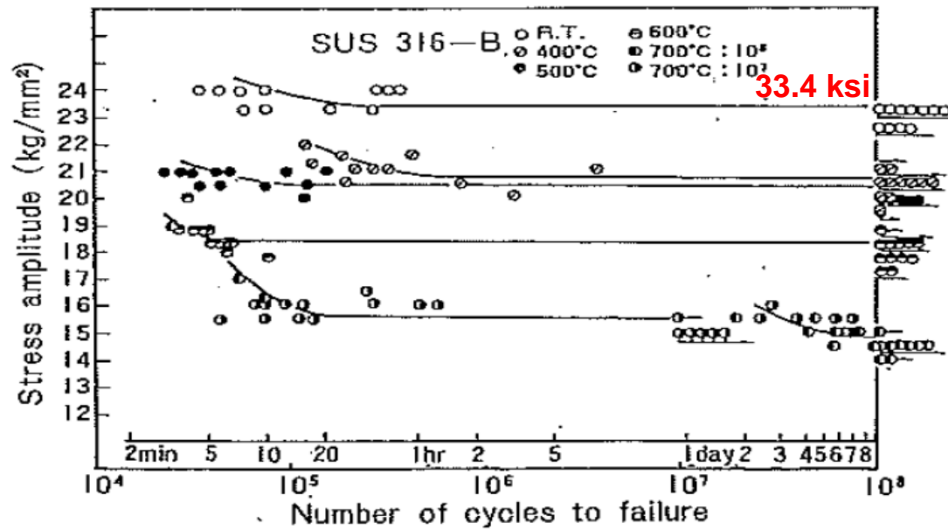
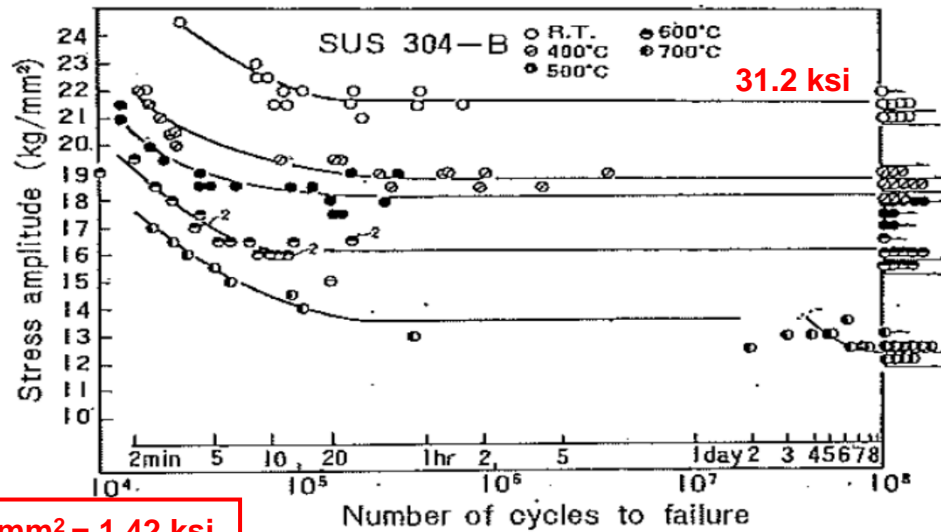
Jaske-O'Donnell Curve



Kanazawa Papers

- Load Control Bending fatigue tests at temperatures up to 800°C for Type 304, 316, 321 and 347 stainless steel.
 - Room temperature fatigue strength is approximately 22 kg/mm² or 31.2 ksi.
 - There is some reduction in the fatigue strength at higher temperatures.
- The general thumb rule is that the fatigue strength is 0.4-0.5 times the ultimate strength of the material
 - Based on the Kanazawa data, an average value of 0.45 can be used to estimate the fatigue strength at 288°C (550°F)
 - Using the Code minimum tensile strength of 70 ksi at 550°F, the estimated fatigue strength is $0.45 \times 70 = 31.5$ ksi which is close to the fatigue strength from Jaske and O'Donnell

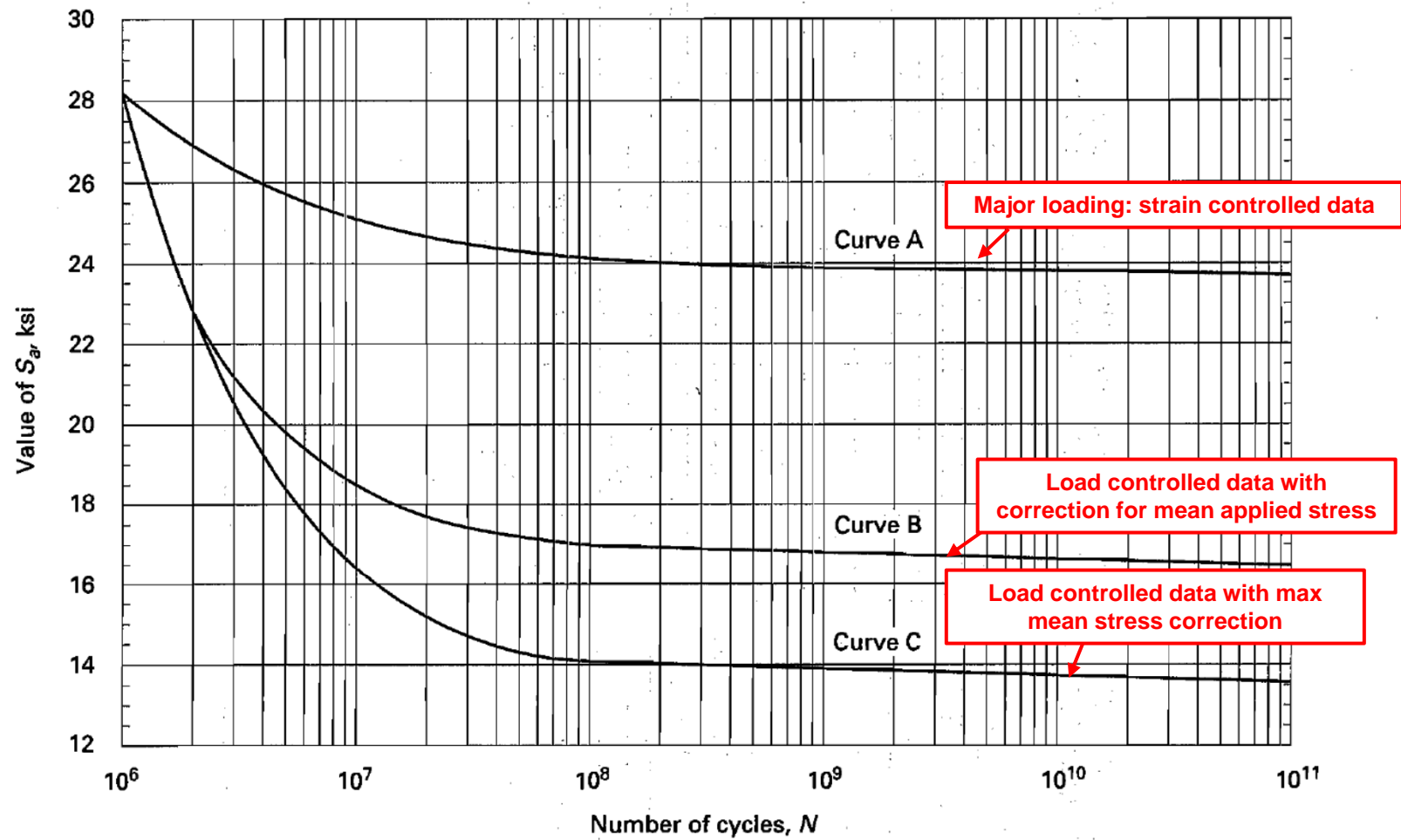
Kanazawa Results



Manjoine and Tome Paper

- The Curves A, B, C in the earlier Code versions (up to the 2007 Edition) were based on the paper by Manjoine and Tome
- The paper proposes fatigue design curves for austenitic stainless steels which extend the existing code curve to 10^{11} cycles.
 - Because of the differences in material behavior between low and high-cycle fatigue, extension curves for three loading conditions are presented.
 - The loading conditions for the three curves are: a) major part of the alternating strain is strain controlled; b) major part of the alternating strain is load controlled and c) major part of the alternating strain is load controlled with the maximum effect of mean stress included.
 - Curve C for high cycle fatigue vibration results in a fatigue limit of 13.6 ksi after including the factor of 2 on stress and the mean stress correction.
- An interesting discussion in the Manjoine and Tome paper concerns the factor of 2 on stress used in the Code.
 - It is known that the factor of 20 on cycles is made up of these factors: Data Scatter: 2.0; Size Effect 2.5; Surface Finish and Atmosphere: 4.0
 - However, there is less information on what the factor of 2 on stress covers.

2007 Code and Curves A, B and C



Manjoine and Tome Paper (continued)

- Manjoine suggests that the factor of 2 on stress covers five variables: (15% reduction for each parameter)
 - Surface Finish: Machining processes may generate beneficial compressive residual stresses that increase the fatigue strength. The 1.15 factor was assigned to this quantity to cover the exceptions to this general observation.
 - Size Effect: This covers the difference between the surface area of the lab specimen and the surface area under peak stress in the component.
 - Material Variability: Test results showed that the fatigue strengths was within +10 percent of the average. Since the fatigue strength increases with the higher strengths, the 1.15 factor for material variability was reasonable.
 - Environment (thin oxide films-no corrosion): This is the temperature effect, not the effect of the water environment. The decrease in fatigue strength with temperature is usually less than that accounted for by the reduction in modulus in calculating the allowable stress intensity.
 - Residual Stress: The fabrication (e.g. machining) residual stresses accounted for by the 15 percent reduction factor. This applies primarily for low stress amplitudes under load control where there may not be enough yielding to overcome the residual stress.

Manjoine and Tome Paper (continued)

- The five factors of 1.15 or a total of $1.15^5 = 2.01$ accounts for the two on stress margin in the Code design curve
- An important conclusion from the Manjoine study is that there is already a temperature effect included in the factor of two and applying an additional factor for the effect of temperature on the modulus is effectively double-booking for the temperature effect

NUREG/CR-6909

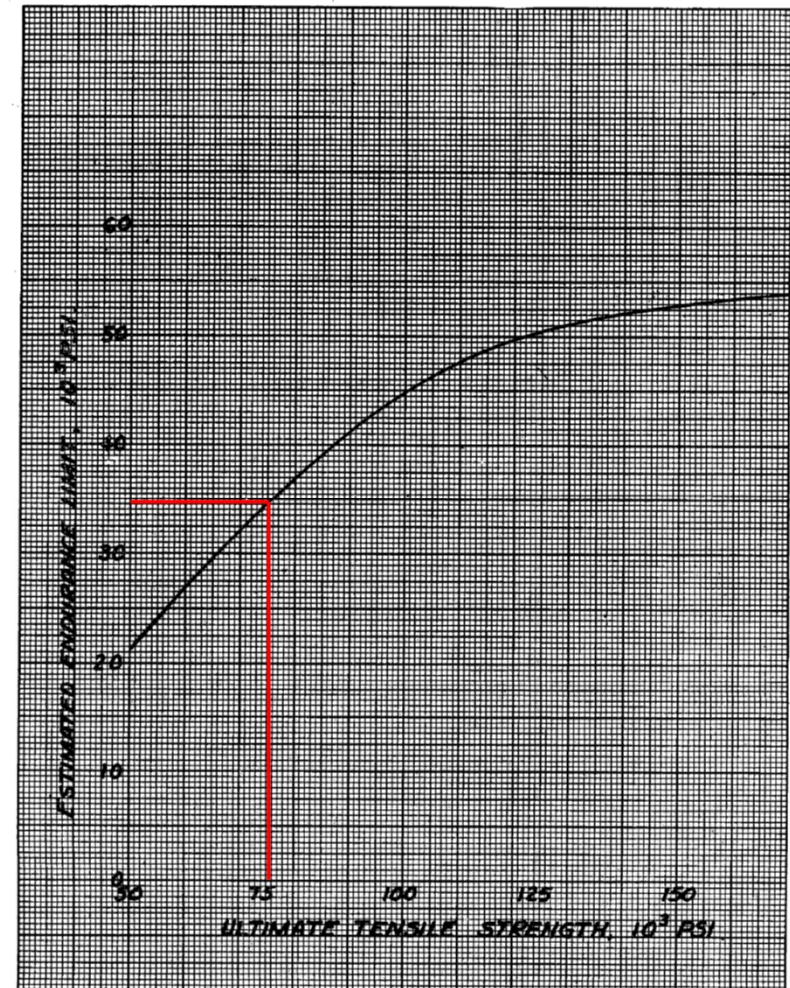
- NUREG/CR-6909 considers fatigue strain vs. cycles data for austenitic stainless steel using the following curve fit:

$$\ln(N) = A - B \ln(\epsilon_a - C) \text{ where } A, B, \text{ and } C \text{ are constants}$$

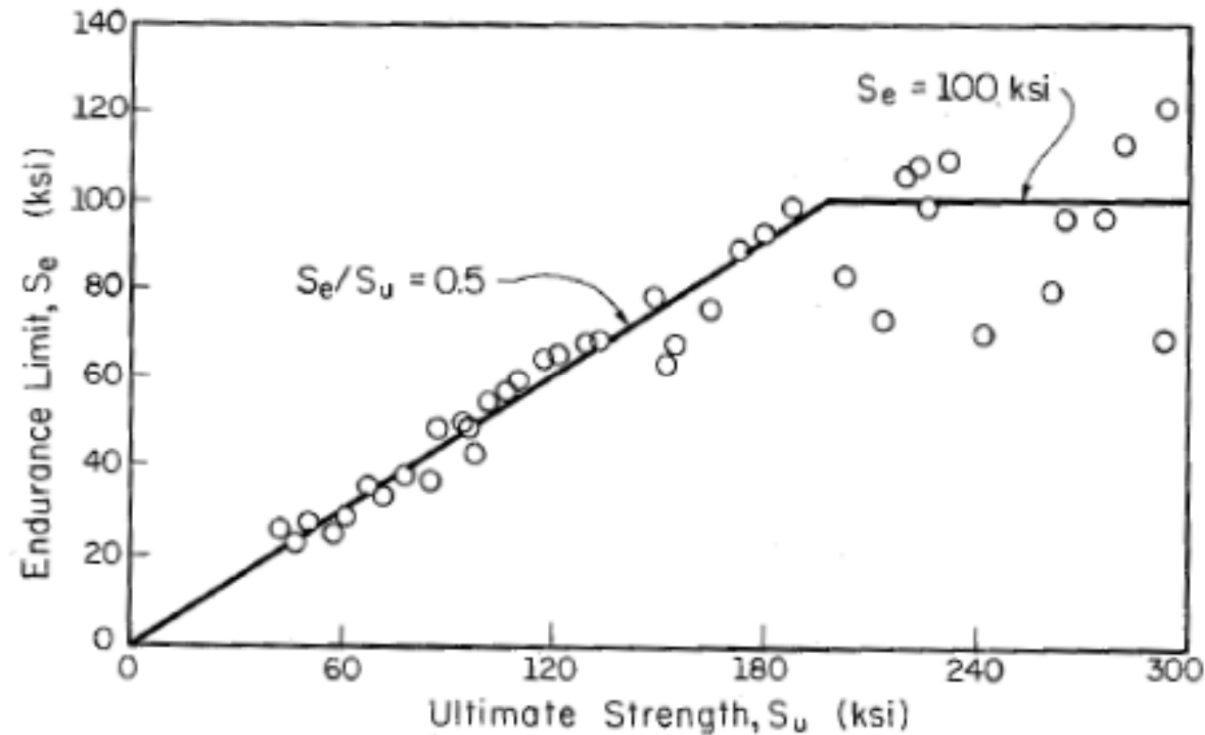
- C represents the fatigue limit of the material; and B is the slope of the line
- The Argonne analysis of the stainless steel air data showed the fit to be $\ln(N) = 6.891 - 1.920 \ln(\epsilon_a - 0.112)$.
 - The slope is somewhat different than the original Code Curve (B=2.0)
 - The fatigue strain limit (0.112%) can be converted to stress by multiplying by E. Assuming $E = 28 \times 10^3$ ksi, **Fatigue limit = $28 \times 10^3 \times 0.112 \times 10^{-2} = 31.4$ ksi**
- Unlike the Code curve which uses the traditional 2 and 20 factors, the NUREG/CR-6909 curve uses a factor of 2 on stress and 12 on cycles.
- Much of the focus in NUREG/CR-6909 is on the low cycle regime where the environmental effects are the highest.
- The recommended stainless steel design curve in NUREG/CR-6909 is identical to that in the 2010 ASME Code

Estimation of Fatigue Limit from Tensile Strength

- **Plot from Tentative Structural Design Basis by the US Navy**
- Relates fatigue limit to Tensile Strength
- Depending upon the tensile strength at temperature, the fatigue limit varies from 30-35 ksi



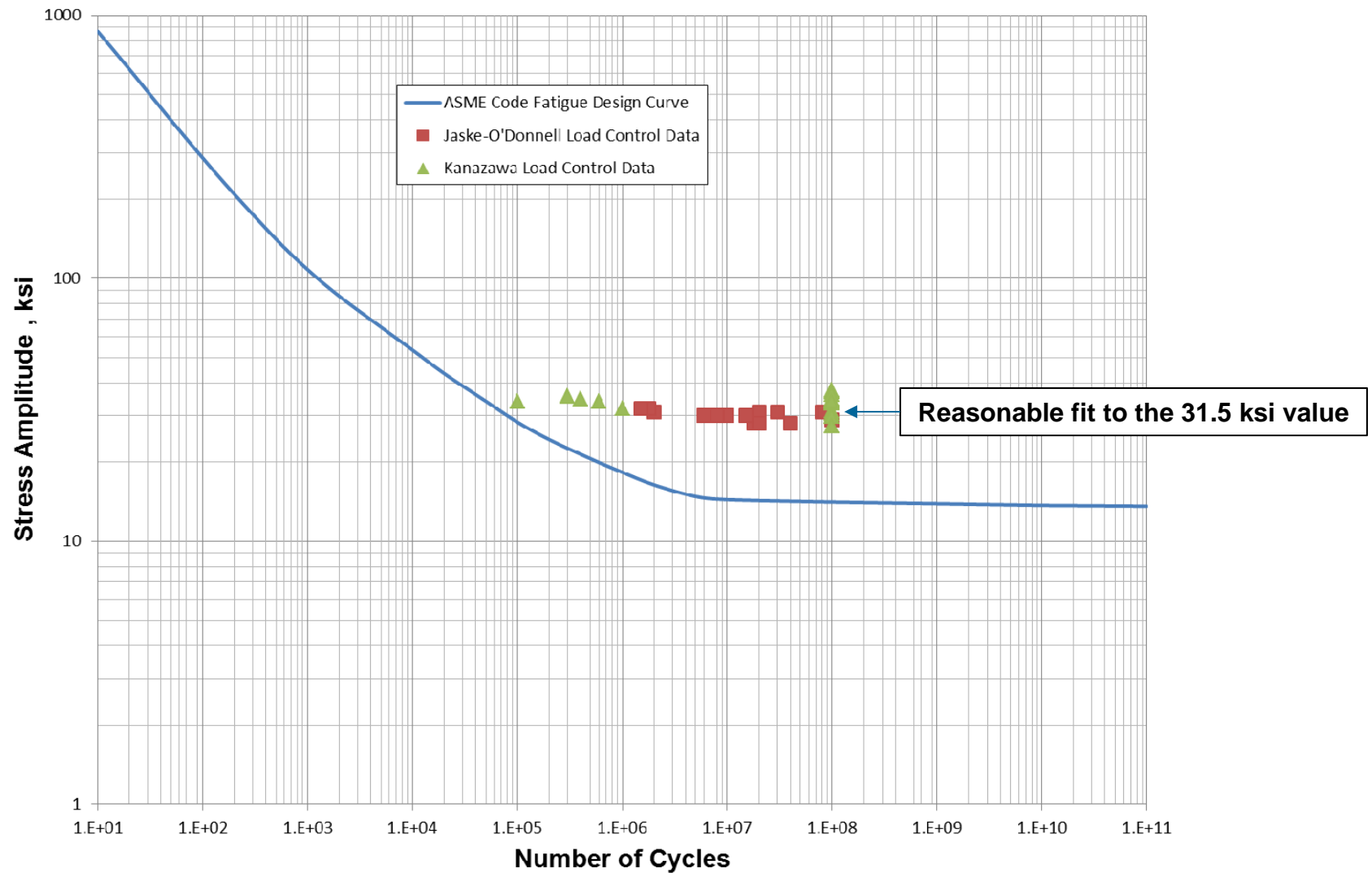
Estimation of Fatigue Limit from Tensile Strength



Ref. Fundamentals of Metal Fatigue Analysis. Bannantine, Comer and Handrock, Prentice Hall

Depending upon the tensile strength at temperature, the fatigue limit varies from 30-35 ksi

Load Controlled High Cycle Test Data



Conclusions from the Review of the Load Control data

- The fatigue limit at the high cycle end at 10^{11} cycles is the same in NUREG-6909, 2010 Code and 2007 Curve C.
 - For low cycle fatigue events such as thermal transients, startup-shutdown cycles, discontinuity stresses which are displacement or strain controlled and include E in the determination of stresses (e.g. thermal stress = $\frac{E\alpha\Delta T}{1-\nu}$) E correction is clearly required.
 - On the other hand for primary load stress such as that due to vibration, the stress is load controlled and is independent of E. In such cases, applying the E correction for temperature results in double-booking and adds excessive conservatism.
- A review of Load control data leads to the mean data fatigue limit of limit of 31.5 ksi. After the factor of 2 and the mean stress correction this leads to design limit of 13.6 ksi. This is independent of E value and since it is based on load control stress data and no E correction is needed.

Discussion of the Different Approaches

- The different approaches discussed here are in general agreement on the overall fatigue limit values for stainless steel.
 - They all agree on a value of around 31.5 ksi at over 10^8 cycles or higher.
 - Both the Jaske-O'Donnell and the NUREG/CR 6909 curves also result in the same fatigue limit of 13.6 ksi at 10^{11} cycles for the Austenitic Stainless Steel design curve.
- The main unresolved question is the issue of temperature dependence (e.g. E-correction for high cycle fatigue) on the fatigue limit at 10^{11} cycles.
- This can be addressed by separating the low and high cycle data and considering only the Load Controlled High Cycle Test Data or exploring other ways to establish a realistic value for the fatigue limit.

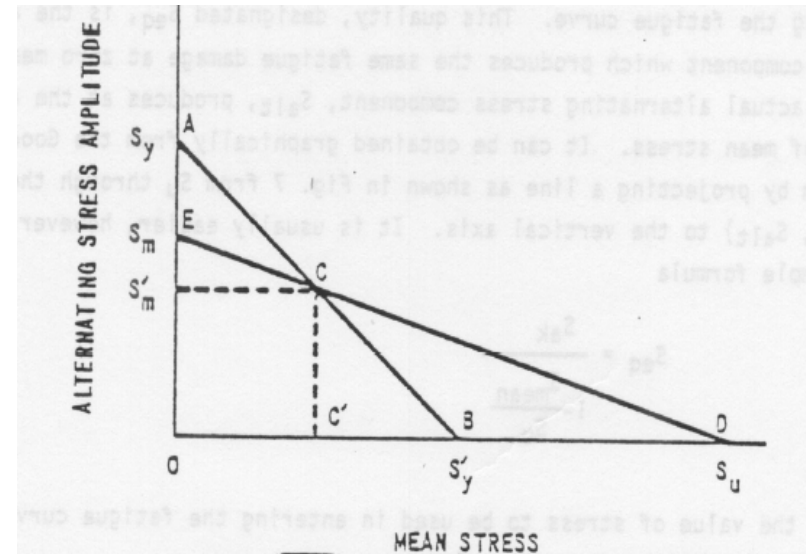
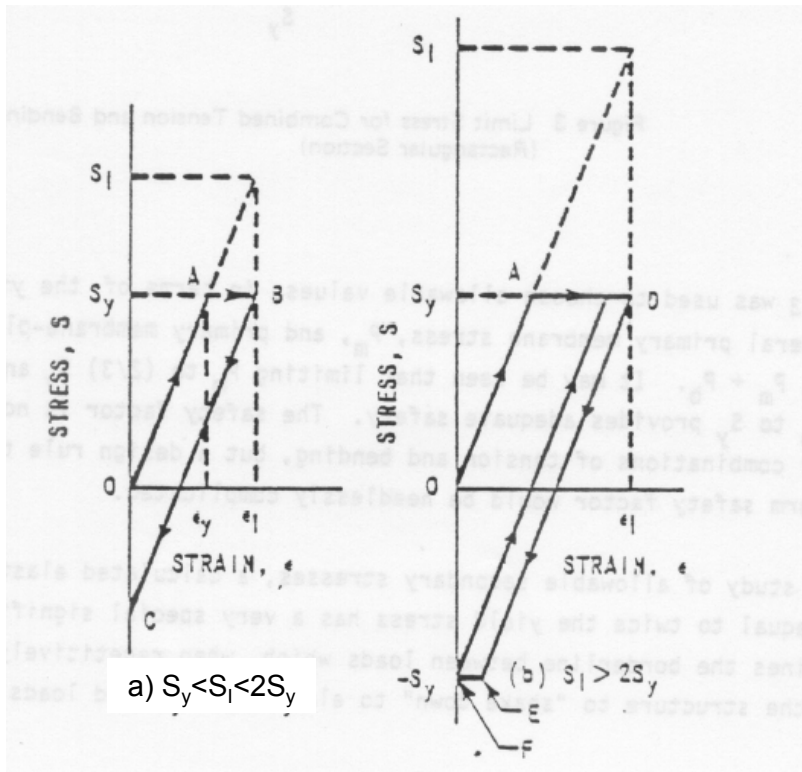
Discussions with the Authors of NUREG/CR-6909

- After discussions with the authors of NUREG/CR-6909 it appeared that there was no agreement on the position that E-correction was not needed for the high cycle (10^{11} cycles) end of the curve
 - The position was that the Code Fatigue Curve (same as that in NUREG/CR-6909) was based on strain controlled data for both the low and high cycle regimes and therefore required E-Correction when converted to stress
 - The fact that the endurance limit of 31.6 ksi could be derived from load control data alone did not resolve the issue
- While there was no agreement on the idea of removing the E correction requirement for high cycle fatigue, alternative approaches were suggested that could be used to justify a more realistic fatigue limit even with the E-correction included.

Alternate Ideas for Determining the Fatigue Limit

- The following approaches were suggested by the authors of NUREG/CR-6909 to justify a higher fatigue limit
 - Derive separate fatigue curves for different temperatures. Specifically, this would involve applying mean stress (MS) correction based on S_y and S_u values from cyclic stress-strain curves at temperature.
 - Derive separate fatigue curves for the different types of austenitic stainless steels e.g. different curves for Type 316 and Type 347 stainless steels which have higher S_u and endurance limits
 - Justify reducing the factor of 2 using arguments in NUREG/CR-5704. It provides the justification for reducing the factor of 2 on stress (part of the 2 and 20 factors on stress and cycles) in the fatigue design curve
- The first approach (i.e. applying mean stress correction based on cyclic S_y and S_u values at temperature) is the most straight forward when limited to high cycle fatigue

Background on the Mean Stress Correction



$$S'_N = S_N \frac{(S_u - S_y)}{(S_u - S_N)} \quad \text{for } S_N < S_y$$

$$S'_N = S_N \quad \text{for } S_N > S_y$$

Mean Stress Correction in the ASME Code Curve

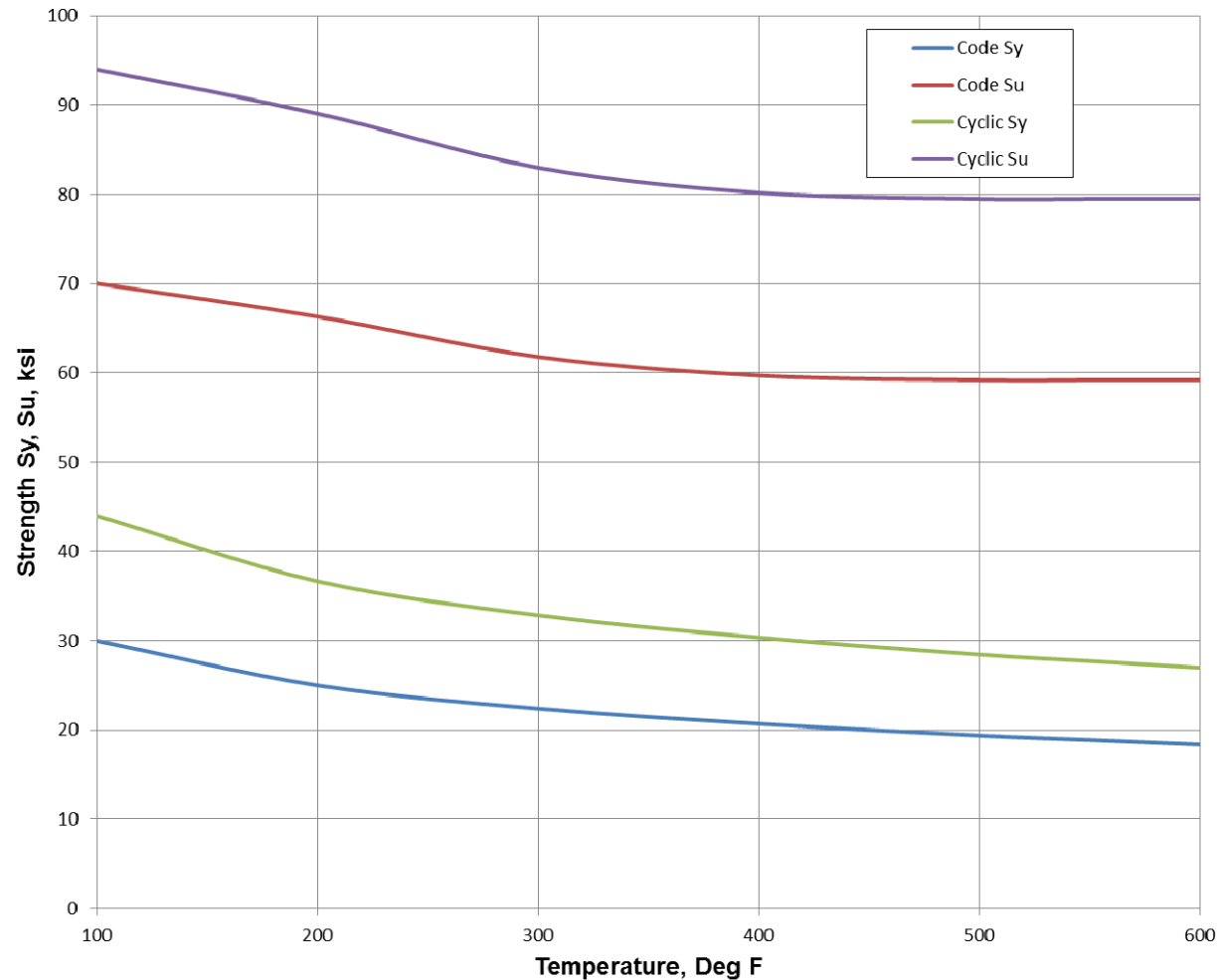
- $S'_N = S_N \frac{(S_u - S_y)}{(S_u - S_N)}$ for $S_N < S_y$
- $S'_N = S_N$ for $S_N > S_y$

Where S_y and S_u are the yield and ultimate strength from the cyclic stress-strain curve and S_n is the completely reversed stress amplitude (from tests with zero mean stress) and S'_n is the reduced stress amplitude due to the maximum possible mean stress.

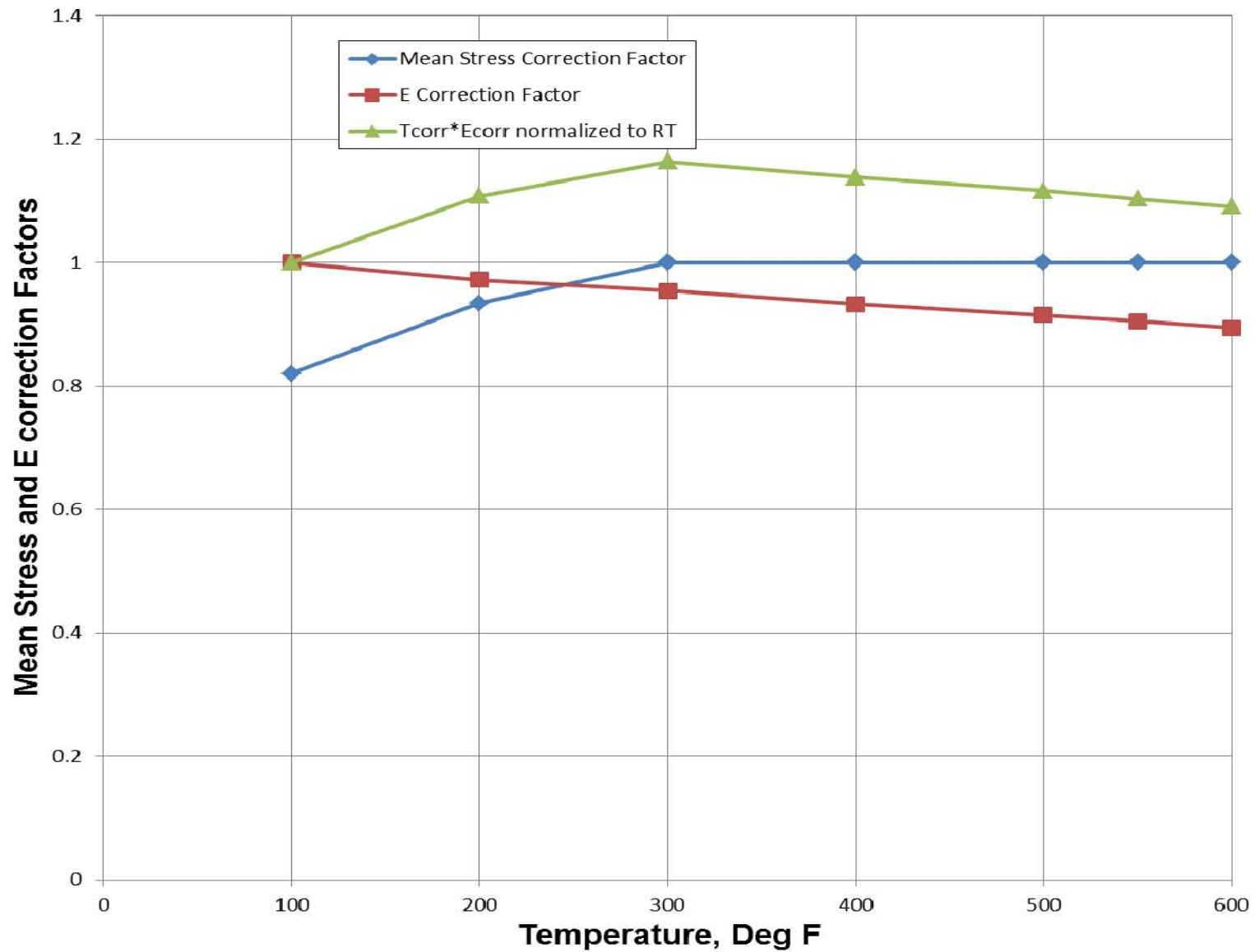
- No mean stress correction for S_n greater than S_y
- The ASME Code Curve is based on the conservative use of the room temperature values of cyclic yield strength ($S_y=44$ ksi) and ultimate strength ($S_u=94$ ksi)
- It is more realistic to use S_y and S_u values at temperature

Temperature Dependent Cyclic Yield, Ultimate Strength

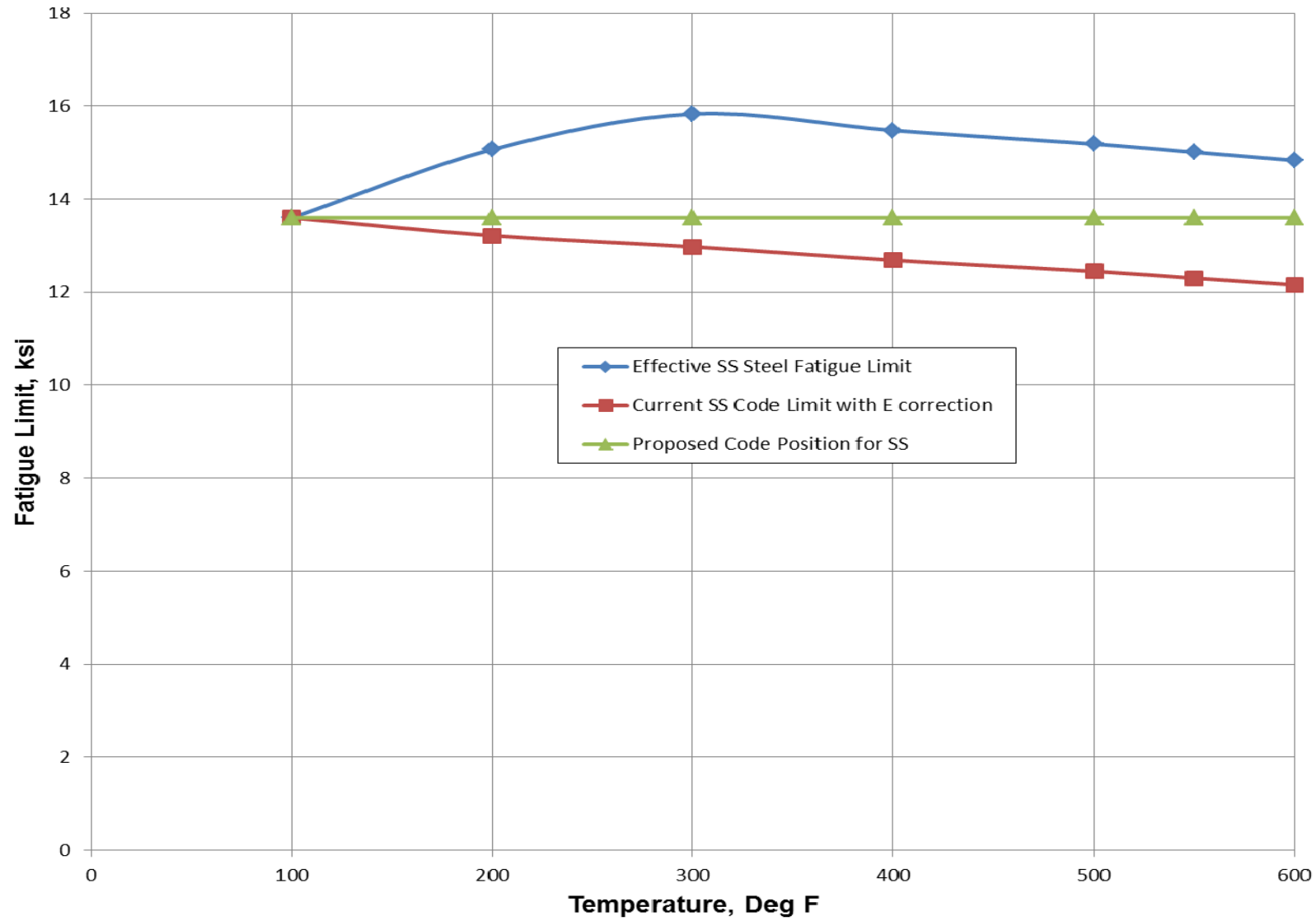
Based on ASME Code



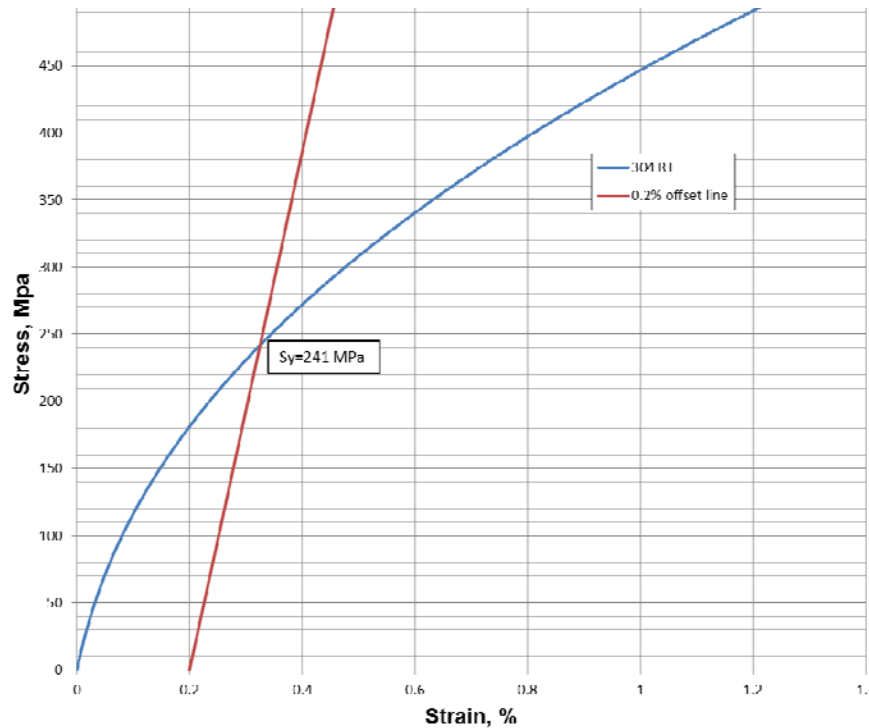
Mean Stress and E Correction at Temperature



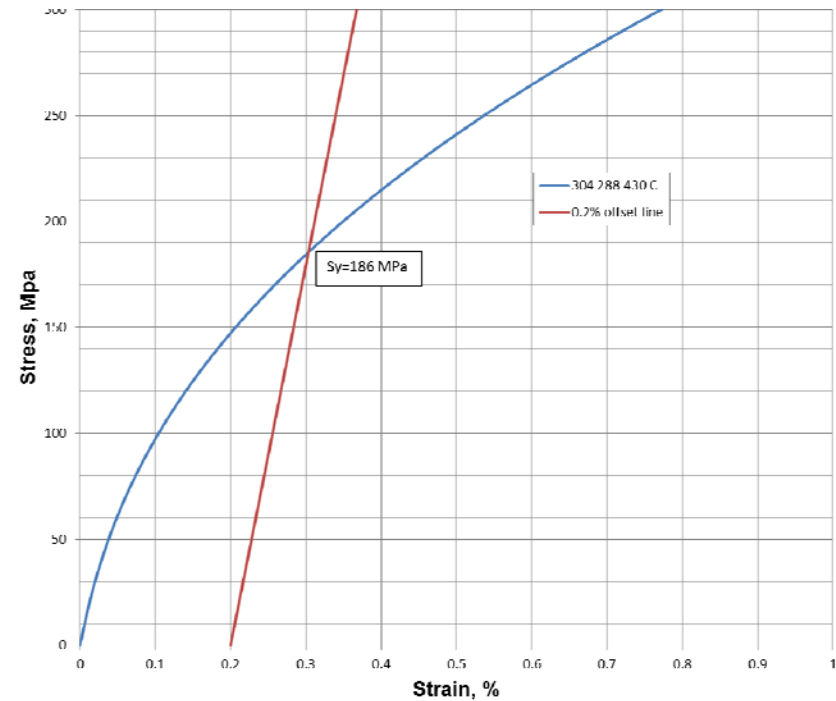
Effective Fatigue Limit Based on ASME Code



Cyclic Stress-Strain Curve from NUREG/CR-5704



Room Temperature
 $S_y = 35$ ksi



Temperature 288-430° C
 $S_y = 27$ ksi

Effective Fatigue Limit Based on NUREG/CR-5704

	Type 304 SS		Type 316 SS	
Temperature °F	100	550	100	550
Sy ksi	35	27	37.3	34.5
Su ksi	80	75	85	80
Effective Fatigue limit, ksi	15.8	17.8	15.1	14.4

Use of Cyclic Stress Strain Curves in NUREG/CR-5704 results in Fatigue limit values in Excess of 13.6 ksi at both RT and 550° F

Conclusions

- Regardless of the approach and the different methods used – NUREG/CR-6909, work of Jaske-O'Donnell, Manjoine-Tome and Kanazawa, consideration of load controlled data and using the relationship of S_e to the ultimate strength, the resulting fatigue limit is the same
- The only question is how to account for temperature effects, specifically E and the mean stress correction
 - There was no agreement with the with the authors of NUREG/CR-6909 on the approach of eliminating the E-correction for temperature
 - There was agreement on the alternate ways of using the mean stress (MS) correction based on properties at temperature
- Results show that the benefit of using temperature based MS correction more than offsets the reduction for E-correction
- A constant fatigue limit value of 13.6 ksi independent of temperature can be justified for vibration analysis of stainless steel components

Next Step

- Submit the following Code case to ASME for consideration:

Proposed Code Case N-XXX

Fatigue Limit of Austenitic Stainless Steel for use in Vibration Evaluation

Section III Division 1

Inquiry: What alternatives to Figure I-9.1 in Section III, Appendices, can be used for the design fatigue limit of austenitic stainless steel for use in vibration evaluation?

Reply: It is the opinion of the committee that, as an alternative to Figure I-9.1 in Section III, Appendices, a constant value of 13.6 ksi (93.8 MPa) can be used as the design fatigue limit of austenitic stainless steel for use in vibration evaluation for temperatures up to 650°F (343°C)



Together...Shaping the Future of Electricity