Proposed ASME Code High Cycle Fatigue Design Curves for Austenitic and Ferritic Steels

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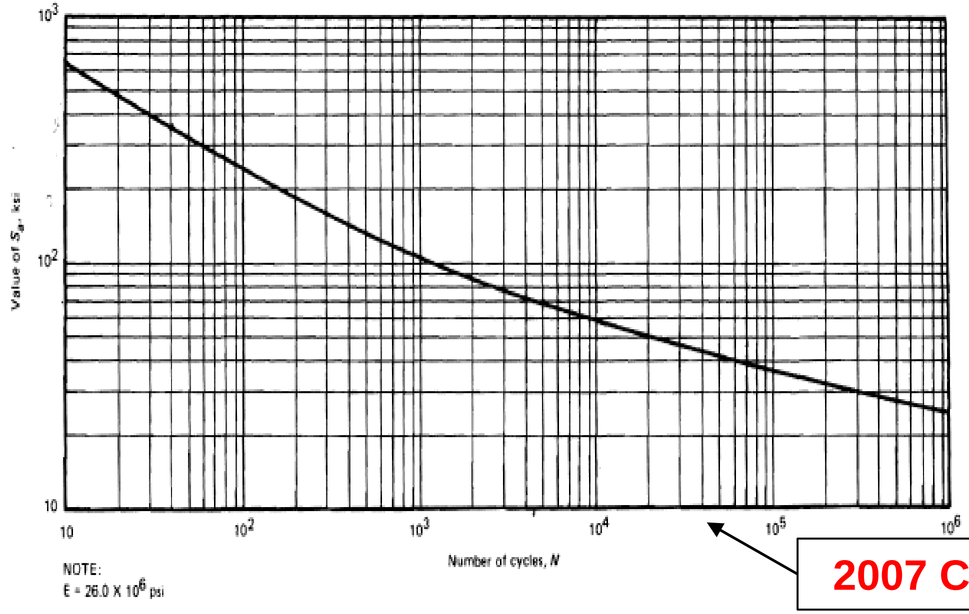
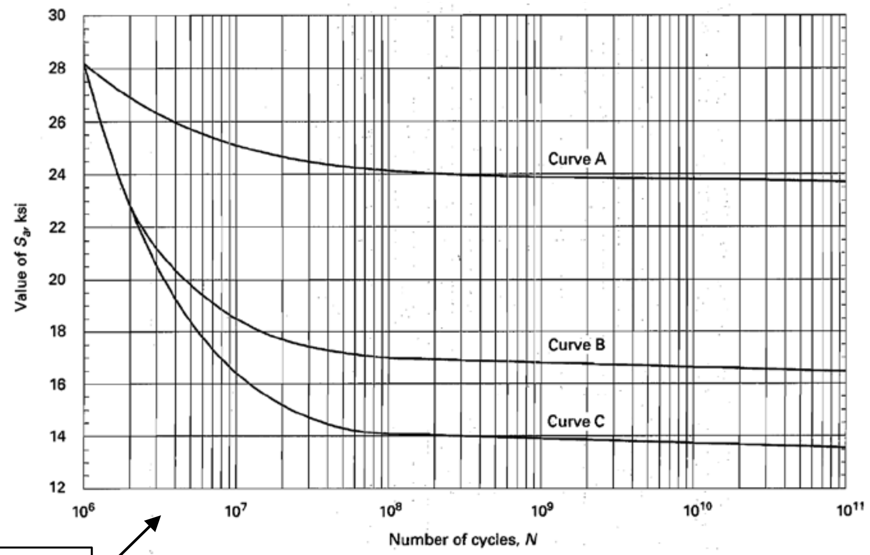
Background

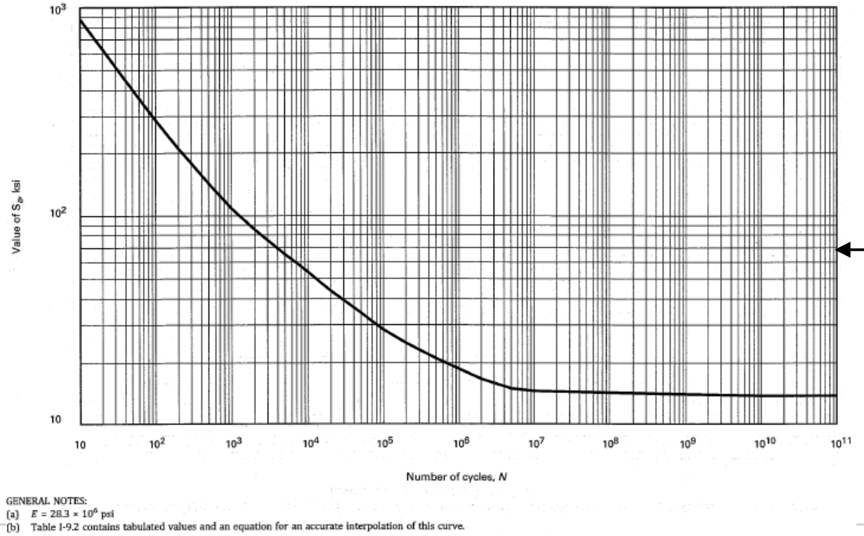
- Reactor internals (e.g. the steam dryer in BWRs) are subjected to fatigue cycling from stress cycles due to operating transients and vibrations
  - ASME Code design fatigue curves are largely based on low cycle fatigue tests with strain cycling. The strains are converted into pseudo-elastic stress by multiplying by the elastic modulus
  - High cycle fatigue associated with vibrations is load controlled, not dependent of E and involves stress amplitudes below S_y
- Earlier versions of the Code (prior to the 2009 addenda) fatigue curves for stainless steels had recognized the difference between high 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 (after the 2009 Addenda) 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 Different Codes





2007 Code



2009 addenda

High Cycle Fatigue Design Curves

- The initial focus of the study was on the fatigue limit (at 10^{11} cycles) of austenitic stainless steel. As the project progressed, it became clear that the High Cycle Fatigue Design Curves for Austenitic and Ferritic Steels in the range 10^6 - 10^{11} cycles should be the final goal
- The first part of presentation addresses austenitic stainless steel components which are used for reactor internals. Specifically, the approach described here uses temperature dependent properties (cyclic yield strength, cyclic ultimate strength) for the mean stress correction (MSC) and the correction for the modulus of elasticity.
- The high cycle fatigue design curve is developed by applying the mean stress and the E correction on the reversing load mean data curve and applying a factor of 2 on stress
- The generic methodology developed for austenitic steel was applied to carbon and low alloy steels also

Fatigue Limit (at 10^{11} cycles) of Austenitic Stainless Steel

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 to10^8 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
- A key assumption was the use of room temperature mechanical properties (cyclic S_y and S_u) in determining the mean stress correction

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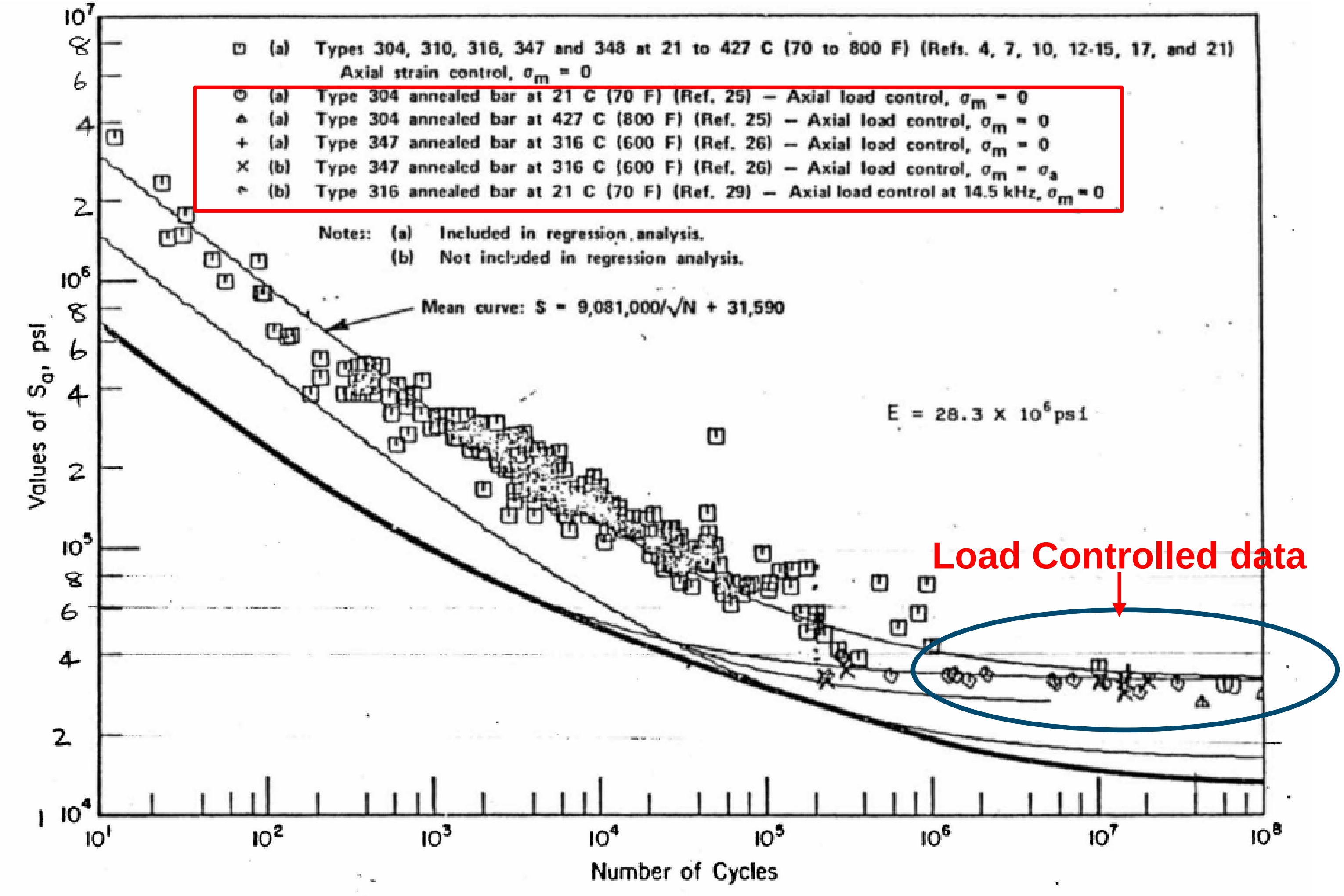
Jaske-O'Donnell Curve



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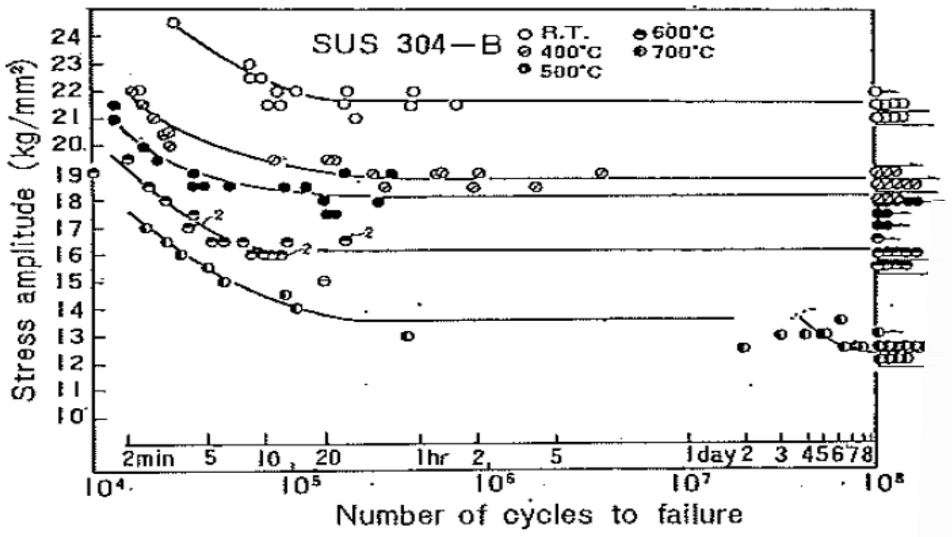
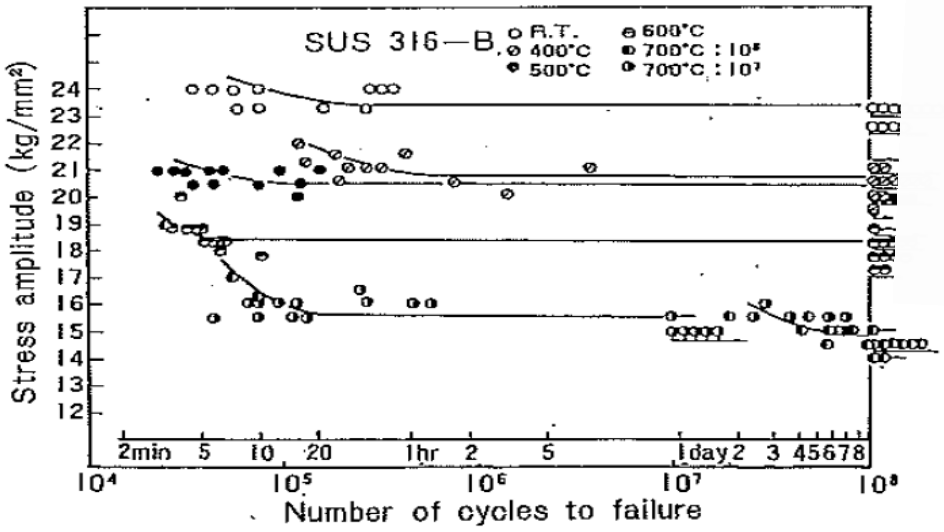
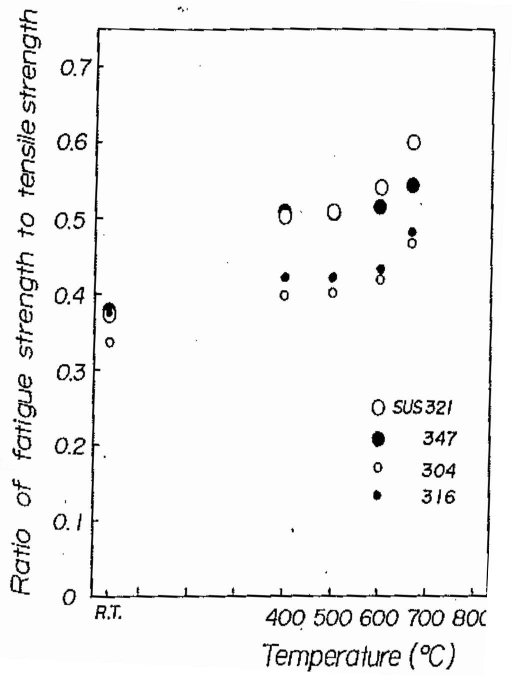
Kanazawa Papers

- 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/mm^2 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*70=31.5 ksi which is close to the fatigue strength from Jaske and O'Donnell







1 kg/mm^2 = 1.42 ksi

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 results in a fatigue limit of 13.6 ksi after the factor of 2 on stress and the MSC
- 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

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 exceptions
  - 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 strength 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.
  - 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

NUREG/CR 6909

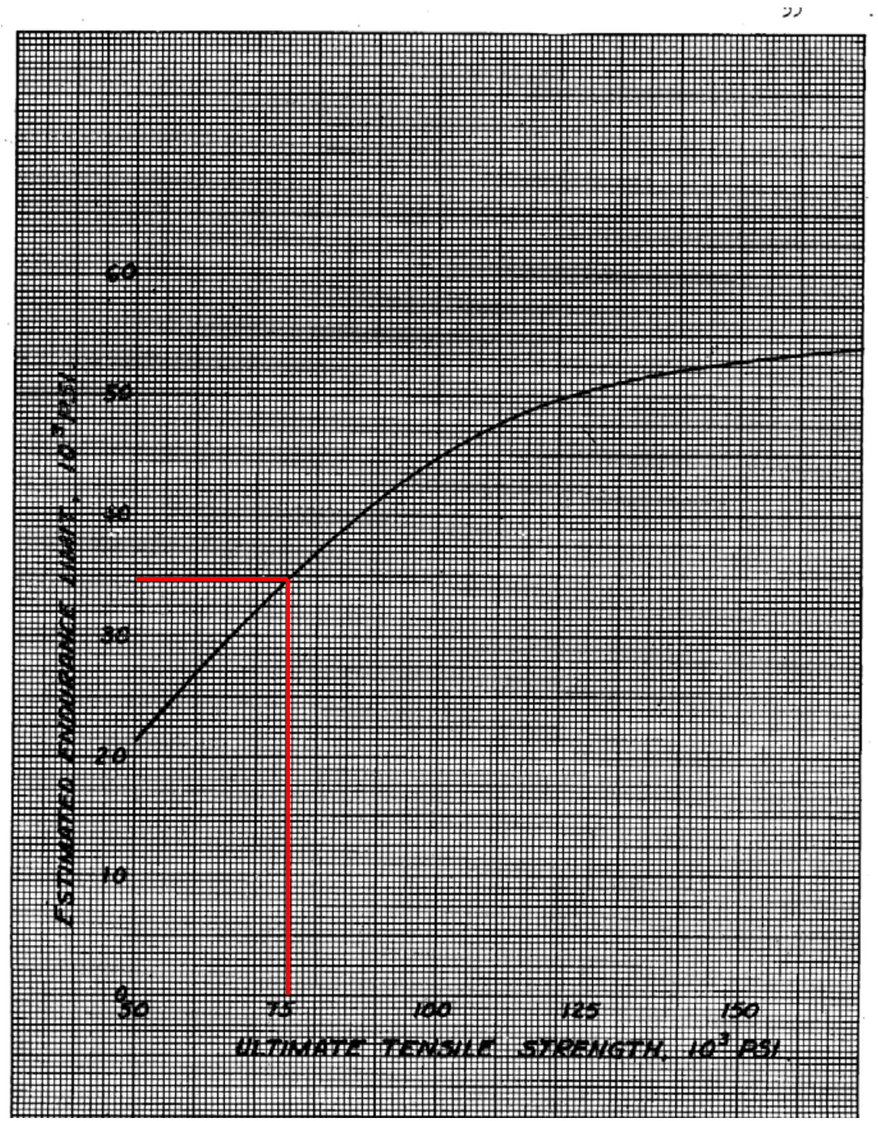
- NUREG/CR 6909 considers fatigue strain vs. cycles data for austenitic stainless steel using the following curve fit:

$$\boxed{\text{Ln}(N) = A - B\ \text{Ln}(\varepsilon_a - C) \text{ where A, B, and C are constants}}$$

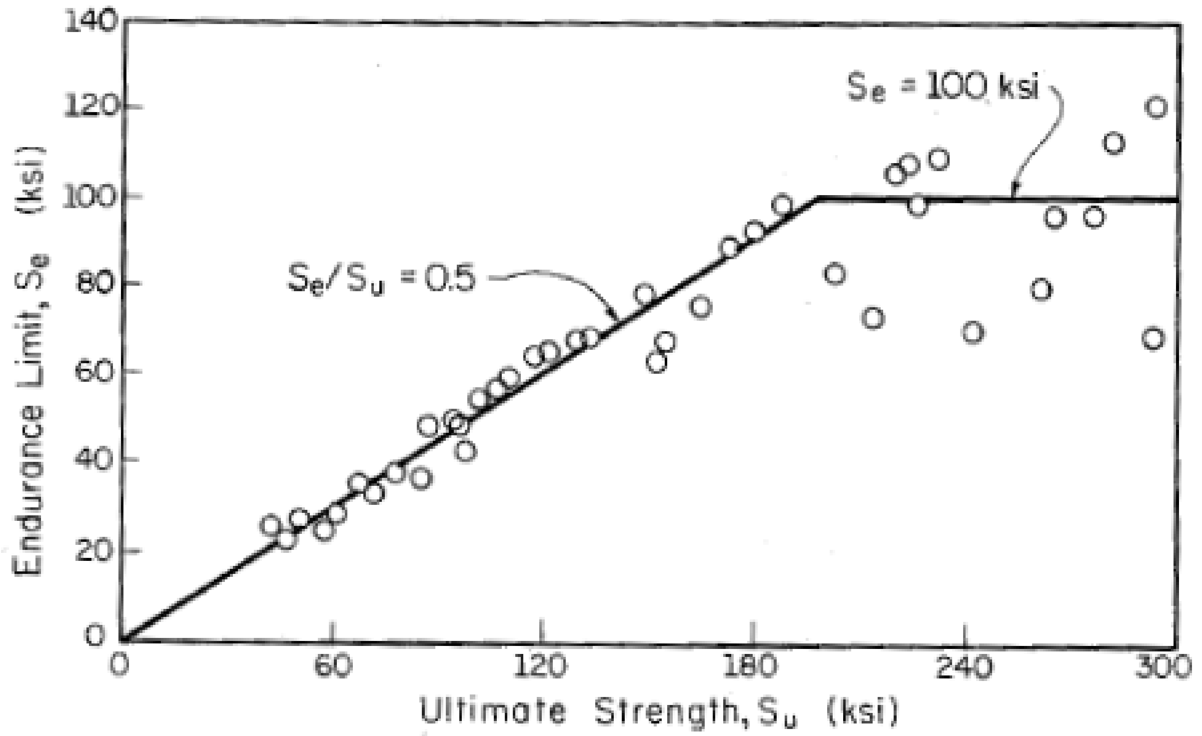
  - C represents the fatigue limit of the material; and B is the slope of the line
- The Argonne analysis of the stainless steel air data showed the fit to be $\text{Ln}(N) = 6.891 - 1.920\ \text{Ln}(\varepsilon_a - 0.112)$.
  - The slope is somewhat different than the original Code Curve (B=2.0)
  - The fatigue strain limit (0.112%) can be converted to stress by multiplying by E. Assuming $E=28\text{x}10^3$ ksi, **Fatigue limit = $28\text{x}10^3 \text{ x } 0.112\text{x}10^{-2} = 31.4$ 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 2009 Addenda, ASME Code

Estimation of Fatigue Limit from Tensile Strength

- Plot from Tentative Structural Design Basis by the US Navy (originally issued in 1958!)
- 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

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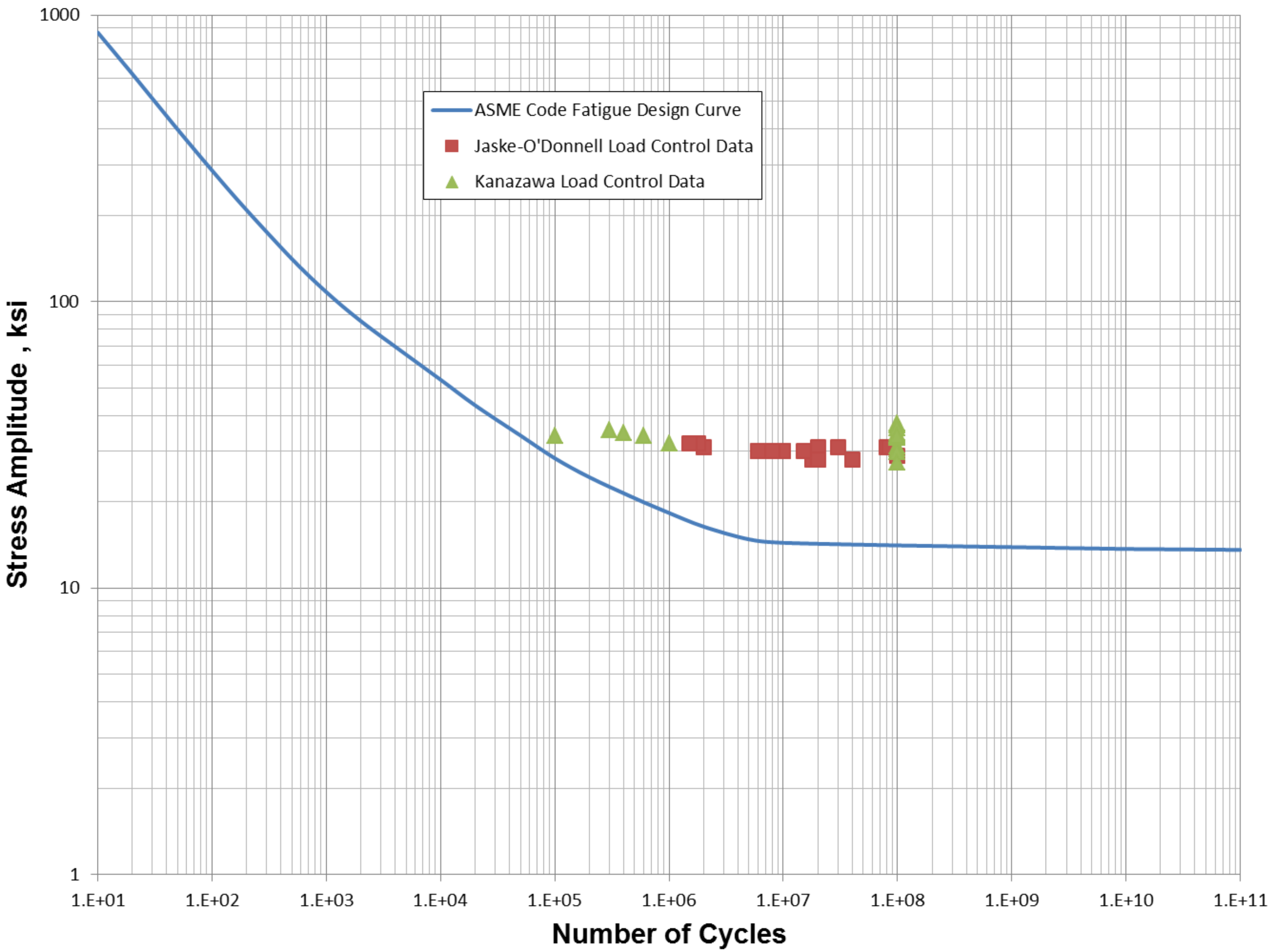
Load Controlled High Cycle Test Data



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Industry Discussions

- 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 30-35 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.
- 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. Therefore the approach of eliminating the E-correction issue was dropped
- 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

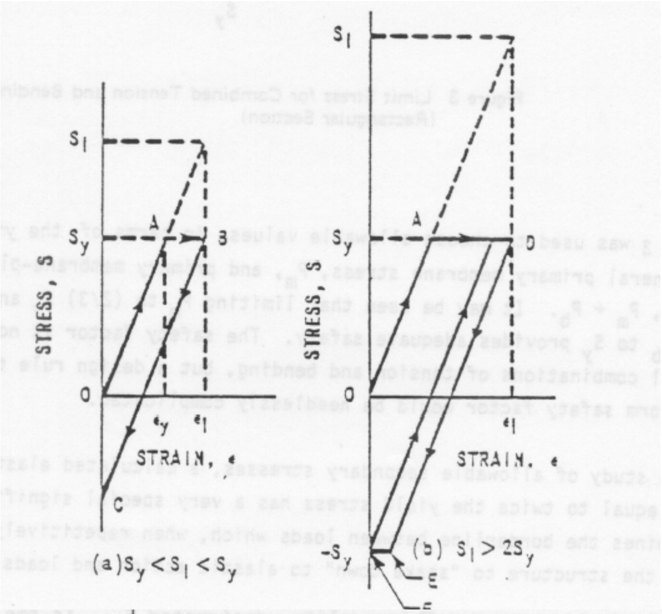
Alternate Ideas for Determining the Fatigue Limit

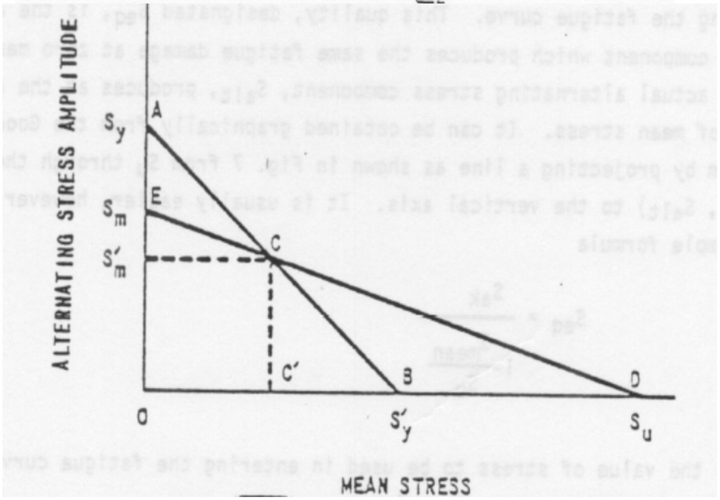
- The following approaches were suggested to justify a higher fatigue limit
  - Derive separate fatigue curves for different temperatures. Specifically, this would involve applying mean stress (MS) correction based on S_y and S_u values from cyclic stress-strain curves at temperature.
  - Derive separate 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 the technical basis in NUREG/CR-5704
  - 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
  - Initial focus was on revising the fatigue limit, but later, the goal was to develop high cycle fatigue design curves in the range 10^6 - 10^{11} cycles

Mean Stress Correction in the ASME Code Curve

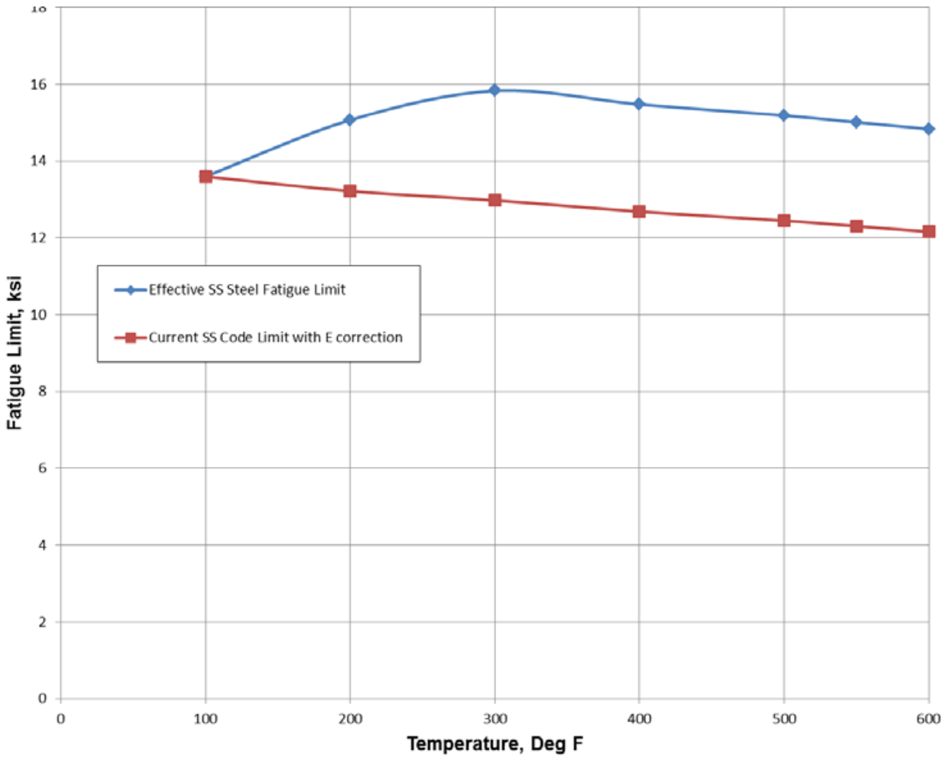
- $S'_N = S_N \frac{(S_u - S_y)}{(S_u - S_N)}$ for $S_N < S_y$
- $S'_N = S_N$ for $S_N > S_y$

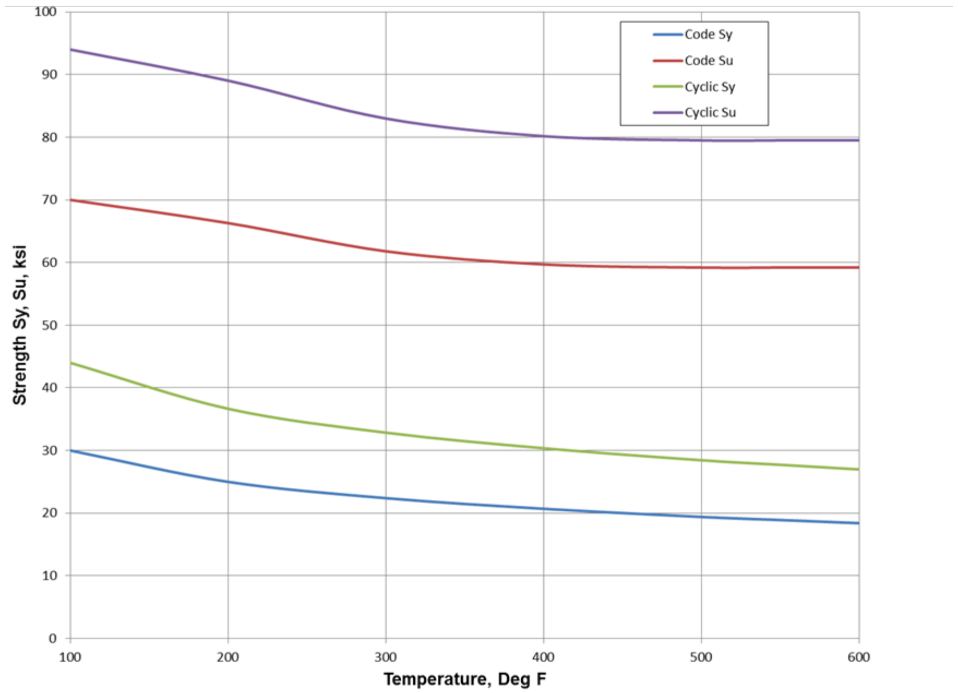
  Where S_y and S_u are the yield and ultimate strength from the cyclic stress-strain curve and S_n is the completely reversed stress amplitude (from tests with zero mean stress) and S'_n is the reduced stress amplitude due to the maximum possible mean stress.
  - No mean stress correction for S_n greater 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





Revised Fatigue Limit-Stainless Steel





Temperature °F	70	200	300	400	500	550	600
Mean Stress Correction Factor (MSC)	0.82	0.93	1.00	1.00	1.00	1.00	1.00
E-correction factor (EC)	1.00	0.97	0.95	0.93	0.92	0.90	0.89
Total Temperature Correction (EC*MSC)	0.82	0.91	0.95	0.93	0.92	0.90	0.89
Revised Fatigue Limit ,ksi	13.6	15.1	15.8	15.5	15.2	15.0	14.8

Cyclic S_{yc} and S_{uc} at temperature based on ratioing the ASME Code values of S_y and S_u

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ASME Code High Cycle Fatigue Design Curves for Austenitic and Ferritic Steels

Development of the Fatigue Curve for 10^6 -10^{11} cycles

- Mean stress is accounted for by the modified Goodman relationship as follows:

$$S'_N = S_N \frac{(S_{uc} - S_{yc})}{(S_{uc} - S_N)} \quad \text{for } S_N < S_y \qquad (1)$$

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

- The temperature dependence of S_{yc} and S_{uc} can be assumed to be similar to that of S_u and S_y in the Code:

$$\frac{S_{yc}, S_{uc}\ at\ temperature\ T}{S_{ycT}, S_{ucT}\ at\ RT} = \frac{S_y, S_u\ at\ temperature\ T}{S_y, S_u\ at\ RT} \qquad (2)$$

- The reversing alternate strength, S_N corresponding to the specified number of cycles (N) at a given temperature is given by:

$$S_N = \frac{2S_{ucT}S_a}{(S_{ucT} - S_{ycT} + 2S_a)} \quad \text{for } S_N < S_y \qquad (3)$$

$$S_N = 2S_a \quad \text{if } \frac{2S_{ucT}S_a}{(S_{ucT} - S_{ycT} + 2S_a)} < S_{ycT}$$

Fatigue Curve for 10^6 -10^{11} cycles (continued)

- The MSC based on temperature dependent properties is:

$$MSC_{temp} = \frac{(S_{ucT} - S_{ycT})}{(S_{ucT} - S_N)} \quad \text{for } S_N < S_{yct} \qquad (4)$$

$$MSC_{temp} = 1 \quad \text{for } S_N > S_{yct}$$

- There are two corrections for temperature: i) for the E correction (EC) and ii) for the mean stress correction (MSC). The total correction (TC) is the EC times MSC

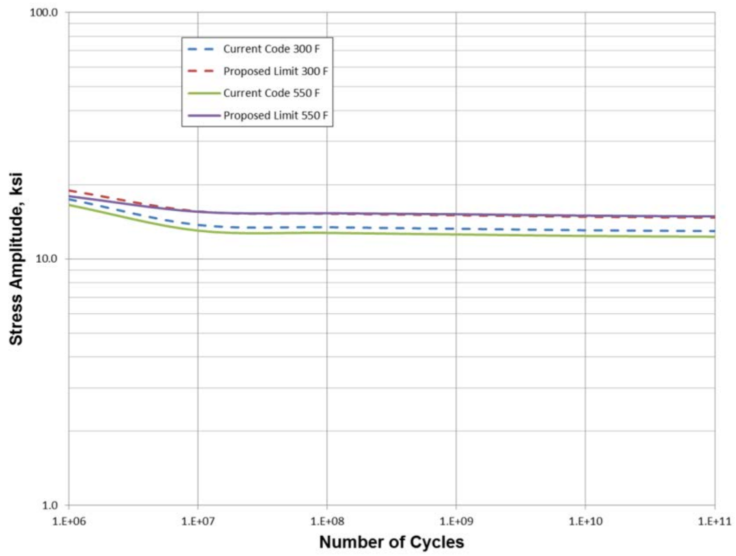
$$TC = EC * MSC_{temp} \qquad (5)$$

- The revised allowable stress, S_R where the number of cycles is in the range 10^6 -10^{11} cycles at a given temperature is determined by multiplying the allowable stress S_a from the Code fatigue design curve (Figures I-9.1 and I-9.2) by the ratio of TC_T at temperature and TC_{RT} at room temperature

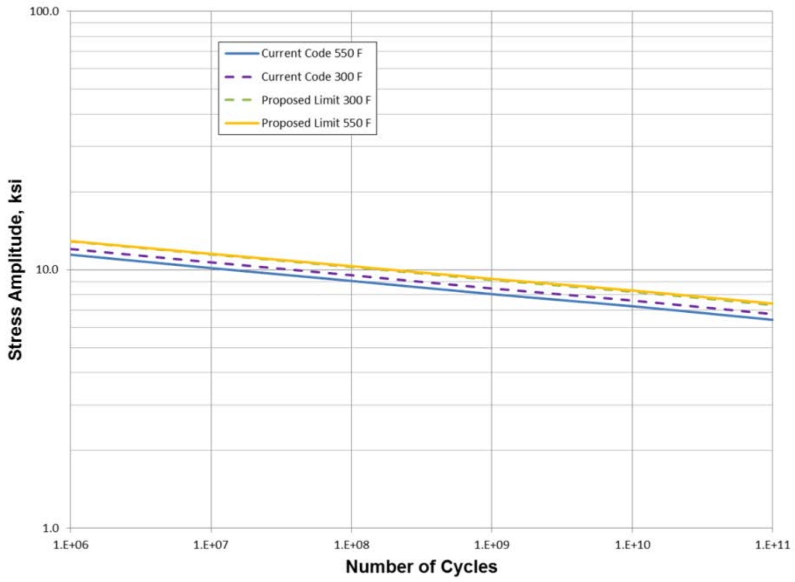
Revised allowable stress, $S_R = \frac{S_a}{(TC_{RT}/TC_T)}$ (6)

- Note that the revised fatigue curve already includes the E correction required by NB-3222.4 and NG-3222.4 and no additional correction is required for E.

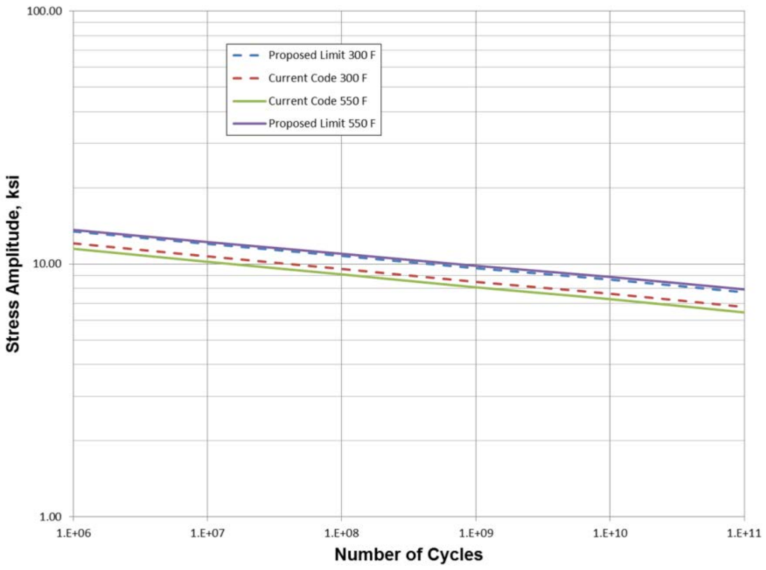
SS, CS and LAS Fatigue Curves (Proposed vs. Current)



Stainless Steel



Carbon Steel

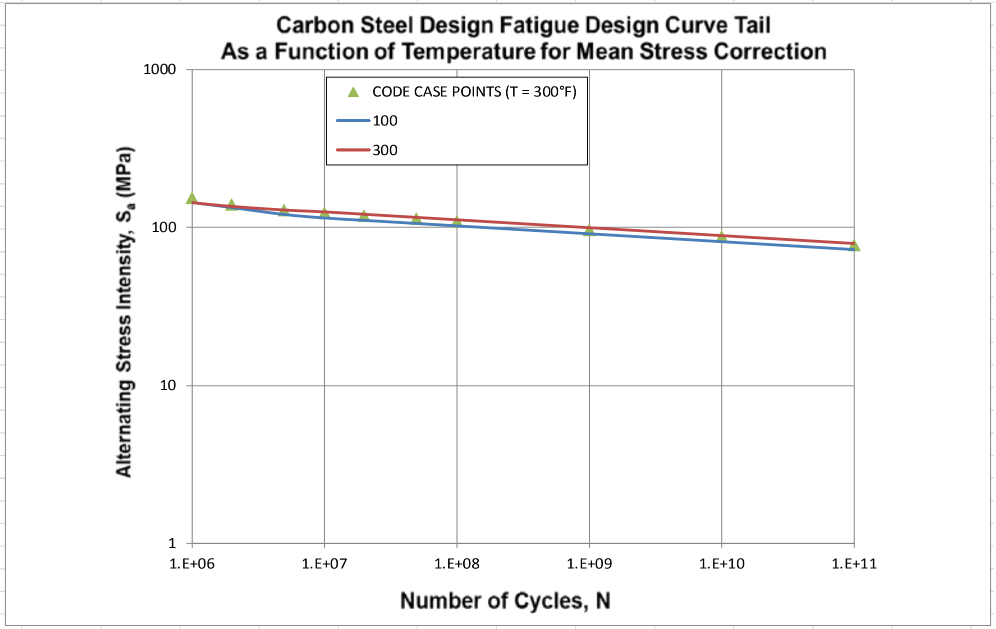


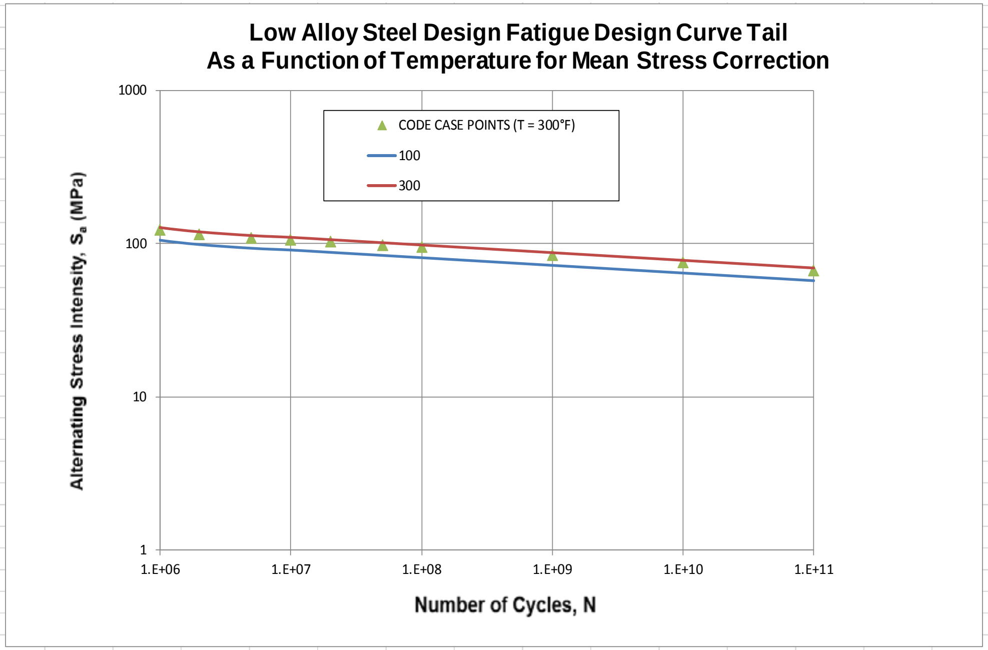
Low Alloy Steel

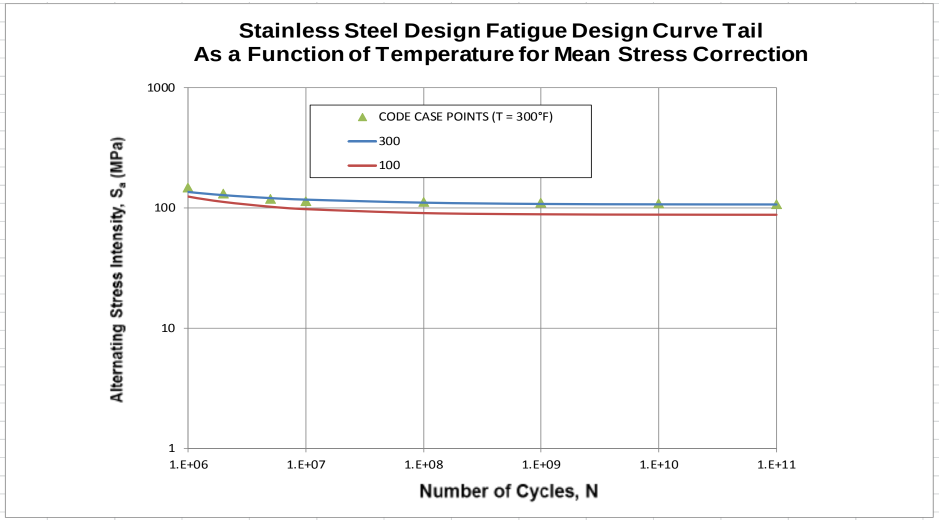
Responses from WG-Fatigue Strength Members

- There were questions about the equations in the Code Case
  - As part of the verification of the equations, Gary Stevens did an independent review and concluded that the equations were correct but he added some clarifications
- There was a comment that for LAS and CS, the high cycle part of the fatigue curve was based on extending the curve with a slope $N^{-0.05}$ at 10^6 cycles and did not have the mean stress correction (MSC)
  - A detailed evaluation was performed from scratch by Gary Stevens starting with the mean data curves from NUREG/CR-6909 Rev.1 to develop the fatigue curve with MSC based on temperature dependent properties. He concluded that the predictions from the equations in the CC were consistent, but slightly conservative when compared with the results from his spreadsheet.
  - The verification from Gary and earlier work by Har Mehta support the code case.

Comparison of Proposed CC with NUREG/CR-6909 Predictions







Responses from WG-Fatigue Strength Members (cont.)

- A comment was made that the E correction was independent of the MSC based on temperature dependent properties and is not a temperature effect but is related to converting strain to stress
  - It is recognized that the E correction is independent of the MSC based on temperature dependent properties and is not a temperature effect but is related to converting strain to stress. However, as a convenience to the user The E effect (which is dependent on the E at temperature) was included along with MSC so that the user does not have to separately correct for E
  - To avoid this confusion, the Code Case was revised such that the E effect is <u>not included</u> along with the MSC effect
  - The user has to make a correction for E separately in accordance with Appendix XIII, XIII-3520(d) starting with the 2017 edition or NG-3222.4 using the temperatures used for the MSC

Status of the Proposed Code Case

- The code case has been discussed extensively in several WG-Fatigue Strength meetings and most of the important comments have been addressed
- Technical basis document and the revised Code Case are being prepared. They will be uploaded to the ASME code web site with the expectation of a letter ballot by the November meeting at Atlanta
  - Voting by WG-Fatigue Strength and subsequently by SG-Design Methodology
- In the long term, all the Code fatigue curves should be updated using mean data curves from NUREG/CR-6909 Rev.1 with MSC based on temperature dependent properties

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