Environmentally-assisted fatigue in NPP piping systems

Solution to the EPRI/NRC example problem

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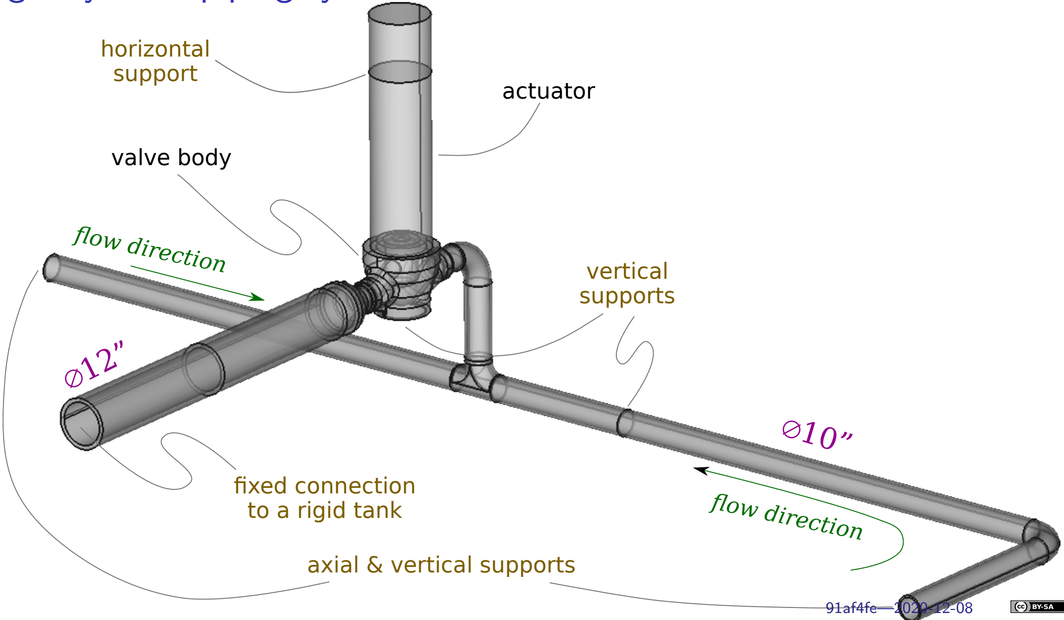
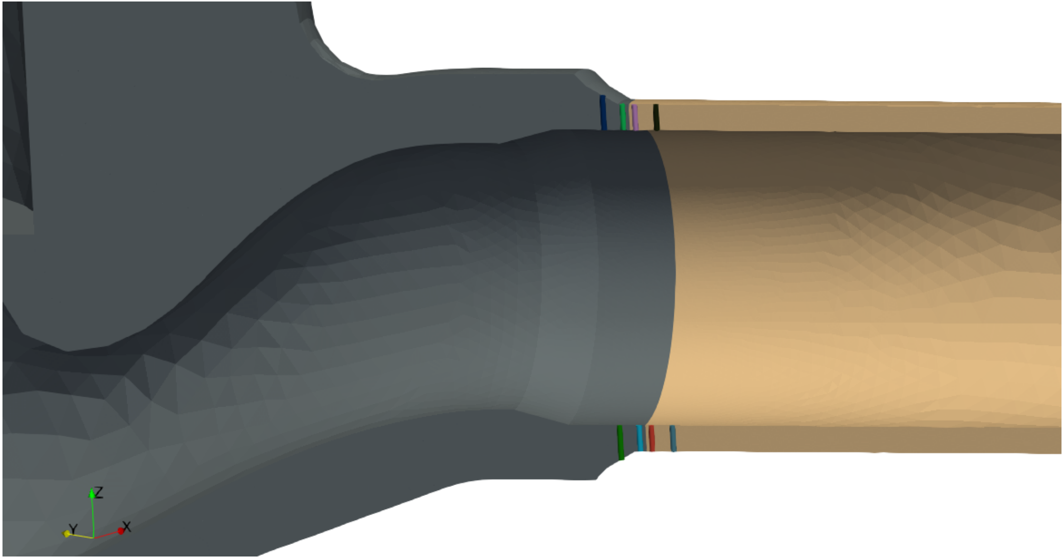
Motivation

- NPP lifetime extension & licensing renewal
- ASME code III-NB recognizes **fatigue** as a **possible mode of failure** in pressure vessel steels and piping materials
- There can be **cyclic** loading on a reactor pressure boundary component
- Operational and incidental transients lead to **cyclic**...
  - changes in the pipe's internal pressure
  - changes in the thermal transients
- Especially important at **dissimilar material interfaces**!

Imaginary NPP piping system



Dissimilar materials and Stress Classification (or Cut) Lines



ASME & EAF

- ASME fatigue design curves have evolved significantly since the initial publication in 1963 for section III (ASME VIII in 1968).
- Paragraph NB-3121 of the 2011 Addenda to ASME Code Section III continues to state that the effects of water environments on the fatigue resistance of materials **were not** addressed in the fatigue design curves.
- Operating reactors whose components were designed in accordance with ASME Code Section III, **may not adequately address** long-term environmental effects on fatigue based on the data available at the time the fatigue design curves were derived.

    i. create a new set of fatigue curves from scratch

    ii. use the existing ones and add modification factors

Landscape of documents, reports & references (chronological)

- Regulatory Guide 1.207: Guidelines For Evaluating Fatigue Analyses Incorporating The Life Reduction Of Metal Components Due To The Effects Of The Light-Water Reactor Environment For New Reactors (NRC, March 2007)
- Case N-792 Fatigue Evaluations Including Environmental Effects, Section III, Division 1 (ASME, August 2012)
- Guidelines for Addressing Environmental Effects in Fatigue Usage Calculations (EPRI, December 2012)
- CR-6909 Effect of LWR Water Environments on the Fatigue Life of Reactor Materials (NRC, May 2018)
- Regulatory Guide 1.207 revision 1 (NRC, June 2018)

EPRI EAF Sample problems

- The sample problems both used the same component model, which represents a typical **piping nozzle**, analyzed using the methods of ASME III NB-3200.

	Input	**Output**
Problem #1	transient $p(t)$ & $T(t)$	stress history[1]
Problem #2	stress history[2]	fatigue estimation (CUF)

- The NB-3600 aspects of were not evaluated in these problems (they require a separate development).
- ASME Section III, "Rules for Construction of Nuclear Facility Components,"
  - Subsection NB "Class 1 Components,"
    - Subarticle NB-3200, "Design by Analysis,"
    - Subarticle NB-3600, "Piping Design,"

[1] stress history $\#1 \neq$ stress history $\#2$

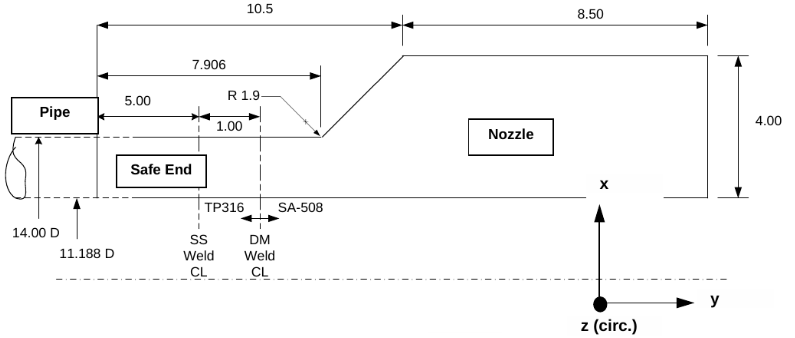
[2] complexity(stress history $\#2$) $>$ complexity(stress history $\#1$)

EPRI EAF Sample problem #2

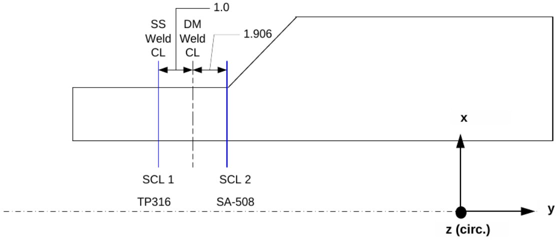
[...] The purpose of this sample problem solution is to demonstrate one example of the use of the methodology described in this report to calculate the F_{en} and $\mathrm{CUF}_{\mathrm{en}}$ for a **relatively simple** problem. The sample problem is not intended to be an exhaustive treatment of more comprehensive component assessments that may be present in operating nuclear power plants.

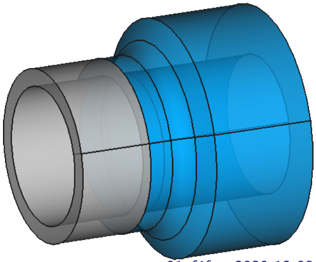
The sample problem selected for solution in this appendix was the second example problem developed and solved by several industry participants. The purpose of the industry's sample problem efforts was to **evaluate the effectiveness of some ASME Code in providing sufficient guidance for environmentally assisted fatigue (EAF) evaluations and to identify any related guidelines that may be useful for industry applications.** The main intentions of the second sample problem were to **ensure that transient pairs occurred between peaks and valleys from different transients,** include a complex transient with multiple peaks and valleys, to incorporate a dynamic load event, and include dissolved oxygen (DO) variations between transients and during at least one transient.

EPRI EAF Sample problem #2—Geometry



a. pagan units
b. not to scale
c. MS Paint?





(Note: All dimensions are in inches. Sketches are not to scale.)

EPRI EAF Sample problem #2—Fatigue curves

Table A-1 Fatigue Design Curves for Carbon and Low Alloy Steels in Air.

	Stress Amplitude, MPa (ksi)		
Cycles	ASME Code Curve	Carbon Steel	Low-alloy Steel
1E+01	3999 (580)	5355 (777)	5467 (793)
2E+01	2827 (410)	3830 (556)	3880 (563)
5E+01	1896 (275)	2510 (364)	2438 (354)
1E+02	1413 (205)	1820 (264)	1760 (255)
2E+02	1069 (155)	1355 (197)	1300 (189)
5E+02	724 (105)	935 (136)	900 (131)
1E+03	572 (83)	733 (106)	720 (104)
2E+03	441 (64)	584 (84.7)	576 (83.5)
5E+03	331 (48)	451 (65.4)	432 (62.7)
1E+04	262 (38)	373 (54.1)	342 (49.6)
2E+04	214 (31)	305 (44.2)	276 (40.0)
5E+04	159 (23)	238 (34.5)	210 (30.5)
1E+05	138 (20.0)	201 (29.2)	172 (24.9)

	Stress Amplitude, MPa (ksi)		
Cycles	ASME Code Curve	Carbon Steel	Low-alloy Steel
2E+05	114 (16.5)	176 (25.5)	141 (20.5)
5E+05	93.1 (13.5)	154 (22.3)	116 (16.8)
1E+06	86.2 (12.5)	142 (20.6)	106 (15.4)
2E+06		130 (18.9)	98 (14.2)
5E+06		120 (17.4)	94 (13.6)
1E+07	76.8 (11.1)	115 (16.7)	91 (13.2)
2E+07		110 (16.0)	88 (12.7)
5E+07		105 (15.2)	84 (12.2)
1E+08	68.5 (9.9)	101 (14.7)	81 (11.8)
1E+09	61.1 (8.8)	90 (13.1)	72.3 (10.5)
1E+010	54.4 (7.9)	81 (11.7)	64.4 (9.3)
1E+011	48.5 (7.0)	72 (10.4)	57.4 (8.3)

ASME fatigue analysis using fatigue curves

The ASME Code fatigue design curves, as given in Mandatory Appendix I to ASME Code Section III, are based on **strain–controlled tests** of small polished specimens at **room temperature in air**.

- ASTM Standard E606-04
  - Nominally homogeneous materials
  - Usage of uniform gauge section specimens
  - Axial strain-controlled, fully reversed cycling ($R = -1$)
- ASTM Standard E468 “Standard Practice for Presentation of Constant Amplitude Fatigue Test Results for Metallic Materials,” (Nov. 2004)
- ASTM Standard E739, “Standard Practice for Statistical Analysis of Linear or Linearized Stress-Life (S–N) and Strain-Life (ε–N) Fatigue Data,” (May 2006)
- ASTM Standard E1823, “Standard Terminology Relating to Fatigue and Fracture Testing,” (March 2009)
- “Fatigue Data Analysis,” of the Metals Handbook (issued 1985) can also be used.

Use of strain-controlled fatigue data

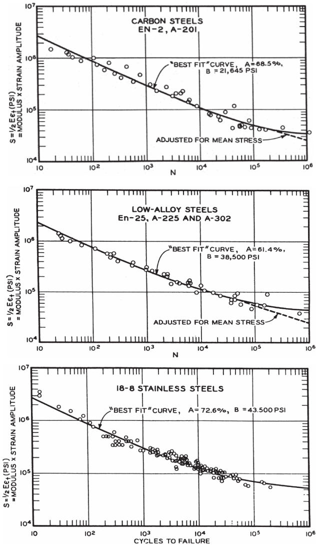
- ASME Companion Guide, Chapter 39 "Code Design and Evaluation for cyclic loading—Sections III and VIII"

$$S_a = \frac{E}{4\sqrt{N}} \ln \frac{100}{100 - \mathrm{RA}} + S_e$$

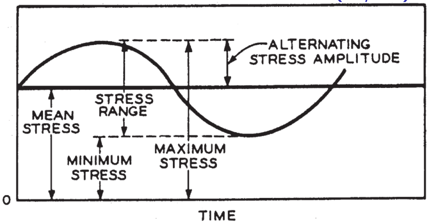
- Coffin-Manson with fixed c + Basquin with uniform elastic component (with a weird $\sqrt{2}$ constant due to historical reasons)

$$\frac{\Delta\varepsilon(N)}{2} = \frac{1}{\sqrt{2}} \cdot \varepsilon'_f(\mathrm{RA}) \cdot [2N]^{-0.5} + \frac{S_e}{E}$$

- Fit parameters are RA and S_e



Effects of mean stress (1/2)

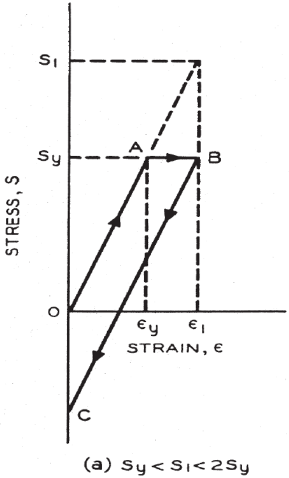


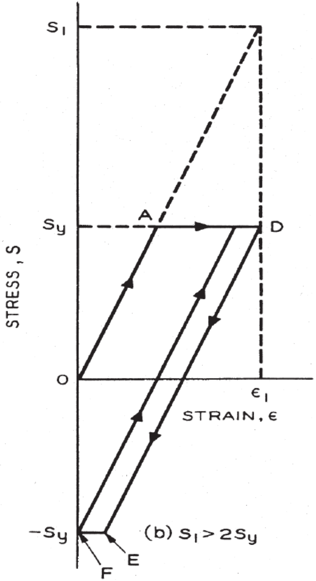
According to load history

$$S'_m = \frac{1}{2}\left(\sigma_{\text{min}} + \sigma_{\text{max}}\right)$$

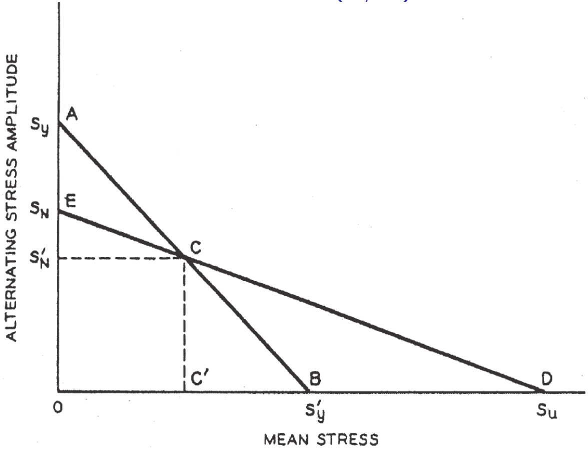
Considering yielding

$$S_m = \begin{cases} \frac{1}{2}\left(\sigma_{\text{min}} + \sigma_{\text{max}}\right) & \text{if } \sigma_{\text{max}} < \sigma_y \\ \sigma_y - \Delta\sigma & \text{for case (a)} \\ 0 & \text{for case (b)} \end{cases}$$





Effects of mean stress (2/2)



Modified Goodman, **constant** N_f

S'_m Mean stress from the load cycle

S_m Effective mean stress for fatigue

1. for $S'_m = S_m = 0$, $\Delta\sigma = S_N$
2. $S'_m \in [O, C']$, $\sigma_{\text{max}} < \sigma_y$
   i. $\Delta\sigma \downarrow EC$
   ii. $S_m = S'_m$
3. $S'_m \in [C', B]$: case (a)
   i. $\Delta\sigma \uparrow CE$
   ii. $S_m \downarrow C'O$
4. $S'_m \in [B, D]$: case (b)
   i. $\Delta\sigma = 2 \cdot \sigma_y$
   ii. $S_m = 0$
5. $\Rightarrow C'$ is the worst-case S_m

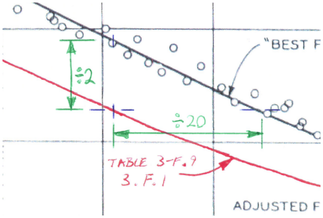
$$C' = S_{m,\text{max}} = S_u \cdot \frac{\sigma_y - S_N}{S_u - S_N}$$

$$S'_N = S_N \cdot \frac{S_u - \sigma_y}{S_u - S_N}$$

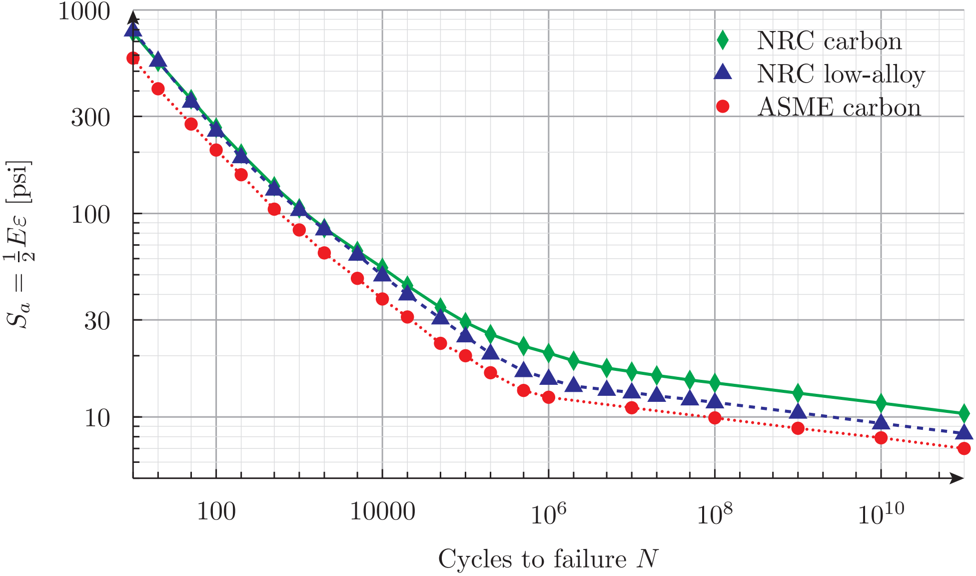
Adjustment factors in ASME's fatigue curves

- The factors of 2 and 20 **are not safety margins**, but *adjustment* factors to account for
  a. data scatter and material variability
  b. differences in surface condition and size between the test specimens and actual reactor components, and
  c. random load cycles as compared to constant strain cycles used to obtain the fatigue ε–N data.

Parameter	**ASME III**	**NRC**
Material Variability and Data Scatter	2.0	2.1–2.8
Size Effect	2.5	1.0–1.4
Surface Finish and Other Factors	4.0	1.5–3.5
Loading History	–	1.0–2.0
Total Adjustment	20	3.15–27.4



EPRI EAF Sample problem #2—Fatigue curves



EPRI EAF Sample problem #2—Material properties

Table C-1 Material Properties for SCL 2 (SA 508 Class 2.)

Temperature (°F)	S_m (psi)	E (psi)
70	30,000	$27.8x10^6$
100	30,000	$27.6x10^6$
200	30,000	$27.1x10^6$
300	30,000	$26.7x10^6$
400	30,000	$26.2x10^6$
500	30,000	$25.7x10^6$
600	30,000	$25.1x10^6$
700	30,000	$24.9x10^6$

Notes: 1. The sulfur content, S, for this material was assumed to be 0.025 weight percent for the purposes of the sample problem.

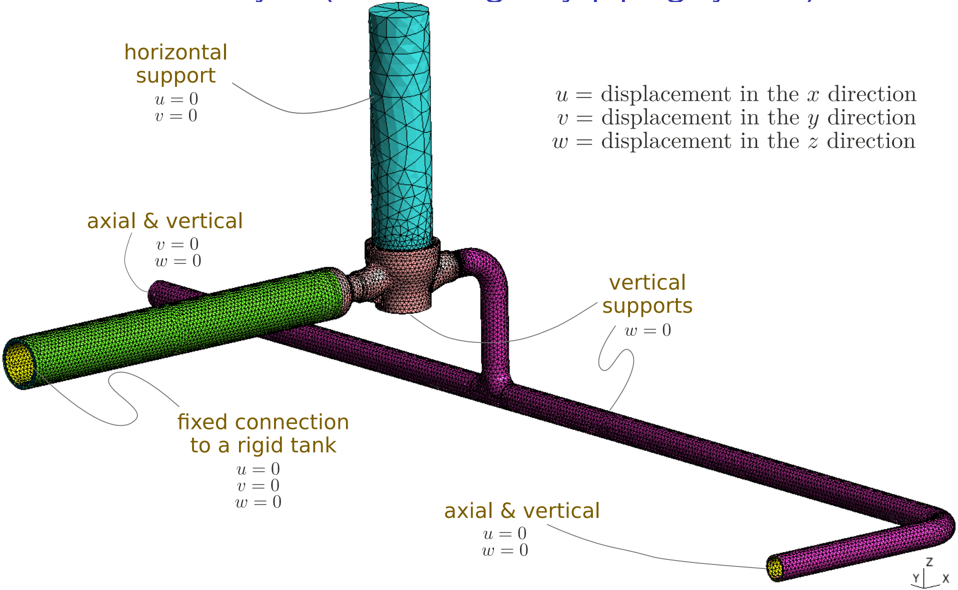
2. The low-alloy steel fatigue curve from Table A-1 in Appendix A was used to calculate CUF using a fatigue curve Young's modulus value of $30.0x10^6$ psi.

EPRI EAF Sample problem #2—Time histories

Table C-2 Sample Problem Transient Definitions.

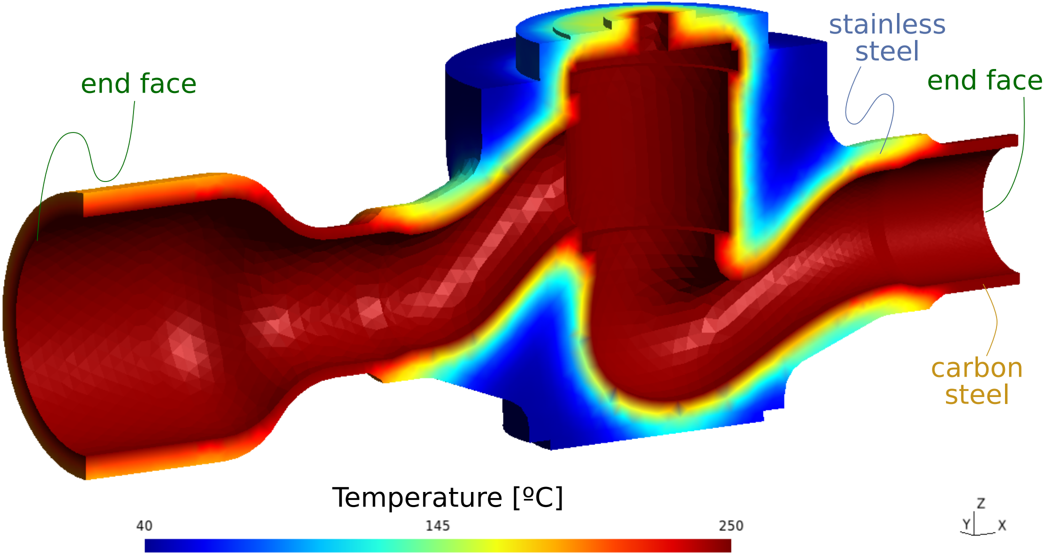
Transient No.	Time (sec)	Fluid Temperature (°F)	Heat Transfer Coefficient, h (BTU/s-in²-°F)	Pressure (psi)	Resultant Moment (in-kips)	DO (ppm)
1 (20 cycles)	0	450	0.003	2,250	-3,000	0.150
	100	450	0.003	2,250	-3,000	0.150
	450	100	0.003	1,000	1,000	0.150
	1,510	100	0.003	1,000	1,000	0.150
	1,710	600	0.003	2,250	-3,000	0.150
	3,210	600	0.003	2,250	-3,000	0.150
2 (50 cycles)	0	500	0.003	1,500	-2,500	0.550
	100	500	0.003	1,500	-2,500	0.550
	260	100	0.003	2,250	1,000	0.550
	1,290	100	0.003	2,250	1,000	0.550
	1,540	350	0.003	2,000	-2,500	0.550
	3,240	350	0.003	2,000	-2,500	0.550
3 (20 cycles)	0	300	0.003	1,600	0	0.050
	50	650	0.003	1,600	0	0.050
	250	650	0.003	1,600	0	0.050
	275	400	0.003	1,600	0	0.050
	400	400	0.003	1,600	0	0.050
	600	550	0.003	1,600	0	0.050
	700	550	0.003	1,600	0	0.050
	900	350	0.003	1,600	0	0.050
	1,000	350	0.003	1,600	0	0.050
	1,200	400	0.003	1,600	0	0.050
	1,300	400	0.003	1,600	0	0.050
	1,500	70	0.003	1,600	0	0.050
	1,600	70	0.003	1,600	0	0.050
	2,000	300	0.003	1,600	0	0.050
	3,800	300	0.003	1,600	0	0.050
4 (100 cycles)	0	70	0.003	400	-3000	0.55
	100	70	0.003	400	-3000	0.55
	3,700	170	0.003	400	-2100	0.442
	7,300	270	0.003	400	-1200	0.334
	8,272	297	0.003	580.32	-957	0.30484
	10,072	347	0.003	914.26	-507	0.25084
	13,672	447	0.003	1582.13	393	0.14284
	17,272	547	0.003	2250	1293	0.3484
	18,100	547	0.003	2250	1500	0.01
	26,000	547	0.003	2250	1500	0.01
5 (5 cycles*)	Operating Basis Earthquake (OBE) Transient OBE loading was defined by resultant moment loads. The resultant moment load was specified as +/- 2,000 in-kips. Each OBE event was assumed to occur at any time during any of the transients. DO= 0.100 ppm. (* Note that the sample problem statement assumed five events with 10 cycles per event; for this analysis, 5 peak cycles during Transient No. 2 were evaluated and the remaining 45 cycles were assumed to self-pair and not contribute to CUF.)					

Finite-element Analysis (of an imaginary piping system)

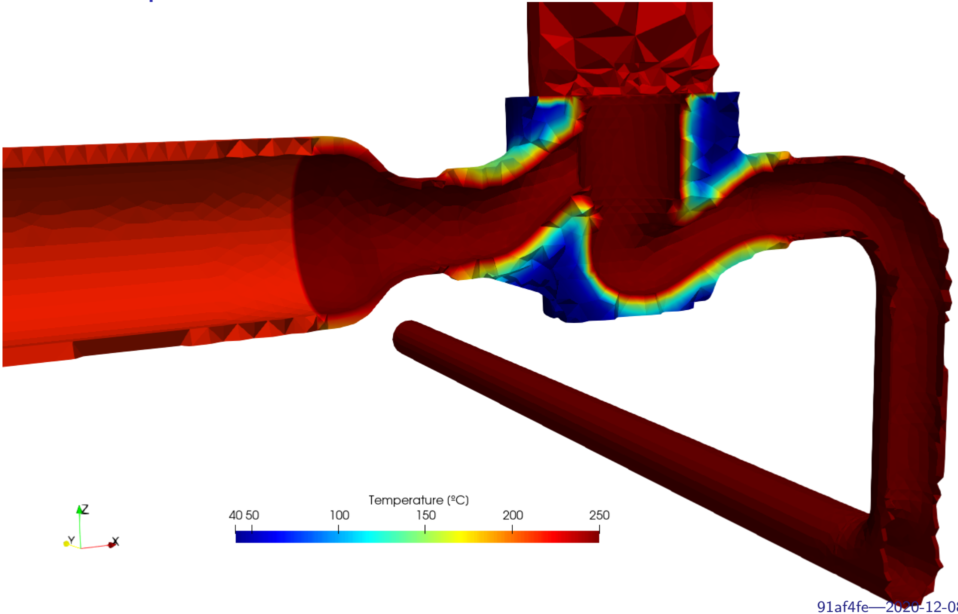


u = displacement in the x direction
v = displacement in the y direction
w = displacement in the z direction

Thermal transient (video is 10x in time)



Mechanical quasi-static transient



NB-3216 Derivation of Stress Differences

1. Constant Principal Stress Direction
   a. consider σ_1, σ_2 and σ_3
   b. Determine $S_{ij} = \sigma_i - \sigma_j$
   c. Determine extremes and find the magnitue of the range for each S_{ij}, call it $S_{r,ij}$ and let $S_{\text{alt},ij} = 0.5 \cdot S_{r,ij}$, then $S_{\text{alt}} = \max\left\{S_{\text{alt},ij}\right\}$ *(i.e. $S_{alt,31}$)*
2. Varying Principal Stress Direction
   a. Consider the six stress components
   b. Choose one point in time where stresses are a extrema (either min. or max.) and identify this time with subscript i
   c. Subtract each of the six stress components σ_i & τ_i from the corresponding components at each point in time and call the result σ' & τ'.
   d. At each point in time compute the principal stresses σ_i'.
   e. Determine the stress differences $S_{ij}' = \sigma_i' - \sigma_j'$ versus time and find the largest absolute magnitude of any stress difference at any time, then S_{alt} is one half of this magnitude.

NB-3228.5 Simplified Elastic–Plastic Analysis.

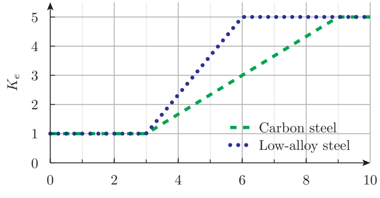
The $3S_m$ (*i.e. the design stress intensity, **not the mean stress***) limit on the range of primary plus secondary stress intensity (NB-3222.2) may be exceeded provided that [...]

b. The value of S_a used for entering the design fatigue curve is multiplied by

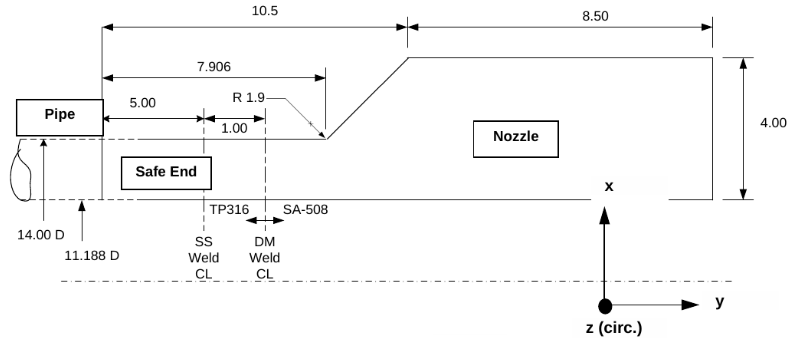
$$K_e = \begin{cases} 1 & \text{for } S_n \leq 3S_m \\ 1 + \left[\frac{1-n}{n\cdot(m-1)}\right]\cdot\left[\frac{S_n}{3S_m} - 1\right] & \text{for } 3S_m < S_n < 3m\cdot S_m \\ 1/n & \text{for } S_n \geq 3m\cdot S_m \end{cases}$$

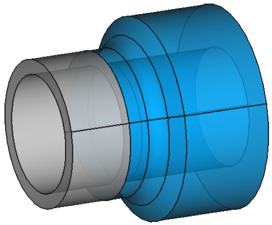
with S_n the range of primary plus secondary stress intensity *(i.e. Tresca)*.

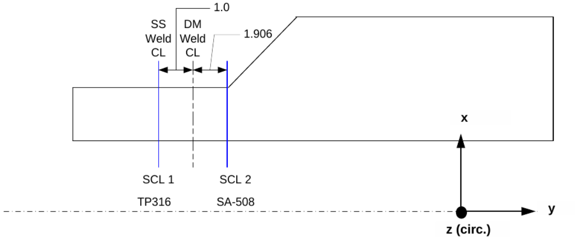
Materials	m	n	T_{max}, °F (°C)
Carbon steel	3.0	0.2	700 (370)
Low alloy steel	2.0	0.2	700 (370)
Martensitic stainless steel	2.0	0.2	700 (370)
Austenitic stainless steel	1.7	0.3	800 (425)
Nickel–chromium–iron	1.7	0.3	800 (425)
Nickel–copper	1.7	0.3	800 (425)



Back to the EPRI problem with the pagan units!

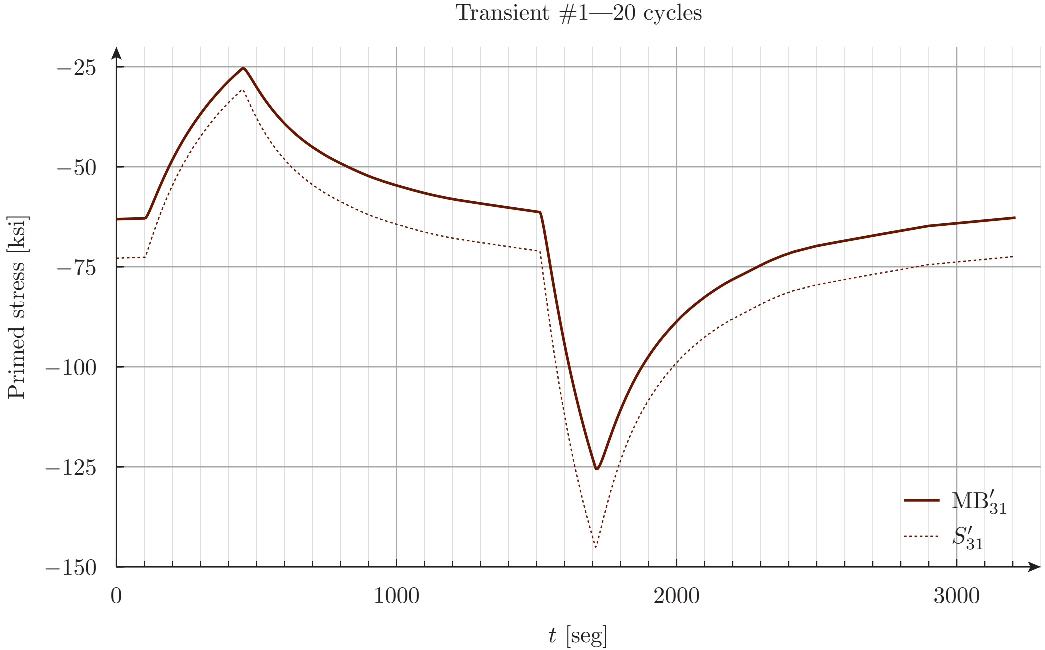


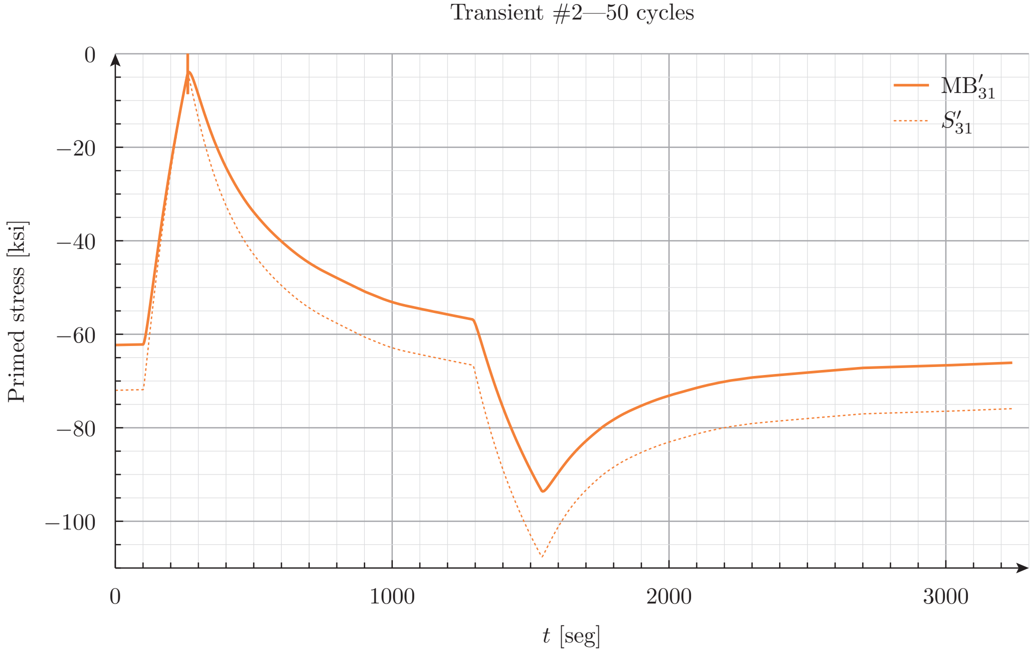




(Note: All dimensions are in inches. Sketches are not to scale.)

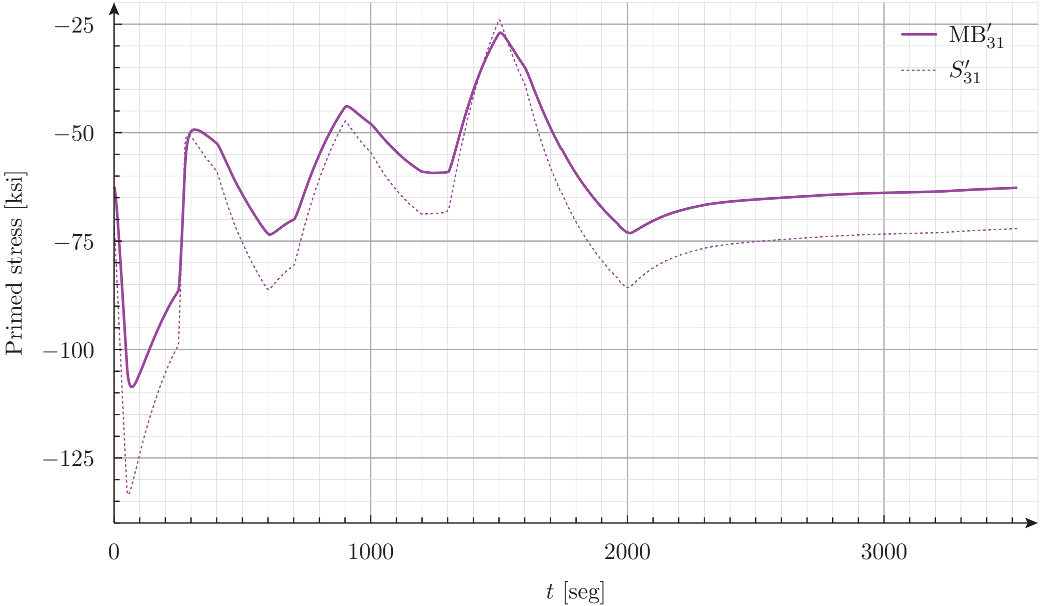
- "Primed" stress history for SCL #2
- Both Tresca and membrane plus bending


Transient #1—20 cycles
Primed stress [ksi]
−25
−50
−75
−100
−125
−150
0
1000
2000
3000
t [seg]
MB'_{31}
S'_{31}

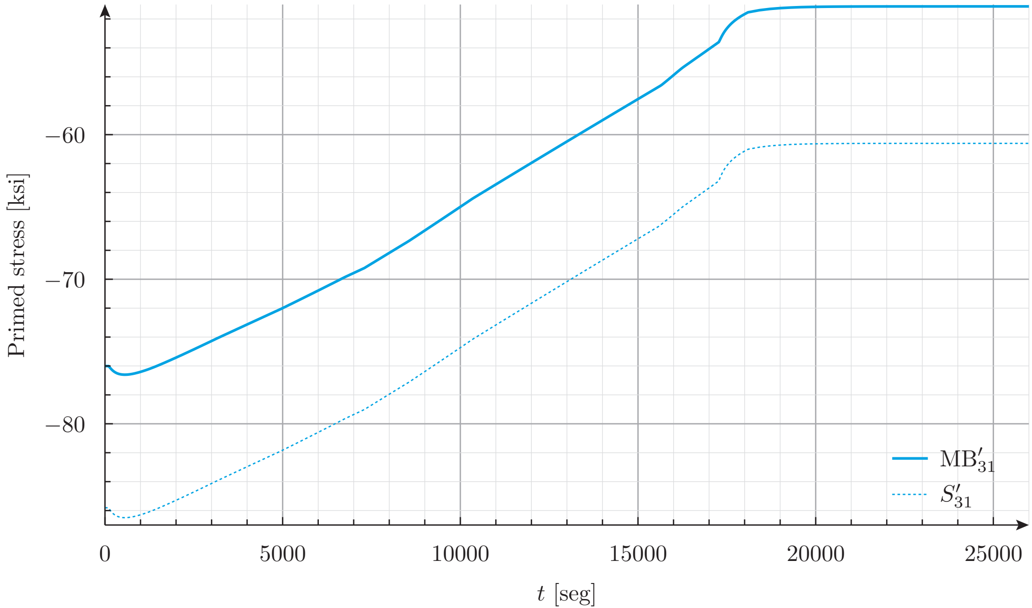


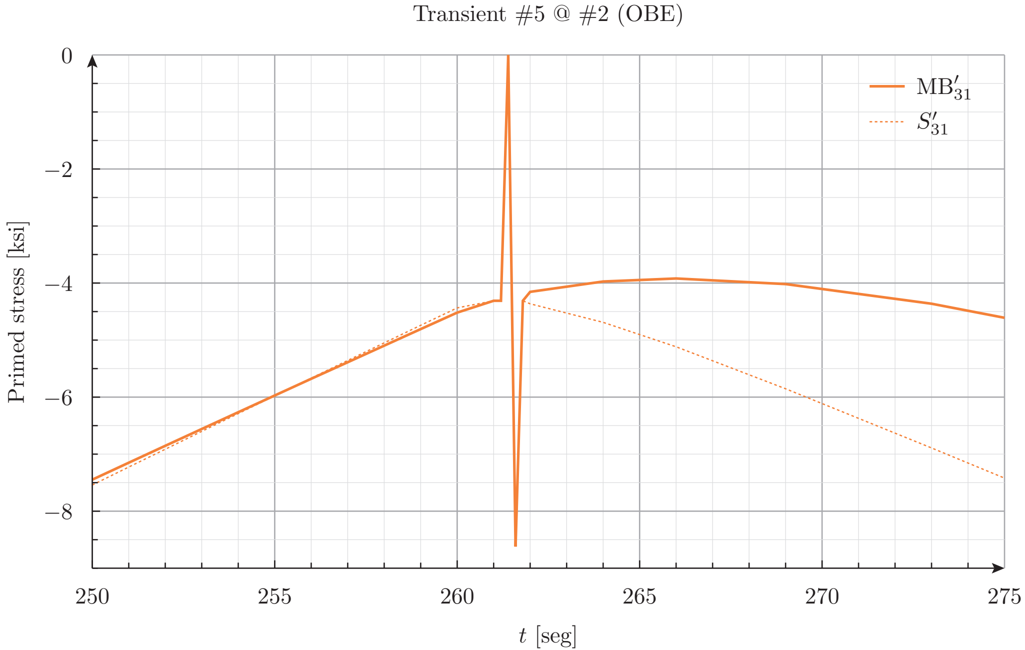
Transient #2—50 cycles
0
−20
−40
−60
−80
−100
Primed stress [ksi]
0
1000
2000
3000
t [seg]
MB'_{31}
S'_{31}

Transient #3—20 cycles



Transient #4—100 cycles





Transient #5 @ #2 (OBE)
0
−2
−4
−6
−8
Primed stress [ksi]
250
255
260
265
270
275
t [seg]
MB'_{31}
S'_{31}

Overview of EAF Analysis Process

The general steps for performing an EAF analysis are as follows:

1. perform an ASME fatigue analysis using fatigue curves for an air environment
2. calculate F_{en} factors for each transient pair in the fatigue analysis
3. apply the F_{en} factors to the incremental usage calculated for each transient pair to determine the CUF_{en}, using

$$\text{CUF}_{\text{en}} = U_1 \cdot F_{\text{en},1} + U_2 \cdot F_{\text{en},2} + \cdots + U_n \cdot F_{\text{en},n}$$

NB-3222.4 Analysis for Cyclic Operation

[...]

4. *Effect of Elastic Modulus.* Multiply S_{alt} (as determined in NB-3216) by the ratio of the modulus of elasticity given on the design fatigue curve to the value of the modulus of elasticity used in the analysis. Enter the applicable design fatigue curve at this value on the ordinate and find the number of cycles in the abscissa. If the service cycle being considered is the only one which produces significant fluctuating stresses, this is the allowable number of cycles.

5. *Cumulative Damage* If there are two or more types of stress cycle which produce significant stresses, their cumulative effect shall be evaluated as stipulated below. *(i.e. computation of CUF, assumes Palmgren-Miner linear damage hypothesis)*.

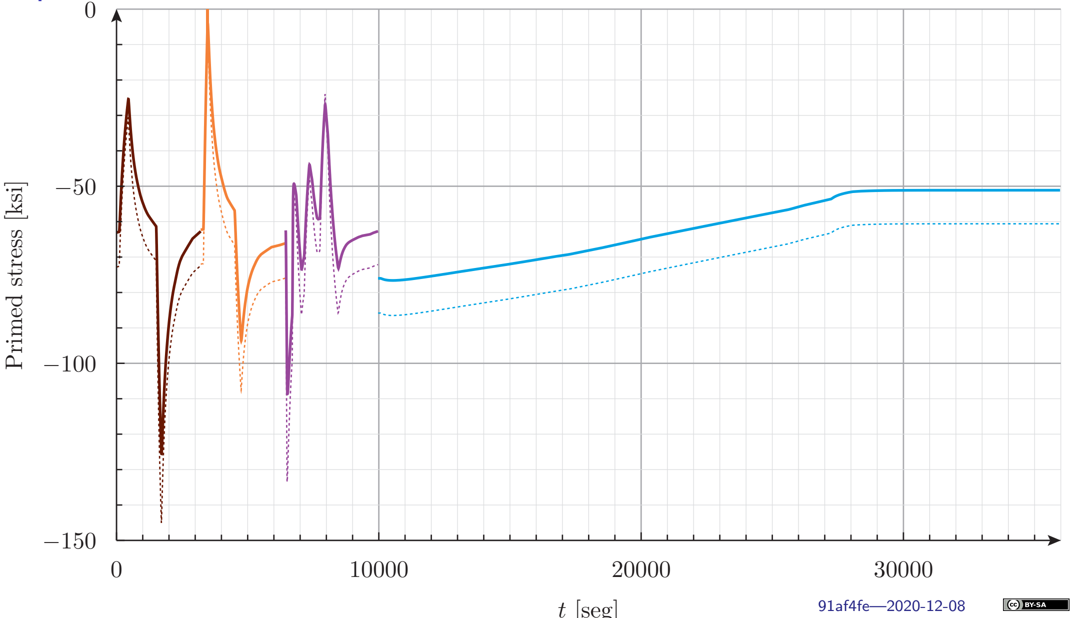
[...]

NB-3222.4 Clarification note about superposition of cycles

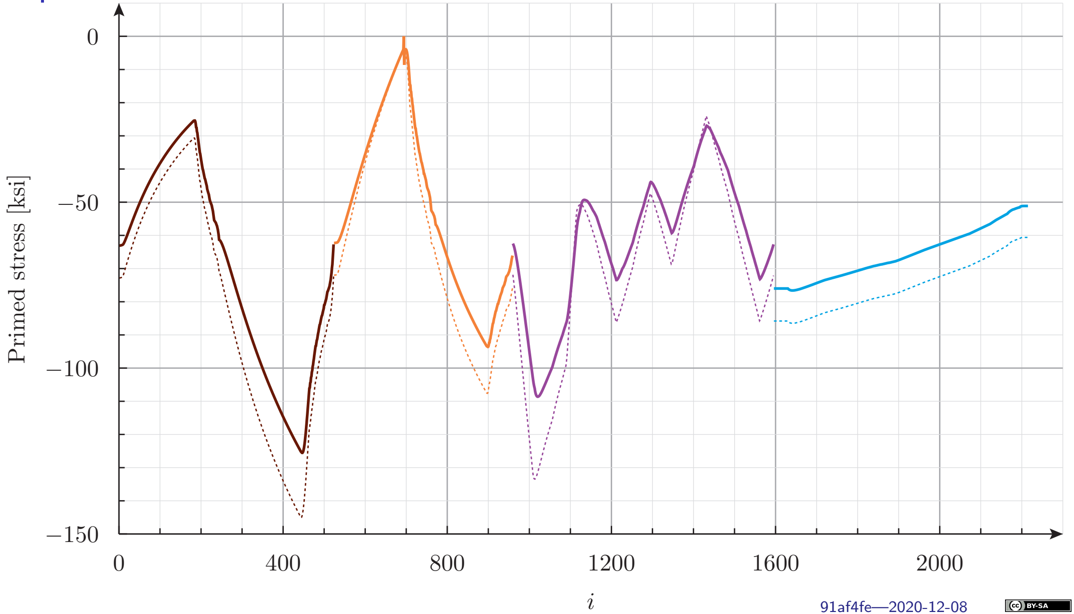
In determining n_1, n_2, n_3, ..., n_j consideration shall be given to the superposition of cycles of various origins which produce a total stress difference range greater than the stress difference ranges of the individual cycles. For example, if one type of stress cycle produces 1,000 cycles of a stress difference variation from zero to +60,000 psi and another type of stress cycle produces 10,000 cycles of a stress difference variation from zero to −50,000 psi, the two types of cycle to be considered are defined by the following parameters:

(a) for type 1 cycle, $n_1 =$ 1,000 and $S_{\text{alt},1} = (60,000 + 50,000)/2$;
(b) for type 2 cycle, $n_2 =$ 9,000 and $S_{\text{alt},2} = (50,000 + 0)/2$.

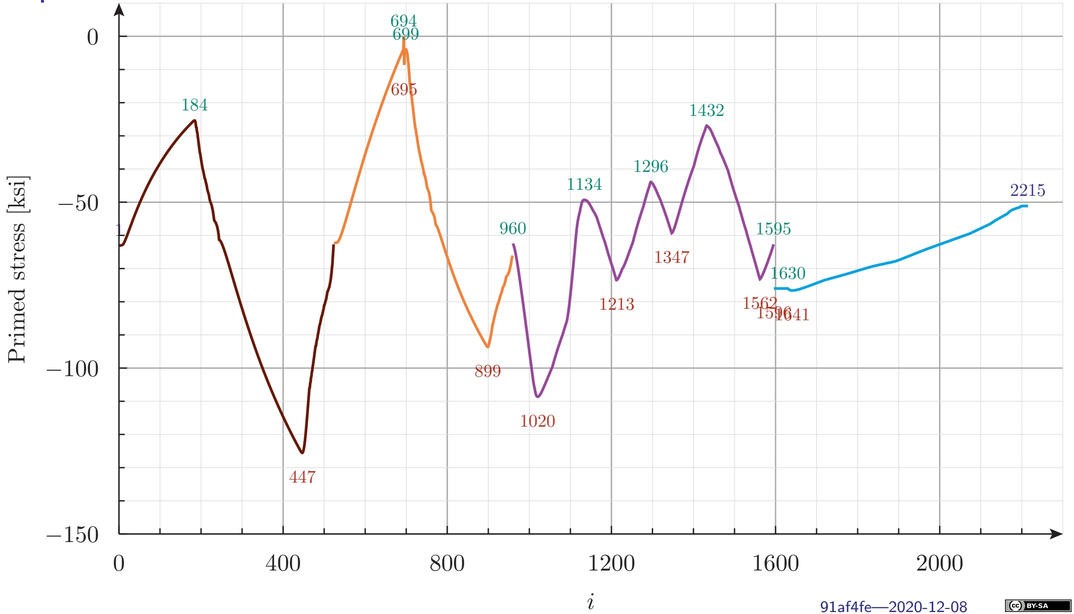
Juxtaposed stress time-histories



Juxtaposed stress index-based-histories



Juxtaposed stress index-based-histories with extrema



Peak cycle counting

1. Find valley-peak pair with largest stress difference and call the points A and B
   - 447–694
2. Subtract $\min[n_A, n_B]$ from n_A and n_B
   - $\min[20, 5] = 5$
   - $n_{447} \leftarrow 20 - 5 = 15$
   - $\cancel{n_{694} \leftarrow 5 - 5 = 0}$
3. Remove all points that reach $n = 0$ and go to 1 with the next pair
   - 447–699, $\min[15, 50] = 15$, $\cancel{n_{447} \leftarrow 15 - 15 = 0}$, $n_{699} \leftarrow 50 - 45 = 35$
   - 699–1020, $\min[35, 20] = 20$, $n_{699} \leftarrow 35 - 20 = 15$, $\cancel{n_{1020} \leftarrow 20 - 20 = 0}$
   - ...

Peak cycle counting

j	A	B	n_A	n_B	ΔS
1	447	694	20	5	125.5
2	447	699	15	50	121.6
3	699	1020	35	20	104.7
4	699	899	15	50	89.7
5	695	899	5	35	85.0
6	899	1432	30	20	66.7
7	184	899	20	10	68.2
8	184	1641	10	100	51.2
9	1296	1641	20	90	32.7
10	1134	1641	20	70	27.3

j	A	B	n_A	n_B	ΔS
11	1641	2215	50	100	25.5
12	1213	2215	20	50	22.3
13	1630	2215	100	30	24.9
14	1347	1630	20	70	16.7
15	960	1630	20	50	13.5
16	1595	1630	20	30	13.3
17	1	1630	20	10	12.9
18	1	1596	10	100	12.9
19	1562	1596	20	90	2.8

Partial Cumulative Usage Factors

For each valley-peak pair j, compute...

1. the maximum temperature $T_{\text{max},j}$ in the interval j between A_j & B_j
2. $K_{e,j}$ from NB-3228.5
3. the alternating stress

$$S_{\text{alt},j} = \frac{1}{2} \cdot K_{e,j} \Delta S_j \cdot \frac{E_{\text{curve}}}{E(T_{\text{max},j})}$$

4. the allowable the number of cycles $N_j(S_{\text{alt},j})$ from the fatigue curves
5. the partial U_j as

$$U_j = \frac{\min[n_{A,j}, n_{B,j}]}{N_j} = \frac{n_j}{N_j}$$

Total Cumulative Usage Factor

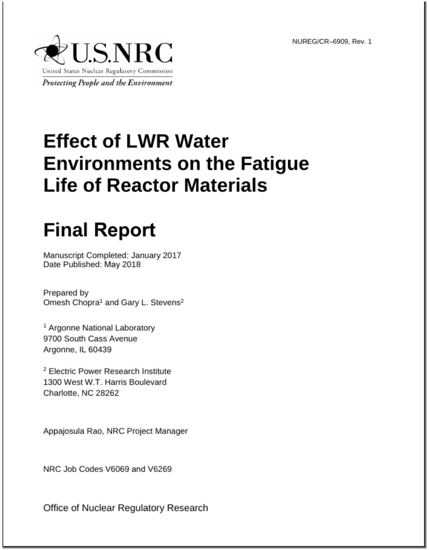
j	A_j	B_j	n_A	n_B	$\Delta \mathrm{MB}'_j$	$k_{e,j}$	S'_j	$S_{\mathrm{alt},j}$	N_j	n_j	U_j	$T_{\max,j}$
1	447	694	20	5	125.5	2.580	144.2	220.5	1.40×10^2	5	3.57×10^{-2}	566.6
2	447	699	15	50	121.6	2.405	139	198.3	1.79×10^2	15	8.38×10^{-2}	566.6
3	699	1020	35	20	104.7	1.653	126.5	124.9	5.77×10^2	20	3.47×10^{-2}	599.2
4	699	899	15	50	89.7	1.000	102.3	57.77	6.37×10^3	15	2.35×10^{-3}	336.1
5	695	899	5	35	84.99	1.000	98.8	55.79	7.06×10^3	5	7.08×10^{-4}	336.1
6	899	1432	30	20	66.67	1.000	83.1	50.07	9.72×10^3	20	2.06×10^{-3}	634.2
7	184	899	20	10	68.23	1.000	76.76	45.87	1.29×10^4	10	7.77×10^{-4}	600.0
8	184	1641	10	100	51.22	1.000	55.83	33.64	3.59×10^4	10	2.78×10^{-4}	634.2
9	1296	1641	20	90	32.69	1.000	38.94	22.12	1.52×10^5	20	1.31×10^{-4}	366.2
10	1134	1641	20	70	27.31	1.000	34.49	19.81	2.34×10^5	20	8.54×10^{-5}	419.2
11	1641	2215	50	100	25.47	1.000	25.89	15.28	1.07×10^6	50	4.67×10^{-5}	547.0
12	1213	2215	20	50	22.34	1.000	25.3	14.93	1.30×10^6	20	1.53×10^{-5}	547.0
									total CUF for SCL 2 =		**0.1607**	

Reference solution (NRC)

Point No. for Load A(1)	Point No. for Load B(1)	Applied Cycles for Load A	Applied Cycles for Load B	M+B Stress (psi)	K_e	Total Stress (psi)	S_{alt} (psi)	N_n	n_n	U_n	Maximum Metal Temp. (°F)	DO (ppm)
694	447	5	20	125542.9	2.580	144164.4	220490.4	140.005	5	0.0357	566.6	0.150
699	447	50	15	121622.8	2.405	139047.0	198300.6	178.958	15	0.0838	566.6	0.550
699	1021	35	20	104691.5	1.653	126037.5	124507.0	582.468	20	0.0343	600.4	0.550
699	899	15	50	89695.4	1.000	102302.8	57864.5	6339.47	15	0.0024	336.1	0.550
695	899	5	35	84993.9	1.000	98798.6	55882.4	7027.83	5	0.0007	336.1	0.550
185	899	20	30	68222.2	1.000	76465.1	43250.2	15549.1	20	0.0013	336.1	0.550
1432	899	20	10	66665.7	1.000	83098.8	47002.3	11892.7	10	0.0008	336.1	0.550
1432	1653	10	100	49437.0	1.000	61950.9	33687.5	35734.8	10	0.0003	103.0	0.522
1296	1653	20	90	32478.6	1.000	38719.1	22025.4	154852	20	0.0001	366.2	0.522
1136	1653	20	70	27045.6	1.000	33751.1	19388.7	258499	20	0.0001	417.7	0.522
2215	1653	100	50	25255.9	1.000	25668.1	15147.6	1.15E+06	50	0.0000	547.0	0.522
2215	1213	50	20	22343.7	1.000	25298.3	14929.4	1.30E+06	20	0.0000	547.0	0.050
2215	1562	30	20	22047.7	1.000	24970.1	14735.7	1.46E+06	20	0.0000	547.0	0.050
2215	1	10	20	11956.0	1.000	12255.6	7232.5	1.00E+11	10	0.0000	547.0	0.150
1347	1	20	10	3786.5	1.000	4173.0	2412.1	1.00E+11	10	0.0000	450.0	0.150
1347	1595	10	20	3408.0	1.000	3430.2	1963.3	1.00E+11	10	0.0000	398.7	0.050
960	1595	20	10	241.8	1.000	259.9	146.0	1.00E+11	10	0.0000	299.5	0.050

TOTAL CUF = 0.1596

Environmental correction factors



U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

NUREG/CR–6909, Rev. 1

Effect of LWR Water Environments on the Fatigue Life of Reactor Materials

Final Report

Manuscript Completed: January 2017
Date Published: May 2018

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NRC Job Codes V6069 and V6269

Office of Nuclear Regulatory Research

- A detailed 589 pages report!
- A fit of results in water shows that

$$\ln N = A - B \cdot \ln(\varepsilon_a - C) + D \cdot S^\star T^\star O^\star \dot{\varepsilon}^\star$$

- Starred means "transformed" (*i.e. non-dimensional*)
  - S sulfur content
  - T temperature
  - O dissolved oxiygen level
  - $\dot{\varepsilon}$ strain rate

$$F_{\text{en}} = \frac{N_{\text{air}}}{N_{\text{water}}}$$

$$\ln F_{\text{en}} = \ln N_{\text{air}} - \ln N_{\text{water}}$$

$$\ln F_{\text{en}} = A_{\text{air}} - A_{\text{water}} - D_{\text{water}} \cdot S^\star T^\star O^\star \dot{\varepsilon}^\star$$

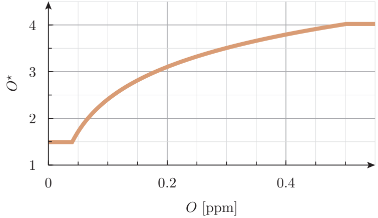
Carbon and low-alloy steels (1/3)

Environmental correction factor

$$F_{\text{en}}(t) = \begin{cases} 1 & \text{if } \dot{\varepsilon} \leq 0 \\ \exp\left[\left(0.003 - 0.031 \cdot \dot{\varepsilon}^\star(t)\right) \cdot S^\star(t)\, T^\star(t)\, O^\star(t)\right] & \text{if } \dot{\varepsilon} > 0 \end{cases}$$

Dissolved oxygen in the water

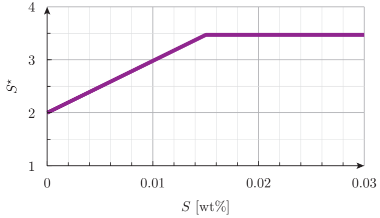
$$O^\star(t) = \begin{cases} 1.49 & \text{if } O(t) \leq 0.04 \text{ ppm} \\ \log\left(\dfrac{O(t)}{0.009 \text{ ppm}}\right) & \text{if } 0.04 < O(t) \leq 0.50 \text{ ppm} \\ 4.02 & \text{if } O(t) > 0.50 \text{ ppm} \end{cases}$$



Carbon and low-alloy steels (2/3)

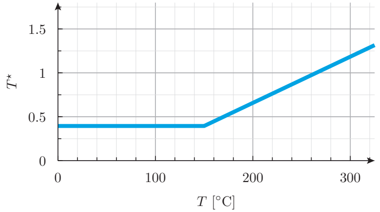
Sulfur content in the steel

$$S^\star(t) = \begin{cases} 2.0 + 98\ (\text{wt\%})^{-1} \cdot S & \text{if } S \leq 0.015 \text{ wt\%} \\ 3.47 & \text{if } S > 0.015 \text{ wt\%} \end{cases}$$



Temperature

$$T^\star(t) = \begin{cases} 0.395 & \text{if } T(t) \leq 150 \text{ ºC} \\ \dfrac{T - 75 \text{ ºC}}{190 \text{ ºC}} & \text{if } T(t) > 150 \text{ ºC} \end{cases}$$

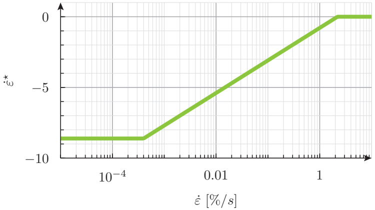


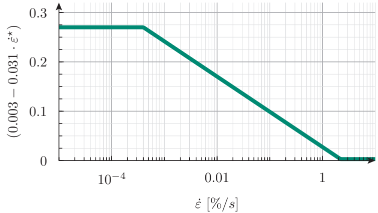
Carbon and low-alloy steels (3/3)—Strain rate

$$\dot{\varepsilon}^{\star}(t) = \begin{cases} 0 & \text{if } \dot{\varepsilon}(t) > 2.2\ \%\cdot\mathsf{s}^{-1} \\ \log\left(\dfrac{\dot{\varepsilon}(t)}{2.2\ \%\cdot\mathsf{s}^{-1}}\right) & \text{if } 0.0004\ \%\cdot\mathsf{s}^{-1} < \dot{\varepsilon}(t) \le 2.2\ \%\cdot\mathsf{s}^{-1} \\ \log\left(\dfrac{0.0004\ \%\cdot\mathsf{s}^{-1}}{2.2\ \%\cdot\mathsf{s}^{-1}}\right) & \text{if } \dot{\varepsilon}(t) \le 0.0004\ \%\cdot\mathsf{s}^{-1} \end{cases}$$

$$\dot{\varepsilon}(t) = \frac{d}{dt}\left[\frac{S'_{31}}{E(T(t))}\right]$$

with/out K_e?
E in/out d/dt?





$$F_{\mathsf{en}}(t) = \begin{cases} 1 & \text{if } \dot{\varepsilon} \le 0 \\ \exp\left[\left(0.003 - 0.031\cdot\dot{\varepsilon}^{\star}(t)\right)\cdot S^{\star}(t)\,T^{\star}(t)\,O^{\star}(t)\right] & \text{if } \dot{\varepsilon} > 0 \end{cases}$$

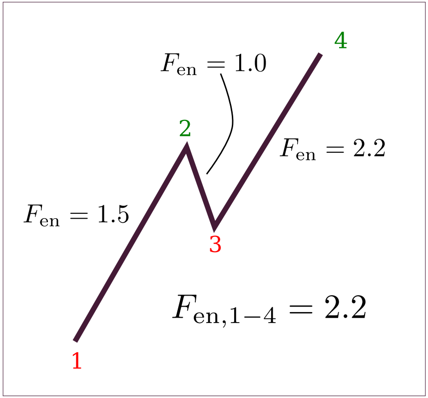
F_{en}, j for the j-th pair—Simplified method

These expressions define $F_{\text{en}}(t)$ but we need one single F_{en}, j for the pair $[A_j, B_j]$

i. Average (or simplified) method
   a. Compute the average strain rate between each **adjacent** valley and peak with positive $\dot{\varepsilon}$

$$\dot{\varepsilon} = \frac{S'_{\text{peak}} - S'_{\text{valley}}}{E \cdot (t_{\text{peak}} - t_{\text{valley}})}$$

   b. Compute F_{en} between each adjacent valley and peak and as the worst F_{t} in the range and assign it to both.
   c. When pairing the j-th valley and peak use the largest of the two to compute F_{en}, j



Too conservative!

F_{en}, j for the j-th pair—Modified strain rate method

F_{en} is assumed to increase linearly from a minimum value of 1.0 with strain

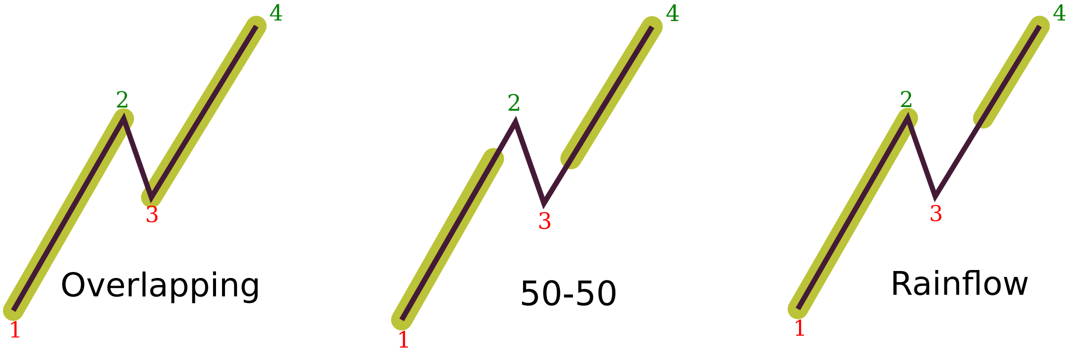
$$dF_{\text{en}} = \frac{F_{\text{en}} - 1}{\varepsilon_{\text{max}} - \varepsilon_{\text{min}}} d\varepsilon$$

$$F_{\text{en}}\Big|_{\varepsilon_{\text{min}}}^{\varepsilon_{\text{max}}} = F_{\text{en}}(\varepsilon_{\text{max}}) - 1 = \frac{\displaystyle\int_{\varepsilon_{\text{min}}}^{\varepsilon_{\text{max}}} F_{\text{en}}(\varepsilon)\, d\varepsilon}{\displaystyle\int_{\varepsilon_{\text{min}}}^{\varepsilon_{\text{max}}} d\varepsilon} - \frac{\displaystyle\int_{\varepsilon_{\text{min}}}^{\varepsilon_{\text{max}}} d\varepsilon}{\displaystyle\int_{\varepsilon_{\text{min}}}^{\varepsilon_{\text{max}}} d\varepsilon}$$

$$F_{\text{en}}(\varepsilon_{\text{max}}) = \frac{\displaystyle\int_{t_{\text{min}}}^{t_{\text{max}}} F_{\text{en}}(t) \cdot \dot{\varepsilon}\, dt}{\displaystyle\int_{t_{\text{min}}}^{t_{\text{max}}} \dot{\varepsilon}\, dt}$$

$F_{\text{en},j}$ for the j-th pair—Transient linking

- $F_{\text{en}} = 1$ if $\dot{\varepsilon} < 0$ so the integration should be made only for $\dot{\varepsilon} > 0$
- The denominator can be $> \varepsilon_{\text{max}} - \varepsilon_{\text{min}}$!



Total CUF_en—Modified strain approach & overlapped integration

j	i_A	t_A	i_B	t_B	U_j	$F_{\text{en},j}$	$\text{CUF}_{\text{en},j}$
1	447	1716.0	694	3471.4	3.57×10^{-2}	15.53	5.55×10^{-1}
2	447	1716.0	699	3476.0	8.38×10^{-2}	15.14	1.27
3	699	3476.0	1020	6518.0	3.47×10^{-2}	7.08	2.46×10^{-1}
4	699	3476.0	899	4754.0	2.35×10^{-3}	1.00	2.35×10^{-3}
5	695	3471.6	899	4754.0	7.08×10^{-4}	1.00	7.08×10^{-4}
6	899	4754.0	1432	7955.0	2.06×10^{-3}	4.50	9.26×10^{-3}
7	184	451.0	899	4754.0	7.77×10^{-4}	15.15	1.18×10^{-2}
8	184	451.0	1641	10 519.0	2.78×10^{-4}	8.81	2.45×10^{-3}
9	1296	7356.0	1641	10 519.0	1.31×10^{-4}	1.97	2.58×10^{-4}
10	1134	6764.0	1641	10 519.0	8.54×10^{-5}	2.87	2.45×10^{-4}
11	1641	10 519.0	2215	35 971.0	4.67×10^{-5}	11.26	5.26×10^{-4}
12	1213	7059.0	2215	35 971.0	1.53×10^{-5}	4.63	7.10×10^{-5}
					total CUF_en for SCL 2 =		**2.0973**

Reference solution (NRC)—modified strain approach

Point No. for Load A	Time for Load A (seconds)	Point No. for Load B	Time for Load B (seconds)	$F_{en\text{-}nA}$	$F_{en\text{-}nB}$	U_n	$F_{en\text{-}n}$	$CUF_{en\text{-}n}$
694	3471.40	447	1716.00	15.520	15.520	0.0357	15.520	0.5543
699	3476.00	447	1716.00	1.517	15.520	0.0838	15.520	1.3009
699	3476.00	1021	6520.00	1.517	5.065	0.0343	5.065	0.1739
699	3476.00	899	4754.00	1.517	6.429	0.0024	6.429	0.0152
695	3471.60	899	4754.00	1.517	6.429	0.0007	6.429	0.0046
185	454.00	899	4754.00	4.298	6.429	0.0013	6.429	0.0083
1432	7955.00	899	4754.00	2.009	6.429	0.0008	6.429	0.0054
1432	7955.00	1653	10999.00	2.009	11.465	0.0003	11.465	0.0032
1296	7356.00	1653	10999.00	4.184	11.465	0.0001	11.465	0.0015
1136	6770.00	1653	10999.00	5.065	11.465	0.0001	11.465	0.0009
2215	35971.00	1653	10999.00	11.465	11.465	0.0000	11.465	0.0005
2215	35971.00	1213	7059.00	11.465	4.184	0.0000	11.465	0.0002
2215	35971.00	1562	8461.00	11.465	1.886	0.0000	11.465	0.0002
2215	35971.00	1	0.00	11.465	4.298	0.0000	11.465	0.0000
1347	7689.00	1	0.00	2.009	4.298	0.0000	4.298	0.0000
1347	7689.00	1595	9969.00	2.009	1.886	0.0000	2.009	0.0000
960	6450.00	1595	9969.00	6.429	1.886	0.0000	6.429	0.0000
960	6450.00	960	6450.00	6.429	6.429	0.0000	6.429	0.0000
					TOTALS	**0.1596**	---	**2.0691**

(Overall F_{en} = 12.9607)

- Previous revisions of the report had wrong results (final is 2018)
- The 5th and 6th columns show that this is not an actual modified strain rate approach but an adjacent-only peak-valley integration
- In a real integration scheme two rows could never have the exact same F_{en}
- It does not make much sense to report values as 0.0000
- MS is (still) everywhere: EPRI uses Paint and NRC uses Office
- Still, results seem to **coincide**!

$$\text{CUF}_{\text{en}} = \sum_{j=1} F_{\text{en},j} \cdot \frac{n_j}{N_j} = 2.0973 \approx 2.0691$$