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ABSTRACT

This paper describes an ASME Code Class 1 fatigue evaluation of stainless steel components in a pressurized water reactor including the effects of proposed environmental fatigue rules. It is based on an approach that may be used to evaluate the combination of quasi-steady, thermal transient and dynamic loading effects to develop an environmental correction factor (F_{en}) that may be applied to individual load set pairs. The approach was applied to several components and showed that environmental effects would be quite significant when components are evaluated using the proposed fatigue curves with environmental correction. A critical evaluation of the applicability of the environmental correction factors is provided.

INTRODUCTION

Numerous studies have determined that the water environment in light water reactors can affect the fatigue life of components. An evaluation methodology had been previously developed by EPRI where an environmental correction factor (F_{en}) could be applied to each of the partial usage factors determined in a conventional ASME Code fatigue analysis [1]. This methodology has been used as the basis of an industry position regarding the management of environmental fatigue. The basic concepts of this methodology were applied in several system-specific analyses to demonstrate use of the methodology and the general impact of reactor water effects on component fatigue [2-5]. During these studies, modified procedures were developed as new research results became available [6], including revised equations for carbon/low-alloy steel [7] and for stainless steel [8].

To assess the effects of environment on fatigue in representative pressurized reactor components, a Class 1 fatigue analysis was performed on the nonisolable piping attached to the reactor coolant system at Oconee Nuclear Station. All components were austenitic stainless steel. The original piping system analysis had been conducted to the requirements of ANSI B31.7 Class 2 (B31.1). The analysis included the effects of thermal stratification in some portions of the piping that had been identified during in-plant testing. The proposed environmental rules were then used to develop environmental factors that could be applied to the ASME Class 1 usage factor analysis.

NOMENCLATURE

S_p = peak stress intensity range
S_{alt} = alternating stress intensity
K_1, K_2, K_3 = local stress indices
C_1, C_2, C_3 = secondary stress indices
D_o = outer diameter of pipe
t = nominal wall thickness
P_o = range of service pressure
I = moment of inertia
M_i = resultant range of moment
T_a, T_b = range of average temperature on side a, b
ΔT_1 = range of linear part of through-wall thermal gradient
ΔT_2 = range of non-linear part of through-wall thermal gradient
α_a α_b = coefficient of thermal expansion on side a, b
E_{ab} = average modulus of elasticity
$E\alpha$ = elastic modulus times expansion coefficient
ν = Poisson's ratio = 0.3
K_e = elastic-plastic factor

Other symbols are defined in the body of the paper.

COMPONENTS EVALUATED

ASME Code fatigue analyses were performed on Class 1 piping systems attached to the reactor coolant system out to and including the first isolation valve. Each piping system was subsequently evaluated for the effects of reactor water environment on the calculated fatigue usage. The following piping systems were examined:

- Core Flood
- Pressurizer Spray
- High-Pressure Emergency Injection and Normal Makeup
- Decay Heat Removal
- Letdown
- Loop Drain

The Decay Heat Removal, Letdown and Loop Drain piping were shown to be exempt from the requirements for a cyclic fatigue analysis. These were not evaluated further since fatigue effects would be expected to be minimal.

DEFINITION OF F_{en}

The environmental correction factor F_{en} is defined as the ratio between the fatigue life in air to that in water, both at the same temperature. It may be a function of several variables, including material, water oxygen content, strain rate, and temperature. (For ferritic materials, the sulfur content is also a factor.) Typically, a separate F_{en} factor is applied to each of the partial usage factors (for the stress intensity amplitude associated with each load set pair) determined in a conventional ASME Code fatigue analysis. The equations for describing F_{en} for stainless steels [11] used in this study are as follows:

$$F_{en} = \exp\,[0.935 + \eta^* (T_1^* - T_2^* O^*)]$$

where:

$\eta^* = 0$ (for $\eta > 0.4$%/sec)
$\eta^* = \ln(\eta/0.4)$ (for $0.0004 \le \eta \le 0.4$%/sec)
$\eta^* = \ln(0.0004/0.4)$ (for $\eta < 0.0004$ %/sec)
η = strain rate, %/sec

$T_1^* = 0$ (for T < 250°C)
$T_1^* = [(T - 250)/525]^{0.84}$ (for $250 \le T < 400$°C)
$T_2^* = 0$ (for T < 200°C)
$T_2^* = 1.0$ (for $T \ge 200$°C)
T = material temperature, °C

$O^* = 0.260$ (for DO < 0.05 ppm)
$O^* = 0.172$ (for DO $\ge$ 0.05 ppm)
DO = dissolved oxygen, ppm

There is a low value of strain amplitude (0.097 percent) where there is no effect of environment [6].

ENVIRONMENTAL EVALUATION OF LOAD SET PAIRS

Effective Environmental Factor (F'_{en})

In actual reactor operating conditions, the conditions that exist for two load set pairs may be different and the strain rate and local surface temperature will vary. Reference 7 presented an "improved rate approach" with an effective environmental factor.

$$F'_{en} = 1 + \int_{\varepsilon_{th}}^{\varepsilon_{max}} \frac{F_{en} - 1}{\varepsilon_{max} - \varepsilon_{th}}\, d\varepsilon$$

or

$$F'_{en} = \int_{\varepsilon_{th}}^{\varepsilon_{max}} \frac{F_{en}}{\varepsilon_{max} - \varepsilon_{th}}\, d\varepsilon$$

where:

F_{en} = instantaneous environmental factor based on current conditions
ε = strain, relative to that at the most compressive stress state
ε_{max} = algebraic maximum strain for load set range pair
ε_{th} = strain threshold value

For a load set pair, the strain range, equivalent to ε_{max} - ε_{min}, may be determined as:

$$\varepsilon_{max} - \varepsilon_{min} = \frac{2S_{alt}}{E}$$

where:

ε_{min} = algebraic minimum value of strain for load set pair, arbitrarily taken as zero for the integration process
S_{alt} = alternating stress from fatigue analysis, ksi
E = modulus of elasticity from fatigue curve, ksi

Piping Analysis Equations

The stress range and alternating stress amplitude for a load set pair for piping analysis is given by Equations 11 and 14 of ASME Section III, NB-3650 [9]:

$$S_p = K_1 C_1 \frac{D_0 P_0}{2t} + K_2 C_2 \frac{D_0}{2I} M_i + K_3 C_3 E_{ab} \left|\alpha_a T_a - \alpha_b T_b\right| + \frac{1}{2(1-\nu)} K_3 E\alpha \left|\Delta T_1\right| + \frac{1}{1-\nu} E\alpha \left|\Delta T_2\right|$$

and

$$S_{alt} = \frac{K_e\, S_p}{2}$$

The factor K_e is determined based on Equation 10, that describes the range of primary plus secondary stresses for the load set pair. The nomenclature is given in the ASME Code and will not be repeated here.

The alternating stress amplitude may be a function of pressure changes, change in moments, and changes in thermal conditions. When evaluating strain rate effects, strain rates associated with pressure and thermal expansion moment changes are expected to be relatively low and may or may not occur simultaneously with the thermal effects. The strain rates due to thermal effects may be high or low, depending upon the transient; high strain rates are expected to occur simultaneously with high stress range thermal transients. Dynamic loading (e.g., due to an earthquake, if present) would be expected to have a very high strain rate.

In a piping analysis, the stress range is generally calculated based on the extreme range of pressure and moment for the two events for the load set pair. For the local thermal effects, the maximum contribution of each of the terms may be added directly, or time phasing may be considered. The stress indices are defined such that the maximum multiplier is used for each individual term in the expression for stress intensity. Thus, the reported total stress range is a conservative assessment of the potential stress intensity excursion between two load states.

Synthesis of Transient Components for Strain Rate Analysis

Figure 1 depicts the stress time history between two states of a load set pair. State 1 is chosen as that event with causes relatively compressive thermal stresses when the thermal terms are combined. State 2 creates a state of stress that is tensile relative to State 1 when all stresses are combined. Dynamic (seismic) stresses can increase the overall strain range and would typically be assumed in analysis to occur with one or both of the thermal stress extremes.

For evaluating an effective environmental factor (F'_{en}), only the rising strain portion of the transient that exceeds the threshold strain (ε_{th}) is evaluated since the integration is from the positive strain threshold to a larger value of strain. This is reasonable since it is the tensile straining that tends to rupture the material surface layer that protects it from the water environment.

Evaluation of F'_{en}

The thermal stress time history may be determined based on a combination of the three thermal terms from Equation 11 of ASME Section III, NB-3650. Thus, for the inside surface of piping, where significant thermal effects are experienced,

$$S_{th} = K_e\left[\frac{K_3 E\alpha\Delta T_1}{(2)(1-\nu)} - \frac{E\alpha\Delta T_2}{1-\nu} \pm K_3 C_3\, E_{ab}\left(\alpha_a T_a - \alpha_b T_b\right)\right]$$

In this equation, each of the thermal terms is a function of time. It is assumed that the effect of the elastic-plastic multiplier K_e is uniformly distributed over the total strain range. Since the piping analysis equations combine stress ranges using absolute values, the sign of the third term is chosen as that which produces the maximum stress range between two event pairs. This thermal stress time history is determined for each of the two load set states.

The time history of strain rate may be determined from:

$$\frac{d\varepsilon}{dt} = \frac{1}{E}\frac{d\,S_{th}}{dt}$$

The inside surface temperature, which can potentially be used to assess environmental factors, can be determined from the time history of temperatures, as illustrated in Figure 2 for a decreasing-temperature transient:

$$T_{surf} = \frac{T_a + T_b}{2} - \frac{\Delta T_1}{2} + \Delta T_2$$

Note that when evaluating the complete stress range between two thermal transients, the maximum thermal stress near the end of State 1 may not be equal to the minimum thermal stress near the beginning of State 2. This difference of thermal stress must be considered, and can be considered to have a very slow strain rate since States 1 and 2 may not necessarily be closely related, or even occurring at the same time. For example, State 1 could represent heatup and State 2 could represent cooldown, with other less severe transients occurring between them.

The stress range due to other load changes such as pressure and thermal expansion moments (δS_o) can be determined from:

$$\delta S_o = 2S_{alt} - \delta S_{th} - \delta S_{dyn}$$

where:

δS_{dyn} = stress range due to dynamic loads, including effects of K_e

δS_{th} = stress range due to thermal effects, including effects of K_e

The stress intensity range due to dynamic loads may be determined separately (e.g., by comparing the stress range for the load set pair with and without the seismic event).

In evaluating each load set and load set pair, State A is defined as that with the most compressive stress, or with an upward thermal transient. State B is defined as the other event. In addition, each of the states may or may not include a significant thermal transient. Also, the load set pair may or may not include an earthquake or other dynamic event.

In Reference 1, any load set pair with seismic content was considered to exclude environmental effects. This assumes that the seismic strain range would be relatively large. If the seismic contribution were small, there could still be environmental effects. Thus, for any pair where the dynamic loading is a contributor, the F'_{en} will be evaluated using a high strain rate for the dynamic strain range contribution that will minimize environmental effects for the dynamic contribution. The seismic stress range will be considered to be with State A and/or State B per the original non-environmental fatigue analysis. Thus, for determining environmental factors there are five strain contributions that are evaluated.

ε_1 - This strain range is associated with a dynamic event associated with a relatively compressive state. This strain range exists only if a dynamic load is defined for State A.

ε_2 - This strain range is associated with a thermal transient with State A. This range exists only if State A contains a thermal transient.

ε_3 - This strain range is that associated with "slow" events and is equal to the total strain range, minus the dynamic and thermal ranges associated with both states A and B

ε_4 - This thermal range is similar to ε_2 except that it is associated with State B transient conditions.

ε_5 - This range is similar to ε_1, except that it is associated with State B.

In determining F'_{en}, only the portion of the strains above the strain amplitude threshold are considered.

Evaluation of Oxygen and Temperature Effects

During normal power operation in pressurized water reactors, reactor coolant system oxygen concentration is typically below the threshold of detection of about 0.002 ppm. Since the components analyzed are all stainless steel, low oxygen is controlling in that it yields a higher environmental factor. Since at least one of the load states was always at normal operating conditions, environmental factors were based on low oxygen (< 0.05 ppm).

Assessment of temperature affects on environmental factors is more complex and not well defined. The question is: What temperature should one use in the fatigue equations to assess the values of F_{en}? Several choices existed:

- Use instantaneous surface temperature in the integration of $F_{en,}$
- Use maximum F_{en} over the temperature range, or
- Use an average F_{en} over the temperature range.

Four approaches were evaluated (Table 1) to show the sensitivity of the temperature assumption on the analysis outcome. Different approaches were applied to the dynamic strain ranges as compared to the quasi-steady portion of the range.

In determining the environmental factor for the quasi steady non-transient portions of the range, the approaches to determine F_{en} were:

Cases 1 and 3: F_{en} is evaluated over the complete range of temperature associated with the two associated load states. The maximum F_{en} factor over the range was conservatively chosen.

Cases 2 and 4: An alternate means of determining the temperature effects was evaluated as suggested in Reference 7:

1) If the maximum temperature is below the temperature threshold, then an average F_{en} is determined over the actual temperature range, by choosing a number of temperature steps over the interval and determining an integrated average. For the cases examined herein F_{en} in this case is constant and equal to exp (0.935).

2) If the maximum temperature is above the temperature threshold and the minimum temperature is below the threshold, then an average F_{en} is determined over the range between the maximum and the threshold, using an integrated average as above.

3) If the minimum temperature is above the temperature threshold, then an integrated average F_{en} is determined over the actual temperature range.

For determination of the factors for thermal transients, the actual surface temperature during the transient was used for Cases 1 and 2. As a more conservative alternative, the fluid temperature in the range leading to the highest value of F_{en} considering both load sets were used for Cases 3 and 4.

For any dynamic portions of the strain range, the temperature for the associated quasi-steady or thermal transient condition was used.

Adjustment of F'_{en}

The current ASME Code fatigue curves contain nominal factors of 2 on stress and 20 on cycles over the developed mean curve. A portion of the factor of 20 on cycles was to account for moderate environmental effects. Thus, after computing F'_{en}, for any load set pair evaluated using the ASME Code fatigue design curves, the value may be adjusted to account for this factor. Thus, the final adjusted effective environmental factor is determined by:

$$F^*_{en} = \frac{F'_{en}}{\phi} \text{ (but} \geq 1)$$

For carbon and low alloy steels, $\phi = 4$[2]. For stainless steels, $\phi = 2.0$ [2]. The NRC, in recent interaction, indicated that the factor for carbon/low-alloy steels should be 3.0 and for stainless steels the factor should be 1.5 [6]. In the analyses described in this report, 1.5 is used for stainless steel.

For Alloy 600 materials the F'_{en} was previously defined as a constant value of 1.49. It is reasonable to assume that the same environmental factor inherent in the ASME Code fatigue design curves for carbon/low-alloy steels and stainless steels is also inherent in the fatigue design curve for Alloy 600. Assuming that the factor of 1.5 also applies to Alloy 600, there would be no net effect of environment for Alloy 600 since F'_{en} is a constant (1.49). Thus, environmental effects of any Inconel 600 weldments were not evaluated.

RESULTS OF ENVIRONMENTAL EVALUATION

Several piping systems attached to the reactor coolant system at Oconee Nuclear Station were analyzed to the Class 1 requirements of the 1983 ASME Code [9]. For performing the environmental evaluation, the piping analysis was not “fine tuned” to reduce any conservatisms prior to addressing environmental effects. The analysis was conducted using standard techniques, making reasonable assumptions to assure that the usage factors and other Code limits could be met without consideration of environmental effects. Some representative locations with relative high computed cumulative fatigue usage (CUF) were chosen to assess the effects of environment as shown in Table 2.

Table 3 lists the transients analyzed, along with the transient numbers used in the fatigue tables. Note that in some cases, transients were grouped to reduce analytical effort where the transients were not especially severe. For spray transients, S1, S2, etc. in a transient number refer to a pressurizer spray event during that transient. For the transients, “up” indicates increasing temperature transients (causing initial compressive stress) and “down” indicates decreasing temperature transients (causing initial tensile stress). Some transients had both “up” and “down” portions. In addition, there were specific stratification transients identified for each system, identified with only a letter designator.

The environmental assessment was based on the fatigue tables taken from the original fatigue analysis output. Load sets with no transient, or with a slow transient, or with stress always decreasing during the transient were treated as quasi-steady state. For load sets with thermal transients, beginning and end times were chosen to capture only increasing thermal stresses, thus defining times of ε_{min} and ε_{max}.

Table 4 summarizes the results, showing all four cases. The difference in the approaches for choosing F_{en} as a function of temperature were minor for the various cases. Tables 5 through 9 give detailed fatigue usage calculations, both with and without environmental effects, for the most conservative evaluation approach (Case 3). Details regarding the method to determine F_{en} is provided elsewhere [10].

COMMENTARY ON PIPING ANALYSIS AND ENVIRONMENTAL EFFECTS

ASME Class 1 piping analysis is conducted to the rules in ASME Section III, NB-3650. A set of equations is provided that conservatively shows that the rules of NB-3200 are met. There are many conservatisms in the “design by rule” approach using the piping equations. There have been no identified cases where the process is not conservative, except for cases where the loading conditions were not known at the time of the initial plant design.

The proposed environmental rules have been developed using laboratory tests in a light water reactor environment. In order to complete testing in a reasonable amount of time, the testing must be conducted continuously. The resulting stress(or strain) time history bears little resemblance to that which occurs in an operating nuclear plant, or the stress range pairing required by the ASME Code. The proposed environmental rules provide another level of conservatism into the piping design equations, and considerably add to the complexity and labor needed to design and analyze piping systems.

Consider the fatigue analysis in Table 6, discarding the fact that the earthquake loadings have been considered to occur simultaneously with the most severe thermal transients. The first transient pairing is that of the termination of an HPI injection with the initiation of an HPI injection. Certainly, these are closely related transients, but for the environmental evaluation, the combination includes first the termination and then the injection, which is backwards relative to reality. The next load set pair is end of heatup paired with termination of HPI injection following a rapid depressurization. In this case, the range of pressures is certainly opposite of the thermal stresses, and the two transients are not mechanistically connected. Further down the table, there is a combination of stratification and no stratification. For the stratification case, the events could be closely connected such that the compressive stress followed by tensile stress sequencing could occur.

For the HPI Makeup piping, the transient pairing could be mechanistic in that one of the controlling combinations is a loss of makeup followed by reinitiation of makeup. In this case, the tensile transient would closely follow the compressive transient. This type of transient is generally not the general rule in reactor systems, however. What is found in most fatigue analyses is that there is no relationship between the transients such that there would be long periods of time between the two transients of a load set pair for the material passivating layer to re-establish. This long period of re-passivating between the extreme of the strain cycles did not exist in the fundamental test data that establish the environmental fatigue equation.

The conservatism in the design analysis environmental approach was also demonstrated in industry evaluations of components at another PWR where actual plant data was evaluated using a fatigue monitoring approach [2]. With this approach, actual plant transient sequence and magnitudes were considered. The resulting multipliers on fatigue usage to account for environmental effects (without consideration of the factor ϕ) were 1.4 to 1.6 [2]. Thus, using a design basis approach is extremely conservative.

CONCLUSIONS

Increases in CUF for piping fatigue analyses when environmental effects are considered in a design analysis were shown to be quite significant in all cases, and ranged from a factor of 2.8 to 8.8. CUF values exceeded the ASME Code limits for some locations.

It should be noted that the methodology for analyzing piping systems in the ASME Code, NB-3650 in Section III, contains a number of individual conservative assumptions which contribute to the overall conservatism of an environmental effects analysis. For example, there is no consideration of cycle sequence; in that compressive transients might mechanistically follow tensile transients in event pairing. The analysis and the proposed environmental fatigue curves also do not account for long periods of steady state stress conditions between transients that may mitigate some environmental effects.

The extent of the increases in CUF leads to a prediction of piping failures due to fatigue. The fact that design basis transients fatigue failures are not common indicates that there is a large amount of conservatism in the combination of the original fatigue calculations and in the formulas used to calculate environmental effects.

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11. Mehta, H.S., "An Update on the EPRI/GE Environmental Fatigue Evaluation Methodology and its Applications", PVP Vol. 356, *Probabilistic and Environmental Aspects of Fracture and Fatigue*, ASME 1999, pp. 183-193.Table 1. Cases for Evaluating F_{en} Variation with Temperature

Table 1. Cases for Evaluating F_{en} Variation with Temperature

Case	Non-Transient Loads	Thermal Transients
1	maximum F_{en} over temperature range	surface temperature at each time point
2	average F_{en} over temperature range	surface temperature at each time point
3	maximum F_{en} over temperature range	maximum F_{en} over input temperature range
4	average F_{en} over temperature range	maximum F_{en} over input temperature range

Table 2. Locations for Environmental Assessment

System	Unit	Location	Description	CUF
Core Flood	1-3	5	Nozzle safe-end to pipe weld	0.033
HPI/Emergency	1	175A	Nozzle safe-end to pipe weld	0.193
HPI/Makeup	1	116	Pipe to valve weld	0.177
HPI/Emergency	2&3	160	Pipe to valve weld	0.640
HPI/Makeup	2&3	305	Pipe to valve weld	0.291
Pressurizer Spray	1	135C 130	Pipe to aux. spray tee weld Pipe to valve weld	0.052 0.042
Pressurizer Spray	2&3	210A	4" pipe to reducer weld	0.081

Table 3. List of Transients and Transient Groups

Number	Transient Description
1A	Heatup, may include hydrotest (at pressure indicated)
1ACF	Core Flood Check Valve Test During Heatup
1BCF	Cooldown with Core Flood Decay Heat Removal Start
1B	Cooldown (zero load if so indicated)
2A/2B	Power Increase/Decrease
3	Power Loading
4	Power Unloading
5	Step Load Increase
6	Step Load Decrease
7	Step Load Reduction
8A	Reactor Trip, Loss of Flow
8B	Reactor Trip, High Temp.
8C	Reactor Trip, High Press.
8HPI	Manual HPI Activation after Trip
9	Rapid Depressurization
10	Change of RCS Flow
11	Control Rod Withdrawal
12	Hydrotest
14	Control Rod Drop
16	Steam Line Failure
15	Loss of Station Power
17A	Loss of Feedwater
17B	Turbine Bypass
19A	Feed and Bleed Operations
20D	Loss of Makeup
22A	HPI System Test
22C	Pressurizer Heat Loss Evaluation
Groups M down and M up	Transients 2A/2B, 3, 4, 5, 6, and 10 for HPI and Core Flood analyses
Group S down	Transients 7, 8A, 8B, 8C, 14, 15, and 17A for HPI and Core Flood analyses
Group S up	Transients 7, 8A, 8B, 14, and 15 for HPI and Core Flood analyses
Group T down	Transients 11 and 17B for HPI and Core Flood analyses
Group T up	Transients 8C, 11, 17A, and 17B for HPI and Core Flood analyses
Group S1 down	Transients 3, 5, and 10 for Pressurizer Spray analyses
Group S2 up	Transients 2, 3, 4, and 14 for Pressurizer Spray analyses
Group S3 up	Transients 7 and 8B for Pressurizer Spray analyses
Group S4 up	Transients 11, 16, 17A, and 17B for Pressurizer Spray analyses

Table 4. Cumulative Fatigue Usage Factors with and without Environmental Effects

System	**Loc'n**	**Original**	**Case 1**	**Case 2**	**Case 3**	**Case 4**
Core Flood	5	0.033	0.092 (2.75)	0.092 (2.75)	0.092 (2.75)	0.092 (2.74)
HPI/Emerge	175A	0.193	0.844 (4.36)	0.756 (3.92)	0.904 (4.69)	0.812 (4.21)
HPI/Makeup	116	0.177	1.562 (8.83)	1.560 (8.82)	1.563 (8.84)	1.528 (8.64)
HPI/Emerge	160	0.640	2.131 (3.33)	1.963 (3.07)	2.443 (3.82)	2.275 (3.56)
HPI/Makeup	305	0.291	2.313 (7.95)	2.311 (7.94)	2.316 (7.96)	2.215 (7.61)
Pressurizer	130	0.042	0.165 (3.94)	0.148 (3.55)	0.208 (4.97)	0.191 (4.56)
Pressurizer	210A	0.081	0.508 (6.27)	0.425 (5.25)	0.601 (7.43)	0.519 (6.41)

Note: Numbers in parentheses are overall increase in CUF relative to no environmental

Table 5. Fatigue Results - Core Flood Location 5 (Case 3)

State A	**State B**	**K_e**	**S_{alt} (ksi)**	**Cycles**	**$N_{allowed}$**	**CUF_a**	**F^*_{en}**	**CUF_{en}**
Trans. 1ACF up+OBE	Trans. 1BCF+OBE	1	67.05	2	8412	0.00024	3.533	0.00085
Trans. 1ACF up+OBE	Trans. 1BCF	1	63.58	1	10330	0.00010	3.708	0.00037
Trans. 1ACF up	Trans. 1BCF	1	60.12	357	13647	0.02616	3.017	0.07892
Group T up	Trans. 1ACF down	1	46.86	211	47092	0.00448	1.698	0.00761
Trans. 1A P=3192	Trans. 1ACF down	1	45.61	1	54293	0.00002	1.698	0.00003
Group S up	Trans. 1ACF down	1	44.21	148	64392	0.00230	1.698	0.00391
					Total =	0.033	Total =	0.092

Table 6. Fatigue Results - HPI/Emergency Location 175A (Case 3)

State A	**State B**	**K_e**	**S_{alt} (ksi)**	**Cycles**	**$N_{allowed}$**	**CUF_a**	**F^*_{en}**	**CUF_{en}**
8HPI up+OBE	8HPI dn + OBE	1	129.25	2	785	0.00255	3.021	0.00770
8HPI up+OBE	Trans. 8HPI dn.	1	126.66	1	833	0.00120	3.048	0.00366
Trans. 8HPI up	Trans. 8HPI dn.	1	124.28	67	881	0.07605	2.909	0.22122
Trans. 1A, P=3192	Trans. 9 dn.	1	118.73	1	1008	0.00099	3.267	0.00324
Trans. 1A, P=2567	Trans. 9 dn.	1	117.30	14	1055	0.01327	3.156	0.04188
Trans. 1A, P=2252	Trans. 9 dn.	1	116.57	25	1080	0.02315	3.098	0.07172
Trans. 1A, P=2252	Trans. 16 dn.	1	102.04	1	1769	0.00057	3.367	0.00192
Trans. 16 up	Trans. 22A dn.	1	100.81	1	1851	0.00054	3.150	0.00170
Trans. 1A, P=2252	Trans. 22A dn.	1	97.26	39	2115	0.01844	3.199	0.05900
Trans. 9 up	Trans. 12	1	60.81	5	12894	0.00039	10.232	0.00399
Trans. 9 up	Trans. 1B	1	58.41	35	15747	0.00222	10.232	0.02272
Trans. 22A up	Trans. 1B	1	48.04	40	41638	0.00096	10.358	0.00994
Trans. 1A, P=2252	Trans. 1B	1	46.88	280	46994	0.00596	10.206	0.06083
No Strat.	Stratification A	1	27.5	22302	-	0.03769	10.232	0.38565
No Strat.	Stratification B	1	24.01	14868	-	0.00887	1	0.00887
					Total =	0.193	Total =	0.904

Table 7. Fatigue Results - HPI/Makeup Location 116 (Case 3)

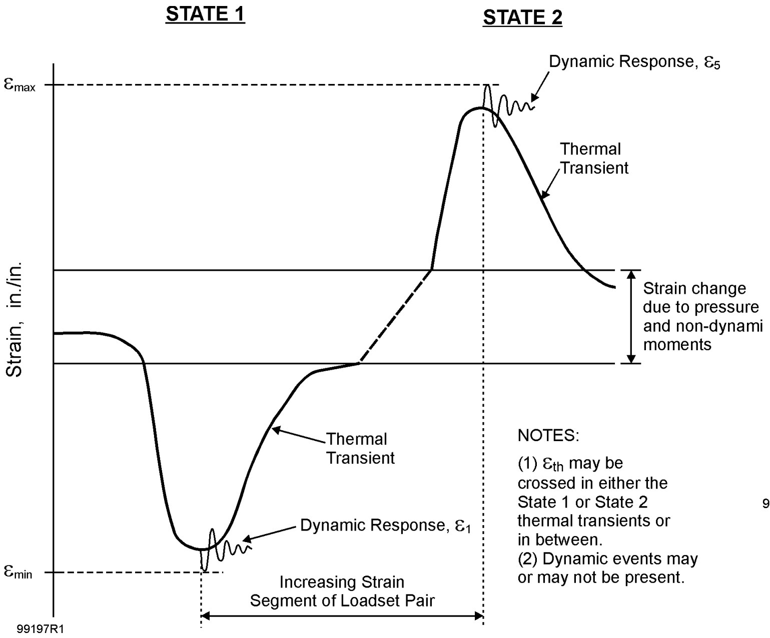
State A	**State B**	**K_e**	**S_{alt} (ksi)**	**Cycles**	**$N_{allowed}$**	**CUF_a**	**F^*_{en}**	**CUF_{en}**
1A, P=3192+OBE	20D up+OBE	2.11	229.11	1	147	0.00680	9.722	0.06611
1A, P=2567+OBE	20D up+OBE	1.96	209.91	1	189	0.00529	9.708	0.05136
1A, P=2567+OBE	Trans. 20D up	1.73	179.54	1	299	0.00334	10.022	0.03347
Trans. 1A	Trans. 20D up	1.51	150.99	7	498	0.01406	10.006	0.14069
Trans. 1A	Trans. 20D dn.	1.27	133.47	5	714	0.00700	5.461	0.03823
Trans. 1A	Trans. 20D dn.	1.19	124.67	5	872	0.00573	5.361	0.03072
Trans. 1A	Trans. 16 down	1	62.01	1	11750	0.00009	1.698	0.00015
Trans. 1A	Trans. 9 dn.	1	61.37	40	12391	0.00323	1.698	0.00549
Trans. 1A	Trans. 8HPI dn.	1	59.08	70	15061	0.00465	1.698	0.00790
Trans. 1A	Trans. 22A dn.	1	56.74	40	18518	0.00216	1.698	0.00367
Trans. 1A	Trans. 9 up	1	56.01	40	19782	0.00202	1.698	0.00343
Trans. 16 up	Trans. 1A	1	55.15	1	21417	0.00005	1.698	0.00009
Trans. 1A	Trans. 19A dn.	1	54.45	148	22862	0.00647	1.698	0.01099
Trans. 8HPI up	Trans. 1B dn., Zero	1	34.89	70	265321	0.00026	1.698	0.00044
Group T up	Trans. 1B dn., Zero	1	29.49	170	756245	0.00022	1.698	0.00037
Trans. 19Bup	Trans. 1B dn., Zero	1	28.62	120	911810	0.00013	1.698	0.00022
Trans. 1B up	Trans. 19A (dn.)	1	26.59	630	1284179	0.00049	1	0.00049
No Stratification	Stratification A	1	52.37	3186	27895	0.11421	10.232	1.16863
No Stratification	Stratification B	1	21.37	2124	3248937	0.00065	1	0.00065
					Total =	0.177	Total =	1.563

Table 8. Fatigue Results - HPI/Emergency Location 160 (Case 3)

State A	**State B**	**K_e**	**S_{alt} (ksi)**	**Cycles**	**$N_{allowed}$**	**CUF_a**	**F^*_{en}**	**CUF_{en}**
8HPI dn. + OBE	8HPI up+OBE	2.428	241.1	2	123.42	0.016204	3.123	0.05061
Trans. 8HPI up	8HPI dn. + OBE	2.301	224.4	1	149.32	0.006697	3.062	0.02050
Trans. 8HPI up	Trans. 9 down	2.238	212	40	173.63	0.230374	3.236	0.74543
Trans. 8HPI dn.	Trans. 8HPI up	2.181	209	27	180.32	0.149731	3.088	0.46236
Trans. 8HPI dn.	Trans. 16 up	2.151	202	1	197.38	0.005066	3.095	0.01568
Trans. 8HPI dn.	Trans. 9 up	2.046	182.9	39	265.28	0.147012	3.188	0.46874
Trans. 9 up	Trans. 16 down	1.762	141.8	1	572.85	0.001746	3.580	0.00625
Trans. 1A, P=3192	Trans. 22A down	1	94.2	1	2232.57	0.000448	2.544	0.00114
Trans. 1A, P=2567	Trans. 22A down	1	92.7	14	2371.3	0.005904	2.368	0.01398
Trans. 1A, P=2252	Trans. 22A down	1	92.0	25	2439.77	0.010247	2.284	0.02340
Trans. 1B, P = 0	Trans. 22A up	1	52.1	40	27532	0.001453	10.232	0.01487
Trans. 1A, P = 2252	Trans. 1B, P=0	1	42.8	320	76928	0.00416	10.194	0.04241
No Stratification	Stratification A	1	>27.5	28674	-	0.05606	10.232	0.57368
No Stratification	Stratification B	1	<27.5	8496	-	0.00444	1	0.00444
No Stratification	Stratification C	1	23.42	1062	-	0.00048	1	0.00048
No Stratification	Stratification D	1	24.15	6372	-	0.00330	1	0.00330
					Total =	0.640	Total =	2.443

Table 9. Fatigue Results - Pressurizer Spray Location 210A (Case 3)

State A	State B	K_e	S_{alt} (ksi)	Cycles	$N_{allowed}$	CUF_a	F^*_{en}	CUF_{en}
Trans. 1BS1 up+OBE	Trans. 8AS1+OBE	3.16	186.472	2	268	0.00746	6.553	0.04889
Trans. 1BS4 up	Trans. 8AS1+OBE	2.46	126.223	1	841	0.00119	7.392	0.00880
Trans. 1BS2 up	Trans. 8AS1	1.94	88.1531	77	3046	0.02528	7.778	0.19664
Stratification A	Trans. 1BS2 up	1.6	70.4849	13	6989	0.00186	5.918	0.01101
Stratification A	Trans. 1BS4 up	1.6	70.4849	267	6989	0.03820	7.244	0.27674
Stratification A	Trans. 1AS1	1.43	60.7184	80	12991	0.00616	9.474	0.05836
Trans. 1B	Trans. 1BS4 down	1	26.7159	270	1432151	0.00019	1	0.00019
Trans. 1A	Trans. 1AS2	1	26.5965	199	1475441	0.00013	1	0.00013
Stratification A	Group S1 down	1	22.6826	1492	4248321	0.00035	1	0.00035
Stratification B	Group S1 down	1	17.8494	1800	2.1E+07	0.00009	1	0.00009
					Total =	0.081	Total =	0.601



NOTES:
(1) ε_{th} may be crossed in either the State 1 or State 2 thermal transients or in between.
(2) Dynamic events may or may not be present.

Figure 1. Transient Pair Strain Range

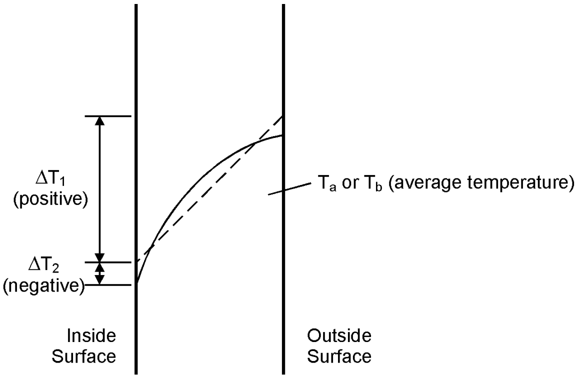


Figure 2. Definition of Thermal Parameters