Elevated Temperature Load-Order Effects on Austenitic Steel Life Predictions

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INTRODUCTION

The design of nuclear pressure vessel components may typically involve a few hundred or more cyclic thermal loadings of various levels coupled with steady mechanical loads. Ordering of these loading events may not be detailed in the design specification. Thermal loading usually implies plastic deformation, and elevated temperature design must consider creep deformation and damage. Plastic and creep solutions are history dependent. Even if some ordering is given in a design specification, practical cost considerations of inelastic analysis may impose a need to group transients. The analyst is frequently faced with the task of showing that his choice of load sequence in an elevated temperature design analysis is a conservative one. In facing such a task, the inelastic strain accumulation and creep-fatigue interaction criteria of the ASME N-47 (ASME 1986) Code Case usually govern.

An effort associated with the Fast Flux Test Facility was to study the effects of load ordering in light of these criteria. The effects of a seismic disturbance were included. An additional interest was the effect of the alphareset hardening modification (Corum, 1987), which prevents undue drift of the yield surface. An effect of reverse plasticity on subsequent creep, the beta effect, was also used. About two hundred inelastic analyses of a thin cylinder were carried out. The scope of work reported in this paper includes a study by J. Phillips (Phillips, 1982), extended with damage calculations.

LOADING AND MATERIAL PROPERTIES

All computing was done with a modified version of the program described by J.M. Chern (Chern, 1972). The program uses an integral equation formulation to solve the one-dimensional thick cylinder problem with plasticity and creep effects. Loading generally involves a sustained stress, Sp, produced by internal pressure and a cyclic stress, St, produced by a thermal transient. The thermal stress is generally a downshock from the inside modelled with temperature distributions, which are always linear through the wall. Load levels are coded approximately; e.g., X5Y3 means X = 10Sp/Sy = 5 and Y = St/Sy = 3 (1.5 was rounded to 1). Here, Sy is the yield stress at the average temperature. Each transient was typically followed by a 200 h to 250 h hold period at 1050 ^{o}F (566 ^{o}C) or a 75 h to 150 h period at 1200 ^{o}F (649 ^{o}C). Transient placements are shown and coded in Fig. 1. A generalized plane strain condition usually applies in the axial direction.

The basic 316SS plasticity, creep, stress rupture and fatigue properties are consistent with N-47. A bilinear stress-strain appropriate for a maximum strain of 0.2% was used. The alpha reset option in the program scales the kinematic hardening shift vector toward zero during unloading and keeps the yield surface at the load point. The purpose is to prevent an indefinite growth of maximum stress caused by the shift vector in a ratcheting environment. No partial reset was considered. Generally, work with the alpha reset option also used the beta option, in which plastic deformation in one direction, say tension, has an effect on subsequent creep in compression. In this sense, plastic and creep strains are lumped together in auxiliary creep rules that employ two origins for creep and allow for recovery of primary creep noted in loading reversals. Experimental evidence giving validity to these options is given by J.M. Corum (Corum, 1987).

SUMMARY OF RESULTS

The most influential ordering effect occurred with a small up transient placed with a larger down transient, DLB and DLE, Fig. 1. If the up transient is placed at the start of the hold, i.e., immediately after the down transient, there may be a large reduction of stress at the start of the hold period (see Fig. 2) and a substantially unconservative damage calculation results. Several exceptions were found. The higher sustained load levels generally did not give significantly unconservative results. A drastic damage reduction could be mistakenly inferred by considering damage values only at the inside and outside surfaces. The maximum damage may occur at the wall interior as in the X5Y3 1050 ^{O}F case (see Table 1). Unlike creep-fatigue damage, strain accumulation was relatively insensitive to the up transient location.

Mixing of routine and overload transients on a 4:1 basis is summarized in Table 2. Analyzing the individual types of transients separately and summing with 4:1 weights (MWS) is unconservative. As shown in Fig. 3, it is conservative to replace each routine transient with an overload (MO). With alpha reset, the error of this approach widened considerably. A better result was obtained by removing the routine transients [but not their hold periods (MZ)]. Clearly, this conclusion is based on an overload transient that is substantially more severe than the routine transient. It mattered little if the overload routine transients started the process. The routine transients amount to elastic excursions along the relaxation of residual stresses from the overload transient (see Fig. 4).

An earthquake can impose both primary and secondary cyclic stresses. Typically, only a few earthquakes are considered to occur in a plant lifetime. The effects of cyclic primary membrane stresses were investigated by introducing a pressure pulse giving an Sm maximum membrane stress. Thermal transients typically showed 5% to 15% changes in damage over twenty cycles attributable to the single seismic pulse. For seismic secondary stresses, the overload/routine scheme above was used with fifty routine transients to one (seismic) overload. Fig. 5 illustrates the effect of seismic secondary overload. Considering transients separately, a good approximation to the total damage would be obtained by running each type over the same time period of interest in spite of duplication.

Relocation of a short uniform overheat transient produced negligible changes when the basic thermal loading was the typical through-wall gradient. However, there was an interest in overall constraint of, say, a piping system, and the cylinder was constrained axially under uniform temperature changes. More damage, Fig. 6, was obtained by placing the overheat transient at the end of the hold period. Note the strong deceleration.

Consideration was given to groupings of equally severe up- and down-shock thermal transients. It was believed at the time that the back-to-back DU placement would be the most conservative compared to other combinations such as two down-shocks together (DD), two up-shocks together (UU) or up- and down-shock classes analyzed separately (D+U). In terms of damage accumulation with kinematic hardening, the I-placement that intersperses the hold times between the up-and-down shocks was usually most conservative. With the alpha reset and beta options, however, no sweeping damage conclusions could be made. The interspersed system almost always gave the greatest strain with or without alpha reset.

Comparisons were made with and without the alpha reset and beta options. A typical kinematic hardening hysteresis plot is given in Fig. 7. The stresses at the beginning and end of each hold period move toward one another from cycle to cycle with a more or less uniform damage accumulation. Fig. 8 illustrates how the hold periods repeat themselves with the alpha reset and beta options. This is attributed to recovery of primary creep at each cycle, and the cycle-to-cycle damage accumulation is constant. If the beta option is omitted, as illustrated in Fig. 9, then the stress at the start of each hold period is always reset and primary creep is not recovered. In view of the experimental evidence it is considered best to use the alpha reset and beta option together. Constant damage accumulation and generally decreasing strain accumulation rates are observed with the alpha reset and beta options. The nature of these effects may permit extrapolation of costly inelastic analysis results with confidence. The alpha reset and beta options almost always gave more conservative results than did kinematic hardening alone. They have a much stronger influence on damage than on strain. Roughly, the effect on damage decreases with increasing temperature.

CONCLUSIONS AND GUIDELINES

Grouping of transients is frequently done on the basis of elastic stress estimates. For example, commonly available thin cylinder solutions give peak or linearized stress as a function of fluid temperature rate, total temperature change, thickness and material properties. Transients may then be ranked in severity by the elastically calculated stress and grouped accordingly. After grouping, some form of ordering through the design life is required. Intuitively, the more severe transients would be expected early in plant life, but clearly the most conservative orderings must be sought out. The tools available for this are experience, documented cases and simplified analyses.

The behavior of a small up transient illustrates a general guideline: transients should be ordered to give the largest hold-time stresses. This reflects the experience that the N-47 linear creep damage rule has been found to almost always dominate the creep-fatigue damage fraction. However, applying this guideline is not a panacea, but it is a helpful tool.

There is a tendency to subdivide the design life into equal hold periods and assign one to each transient. The practice of segregating and analyzing each type of transient in this way is unconservative. With inelastic analysis, a severe transient followed by several moderate transients may give the result of Fig. 6. Damage should be computed with the design life allocated uniformly among the severe transients, and then the design life should be reallocated among the moderate transients. The practice is conservative, but generally not excessively so.

If the moderate transients do not amount to elastic excursions, stresses will be raised. The double allocation of the design life to the two types of transients might not be conservative. There are several procedures used for assessing whether or not the moderate transient remains elastic. The simplest is to ensure that the elastically calculated stress range is less than the sum of relaxation strength and of the yield stress. At the other extreme, the moderate transient may be appended to the inelastic analysis of the severe transient using restart capabilities found with finite element programs.

Seismic loads also become involved with ordering considerations. Primary membrane stresses considered herein were found to be low enough to have a minor influence on creep damage accumulation. Secondary stresses, such as discontinuity stresses, and peak stresses resulting from seismic loads may be substantially larger, and the double allocation of design life described above might be appropriate.

Tools for assessing ordering effects at transients are one-dimensional analyses and possibly two-and-three-dimensional inelastic analyses. Although the latter ones are expensive, some information may be obtained at moderate cost through a restart capability with the advantage of settling ordering questions with actual geometry. One-dimensional analysis, on the other hand, costs much less, and runstreams with complex loading histories are not too difficult to prepare.

REFERENCES

ASME (1986). Class 1 Components in Elevated Temperature Service, Section III, Division 1. American Society of Mechanical Engineers Boiler and Pressure Vessel Code Case N-47-25.

Corum, J.M. and Sartory, W.J. (1987). Assessment of Current High Temperature Design Methodology based on Structural Failure Tests, Journal of Pressure Vessel Technology (ASME), Vol. 109, pp. 160-168.

Phillips, J. (1982). The Effect of Infrequent Overloads on the Behavior of Plates Subject to Mechanical and Cyclic Thermal Loading. ASME 1982 PVP Conference, Orlando, FL.

Chern, J.M. and Pai, D.H. (1973). A Simplified Tool for the Elevated Temperature Cyclic Analysis of Pressure Components. Second International Conference on Pressure Vessel Technology, Part 1; Design and Analysis, pp. 264-275.

Table 1. Small Up-Transient Damage

UP DT	HDNG	LOAD	TRANSIENT TYPE	
(^{O}F)	RULE	LEVEL	DLB	DLE
33	KH	X2Y2	.0023	.021
	AR-B		.0077	.059
50	KH	X5Y3	.031*	.033
	AR-B		.053	.080
25	KH	X2Y1	.00076	.00075
	AR-B		.0014	.0014
50	KH	X3Y1	.00043	.00067
	AR-B		.00081	.00112
	KH	X4Y1	.00085	.00085
	AR-B		.0010	.0013
	KH	X5Y1	.0036	.0036
	AR-B		.0049	.0048

Notes: 250 h holds at 1050 ^{O}F
20 Cycles.
*.004 max at walls.
UP DT = Small up transient temperature differences.

Table 2. Mixed Series Damage Fractions

TEMP	HDNG	LOAD		TRANSIENT TYPE		
(^{O}F)	RULE	LEVEL	MLB	MWS	MO	MZ
1100	KH	X4Y1**	.088	.030	.110	.090
	AR-B		.123	.086	.35	.136
1050	KH	X2Y1	.023	.006	.207	.024
	AR-B		.068	.031	.149	.070
	KH	X3Y1	.026	.007	.031	.027
	AR-B		.070	.032	.154	.072
	KH	X4Y1	.032	.009	.037	.033
	AR-B		.074	.033	.156	.077
	KH	X5Y1	.046	.014	.110	.046
	AR-B		.079	.037	.165	.085

Notes: Ten composite cycles, 1,000 h ea.
AR-B = Alpha Reset-Beta.
HDNG = Hardening.
KH = Kinematic Hardening.
**Y = 1.8 (routine).

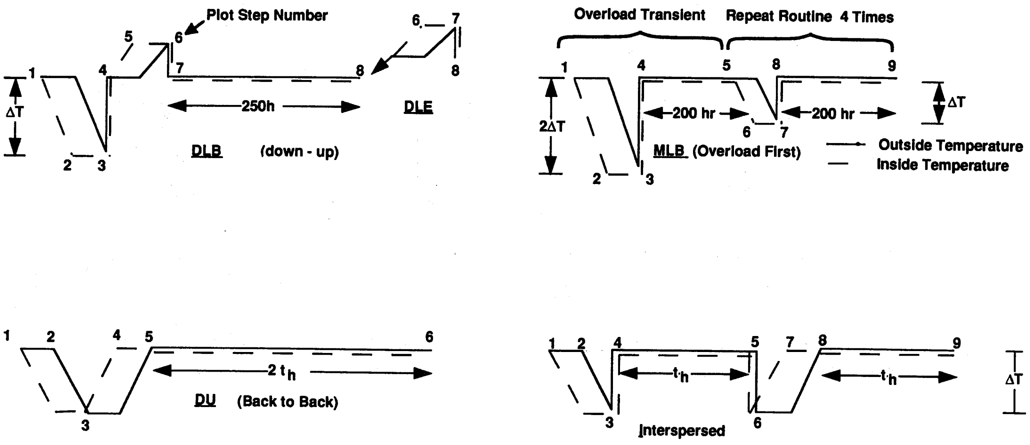

Figure 1. Placement of Transients.

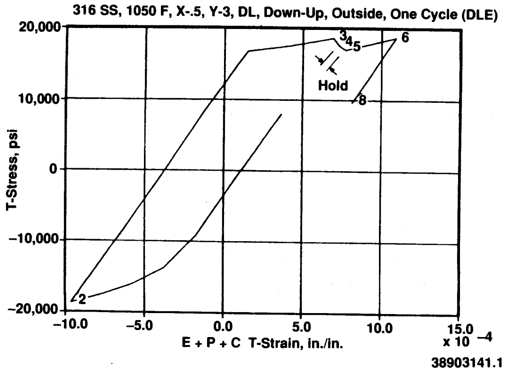

Figure 2a. Small Up Transient at the Hold End.

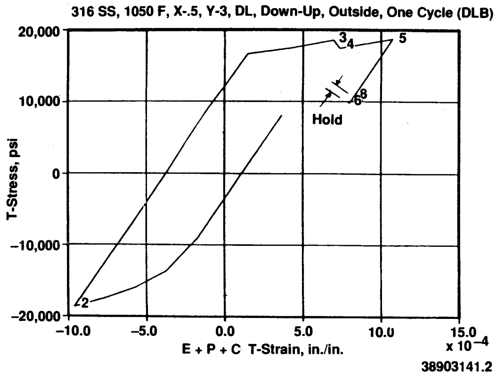

Figure 2b. Small Transient at the Hold Start.

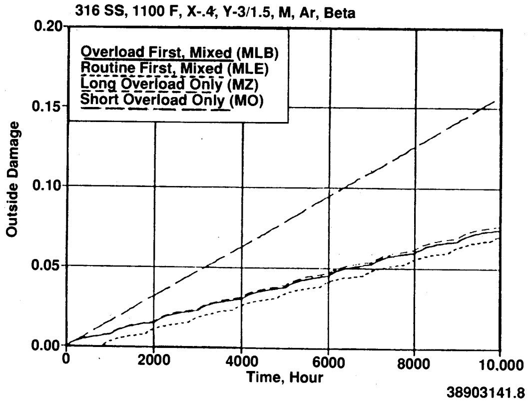

Figure 3. Routine and Overload Transients Damage Accumulation.

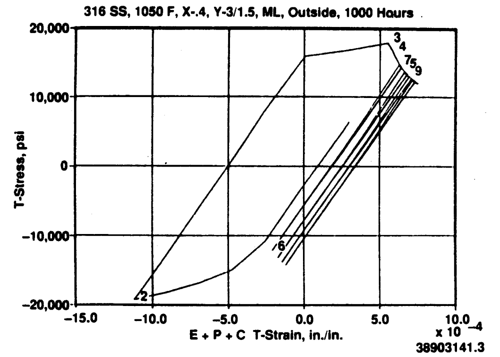

Figure 4. Routine and Overload Transient Hysteresis.

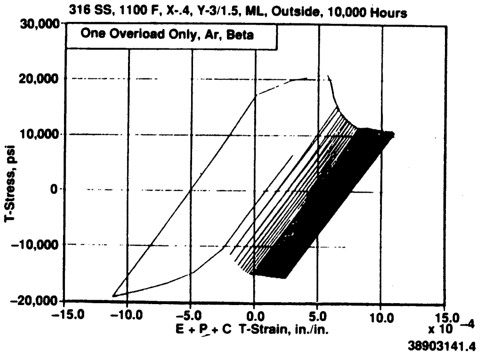

Figure 5. Effect of Seismic Secondary Overload.

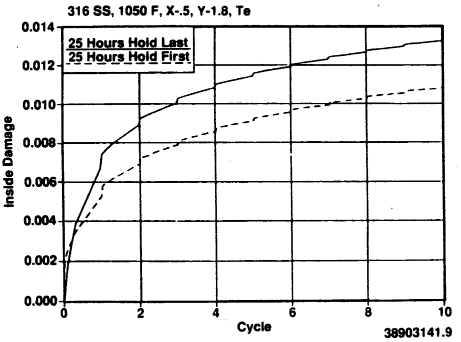

Figure 6. Uniform Thermal Expansion Effect.

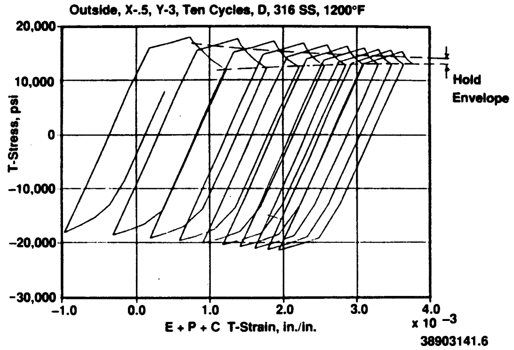

Figure 7. Typical Kinematic Hardening Hysteresis.

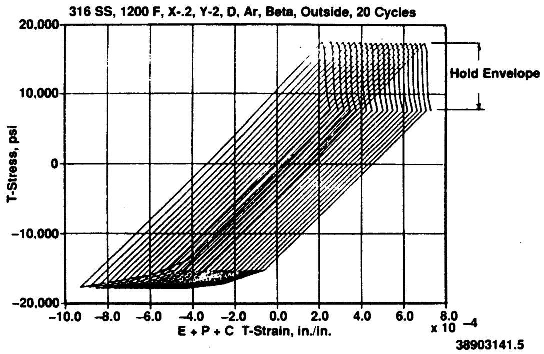

Figure 8. Typical Alpha Reset and Beta Option Hysteresis.

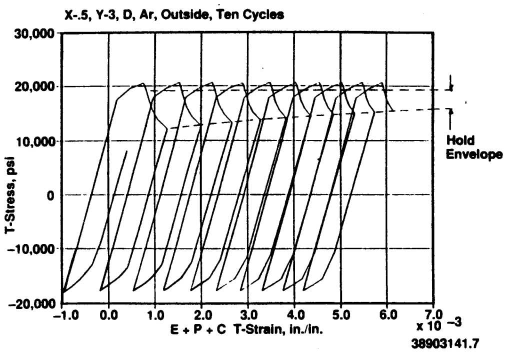

Figure 9. Typical Hysteresis with Alpha Reset Alone.