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A PARAMETRIC STUDY TO ESTABLISH DESIGN CURVES
AND TO EVALUATE DESIGN RULES FOR RATCHETTING

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ABSTRACT: With inelastic analyses requiring a substantially greater expenditure of effort over elastic analyses, there is strong incentive to establish an elastic design criterion for ratchetting that is not excessively conservative and consequently restrictive.

To establish the design curves for ratchetting, the ANSYS computer program was used to develop elastic-plastic-creep solutions for several cases of a long, sodium-filled pipe. The pipe was subjected to a fluid temperature history which consists of a rapid down-transient followed by a gradual rise to operating temperature, and a 500 hr. hold time at that temperature. The parameters of the analytical solutions covered the range of interest for sodium-cooled nuclear systems. The only material considered was 304 stainless steel.

Design curves were developed for ratchet strain as a function of elastic primary and secondary stress intensities and temperature.

The results of this study indicate that the existing design rules of FRA-152 rev. 3 and of the proposed LMEC revision to the ASME Code Case 1331-5 for loading cycles with long hold times are very conservative, with one exception. That exception is rule A.2.1.2(4) of the proposed revision to the ASME Code. When compared to the results of the study, the rule is consistently and reasonably conservative for all loadings and temperatures studied.

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INTRODUCTION

In previous investigations the complexity of the elastic-plastic-creep ratchetting problem has dictated that numerous assumptions be made to reduce the problem to a manageable form. Bree [1-2], who developed a generally applicable closed-form solution for incremental growth, found it necessary to limit his analysis to a uniaxial stress model, to linear temperature distributions through the model, and to several approximations concerning the material properties. The material property assumptions of Bree were the consideration of perfect plasticity for most of the cases, the neglecting of the Bauschinger effect, and the use of a steady-state creep representation.

The broad capabilities of the finite element method have made it possible to solve the ratchetting problem without many of the restrictions that were necessary in Bree's closed form solution. Minami and Roberts [3] demonstrated the use of the finite element method to solve specific ratchetting problems. They considered long circular pipes of 3/8" and 5/8" wall thickness. The temperature distributions in the cylinder wall of their study resulted from transient temperature solutions. A simulated 30°F/sec. fluid temperature down-transient in the pipe produced the thermal conditions. They further considered bilinear, temperature-dependent stress-strain curves, kinematic hardening, and a steady-state creep representation. Since only two cases were studied, the Minami and Roberts work does not have sufficient quantitative results to make it generally applicable to design.

For the present parametric ratchet study, newer, more general finite element programs were available. The ANSYS program [4] was used to solve all the ratchetting cases of this study. With ANSYS we considered a multi-

linear stress-strain curve, fully temperature-dependent properties, kinematic hardening, and strain hardening creep. However, due to the limitations of ANSYS and of computer run time, we were still limited to long axisymmetrical cylindrical geometries with axisymmetric loadings.

The November 15, 1971 version of the ANSYS program was used on a CDC 6600. The computer is located at the AEC Computer Center of New York University.

Using a "brute force" approach with the finite element method, an attempt was made in this study to obtain generally applicable design curves for ratchetting. We were limited in that we could not cover the full range of ratchetting parameters or materials of interest in a continuous manner, but could only examine selected values of the parameters and only one material. Continuous design curves for the one material were interpolated between the isolated numerical results.

The primary intent of the study was to support FFTF and SPTF component and piping design. Therefore, the parameters of the ratchet cases considered were selected to cover the range of interest in the two liquid metal programs. For example, the material considered was 304 stainless steel, and the selection of the thermal transients and pressure conditions was based on design specifications for FFTF and SPTF components.

The form of the temperature history considered was similar to that used by Minami and Roberts. In the temperature history used for the present study, the severe down-transient is followed by a short hold time at the lower

temperature of approximately one-half hour. The fluid temperature was then slowly raised to the upper temperature and was held there for 500 hrs. For the twenty-six ratchet cases of this study the pressure was not cycled but was held constant through the entire cycle. Down-transients of $40^{\circ}\text{F}/\text{sec.}$, $30^{\circ}\text{F}/\text{sec.}$, $10^{\circ}\text{F}/\text{sec.}$, and $2^{\circ}\text{F}/\text{sec.}$ were considered. Temperature drops during the transients of 400°F and 300°F were considered. The operating temperatures considered were 1000°F , 1100°F , and 1200°F . Pipe wall thicknesses of 0.375" to 1.35" were considered.

ANALYSIS

Finite Element Model

With the nodal coupling options available in ANSYS, a long axisymmetric cylinder was idealized as shown in Fig. 1. For all ratchet cases considered, there were sixteen equal quadrilateral axisymmetric ring elements taken through the wall thickness as shown in Fig. 1. The nodes on one lateral face of the model were free to move only in the radial direction; on the other lateral face, the nodes were constrained to move uniformly in the axial direction while being free in the radial direction. This set of constraints simulates the long pipe by placing the model in a state of generalized plane strain. The nodes of the same radius were also forced to move equally in the radial direction. The nodal coupling in the two directions reduces the number of displacement unknowns from thirty-four to eighteen.

The same model geometry was used for the solution of the associated thermal problem. In the thermal solution only nodes at equal radii were temperature coupled.

Plasticity Solution Technique

The ANSYS program uses the initial strain approach for the plastic and creep strains in the formulation of the finite element system of equations. In this technique, for small displacement analysis, only the right-hand side of the equation is modified for each change in the loading or inelastic strains. However, in the ratchet cycle there are large temperature changes; thus, it was necessary to modify the stiffness matrix, which is a function of the temperature-dependent elastic properties, for each iteration that involved a temperature change. For subsequent iterations of the elastic-plastic solution at a given input temperature distribution, the current stiffness matrix was saved. Approximately thirty-five temperature distributions were used in the elastic-plastic solution for each ratchet cycle, and at each of these temperature steps, six iterations were taken to converge the solution.

The plasticity subroutine of ANSYS requires the stress-strain curves to be input in the form of multilinear curves of five segments for each temperature of interest. The stress-strain curves used in this study represent the average properties of 304 s.s. and are given in tabular form in Table 1. The bilinear stress-strain curve could have been used as a special case of the multilinear representation. However, it was decided that the bilinear representation would not be helpful since the plasticity logic in ANSYS was not developed from a consistent theory that requires the bilinear curves.

In this study no attempt was made to include the effects of cyclic changes of the stress-strain curve. Thus, the monotonic stress-strain curves were used throughout the cyclic loading.

In ANSYS the non-isothermal conditions are accounted for by linear interpolation between input temperature-dependent stress-strain curves and physical properties at each iteration.

The ANSYS plasticity subroutine considers the input stress-strain curves as generalized stress-strain curves for both isotropic and kinematic hardening. Within the ANSYS kinematic hardening option for the monotonic portion of a cyclic loading, the plastic strain increments are calculated by a method of isotropic hardening. The multiaxial plastic stress-strain relation used is the "modified total strain" version of the Prandtl-Reuss equation as described by Mendelson [5]. If used directly for reversed loading cases, the Mendelson approach is one of isotropic hardening. However, in the ANSYS kinematic scheme, when the largest elastic strain component changes sign relative to its corresponding plastic strain component during a load reversal, the required kinematic shift in the origin of the yield surface takes place. During this shift the initial size of the yield surface is resumed.

It is clear that the ANSYS kinematic hardening scheme is not an analytically consistent hardening theory. However, for the particular case under consideration, i.e., the thermal ratchet of a straight pipe, the ANSYS inconsistencies do not appear to lead to serious problems. The reason is

that the loading on the pipe is predominately thermal. Thus the loading is approximately radial with σ_1 equal to σ_2 . In the region of the yield surface near this radial loading line, the yield surfaces from the ANSYS development and a more analytically consistent theory are not significantly different. Therefore, for the pipe ratchetting study we considered the analytical development of the ANSYS kinematic hardening subroutine to be adequate.

Creep Solution Technique

A strain hardening form of the equation of state was used throughout this study. The particular form used was governed by the ANSYS creep expression library. The expression selected is given in Eq. 1.

$$\frac{d\epsilon_c}{dt} = C_1 e^{-C_2/T} \sigma^{C_3} \epsilon_c^{C_4} + C_5 e^{-C_6/T} \sigma^{C_7} \quad \text{Eq. (1)}$$

where,

ϵ_c = total time-dependent strain

C_i = constants

T = temperature, °R

t = time, hr.

σ = stress, psi

The constants of Eq. 1 were determined by a least-squares fit to the average creep properties of 304 stainless steel as reported by Blackburn [6].

The values of the constants that result from this least-squares fit are:

$$C_1 = 3.9204 \times 10^{-21}$$

$$C_5 = 6.5232 \times 10^{-14}$$

$$C_2 = 8.4281 \times 10^4$$

$$C_6 = 8.4281 \times 10^4$$

$$C_3 = 8.4214$$

$$C_7 = 7.2069$$

$$C_4 = -0.96336$$

The multiaxial creep relations of ANSYS are the Prandtl-Reuss equations for creep strain increments as given in Mendelson [5]. These equations are of the isotropic hardening type. The particular ratchet program under consideration is an intermittent creep problem and not a creep reversal problem. Therefore, the ANSYS creep solution is completely adequate.

Post-Run Analysis: Evaluation of the Finite Element Results

To summarize the numerical results, the primary figure used is the ratchet growth (cumulative strain) plotted as a function of the elastic thermal stress and the pressure stress. For the present study the value plotted as the abscissa is the primary stress intensity, P_m . On the ordinate the value plotted is the equivalent linear elastic secondary stress intensity, Q_{EL} . The following formulas were used to calculate these two quantities:

$$P_m = \frac{1}{a} \int_0^a \sigma_\theta dr - \frac{1}{a} \int_0^a \sigma_r dr \quad \text{Eq. (2)}$$

$$Q_{EL} = \frac{6}{a^2} \int_{-\frac{a}{2}}^{\frac{a}{2}} \sigma_\theta r dr - \sigma_{ri} \quad \text{Eq. (3)}$$

where,

a = pipe wall thickness

σ_θ = hoop stress from elastic calculation

r = radius

σ_r = radial stress from elastic calculation

σ_{ri} = radial stress at inside diameter

To obtain the elastic results necessary to compute P_m and Q_{EL} , an elastic-only finite element solution was made. This solution used the same temperature input that was used in the corresponding cyclic elastic-plastic-creep solution.

INPUT PARAMETERS AND COMPUTER RUN TIMES FOR THE RATCHET CASES

Table 2 presents the input parameters for the ratchet cases used in this study. The heat transfer coefficient at the wetted surface for each ratchet case was 50 Btu/hr-in²-°F. In an attempt to avoid the complicating influence of thick cylinder effects, an inside diameter of 30 in. was used for all cases. A 500 hr. hold time was considered for all runs.

This 500 hr. hold time represents an "arbitrary average" of the estimates of the hold times for SPTF and FFTF components. The 500 hr. hold time was also easily manageable in a computer solution.

The internal pressure of the runs was limited by the requirement of existing criteria [7] that $P_m \leq \bar{S}_m$. The $\bar{S}_m$ values used are:

$$\bar{S}_m = 11,500 \text{ psi @ } 1000^\circ\text{F}$$

$$\bar{S}_m = 7,250 \text{ psi @ } 1100^\circ\text{F}$$

$$\bar{S}_m = 4,400 \text{ psi @ } 1200^\circ\text{F}$$

The ratchet cases each required approximately 3000 central processor seconds on the CDC 6600. The iteration schemes used were probably conservative in that more load-time steps were taken than are required for an accurate solution. However, even if the number of steps were cut in half and an accurate solution resulted, the implications are that ratchetting analysis on any but the simplest geometry is going to be very expensive.

To indicate the form of the computer results for a typical ratchet case the computer plots of hoop stress vs. hoop strain for the inside and outside diameters and the hoop stress vs. time for one of the cases (No. 15, Table 2) are presented in Figs. 2-4.

RESULTS

Cumulative Strain

The values for the incremental strain growth are based on differences between the hoop strain at the inner surface from cycle to cycle, the hoop strain being the maximum positive principal strain. The inelastic ratchet calculations were done for five cycles. The incremental growth did not in every case settle to a steady value by the fifth cycle. Therefore, it was necessary to make some approximation concerning the steady-state growth per cycle. At one point we considered using an extrapolation procedure to determine the steady-state growth value. However, due to present uncertainties of inelastic and creep analyses, it was decided to adopt a more conservative approach and consider the incremental strain growth between the 4th and 5th cycles as the steady-state incremental strain growth. The total strain growth after $n+5$ ratchet cycles was thus calculated as shown in Eq. 4.

$$\epsilon_{\theta} = \epsilon_{\theta 5} + n\delta_{\theta 4-5} \quad \text{Eq. (4)}$$

where for Eq. 4,

ϵ_{θ} is the final total hoop strain (minus hoop thermal strain), maximum value of cycle for inside surface.

$\epsilon_{\theta 5}$ is the total hoop strain (minus hoop thermal strain), maximum value of 5th cycle for inside surface.

$\delta_{\theta 4-5}$ incremental strain growth from 4th to 5th cycle, $\epsilon_{\theta 5} - \epsilon_{\theta 4}$

The maximum hoop strain for the cycle as opposed to the strain at thermal transient free state was used in the cumulative strain calculations to present a conservative value for the hoop strain increase. Using Eq. 4, 100 cycle cumulative strain results were calculated and are presented in Figs. 5-7. In these figures approximate contours are sketched between the data points.

Comparison of Results to FRA-152 rev. 3 (FRA-152 rev. 3 ratchetting rules are reproduced in Appendix 1)

In the comparison of the results of this study to the ratchetting rules of FRA-152 rev. 3 considerable liberty has been taken. First of all, FRA-152 rev. 3 states that the maximum absolute accumulated inelastic strain be used in the deformation limit evaluation. We considered the maximum positive principal strain as opposed to the maximum absolute principal strain in the cumulative strain calculations. Secondly, in para. 4.2.4.2(b)2, FRA-152 rev. 3 states that thermal stresses from all sources be less than $2\sigma_{y\min}$. We did not consider the peak stress in our evaluation of this paragraph; therefore, the requirements of the paragraph were relaxed to limiting Q_{EL} to be less than or equal to $2\sigma_{y\min}$.

There are essentially three ratchetting rules in FRA-152 rev. 3. The first ratchetting rule, para. 4.2.4.2-(a) requires $(P_m + Q_{EL})_{\text{range}} \leq \sigma_y$. Examination of Figs. 5-7 shows this limit to be very conservative when compared to the 100 cycle cumulative strains of this study. Note however, that this rule applies for any operational life. If we, from Figs. 5-7, make an estimate of the cumulative strain at 350 cycles (approximately equal to 20 years operational life) we see that the rule of para. 4.2.4.2-(a) would still be quite conservative, especially for the 1000°F curves.

The second and third rules of FRA-152 rev. 3 for ratchetting are each made up of three sections. The first and second sections of the two rules are identical. And for the cycle of the ratchet study the third sections of the rules, i.e., para. 4.2.4.2(b)3 and para. 4.2.4.2(c), are equally restrictive. Using the isochronous stress-strain curves given in FRA-152 rev. 3, rules 4.2.4.2(b) and 4.2.4.2(c) can only be invoked if the life in hours is less than the values shown below.

APPLICABILITY OF PARAS. 4.2.4.2-(b) 3 & (c) OF FRA-152 REV. 3 FOR 304 S.S.			
Temperature, °F	1000	1100	1200
Life, hrs.	10^4	$<10^3$	0

Thus the 100 cycle life investigated in Figs. 5-7 is too long to be considered by the second and third rules of FRA-152 rev. 3. However, for completeness the limit lines (modified for this study) of para. 4.2.4.2-(b) 1 & 2, i.e., $Q_{EL} \leq 2\sigma_{y_{min}}$ and $P_m \leq 0.5\sigma_{y_{min}}$, are shown on Figs. 5-7.

Comparison of Results to the Ratchetting Rules of the Proposed Supplement for Ratchetting to the ASME Code Case 1331-5, Revision A [8 & 9] (Revision A rules of the ASME Code are Reproduced in Appendix 2).

For the simple straight pipe model used for the ratchet cases, the rule A.2.1.2(1) of Revision A is approximately the $(P_m + Q_{EL})_{range} \leq \sigma_y$ rule discussed for FRA-152 rev. 3 and the same comments apply.

The ratchet limit curve given in Revision A, A.2.1.2(2a) is shown in each of Figs. 5-7. However, this limit curve is not applicable to 100 cycle lives because of the second part of this rule para. (2b). From the

isochronous stress-strain curves of the Code, para. (2b) limits the design life for 304 s.s. to the following:

APPLICABILITY OF RULE A.2.1.2(2b) OF 1331-4, REVISION A FOR 304 S.S.			
Temperature, °F	1000	1100	1200
Life, hrs.	10^4	<500	<50

Para. (2c) is satisfied for all the ratchet cases of this study.

For the cycle used in this study, the limits set by rule A.2.1.2(3) are approximately as restrictive as the limits set by rule A.2.1.2(2a,b,&c).

The limits set by rule A.2.1.2(4a) are specified by two equations, Eq. 13(e) and 13(f) of the Code's Revision A. Equations 13(e) and 13(f) were calculated for each of the temperatures considered. The resulting curves are plotted in Figs. 5-7.

From Figs. 5-7 it is seen that the present analysis indicates that rule A.2.1.2(4) is conservative with respect to the 2% surface strain limit of the Code. However, because of the uncertainties of the present analysis and the unknowns that may enter due to more complex temperature and pressure cycles and more complex geometries, we do not think that the present analysis indicates that the rule is excessively conservative.

CONCLUSIONS

Although there is some question about the kinematic hardening scheme of ANSYS, the results presented in this study indicate that the program can produce reasonable results which show the essential features of a more consistently developed hardening scheme.

The results presented in Figs. 5-7 are useful in that they indicate the analytically predicted growth as a function of elastic primary and secondary stress intensities. The growth curves were generated for a 500 hr. hold time but should also apply conservatively to a loading sequence where hold times are less than 500 hrs. These results may not be overly optimistic for hold times in excess of 500 hrs., since most of the stress relaxation has occurred before the end of the 500 hrs. However, it should be noted that experimental pipe ratchet results and further analytical solutions are necessary to completely evaluate the results of the present study.

The present analysis indicates that the ratchetting rules presented in both FRA-152 rev. 3 and in the proposed Revision A to ASME Code Case 1331-5 for loadings with long hold times are very conservative, with one exception. That exception is rule A.2.1.2(4) of the proposed revision to the ASME Code. When compared to the results of this analysis, the rule A.2.1.2(4) of the Code is consistently and reasonably conservative for all loadings and temperatures studied.

The analysis indicates that a complete ratchetting study of any complex structure is going to be an expensive undertaking due to the large computer run times necessary. Therefore, it is our opinion that an important area of study in the near future, in addition to the ratchetting experiments, will be in the development of standard techniques to construct simplified finite element models from large complex finite element idealizations. The simpler models must be manageable from a computer-run-time point of view, and also must realistically represent the boundary conditions imposed by the larger parent model.

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TABLE 1

ANSYS INPUT FOR AVERAGE PROPERTIES OF 304 STAINLESS STEEL
BASED ON WADCO (BLACKBURN) EXPRESSION OF NOVEMBER 1, 1971.

<u>STRAIN in/in</u>					
<u>STRESS psi</u>					
<u>Temperature</u>					
600°F	15011	19400	21800	25500	32900
800	14243	17900	20100	23700	31200
1000	13297	16100	18300	21900	29600
1100	12825	15200	17500	21100	28700
1200	12352	14300	16700	20300	27200

TABLE 2

RATCHET-RUN INPUT PARAMETERS					
<u>RUN NO.</u>	<u>OPERATING TEMPERATURE</u>	<u>THERMAL TRANSIENT</u>	<u>ΔT</u>	<u>WALL THICKNESS</u>	<u>INTERNAL PRESSURE</u>
1	1000°F	-40°F/sec.	400°F	0.851 in.	635 psi
2					423 psi
3					211 psi
4		-30°F/sec.	300°F	1.35 in.	992 psi
5					496 psi
6					400 psi
7		-10°F/sec.	300°F	0.531 in.	266 psi
8					787 psi
9					400 psi
10	1100°F	-40°F/sec.	400°F	0.851 in.	300 psi
11		-30°F/sec.	300°F	1.35 in.	624 psi
12					208 psi
13				0.851 in.	300 psi
14				0.375 in.	134 psi
15		-10°F/sec.	300°F	0.700 in.	331 psi
16					220 psi
17				0.531 in.	189 psi
18		- 2°F/sec.	300°F	0.851 in.	400 psi
19	1200°F	-40°F/sec.	400°F	0.851 in.	195 psi
20		-30°F/sec.	300°F	1.35 in.	457 psi
21					220 psi
22		-10°F/sec.	300°F	0.700 in.	243 psi
23					81 psi
24					0.531 in.
25					123 psi
26		- 2°F/sec.	300°F	0.851 in.	293 psi

FIGURE 1. SIXTEEN ELEMENT MODEL SHOWING BOUNDARY CONDITIONS USED TO SIMULATE A LONG STRAIGHT PIPE.

**FIGURE 2. HOOP STRESS VS. HOOP STRAIN AT INSIDE DIAMETER,
THERMAL TRANSIENT $-10^{\circ}\text{F}/\text{sec.}$ for 30 sec.
WALL THICKNESS 0.700 in.
HOLD TEMPERATURE 1100°F
INTERNAL PRESSURE 331 psi**

**FIGURE 3. HOOP STRESS VS. HOOP STRAIN AT OUTSIDE DIAMETER,
THERMAL TRANSIENT -10°F/sec. for 30 sec.
WALL THICKNESS 0.700 in.
HOLD TEMPERATURE 1100°F
INTERNAL PRESSURE 331 psi**

FIGURE 4. HOOP STRESS VS. TIME FOR ELEMENTS 1, 2, 6, 10, AND 16,
THERMAL TRANSIENT -10°F/sec. for 30 sec.
WALL THICKNESS 0.700 in.
HOLD TEMPERATURE 1100°F
INTERNAL PRESSURE 331 psi

FIGURE 5. COMPARISON OF THE CUMULATIVE HOOP STRAIN AFTER 100 RATCHET CYCLES AT AN OPERATING TEMPERATURE OF 1000°F TO THE LIMIT LINES OF EXISTING AND PROPOSED RATCHET RULES.

FIGURE 6. COMPARISON OF THE CUMULATIVE HOOP STRAIN AFTER 100 RATCHET CYCLES AT AN OPERATING TEMPERATURE OF 1100°F TO THE LIMIT LINES OF EXISTING AND PROPOSED RATCHET RULES.

FIGURE 7. COMPARISON OF THE CUMULATIVE HOOP STRAIN AFTER 100 RATCHET CYCLES AT AN OPERATING TEMPERATURE OF 1200°F TO THE LIMIT LINES OF EXISTING AND PROPOSED RATCHET RULES.

APPENDIX 1. RATCHETTING RULES OF FRA-152 REV. 3 [7]

4.2.4 Ratchetting

As indicated in Code Case 1331-4, the rules of N-417.3 of Section III do not ensure freedom from ratchetting for operation within the creep range. However, complete shakedown and freedom from ratchetting within the creep range may not be achievable, and the intent of these requirements is considered to have been met if the end-of-life deformation limits (either structural or functional, as applicable) are not exceeded. The following supplemental requirements are therefore specified and will be considered to meet the intent of paragraphs 1(a) and (6) of that case.

4.2.4.1 Inelastic Analysis

When inelastic analysis is used and when the resulting strains and deformations everywhere within the components are within the limits specified in paragraph 4.3.1 and within those alluded to in paragraph 4.3.2, freedom from ratchetting is considered to have been demonstrated.

4.2.4.2 When elastic analysis is used, requirements on ratchetting and/or excessive structural deformation, but not necessarily those concerning excessive functional deformation, are considered to have been demonstrated if any one of the following conditions is met. However, if none of these conditions is met, inelastic analysis is required.

- a) Ratchetting, hence structural deformation, requirements are considered to have been satisfied if the primary-plus-secondary stress intensity range does not exceed the minimum yield strength, Figures B-1¹ and B-6¹, at the maximum operating metal temperature at the location under consideration.
- b) Structural deformation requirements are considered to have been satisfied, and ratchetting analysis need not be performed, if the following four conditions are met:
 - (1) Membrane stress intensity from all sources is less than 50% of the minimum specified yield strength at the maximum metal temperature of operation for the location being considered.
 - (2) All thermal stresses and secondary stresses (from mechanical loads) do not exceed twice the minimum specified yield strength at the maximum metal temperature of operation for the location being considered.

⁽¹⁾ For 304 and 316 stainless steel, respectively.

- (3) The minimum specified yield strength is less than 80% of the average stress required to produce 1.0% total strain in the design life of the plant at the maximum metal temperature of operation for the location being considered.

The isochronous curves of Figures B-3¹ and B-8¹ shall be used to estimate the value of average stress to produce 1% total strain.

- c) The same as 4.2.4.2(b) above except that condition (3) will be considered to be satisfied if the following condition is satisfied

$$\sum_{j=1}^m \left(\frac{t_N}{t_D} \right)_j \leq 1.0$$

where Figures B-3¹ and B-8¹ provide 100% of the average stress to achieve 1.0% total strain as a function of time.

m is the total number of operational periods, j , considered.

t_N is the time for which the temperature at the point being considered exceeds 900°F (800°F) during the operational period, j .

t_D is the time to achieve 1.0% strain at a stress equal to 125% of the minimum specified yield strength at the maximum metal temperature during the operational period, j .

(1) For 304 and 316 stainless steel, respectively.

APPENDIX 2. RATCHETTING RULES OF THE LMEC
PROPOSED SUPPLEMENT TO THE ASME
CODE CASE 1331-5 [8 & 9]

5.2(b) Strain Limits for Elastic Analysis - When elastic analysis is used, freedom from ratchetting and/or excessive deformation is considered to have been demonstrated if the conditions of any one of the following four paragraphs are satisfied. If none of these conditions are satisfied, an inelastic analysis is required.

- (1) Retain the rule in Article 5.2(b) except renumber equation (13) to be (13a).
- (2) Structural deformation requirements are considered to have been satisfied, and ratchetting analysis need not be performed, if the following three conditions are satisfied.

(a) As shown on Figure 9

$$\left[\left(P_L + \frac{P_b}{K} \right)_{\max} + 1/4 Q_R \right] \leq S_y \quad (13b)$$

$$\text{for } \left(P_L + \frac{P_b}{K} \right)_{\max} \geq 0.5 S_y$$

$$\left[\left(P_L + \frac{P_b}{K} \right)_{\max} \cdot Q_R \right] \leq (S_y)^2 \quad (13c)$$

$$\text{for } \left(P_L + \frac{P_b}{K} \right)_{\max} \leq 0.5 S_y$$

where

$$\left(P_L + \frac{P_b}{K} \right)_{\max} \text{ is defined as in 5.2(b)(1).}$$

- (b) The minimum specified yield strength S_y at the maximum operating metal temperature is less than 80% of the average stress to produce 1% total strain in the design life of the plant at the maximum operating metal temperature at that location being considered. The isochronous curves of Figures 7A and 7B for total strain shall be used to determine the value of the average stress to produce 1% total strain for 304 and 316 stainless steel respectively.
- (c) One extreme of the temperature cycle which describes the range of secondary stress, Q_R , must be at a temperature below 900°F.
- (3) The same as 5.2.6(2) above except that condition (b) will be considered to be satisfied if the following condition is satisfied.

$$\sum_{j=1}^n \left(\frac{t_n}{T_D} \right)_j \leq 0.7 \quad (13d)$$

where

- n = the total number of operational periods above 900°F.
- t_n = the time for which the temperature at the point being considered exceeds 900°F during the operational period, j .
- T_D = the time to achieve 1% time-dependent strain at a stress equal to 125% of the minimum specified yield strength at the maximum metal temperature during the operational period, j .

The isochronous curves of Figures 7A and 7B for total strain may be used to estimate the value of the average stress to produce 1% time-dependent strain for 304 and 316 stainless steel, respectively.

- (4) Structural deformation requirements are considered to have been satisfied, and ratchetting analysis need not be performed, if the following two conditions are satisfied.

(a)

$$\left[\left(P_L + \frac{P_b}{K} \right)_{\max} + 1/4 Q_R \right] \leq S_C \quad (13e)$$

$$\text{for } \left(P_L + \frac{P_b}{K} \right)_{\max} \geq 0.5 S_C$$

$$\left[\left(P_L + \frac{P_b}{K} \right)_{\max} \cdot Q_R \right] \leq (S_C)^2 \quad (13f)$$

$$\text{for } \left(P_L + \frac{P_b}{K} \right)_{\max} \leq 0.5 S_C$$

where $\left(P_L + \frac{P_b}{K} \right)_{\max}$ is defined as in 5.2(b)(1).

and

$$S_C = \sqrt{S_y \cdot S_{.01}} \quad (13g)$$

- S_y = The minimum specified yield stress at the maximum operating metal temperature at the location being considered.
- $S_{.01}$ = The lesser of S_y above or 80% of that stress which yields 1% deformation in the specified operating life of the plant at temperatures above 900°F at the maximum operating metal temperature at the location being considered. The isochronous curves of Figures 7A and 7B for total strain shall be used to determine the value of the average stress to produce 1% total strain for 304 and 316 stainless steels respectively.
- (b) One extreme of the temperature cycle which describes the range of secondary stress, Q_R , must be at a temperature below 900°F.