pages used for Ref Hi-tb (Case N-47-32 -- Aug-94)		
13	title page	
13 to 16	contents	4
16	aspects covered	
19	design parameters	
19 to 20	loading categories & service loadings	2
20	load histograms	
22 to 27	design by analysis; terms defined	6
27 to 28	stress intensities & design rules/limits	1
29 to 31	<u>classification of stresses</u>	3
32	<u>flow diagram for analysis</u>	1
33 to 35	service limits	3
36 & 53 & 63	S_u & S_o & S_y for several materials (incl. 316 SS)	3
69 & 70	E & alpha	2
55 & 60	S_{mt} for 316 SS	2
65	S_r for 316 SS	1
81 to 83	Rules for Strain, Deformation & Fatigue	3
87 & 88 & 93 to 95	Creep-Fatigue Evaluation	5
90	Design Fatigue curve for 316 SS	1
		37

Approval Date: August 5, 1994
See Numerical Index for expiration and any reaffirmation dates.

Case N-47-32
Class 1 Components in Elevated Temperature Service
Section III, Division 1

Inquiry: Under what rules for materials, design, and stamping shall Section III, Division 1, Class 1 components be constructed when metal temperatures exceed those for which allowable stress values are given by Section III, Division 1?

Reply: It is the opinion of the Committee that rules governing the construction of Section III, Division 1, Class 1 components which are to experience temperatures above those now provided for in Section III, Division 1, are under preparation by the Committee. In the interim, it is the opinion of the Committee that Class 1 components for elevated temperature service shall be constructed in accordance with the following considerations:

(1) The rules for materials in NB-2000 shall apply except as modified by this Case;

(2) The rules for design in this Case shall replace the rules of NB-3000; and

(3) The stamping and Data Report shall indicate this Case number and the revision applied.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

TABLE OF CONTENTS (Cont'd)

TABLE OF CONTENTS (Cont'd)

-1000 INTRODUCTION

-1100 Scope

-1110 Aspects of Construction Covered by These Rules

(a) This Case contains rules for materials and design of Class 1 components, parts and appurtenances which are expected to function even when metal temperatures exceed those covered by the rules and stress limits of Subsection NB and Tables I-1.0 of Appendix I.

(b) The rules of this Case are applicable to Class 1 components independent of the type of contained fluid — water, steam, sodium, helium, or any other process fluid.

(c) The stress limits and design rules of Subsection NB are applicable only to service conditions where creep and relaxation effects are negligible. Consequently, the rules of Subsection NB only guard against the time-independent failure modes — ductile rupture, gross distortion (buckling and incremental collapse) and fatigue. Therefore, those portions of the component, part or appurtenance which are at all times experiencing temperatures within the range covered by Tables I-1.0 of Appendix I may be designed in compliance with the rules of -3000 in this Case, or alternatively, in compliance with the rules of NB-3000. In addition the rules of this Case extend specific rules of NB-3000 to elevated temperature service provided the designer can demonstrate that the combined effects of temperature, stress level, and duration of loading do not introduce significant creep effects.

(d) At temperatures and loading conditions where creep effects are significant, the design analysis shall also consider the time-dependent material properties and structural behavior by guarding against the four modes of failure shown below:

(1) Ductile rupture from short-term loadings

(2) Creep rupture from long-term loadings

(3) Creep-fatigue failure

(4) Gross distortion due to incremental collapse and ratcheting

Brief guidelines are also provided in this Case for the three modes of failure shown below:

(5) Loss of function due to excessive deformation

(6) Buckling due to short-term loadings

(7) Creep buckling due to long-term loadings

(e) Design procedures and materials data not con-

under service or test loadings, including additional pressure due to static and dynamic head of liquids;

(c) superimposed loads such as from other components, operating equipment, insulation, corrosion-resistant or erosion-resistant linings and piping;

(d) wind loads, snow loads, vibrations and earthquake loads where specified;

(e) reactions of supporting lugs, rings, saddles or other types of supports;

(f) temperature effects;

(g) impact forces caused by either external or internal events.

-3112 Design Parameters

(a) The design parameters are the pressures, temperatures, and mechanical load forces applicable to the design of nuclear power plant components. The simplest set of design parameters would consist of the temperature, pressure, and load forces that exist at some given time.

(b) To design a zone of a component for service at elevated temperature, two types of design parameter data are needed in the Design Specifications (NCA-3250) . . . first, an expected loading history which consists of how each design parameter varies as a function of time; and second, a list of events which occur under each loading category defined in -3113.

(c) The design parameter data stipulated in (1) and (2) below shall be specified in the Design Specifications (NCA-3250) for each component:

(1) The loading event history to be used in the structural analysis;

(2) The design parameters from which the designer will determine the most severe loading for each loading category defined in -3113. (If fluid conditions are specified, the designer eventually must convert the data to metal temperatures and surface pressures.)

(d) It is permissible for the designer to establish the zone boundaries inside the component. However, the zone boundaries and applicable design parameters shall be fully described in the Stress Report.

-3112.1 Specified Pressure

(a) The specified internal and external pressure histories shall describe pressure values not less than the maximum pressure differences between the inside and outside of the pressure boundary in a given zone of the component, or between any two chambers of a combination unit.

(b) The specified pressure histories shall be used in the computations made to show compliance with the limits of -3200.

(c) All pressures referred to in this Article are to be taken as the value above atmospheric pressure unless otherwise stated.

-3112.2 Specified Temperature. The specified temperature history for the loading category shall enable the designer to describe a temperature value not less than the maximum local wall-averaged temperature that will exist in the structural metal in a given zone of the component. And for the particular analyses of Service Loadings (-3113.2), the designer shall determine the history of the maximum local metal temperature in a given zone and shall use these metal temperature histories in the computations to show compliance with the limits of -3200.

(a) All temperatures referred to in this Article are the metal temperatures expressed in degrees Fahrenheit (F) unless otherwise stated.

(b) Where a component is heated by trace heating, induction coils, jacketing or by internal heat generation, the designer shall consider the effect of such heating in the establishment of the design temperature histories.

(c) Elevated temperature mechanical properties are extremely sensitive to temperature. The Design Specifications shall specify any inaccuracies in temperature measurement and prediction that are to be considered in the design analyses made to show compliance with the limits of -3200.

-3112.3 Specified Mechanical Load Forces. The specified load forces for a given loading category (-3113) shall define all expected mechanical loadings which must be considered in design analysis computations made to show compliance with the limits of -3200.

-3113 Loading Categories. Loading categories used in this Subsection consist of Design Loading, Service Loadings (Levels A, B, C, and D), and Test Loadings.

-3113.1 Design Loadings. The specified design parameters for the Design Loadings category shall equal or exceed those of the most severe combination of coincident pressure, temperature, and load forces specified under events which cause Service Level A Loadings (-3113.3) for the same zone of the component. These specified design parameters for Design Loadings shall be called Design Temperature, Design Pressure, and Design Mechanical Loads. These specified design parameters shall be used in computations to show compliance with the requirements on Design Limits in -3222.1.

-3113.2 Service Loadings. Each loading to which the component may be subjected shall be categorized in accordance with the following definitions and shall be described in the Design Specifications (NCA-3250) in such detail as will provide a complete basis for construction in accordance with these rules. The Service Loading categories shall be as defined in the next four subparagraphs below.

-3113.3 Level A Service Loadings. Level A Service Loadings are any loadings arising from system startup, operation in the design power range, hot standby, and system shut-down, and excepting only those loadings covered by Levels B, C, and D Service Loadings or Test Loading.

-3113.4 Level B Service Loadings. (From incidents of Moderate Frequency). These are deviations from Level A Service Loadings that are anticipated to occur often enough that design should include a capability to withstand the loadings without operational impairment. The events which cause Level B Service Loadings include those transients which result from any single operator error or control malfunction, transients caused by a fault in a system component requiring its isolation from the system, and transients due to loss of load or power. These events include any abnormal incidents not resulting in a forced outage and also forced outages for which the corrective action does not include any repair of mechanical damage. The estimated duration of a Level B Service Loading shall be included in the Design Specifications.

-3113.5 Level C Service Loadings. (From infrequent Incidents). These are deviations from Level A Service Loadings which require shutdown for correction of the loadings or repair of damage in the system. The conditions have a low probability of occurrence but are included to provide assurance that no gross loss of structural integrity will result as a concomitant effect of any damage developed in the system. The total number of postulated occurrences for such events may not exceed 25. If more than 25 are expected, then some types of events must be evaluated by the more stringent requirements of the Level B Service Limits.

-3113.6 Level D Service Loadings. (From Limiting Faults). These are combinations of loadings associated with extremely low probability, postulated events whose consequences are such that the integrity and operability of the nuclear energy system may be impaired to the extent that only considerations of public health and safety are involved.

-3113.7 Test Loadings. These are pressure loadings which occur during hydrostatic tests, pneumatic tests and leak tests. Other types of tests shall be classified under either Service Level A or B loading categories given in the above subparagraphs. If any elevated temperature tests are specified as Test Loadings for a component, then these loadings shall be considered as part of the Service Level B loadings for the component.

-3114 Load Histogram

-3114.1 Level A and B Service Events. The Design Specifications (NCA-3250) shall include an expected loading history or load histogram for all Service Loadings from Level A and B service events, (including all Test Loadings). These load histograms shall give all expected mechanical load forces, pressure and temperatures for the various zones of the component throughout its service life. These histograms are then used in meeting the analysis requirements of -3200.

-3114.2 Level C Service Events. The Design Specifications shall include a time history of the design parameters during each type of Level C Service event. However, these events need not be specified as to time of occurrence during the service life of the component. The design parameter data shall be used in meeting the analysis requirements of -3200. Level C Service events may be assumed as occurring between operational cycles (-3213.15) of Level A Service events unless otherwise specified in the Design Specifications (NCA-3250).

-3130 General Design Rules

-3131 Scope. Design rules generally applicable to all components are provided in -3130. The Design Subarticle for the specific component provides rules applicable to that particular component. In case of conflict between -3130 and the design rules for a particular component, the component design rules shall govern.

-3132 Dimensional Standards for Standard Products. Dimensions of standard products shall comply with the standards and specifications listed in Table NB-3132-1 when the standard or specification is referenced in the specific design Subarticle. However, compliance with these standards does not replace or eliminate the requirements for stress analysis when called for by the design Subarticle for a specific component.

-3133 Size Restrictions in Nozzle, Branch, Piping and Other Connections. The size of certain design features is restricted on nozzle, branch, piping, and

-3137 Design Considerations Related to Other Articles of the Code

-3137.1 Design Considerations for Static Pressure Testing. Since every component and appurtenance must eventually undergo a static pressure test, the designer shall ensure that such a test can be performed. If the only available test fluid can leave harmful residues on surfaces, the design shall preferably be such as to leave surfaces accessible for cleaning following the static pressure test. Special access hatches as well as drain lines may be required.

-3137.2 Design Considerations for Overpressure Protection of the System

(a) Each component and the system into which it will be installed shall be protected against overpressure events as required by the rules on overpressure protection of Class 1 components and systems exposed to elevated temperature service.

(b) The Service Loadings listed in the Design Specifications include those overpressure events which the designer shall consider in the design of that particular component. However, the component designer shall also review the final design to determine if additional overpressure transients can arise from one of the following:

(1) Failure of non-pressure-boundary parts of the component;

(2) Failure of external power sources to the component;

(3) Functioning of the component in conjunction with specified plant and system service conditions (Levels A, B, C, and D).

The designer shall report to the Owner regarding all sources of overpressure transients that can arise from (1), (2) and (3).

-3138 Elastic Follow-up

(a) When only a small portion of the structure undergoes inelastic strains while the major portion of the structural system behaves in an elastic manner, the calculations of load forces, stresses and strains shall consider the behavior of the entire structural system. In these cases, certain areas may be subjected to strain concentrations due to the elastic follow-up of the rest of the connected structure. These abnormally large strain concentrations may result when structural parts of different flexibility are in series and the flexible portions are highly stressed. Examples include:

(1) Local reduction in size of a cross section or local use of a weaker material.

(2) In a piping system of uniform size, a configuration for which most of the system lies near the hypothetical straight line connecting the two anchors, (stiffeners, flanges, or other stiff members), and with only a small portion departing from this line. Then the small portion absorbs most of the expansion strain.

(b) If possible, the above conditions should be avoided in design. Where such conditions cannot be avoided, the analysis required in -3250 will determine the acceptability of the design to guard against harmful consequences of elastic follow-up.

-3139 Welding

-3139.1 Abrupt Changes in Mechanical Properties at Weld and Compression Contact Junctions. In satisfying the requirements of -3000, particular considerations shall be given to the design, analysis and construction of welded and compression contact junctions between two materials which have different mechanical properties. Such properties at elevated temperatures include thermal expansion, creep rate, creep ductility and fatigue life. Examples of such junctions are bimetallic welds, brazed joints, compression or shrink fits, bolted flanges and other types of mechanical joints. When temperatures cycle between low temperatures and elevated temperatures, the inelastic strains ca result in significant localized strain accumulation neai an abrupt change in mechanical properties.

-3139.2 Weld Design. All welds shall comply with the roles of NB-3350. Exceptions to this requirement are allowed only if a specific callout is made in either -3400, -3500 or -3600.

-3200 DESIGN BY ANALYSIS

-3210 Design Criteria

-3211 Requirements for Acceptability. For a Class 1 component intended for elevated temperature service, the requirements for the acceptability of a design based on analysis shall be as stipulated in (a) through (d) below.

(a) The design shall be such that the calculated or experimentally-determined stresses, strains, and deformations will not exceed the limits described in this Subarticle;

(b) The design details shall conform to the rules of -3100 and to those given in subsequent Subarticles applicable to the specific component;

(c) If the designer has demonstrated that the elevated temperature service parameters (time, stress level and temperature) do not introduce significant cre

effects[3], then the experimental and analytical methods of Subsection NB shall be applicable. The other restrictions on temperature maxima that appear in Subsection NB [see NB-3228.3(e)] shall not apply provided the designer demonstrates the validity of values and methods for the higher temperatures.

(d) For portions of the component which do not experience elevated temperature service, the rules of NB-3000 may be used to satisfy (a) and (b) above. Alternatively, properties and allowable stress values from Subsection NB may be used in analyses to demonstrate compliance with the rules of -3200.

-3212 Basis for Determining Stress, Strain and Deformation Quantities

(a) For elastic analysis allowed by this Case, the maximum shear stress theory shall be used to determine stress intensities for multiaxial stress states (NB-3212).

(b) For inelastic analysis required by this Code Case, appropriate multiaxial stress–strain relationships and associated flow rules shall be used to combine multiaxial stresses and strains.

-3213 Terms Relating to Analysis. In this Case the stress and strain limits for design evaluation are related to the type of structural behavior under loading. The controlled quantities fall into two general categories:[4]

(a) Load-Controlled Quantities — These quantities are stress intensities which are computed on the basis of equilibrium with the applied forces and moments during plant operation. Included in this category are general primary-membrane, local primary-membrane, primary bending stresses and secondary stresses with a large amount of elastic follow-up.

(b) Deformation-Controlled Quantities — These quantities are strains, cyclic strain ranges or deformations which result from load deflection and/or strain compatibility.

Other terms used in this Case relating to structural analysis are defined in the subparagraphs of -3213.

-3213.1 Elastic Stress Intensity[5] is the equivalent intensity of combined stress. In short, the stress intensity is defined as twice the maximum shear stress. In other words, the stress intensity is the difference between the algebraically largest principal stress and the algebraically smallest principal stress at a given point. Tensile stresses are considered positive and compressive stresses are considered negative.

-3213.2 Gross Structural Discontinuity is a geometric or material discontinuity which affects the stress or strain distribution through the entire wall thickness of the pressure-retaining member. Gross-discontinuity-type stresses are those portions of the actual stress distributions that produce net bending and membrane force resultants when integrated through the wall thickness. Examples of gross structural discontinuities are head-to-shell and flange-to-shell junctions, nozzles and junctions between shells of different diameters or thicknesses.

-3213.3 Local Structural Discontinuity is a geometric or material discontinuity which affects the stress or strain distribution through a fractional part of the wall thickness. The stress distribution associated with a local discontinuity causes only very localized types of deformation or strain and has no significant effect on the shell-type discontinuity deformation. Examples are small fillet radii, small attachments and partial penetration welds.

-3213.4 Normal Stress is the component of stress normal to the plane of reference. (This is also referred to as direct stress.) Usually the distribution of normal stress is not uniform through the thickness of a part, so this stress is considered to be made up in turn of two components, one of which is uniformly distributed and equal to the average value of stress across the thickness under consideration, and the other of which varies from this average value with the location across the thickness.

-3213.5 Shear Stress is the component of stress tangent to the plane of reference.

-3213.6 Membrane Stress is the component of normal stress which is uniformly distributed and equal to the average of stress across the thickness of the section under consideration.

-3213.7 Bending Stress is the variable component

[3]A report documenting the experimental data or calculations based on experimental data or both shall demonstrate that the elevated temperature service does not introduce creep effects. This document shall be incorporated into the Stress Report (NCA-3550) and shall be approved by the Owner by means of a certified revision to the Design Specifications (NCA-3250).

[4]Note that the expansion stress (P_e) defined in NB-3222.3 is deleted for this Code Case. Stresses resulting from the constraint of *free end displacement* and the effects of anchor motion shall be assigned to either primary or secondary stress categories [see -3213(a), -3213(b) and -3217].

[5]This definition of stress intensity is not related to the definition of stress intensity applied in the field of Fracture Mechanics.

of normal stress described in -3213.4. The variation may or may not be linear across the thickness.

-3213.8 Primary Stress is any normal stress or a shear stress developed by an imposed loading which is necessary to satisfy the laws of equilibrium of external and internal forces and moments. The basic characteristic of a primary stress is that it is not self-limiting. Primary-membrane stress is divided into general and local categories. A general primary-membrane stress is one which is so distributed in the structure that no redistribution of load occurs as a result of yielding. Examples of primary stresses are:

(a) general membrane stress in a circular cylindrical or a spherical shell due to internal pressure or to distributed live loads;

(b) bending stress in the central portion of a flat head due to pressure;

(c) stresses in piping due to net cross section load forces (normal or shear) arising from thermal expansion of structural material.

-3213.9 Secondary Stress is a normal stress or a shear stress developed by the constraint of adjacent material or by self-constraint of the structure and thus it is normally associated with a deformation-controlled quantity at elevated temperatures. The basic characteristic of a secondary stress is that it is self-limiting. Local yielding and minor distortions can satisfy the conditions which cause the stress to occur and failure from one application of the stress is not to be expected. Examples of secondary stresses are:

(a) bending stress at a gross structural discontinuity;

(b) bending stress in piping where loads cannot cause excessive creep deformation (e.g., buckling or dimpling) in a local region;

(c) bending stress due to a linear radial thermal strain (αT) profile through the thickness of a section;

(d) bending stress due to an equivalent linear thermal strain profile for the actual (nonlinear) strain profile [The equivalence is based on having the linear profile exert the same net bending moment as that from the actual profile (-3213.13).];

(e) stress produced by an axial temperature distribution in a cylindrical shell;

(f) stress produced by the temperature difference between a nozzle and the shell to which it is attached.

-3213.10 **Local Primary-Membrane Stress.** Cases arise in which a membrane stress produced by pressure or other mechanical loading and associated with a primary or a discontinuity effect produces excessive distortion in the transfer of load to other portions of the structure. Conservatism requires that such a stress be classified as a local primary membrane stress even though it has some characteristics of a secondary stress. A stressed region may be considered local if the distance over which the membrane stress intensity exceeds $1.1S_o$ does not extend in the meridional direction more than $1.0\sqrt{Rt}$, where R is the minimum midsurface radius of curvature and t is the minimum thickness in the region considered. Regions of local primary stress intensity involving axisymmetric membrane stress distributions which exceed $1.1S_o$ shall not be closer in the meridional direction than $2.5\sqrt{Rt}$, where R is defined as $(R_1 + R_2)/2$ and t is defined as $(t_1 + t_2)/2$ (where t_1 and t_2 are the minimum thicknesses at each of the regions considered, and R_1 and R_2 are the minimum midsurface radii of curvature at these regions where the membrane stress intensity exceeds $1.1S_o$). Discrete regions of local primary membrane stress intensity, such as those resulting from concentrated loads acting on brackets, where the membrane stress intensity exceeds $1.1S_o$, shall be spaced so that there is no overlapping of the areas in which the membrane stress intensity exceeds $1.1S_o$. An example of a local primary-membrane stress is the membrane stress in a shell produced by external load and moment at a permanent support or at a nozzle connection.

-3213.11 Peak Stress is that increment of stress which is additive to the primary-plus-secondary stresses by reason of local discontinuities or local thermal stress [see -3213.13(b)] including the effects (if any) of stress concentrations. The basic characteristic of a peak stress is that it does not cause any noticeable distortion and is objectionable only as a possible source of a fatigue crack or a brittle fracture, and, at elevated temperatures, as a possible source of localized rupture or creep-fatigue failure. A stress which is not highly localized falls into this category if it is of a type which cannot cause noticeable distortion. Examples of peak stresses are:

(a) the thermal stress in the austenitic-steel cladding of a carbon steel component;

(b) certain thermal stresses which may cause fatigue but not distortion;

(c) the stress at a local structural discontinuity;

(d) surface stresses produced by thermal shock.

-3213.13 Thermal Stress is a self-balancing stress produced by a nonuniform distribution of temperature or by differing thermal coefficients of expansion. Thermal stress is developed in a solid body whenever a volume of material is prevented from assuming the s and shape that it normally should under a change in temperature. For the purpose of establishing allowable stresses, two types of thermal stress are recognized, depending on the volume or area in which distortion takes place, as described in the following subsubparagraphs.

(a) General thermal stress is associated with distortion of the structure in which it occurs. When thermal stresses are to be considered as primary or secondary loadings, they are in this category. For example, see T-1331(c).

(b) Local thermal stress is associated with almost complete suppression of the differential expansion and thus produces no significant distortion. Such stresses shall be considered only from the fatigue standpoint and are therefore classified as peak stresses. Examples of local thermal stresses are:

(1) the stress in a small hot spot in a vessel wall;

(2) the difference between the actual stress and the equivalent linear stress resulting from a radial temperature distribution in a cylindrical shell;

(3) the thermal stress in a cladding material which has a coefficient of expansion different from that of the base metal.

-3213.15 Operational Cycle is defined as the initiation and establishment of new parameter values followed by a return to the values which prevailed at the beginning of the cycle. The description of the types of plant and system operating conditions, which may occur in a nuclear energy system are beyond the scope of Section III.

-3213.16 Strain Cycle is a condition in which the strain goes from an initial value, through an algebraic maximum value and an algebraic minimum value and then returns to the initial value. In cases where creep or ratcheting are present in the cycle, there will not be a return to the initial strain value. Instead the designer will have to examine the hysteresis loop for inelastic analysis and the stress history for elastic analysis to determine the end point of the cycle. See T-1413 for the method of combining cycles for fatigue analysis. A single operational cycle may result in one or more strain cycles. Dynamic effects shall also be considered as strain cycles.

-3213.17 Fatigue-Strength-Reduction Factor is a stress-intensification or a strain-intensification factor which accounts for the effect of a local structural discontinuity (stress or strain concentration) on the fatigue strength. Factors currently exist only for cycles which do not involve significant creep effects.

-3213.18 Free-End Displacement consists of the relative motions that would occur between a fixed attachment and connected piping if the two members were separated and permitted to move.

-3213.20 Deformation. Deformation of a component part is an alteration of its shape or size.

-3213.21 Inelasticity. Inelasticity is a general characteristic of material behavior in which the material does not return to its original shape and size after removal of all applied loads. Plasticity and creep are special cases of inelasticity.

-3213.22 Creep. Creep is the special case of inelasticity that relates to the stress induced time-dependent deformation under load. Small time-dependent deformations may occur after the removal of all applied loads.

-3213.23 Plasticity. Plasticity is the special case of inelasticity in which the material undergoes time-independent nonrecoverable deformation.

-3213.24 Plastic Analysis. Plastic analysis is that method which computes the structural behavior under given loads considering the plasticity characteristics of the materials including strain hardening and the stress redistribution occurring in the structure.

-3213.25 Plastic Analysis — Collapse Load. A plastic analysis may be used to determine the collapse load for a given combination of loads on a given structure. The following criteria for determination of the collapse load shall be used. A load-deflection or load-strain curve is plotted with load as the ordinate and deflection or strain as the abscissa. The angle that the linear part of the load deflection or load strain curve makes with the ordinate is called θ. A second straight line, hereafter called the collapse limit line is drawn through the origin so that it makes an angle $\phi = \tan^{-1}(2 \tan \theta)$ with the ordinate. The collapse load is the load at the intersection of the load-deflection or load-strain curve and the collapse limit line. If this method is used, particular care should be given to assuring that the strains or deflections that are used are indicative of the load carrying capacity of the structure.

-3213.26 Plastic Instability Load. The plastic instability load for members under predominantly tensile or compressive loading is defined as that load at which unbounded plastic deformation can occur without an increase in load. At the plastic-tensile instability load the true stress in the material increases faster than strain hardening can accommodate.

-3213.27 Limit Analysis. Limit analysis is a special case of plastic analysis in which the material is assumed to be ideally plastic (non-strain hardening). In limit analysis the equilibrium and flow characteristics at the limit state are used to calculate the collapse load. The two bounding methods which are used in limit analysis are the lower bound approach which is associated with a statically admissible stress field, and the upper bound approach which is associated with a kinematically admissible velocity field. For beams and frames the term "mechanism" is commonly used in lieu of "kinematically admissible velocity field."

-3213.28 Limit Analysis — Collapse Load. The methods of limit analysis are used to compute the maximum carrying load for a structure assumed to be made of ideally plastic material. If creep effects exist, then the influence of time-dependent deformations on the collapse load shall be considered.

-3213.29 Calculated Collapse Load-Lower Bound. If, for a given load, any system of stresses can be found which everywhere satisfies equilibrium and nowhere exceeds the material yield strength, the load is at or below the collapse load. This is the lower bound theorem of limit analysis which permits calculations of a lower bound to the collapse load. If creep effects exist, then the influence of time-dependent deformations on the collapse load shall be considered.

-3213.30 Plastic Hinge. A plastic hinge is an idealized concept used in Limit Analysis. In a beam or a frame, a plastic hinge is formed at the point where the moment, shear, and axial force lie on the yield interaction surface. In plates and shells a plastic hinge is formed where the generalized stresses lie on the yield surface.

-3213.31 Strain Limiting Load. When a limit is placed upon a strain, the load associated with the strain limit is called the strain limiting load.

-3213.32 Test Collapse Load. Test collapse load is the collapse load determined by tests according to the criteria given in Article II-1430 of Section III.

-3213.33 Ratcheting is a progressive cyclic inelastic deformation. Total inelastic strain per cycle may vary from cycle to cycle in the most general situation. Stable ratcheting occurs when the net inelastic strain from a given load cycle is constant for subsequent cycles.

(a) Progressive incremental inelastic deformation can occur in a component that is subjected to cyclic variations of mechanical secondary stress, thermal secondary stress; or both in the presence of a primary stress.

(b) Where creep effects are significant, creep ratcheting can occur, even in the absence of plastic yielding. At least two mechanisms are involved in creep ratcheting. First, creep can alter the residual stresses and thus affect the time-independent behavior. Secondly, the time-dependent deformation can be enhanced because of the nonlinear interaction of primary and secondary stresses. This latter effect is referred to as *enhanced creep.*

-3213.34 Shakedown is the absence of significant progressive, cyclic, inelastic deformation, or ratcheting (-3213.23). A structure shakes down if, after a few cycles of load application, the deformation stabilizes.

-3213.35 Design Information on the Nameplate are the Design Temperature and the Design Pressure for the zone of the structure nearest the pressure-relief device (or the top of the component if there are no pressure-relief devices). The values for these parameters shall appear on the nameplate.

-3213.36 Use-Fraction is the material damage due to primary stresses expressed as a time ratio.

-3213.37 Fatigue Damage is that part of the total material damage caused by cyclic deformation which is independent of time effects (e.g., stress holdtime, strain holdtime, frequency). The damage is expressed in terms of a cycle ratio.

-3213.38 Creep Damage is that part of the total material damage caused by time exposure to steady and transient stresses at elevated temperatures, expressed as a time ratio. (Relaxation damage is a form of creep damage.)

-3213.39 Creep-Fatigue Interaction is the effect of combined creep and fatigue on the total creep-fatigue damage accumulated at failure.

-3214 Stress Analysis. A detailed stress analysis of all major structural components shall be prepared in sufficient detail to show that each rule or limit of -3220 and -3230 is satisfied when the component is subjected to the loadings described in -3111. This detailed analysis shall become a part of the Stress Report (NCA-3550).

-3214.1 Elastic Analysis. The analysis guidelines and methods in Article NB-3000 apply (-3211). As a aid to the evaluation of these elastic stresses, formulas and methods for the solution of certain recurring problems have been placed in Appendix A.

-3214.2 Inelastic Analysis. When thermal and mechanical loadings are sufficiently severe to produce yielding and/or when thermal creep processes are active, inelastic design analysis may be required. The rules and limits of Appendix T were established with the expectation that inelastic analyses would sometimes be required, and that such analyses would be sufficiently comprehensive to predict significant behavioral features. Generally, this requires analysis of combined time-independent elastic-plastic material behavior and time-dependent creep behavior capable of predicting stresses, strains, and deformations as functions of time for specific thermal-mechanical load histories.

The constitutive equations, which describe the inelastic behavior, should reflect the following features when they have a significant influence on structural response: the effects of plastic strain hardening including cyclic loading effects and the hardening or softening which can occur with high-temperature exposure; primary creep and the effects of creep strain hardening as well as softening (due to reverse loadings); and the effects of prior creep on subsequent plasticity, and vice-versa.

The basis for choosing the selected methods and relations used should be included in the Design Report.

Since the rules and limits incorporate design factors and margins to account for material property variations and uncertainties, it is generally appropriate to use average stress-strain and creep data in inelastic design analyses. The buckling and instability limits of Appendix T are an exception; in T-1510(g) it is stated that the minimum expected stress-strain curve should be used.

-3214.3 Mechanical Properties. The values of some mechanical properties needed for analysis are listed in Appendix I-14 and in Appendix T of this Case. Properties covered include:

(a) Isochronous stress-strain curves

(b) Yield strength

(c) Stress-to-rupture

(d) Modulus of elasticity

(e) Instantaneous and mean coefficients of thermal expansion

Other mechanical property relations used in the analysis shall be described and justified in the Stress Report.

-3215 Derivation of Stress Intensities. One requirement for the acceptability of a design (-3210) is that the calculated stress intensities shall not exceed specified allowable limits. These limits differ depending on the stress category (primary, secondary, etc.) from which the stress intensity is derived. This paragraph describes the procedure for the calculation of the stress intensities which are subject to the specified limits. The steps in the procedure are stipulated in the following subparagraphs.

(a) At the point on the component which is being investigated, choose an orthogonal set of coordinates such as tangential, longitudinal and radial, and designate them by the subscripts, t, l, and r. The stress components in these directions are then designated σ_t, σ_l, and σ_r for direct stresses and τ_{lt}, τ_{lr} and τ_{rt} for shearing stresses.

(b) Calculate the stress components for each type of loading to which the part will be subjected and assign each set of stress values to one or a group of the following categories:

P_m, P_L = Average primary stress components as defined in -3213.8 and -3213.10.

P_b = Primary bending stress components at a surface as defined in -3213.8.

Q = Secondary stress components as defined in -3212.9.

F = Peak stress components as defined in -3213.11. Tables -3217-1 and -3217-2 provide assistance in the determination of the category to which a stress should be assigned.

It should be noted that each of the symbols for the above stress categories represents six scalar quantities corresponding to the six stress components, σ_t, σ_l, σ_r, τ_{lt}, τ_{ln} and τ_{rt}. In the particular case of the six membrane stress components, each component shall be averaged across the thickness of the structural section.[4]

(c) For each category, calculate the algebraic sum of the σ_t's which result from the different types of loadings and similarly for the other five stress components. Certain combinations of the categories must also be considered.

(d) Translate the stress components for the t, l, and r directions into principal stresses, σ_1, σ_2, and σ_3. (In many pressure component calculations, the t, l, and r directions may be so chosen that the shearing stress components are zero and σ_1, σ_2, and σ_3 are identical to σ_t, σ_l, and σ_r.

(e) Calculate the stress differences S_{12}, S_{23}, and S_{31} from the relations

$$S_{12} = \sigma_1 - \sigma_2$$

$$S_{23} = \sigma_2 - \sigma_3$$

$$S_{31} = \sigma_3 - \sigma_1$$

The stress intensity, S, is the largest absolute value of S_{12}, S_{23}, and S_{31}.

-3216 Derivation of Stress Differences and Strain Differences. The ability of the component to withstand the specified cyclic operation without creep-fatigue failure shall be determined as in -3250. The evaluation shall demonstrate, by evaluating the stresses and strains at selected points of the components, that the combined creep-fatigue damage is everywhere within design limits. Only the stress and strain differences due to the operational cycles as specified in the Design Specifications need be considered.

-3217 Classification of Stresses. Tables -3217-1 and -3217-2 provide assistance in the determination of the category to which a stress should be assigned. For portions of the component not exposed to elevated temperature service, the classification or category may be selected as in NB-3000.

-3220 Design Rules and Limits for Load-Controlled *Stresses in Structures Other than Bolts*

-3221 General Requirements

(a) The rules for design against failure from load-controlled stresses are illustrated in Fig. -3220-1 and are explained in -3220. The allowable stress-intensity values used in -3220 are listed in Tables I-1.0 of Appendix I and Table I-14.0. Note that the strain, deformation and fatigue limits of -3250 require analyses beyond those required by the rules of -3220.

(b) The stress-intensity limits used in Fig. -3220-1 and throughout this Case are defined for base metal and at weldments as follows:

(1) Base Metal

S_o = the maximum allowable value of general primary-membrane stress intensity to be used as a reference for stress calculations under Design Loadings. The allowable values are given in Table I-14.2. (The values correspond to the appropriate S values given in Table I-7.0 and I-8.0 of Appendix I and in Section VIII, Division 1 of the Code.)

S_{mt} = the allowable limit of general primary-membrane stress intensity to be used as a reference for stress calculations for the actual service life and under the Level A and B Service Loadings; the allowable values are shown in Fig. I-14.3 and in Table I-14.3. The S_{mt} values are the lower of two stress intensity values, S_m (time-independent) and S_t (time-dependent).

S_m = the lowest stress intensity value at a given temperature among the time-independent strength quantities which are defined in Article III-2000 as criteria for determining S_m; in this Case, the S_m values are extended to elevated temperatures by using the same criteria.

S_t = a temperature and time-dependent stress intensity limit; the data considered in establishing these values are obtained from long-term, constant load, uniaxial tests. For each specific time, t, the S_t values shall consider test results including: (a) the stress required to obtain a total (elastic, plastic, primary and secondary creep) strain of 1%, (b) the stress to cause initiation of tertiary creep and (c) the stress to cause rupture.

S_y = the yield strength of a material at a given temperature.

(2) Weldments

S_t = temperature and time-dependent stress intensity limit at a weldment, and shall be taken as the lower of the tabulated S_t value from Table I-14.4, or

$$0.8\ S_r \times R$$

where S_r is the expected minimum stress-to-rupture strength given in Table I-14.6, and R is the appropriate ratio of the weld metal creep rupture strength to the base metal creep rupture strength from Table I-14.10. The lowest S_t value of the adjacent base metals shall be utilized for the weldment.

S_{mt} = the allowable limit of general primary membrane stress intensity, and shall be taken as the lower of the S_{mt} value from Table I-14.3, or

$$0.8\ S_r \times R$$

-3222 Design and Service Limits

-3222.1 Design Limits. The stress calculations required for the analysis of Design Loadings (-3113.1)

TABLE -3217-1
CLASSIFICATION OF STRESS INTENSITY IN VESSELS FOR SOME TYPICAL CASES

Vessel Component	Location	Origin of Stress	Type of Stress	Classification
Cylindrical or spherical shell	Shell plate remote from discontinuities	Internal pressure	General membrane Gradient through plate thickness	P_m Q
		Axial thermal gradient	Membrane Bending	Q[4] Q
	Junction with head or flange	Internal pressure	Membrane Bending	P_L Q[5]
Any shell or head	Any section across entire vessel	External load or moment, or internal pressure	General membrane averaged across full section. Stress component perpendicular to cross section	P_m
		External load or moment	Bending across full section. Stress component perpendicular to cross section	P_m
	Near nozzle or other opening	External load or moment, or internal pressure	Local membrane Bending Peak (fillet or corner)	P_L Q F
	Any location	Temp. diff. between shell and head	Membrane Bending	Q[4] Q
Dished head or conical head	Crown	Internal pressure	Membrane Bending	P_m P_b
	Knuckle or junction to shell	Internal pressure	Membrane Bending	P_L[1] Q
Flat head	Center region	Internal pressure	Membrane Bending	P_m P_b
	Junction to shell	Internal pressure	Membrane Bending	P_L Q[5]
Perforated head or shell	Typical ligament in a uniform pattern	Pressure	Membrane (Av. thru cross section) Bending (Av. thru width of lig., but gradient thru plate) Peak	P_m P_b F
	Isolated or atypical Ligament	Pressure	Membrane Bending Peak	Q F F

TABLE -3217-1 (Cont'd)

Vessel Component	Location	Origin of Stress	Type of Stress	Classification
Nozzle (-3227.5)	Within the limits of reinforcement defined by -3334	Pressure and external loads and moments including those attributable to restrained free end displacements of attached piping	General membrane Bending (other than gross structural discontinuity stresses) averaged through nozzle thickness	P_m P_m
	Outside the limits of reinforcement defined by -3334	Pressure and external axial, shear, and torsional loads other than those attributable to restrained free end displacements of attached piping	General membrane stresses	P_m
		Pressure and external loads and moments other than those attributable to restrained free end displacements of attached piping	Membrane Bending	P_L P_b
		Pressure and all external loads and moments	Membrane Bending Peak	P_L Q F
	Nozzle wall	Gross structural discontinuities at nozzle to shell junction	Local membrane Bending Peak	P_L Q F
	Any	Differential expansion	Membrane Bending Peak	Q[4] Q F
Cladding	Any	Differential expansion	Membrane Bending	F F
Any	Any	Radial temp. Distribution[2]	Equivalent Linear stress[3]	Q
			Nonlinear portion of stress distribution	F
Any	Any	Any	Stress concentration (notch effect)	F

Notes to Table -3217-1
[1]Consideration must also be given to the possibility of wrinkling and excessive deformation in vessels with large diameter-to-thickness ratio.
[2]Consider possibility of thermal stress ratchet (see -3250).
[3]Equivalent linear stress is defined as the linear stress distribution which has the same net bending moment as the actual stress distribution
[4]These classifications may be modified for purposes of certain criteria in Appendix T.
[5]If the bending moment at the edge is required to maintain the bending stress in the middle to acceptable limits, the edge bending is classified as P_b. Otherwise, it is classified as Q.

TABLE -3217-2
CLASSIFICATION OF STRESS INTENSITIES IN PIPING, TYPICAL CASES

Piping Component	Locations	Origin of Stresses	Classification[1]	Discontinuities Considered: Gross	Discontinuities Considered: Local
Pipe or tube, elbows, and reducers. Intersections and branch connections except in the crotch regions	Any, except crotch regions of intersections	Internal pressure	P_m	No	No
			P_L and Q	Yes	No
			F	Yes	Yes
		Sustained mechanical loads including weight	P_b	No	No
			P_L and Q	Yes	No
			F	Yes	Yes
		Expansion	P_m, P_b and Q[1,2]	Yes	No
			F	Yes	Yes
		Axial thermal gradient	Q[1]	Yes	No
			F	Yes	Yes
Intersections, including tees and branch connections	In the crotch region	Internal pressure, sustained mechanical loads and expansion	P_L and Q[3]	Yes	No
			F	Yes	Yes
		Axial thermal gradient	Q[1]	Yes	No
			F	Yes	Yes
Bolts and flanges	Any	Internal pressure, gasket compression, bolt load	P_m	No	No
			Q	Yes	No
			F	Yes	Yes
		Thermal gradient	Q[1]	Yes	No
			F	Yes	Yes
		Expansion	P_m, P_b and Q[1,2]	Yes	No
			F	Yes	Yes
Any	Any	Nonlinear radial thermal gradient	F	Yes	Yes
		Linear radial thermal gradient	Q[1]	Yes	No

[1]These classifications may be modified for purposes of certain criteria in Appendix T.
[2]See -3138 and -3213.8.
[3]Analysis is not required when reinforced in accordance with -3643.

shall be based on a linearly-elastic material model. The calculated stress intensity values shall satisfy the limits of (a) and (b) below.

(a) The general primary-membrane stress intensity, derived from P_m, shall not exceed S_o.[6]

$$P_m \leq S_0 \tag{1}$$

(b) The combined primary-membrane-plus-bending stress intensity, derived from P_L and P_b, shall not exceed 1.5 S_o.

$$(P_L + P_b) \leq (1.5)\, S_0 \tag{2}$$

Note that the local primary-membrane stress, P_L, includes the general primary-membrane stress, P_m. As in Subsection NB, the left-hand side of Eq. (2) does not represent a simple algebraic combination since P_L and P_b may each represent as many as six quantities [-3215(b)].

(c) External pressure and other compression-inducing loadings shall be investigated for adequate buckling strength, using the limits of NB-3133 or other limits and time-independent factors permitted under Par. -3252.

-3222.2 Level A Service Limits. The stress intensity limits for Level A Service Limits (-3113.3) also apply to the stresses under both Level A and B Service Loadings. The limits for both are given in -3223.

-3223 Level A and B Service Limits. The stress calculations required for the analysis of Level A and B

[6]To satisfy Eq. (1) for straight cylindrical shapes, the minimum wall thickness may be calculated by the equations in PG-27 of Section I, Power Boilers, using S_o in place of S.

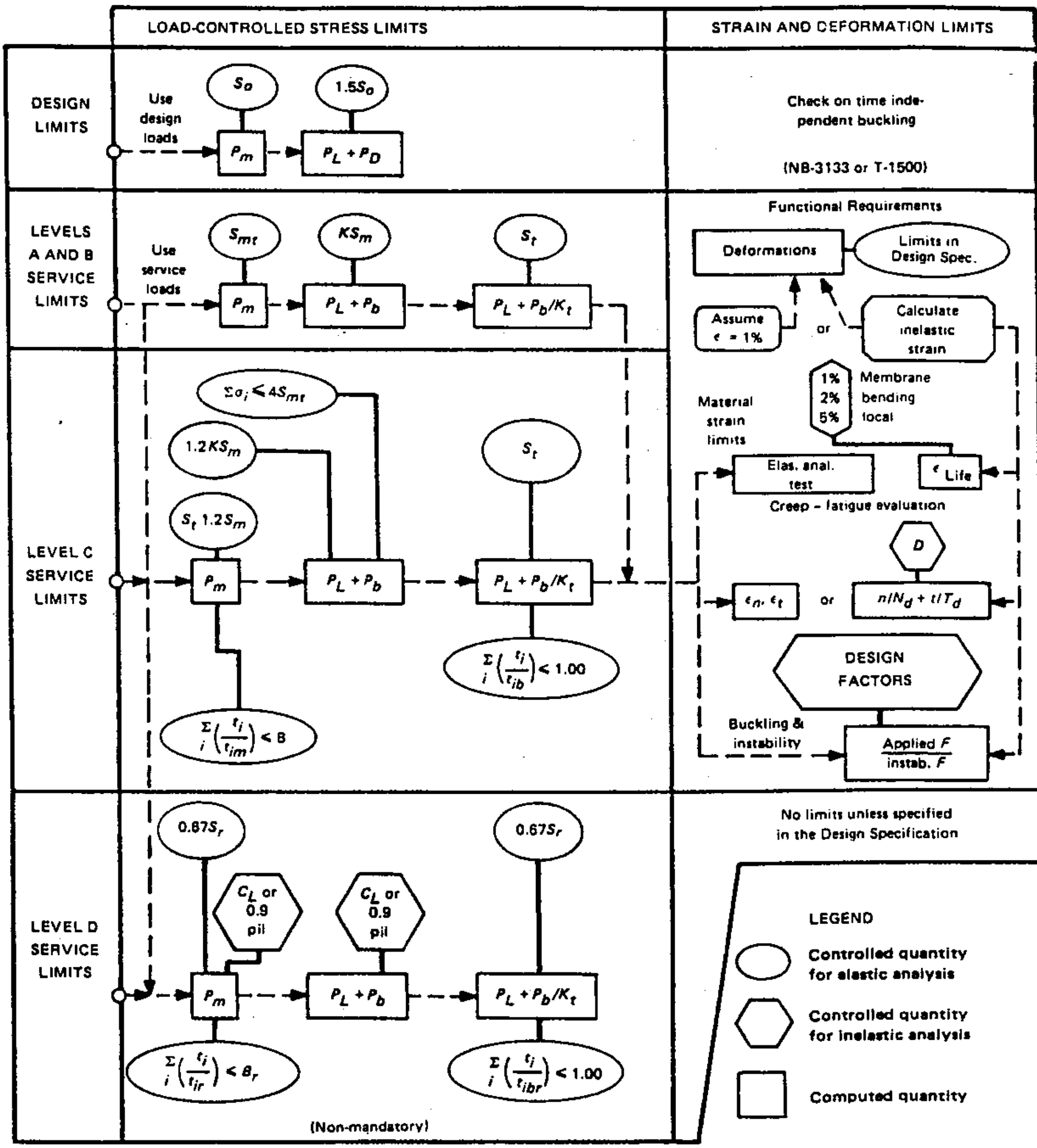


FIG. 3220.1 FLOW DIAGRAM FOR ELEVATED TEMPERATURE ANALYSIS

Service Loadings (-3113.4) are based on a linearly-elastic material model. The calculated stress-intensity values shall satisfy the conditions of (a) through (f) below.

(a) The general primary-membrane stress intensity, derived from P_m for Level A and B Service Loadings, shall not exceed S_{mt}.

$$P_m \leq S_{mt} \tag{3}$$

where S_{mt} is determined for the time, t, corresponding to the total duration of the particular loading during the entire service life, and for temperature, T, corresponding to the maximum wall-averaged temperature that occurs during the particular loading event.

(b) When time, t, [in (a) above] is less than the total specified service life of the component, the cumulative effect of all the loadings shall be evaluated by the use-fraction sum in -3224(b). In addition, it is permissible and often advantageous to subdivide a loading history into several load levels and into several temperatures at any given load level.

(c) The combined primary-membrane-plus-bending stress intensities, derived from P_L and P_b for Level A and B Service Loadings, shall satisfy the following limits with

$$P_L + P_b \leq KS_m \tag{4}$$

$$P_L + P_b/K_t \leq S_t \tag{5}$$

The factor K_t accounts for the reduction in extreme fiber bending stress due to the effect of creep. The factor is given by

$$K_t = (K + 1)/2 \tag{6}$$

The factor, K, is the section factor for the cross section being considered. It is the ratio of the load set producing a fully plastic section to a load set producing initial yielding of the extreme fiber of the cross section. In evaluating the initial yield and fully plastic section capabilities, the ratios of each individual load in the respective load set to each other load in that load set shall be the same as the respective ratios of the individual loads in the specified service load set. Values of K for various sections are given in Table A-9221(a)-1 of Appendix A of Section III.

(d) In evaluating across-the-wall bending of shell-type structures, $K = 1.5$ (for rectangular sections) shall be used. Thus, for across-the-wall shell bending, $K_t = 1.25$ in Eq. (6). Note that the classification of stresses of primary-membrane or primary-bending for use with these section factors shall be consistent with the specific rules for the component type (see -3300 to -3600).

(e) In Eq. (5), the S_t value is determined for the time, t, corresponding to the total duration of the combined stress intensity derived from P_L and P_b/K_t and the maximum wall-averaged temperature, T, during the entire service life of the component.

(f) When t is less than the total service life of the component, the cumulative effect of all $[P_L + (P_b/K_t)]$ loadings shall be evaluated by the use-fraction sum of -3224(d). It is permissible and often advantageous to separate a loading history into several load levels and into several temperatures at any given load level.

(g) Under all conditions where a bending loading occurs across a section, the propensity for buckling of that part of the section in compression shall be investigated under the requirements of -3250.

-3224 Level C Service Limits. The stress calculations required for Level C Service Loadings analysis are based on a linearly-elastic material model. The calculated stress intensity values shall satisfy the conditions of (a) through (d) below.

(a) The general primary-membrane stress intensity, derived from P_m for Level C Service Loadings, shall not exceed the smaller of 1.2 S_m and 1.0 S_t.

$$P_m \leq \begin{cases} 1.2\ S_m \\ 1.0\ S_t \end{cases} \tag{7}$$

(b) In addition, the use-fraction sum associated with the general primary-membrane stresses for all increments of primary loadings during Levels A, B, and C Loadings shall satisfy the following requirements:

$$\sum_i \left(\frac{t_i}{t_{im}}\right) \leq B \tag{8}$$

where

t_i = the total duration of a specific loading, P_{mi}, at elevated temperature, T, during the entire service life of the component. Note that $\Sigma_i t_i$) is that part of the component service life at elevated temperatures (i.e., temperatures above values governed by the rules of Subsection NB as explained in -3211).

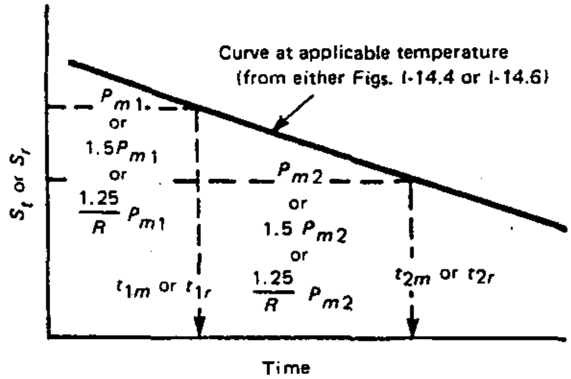


FIG. -3224.1 USE-FRACTIONS FOR MEMBRANE STRESS

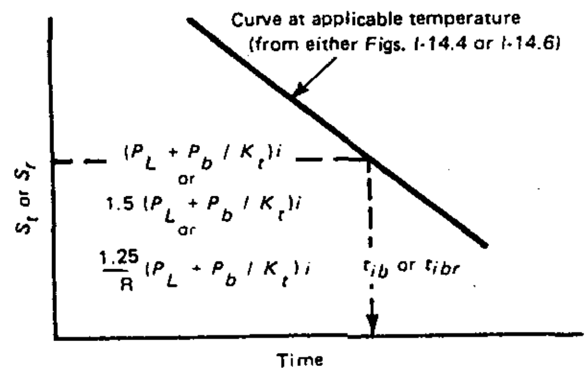


FIG. -3224.2 USE-FRACTIONS FOR MEMBRANE-PLUS-BENDING STRESS

t_{im} = maximum allowed time under the load stress intensity, S_i, as determined from a graph of S_t-vs.-time (see Fig. I-14.4).

B = use-fraction factor and is equal to 1.0 [or less if so specified in the Design Specifications (NCA-3250)].

The use of Fig. I-14.4 for determining t_{im} for two loading conditions at two different temperatures is shown schematically in Fig. -3224.1. In Fig. -3224.1, P_{mi} (i = 1, 2, 3, etc.) represents the calculated membrane stress intensity for the loading condition and temperature in question; and T_i represents the maximum local wall-averaged temperature during t_i. Note that it may be desirable to consider that a given stress intensity, P_{mi}, acts during several time periods, t_i, in order to take credit for the fact that the temperature varies with time.

(c) The combined primary-membrane-plus-bending stress intensities, derived from P_L and P_b for Level C Service Loadings shall satisfy the following limits, with $1.0 < K \leq 1.5$

$$P_L + P_b \leq 1.2KS_m \qquad (9)$$

$$P_L + P_b/K_t \leq S_t \qquad (10)$$

where K_t is defined as in -3223(c).

(d) In addition, the sum of the use-fractions associated with the primary-membrane-plus-bending stresses for all increments of primary loadings during Levels A, B, and C Service Loadings shall not exceed the value, 1.00.

$$\sum_i \left(\frac{t_i}{t_{ib}}\right) \leq 1.00 \qquad (11$$

where t_i is the total duration of the loading at temperature, T_i, and t_{ib} is the time value determined by entering Fig. I-14.4 at a value of stress equal to $P_L + P_b/K_t$, as shown in Fig. -3224.2.

-3225 Level D Service Limits. The rules of this paragraph may be used in the evaluation of components subjected to loads specified as Level D Service Loadings.

(a) The rules in -3225 (and in Appendix F) shall be applied in all instances unless alternative or supplementary criteria, as required by public health and safety considerations for specific components or systems, are defined in, and made applicable by the Owner's Design Specifications [NCA-3250]. The type of analysis (elastic or inelastic) used by the system designer shall be indicated in the Design Specifications (see F-1322.1).

(b) The general primary-membrane stress intensity, derived from P_m for the Level D Service Loadings, shall not exceed the smaller of 0.67 S_r, 0.8 S_rR, and one of the Level D Service Limits in Appendix F. E

$$P_m \leq \begin{cases} \text{Limit in Appendix F for } P_m \\ 0.67\ S_r \\ 0.8\ S_rR \end{cases} \qquad (12)$$

where S_r is the expected minimum stress-to-rupture in time t taken from

Fig. I-14.6 and R is the appropriate ratio of the weld metal creep fatigue strength to the base metal strength from Table I-14.10.

(c) In addition, the use-fraction sum associated with the general primary membrane stresses that arise from all Service Loadings, shall satisfy the requirement:

$$\sum_i \left(\frac{t_i}{t_{ir}}\right) \leq B_r$$

where

t_i = the total duration of a specific loading, P_{mi}, at elevated temperature, T_i, during the entire service life of the component. Note that $\sum_i(t_i)$ is that part of the component service life at elevated temperatures (i.e., temperatures above values governed by the rules of Subsection NB, as explained in -3211).

t_{ir} = maximum allowed time under the load stress intensity 1.5 P_{mi} for base metal or, for weldments, the higher of 1.5 P_{mi} or (1.25/R) P_{mi}. The allowable time under load is determined from the graph of minimum stress-to-rupture vs. time (see Fig. I-14.6).

B_r = use fraction factor and is equal to 1.0 (or less if so specified in the Design Specifications [NCA-3250]).

The use of Fig. I-14.6 for determining t_{ir} for two loading conditions at two different temperatures is shown schematically in Fig. -3224.1. In Fig. -3224.1, 1.5 P_{mi} (i = 1, 2, 3, etc.) represents 1.5 times the calculated membrane stress intensity for the loading condition and temperature in question; and T_i represents the maximum local wall-averaged temperature during t_i. Note that it may be desirable to consider that a given stress intensity acts during several time periods, t_i, in order to take credit for the variation of temperature with time.

(d) The combined primary-membrane-plus-bending stress intensities, derived from P_L and P_b, shall satisfy the following limits, with $1.0 < K \leq 1.5$, and Level D Service Limits in Appendix F for $P_L + P_b$.

$$P_L + P_b/K_t \leq \begin{cases} 0.67\ S_r \\ 0.8\ S_r \times R \end{cases} \qquad (13)$$

where K_t is defined in -3223(c).

(e) In addition, the sum of the use-fractions associated with the primary-membrane-plus-bending stresses that arise from all Service Loadings, shall not exceed the value of 1.00.

$$\sum_i \left(\frac{t_i}{t_{ibr}}\right) \leq 1.00$$

where t_i is the total duration of loading at temperature, T_i, and t_{ibr} is the time value determined by entering Fig. I-14.6 at a value of stress equal to 1.5 (P_L + P_b/K_t) for base metal or higher of 1.5 (P_L + P_b/K_t) or 1.25 (P_L + P_b/K_t)/R for weldments as shown in Fig. -3224.2. For the purpose of Section III, Appendix F calculations the yield strength and tensile strength values shall be defined as follows:

(1) Yield strength values shall be the product of the value shown in Table I-14.5 and the strength reduction factor shown in Tables 3225-2 and 3225-3A and 3225-3B

(2) Tensile strength values shall be the product of the value shown in Table 3225-1 and the strength reduction factor shown in Tables 3225-2 and 3225-3A and B.

where the strength reduction factor is selected as a function of the accumulated time-temperature ' tory to which the component has been exposed p. to the event under analysis. Where a component has been exposed to a varying temperature history the reduction factor employed shall be determined by assuming that the component has operated at the maximum temperature throughout its prior operational life (exclusive of Level D Service Condition.)

-3226 Pressure Testing Limitations. During any static pressure testing, the following limits shall not be exceeded in any structural part:

(a) The general primary-membrane stress intensity shall not exceed 90% of the tabulated yield strength at temperature;

(b) The primary-membrane-plus-bending stress intensity shall not exceed 135% of the tabulated yield stress at temperature.

(c) The external pressure shall not exceed 135% of the maximum pressure allowed by the design rules of -3250.

-3227 Special Stress Limits. The following deviations from the basic stress limits are provided to cover special operating conditions or configurations. Some of these deviations are more restrictive and some are less restrictive than the basic stress limits. In cases of conflict between these requirements a

TABLE 3225-1
TENSILE STRENGTH VALUES (S_u)

For Metal Temperature Not Exceeding, °F	304SS		316SS	Ni-Fe-Cr Alloy 800H	2 $^1/_4$Cr-1Mo
At min. UTS	70.0	75.0	75.0	65.0	60.0
700	59.3	63.5	71.8	61.9	58.2
750	58.9	63.1	78.4	61.9	58.2
800	58.5	62.7	70.9	61.9	58.2
850	57.7	61.9	69.7	61.9	58.2
900	57.0	61.0	68.5	61.8	58.2
950	55.4	59.4	66.5	61.2	58.2
1000	53.9	57.7	64.4	60.2	54.7
1050	51.6	55.3	61.9	59.0	48.8
1100	48.5	52.0	58.6	56.8	36.6
1150	45.4	48.6	55.3	54.0	35.3
1200	42.4	45.4	51.2	50.4	26.1
1250	39.3	42.1	47.0	47.1	. . .
1300	35.4	37.9	42.9	43.5	. . .
1350	30.8	33.0	38.8	39.0	. . .
1400	27.0	28.9	33.8	33.7	. . .
1450	23.1	24.7	29.7	. . .	. . .
1500	19.3	20.7	24.8	. . .	. . .

GENERAL NOTES:

(a) The tabulated values of tensile strength and yield strength are those which the Committee believes are suitable for use in design calculations required by this Section. At temperatures above room temperature, the values of tensile strength tend toward an average or expected value which may be as much as 10% above the tensile strength trend curve adjusted to the minimum specified room temperature tensile strength. At temperatures above room temperature, the yield strength values correspond to the yield strength trend curve adjusted to the minimum specified room temperature yield strength. Neither the tensile strength nor the yield strength values correspond exactly to either "average" or "minimum" as these terms are applied to a statistical treatment of a homogeneous set of data.

(b) Neither the ASME Material Specifications nor the rules of this Section require elevated temperature testing for tensile or yield strengths of production material for use in Code components. It is not intended that results of such tests, if performed, be compared with these tabulated tensile and yield strength values for ASME Code acceptance/rejection purposes for materials. If some elevated temperature test results on production material appear lower than the tabulated values by a large amount (more than the typical variability of material and suggesting the possibility of some error) further investigation by retest or other means should be considered.

TABLE 3225-2
TENSILE AND YIELD STRENGTH REDUCTION FACTOR DUE TO LONG TIME PRIOR ELEVATED TEMPERATURE SERVICE

Material	Service Temp. °F	YS Reduction Factor	TS Reduction Factor
304S/S	≥ 900	1.00	0.80
316S/S	≥ 900	1.00	0.80
800E	≥1350	0.90	0.90
2 ¼Cr-1Mo	≥ 800	[Note (1)]	[Note (1)]

GENERAL NOTE: No reduction factor required for service below the indicated temperature.

NOTE:
(1) See Table 3225-3.

TABLE 3225-3A
YIELD STRENGTH REDUCTION FACTORS FOR 2¼ Cr-1Mo

Temp. °F	1.E0	1.E1	3.E1	1.E2	3.E2	1.E3	3.E3	1.E4	3.E4	1.E5	3.E5
700	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
750	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
800	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
850	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92
900	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.93	0.86
950	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.91	0.85	0.80
1000	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.91	0.85	0.79	0.74
1050	1.00	1.00	1.00	1.00	1.00	0.96	0.90	0.84	0.78	0.72	0.67
1100	1.00	1.00	1.00	1.00	1.00	0.91	0.85	0.79	0.73	0.68	0.63
1150	1.00	1.00	1.00	1.00	0.94	0.86	...	...	...	...	...
1200	1.00	0.90	0.83	0.77	0.70	0.65	...	...	...	...	...

TABLE 3225-3B
TENSILE STRENGTH REDUCTION FACTORS FOR 2¼ Cr-1Mo

Temp. °F	1.E0	1.E1	3.E1	1.E2	3.E2	1.E3	3.E3	1.E4	3.E4	1.E5	3.E5
700	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
750	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
800	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	0.94
850	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	0.92	0.88
900	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.92	0.86	0.82
950	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.91	0.86	0.82	0.77
1000	1.00	1.00	1.00	1.00	1.00	0.97	0.92	0.86	0.82	0.76	0.72
1050	1.00	1.00	1.00	1.00	1.00	0.92	0.88	0.82	0.77	0.71	0.67
1100	1.00	1.00	1.00	1.00	0.94	0.88	0.83	0.77	0.72	0.67	0.62
1150	1.00	1.00	1.00	0.95	0.89	0.83	...	...	...	...	...
1200	1.00	1.00	1.00	0.90	0.84	0.78	...	...	...	...	...

the basic stress limits, the rules of -3227 take precedence for the particular situations to which they apply.

-3227.1 Bearing Loads

(a) The average bearing stress for resistance to crushing under the maximum load, experienced as a result of load categories other than Level D Service Loading, shall be considered.

The average bearing stress for Service Levels A, B and C shall be limited to the lesser of:

(1) the tabulated yield strength at the Service Temperature; or,

(2) the stress at 0.2% offset strain as obtained from the isochronous stress-strain curve for the temperature of service and for the time duration equal to the total service life the component is expected to spend at temperatures greater than those listed in Table I-1.0.

(b) For clad surfaces, the properties of the base metal may be used if, when calculating the bearing stress, the bearing area is taken as the lesser of the actual contact area or the area of the base metal supporting the contact surface.

(c) When bearing loads are applied near free edges, such as at a protruding edge, the possibility of a shear failure shall be considered. The average shear stress shall be limited to 0.6 S_{mt} in the case of load-controlled stresses. For clad surfaces, if the configuration or thickness is such that a shear failure could occur entirely within the clad material, the allowable shear stress for the cladding shall be determined from the properties of the equivalent wrought material. If the configuration is such that a shear failure could occur across a path that is partially base metal and partially clad material, the allowable shear stresses for each material shall be used when evaluating the combined resistance to this type of failure.

-3227.2 Pure Shear

(a) The average primary shear stress across a section loaded in pure shear (for example, keys, shear rings, screw threads), experienced as a result of any loading categories other than Level D Service Loadings, shall be limited to 0.6 S_{mt}.

(b) The maximum primary shear stress, experienced as a result of any loading categories other than Level D Service Loadings, exclusive of stress concentration at the periphery of a solid circular section in torsion, shall be limited to 0.8 S_{mt}.

-3227.3 Progressive Distortion of Non-integral Connections. Screwed-on caps, screwed-in plugs, shear-ring closures and breech-lock closures are examples of non-integral connections which are subject to failure by bell-mouthing or other types of progressive deformation. If any combination of applied loads produces yielding, such joints are subject to ratcheting because the mating members may become loose at the end of each complete operational cycle and start the next cycle in a new relationship with each other, with or without manual manipulation. Additional distortion may occur in each cycle so that interlocking parts, such as threads, can eventually lose engagement. Such nonintegral connections shall not be used where service temperatures are expected to exceed those associated with allowable stress-intensity values for the specific materials as shown in Tables I-1.0.

-3227.4 Triaxial Stresses. The algebraic sum of the three primary principal stresses ($\sigma_1 + \sigma_2 + \sigma_3$) shall not exceed four times the tabulated value of S_{mt}.

-3227.5 Nozzle Piping Transition. The P_m classification of stresses resulting from pressure, external loads, and moments is applicable for that length of nozzle which lies within the limits of reinforcem given by NB-3334, whether or not nozzle reinforcement is provided. Beyond the limits of reinforcement, a P_m classification shall be applied to the general primary-membrane stress intensity averaged across the section (not thickness) resulting from combined pressure and external mechanical loads, a P_L or $P_L + P_b$ classification shall be respectively applied to local primary-membrane or local primary-membrane-plus-bending stress intensities that result from design pressure and external mechanical loads; and a $P_L + P_b + Q$ classification shall be applied to primary-plus-secondary stress intensities resulting from all loads including external load or moment attributable to restrained free end displacement of the attached pipe.

-3227.7 Requirements for Specially Designed Welded Seals

(a) Welded seals, such as omega and canopy seals (NB-4360) shall be designed to meet the pressure-induced general primary-membrane stress intensity limits specified in this Case for their materials of fabrication. (Note that the general primary-membrane stress intensity varies around the toroidal cross-section.)

(b) All other membrane and bending stress in tensities developed in the welded seals may be co

sidered as secondary stress intensities or peak stress intensities, as appropriate.

-3227.8 Cladding. The rules of (a) through (d) below apply to the analysis of clad components constructed of material under this Subsection.

(a) Load-Controlled Stresses. No structural strength shall be attributed to the cladding in satisfying the load-controlled stress limits in -3200.

(b) Design Dimensions. The dimensions stipulated in (1) and (2) below shall be used in the design of the component.

(1) For components subjected to internal pressure, the inside diameter shall be taken at the nominal inner face of the cladding;

(2) For components subjected to external pressure, the outside diameter shall be taken at the outer face of the base metal.

(c) Deformation-Controlled Quantities. No structural strength shall be attributed to the cladding in satisfying requirements on buckling instability. However, the cladding shall be considered in all other calcula-

TABLE I-14.1(b)
PERMISSIBLE WELD MATERIALS

Base Material	Spec. No.	Class
Type 304 SS and 316 SS	SFA-5.4	E 308, E 308L, E 316, E 316L, E 16-8-2
	SFA-5.9	ER 308, ER 308L, ER 316, ER 316L, ER 16-8-2
	SFA-5.22	E 308, E 308T, E 308LT, E 316T, E 316LT-1 EXXXT-G (16-8-2 chemistry)
Ni-Fe-Cr (Alloy 800H)	SFA-5.11	ENiCrFe-2
	SFA-5.14	ERNiCr-3
2¼ Cr-1Mo	SFA-5.5	E 90XX-B3 (>0.05% Carbon)
	SFA-5.23	EB 3, ECB 3
	SFA-5.28	E 90C-B3 (>0.05% Carbon), ER 90S-B3
	SFA-5.29	E 90T-B3 (>0.05% Carbon)

TABLE I-14.2
S_o – MAXIMUM ALLOWABLE STRESS INTENSITY (ksi)
(FOR DESIGN CONDITION CALCULATIONS)

E

Temp., °F	304 SS	316 SS	Ni-Fe-Cr Alloy 800H (Solution Annealed)	2¼ Cr-1 Mo
700	...	...	...	15.0
750	...	...	...	15.0
800	15.2	15.9	15.3	15.0
850	14.9	15.7	15.1	14.4
900	14.7	15.5	14.8	13.1
950	14.4	15.4	14.6	11.0
1000	13.8	15.3	14.4	7.8
1050	12.2	14.5	13.7	5.8
1100	9.8	12.4	12.3	4.2
1150	7.7	9.8	9.8	3.0
1200	6.1	7.4	7.8	1.6
1250	4.7	5.5	6.2	...
1300	3.7	4.1	5.0	...
1350	2.9	3.1	3.9	...
1400	2.3	2.3	3.1	...
1450	1.8	1.7	...	...
1500	1.4	1.3	...	...

TABLE I-14.3B (1)

S_{mt} — ALLOWABLE STRESS INTENSITY VALUES, 1000 PSI TYPE 316 SS - 30-YS, 75-UTS (30-YS, 70-UTS)

Temp.°F	1 hr	10 hr	30 hr	10^2 hr	3 × 10^2 hr	10^3 hr	3 × 10^3 hr	10^4 hr	3 × 10^4 hr	10^5 hr	3 × 10^5 hr
800	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9
850	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7
900	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
950	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5
1000	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4	14.0
1050	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	14.9	12.5	10.7
1100	14.8	14.8	14.8	14.8	14.8	14.8	14.8	13.9	11.5	9.5	7.8
1150	14.7 [(14.6)]	14.7 [(14.6)]	14.7 [(14.6)]	14.7 [(14.6)]	14.7 [(14.6)]	14.2	13.0	10.9	8.9	7.2	5.9
1200	[13.6] 14.6 [(12.7)]	[13.6] 14.6 [(12.7)]	[13.6] 14.6 [(12.7)]	[13.6] 14.2 [(12.7)]	12.4	10.6	9.4	8.3	6.9	5.5	4.5
1250	[12.2] 14.2 [(11.7)]	[12.2] 14.2 [(11.7)]	[12.2] 14.2 [(11.7)]	11.5	9.8	8.3	7.3	6.3	5.4	4.2	3.3
1300	[11.4] 13.8 (13.4) [(10.7)]	[11.4] 12.8 [(10.7)]	10.9 [(10.7)]	9.1	7.5	6.4	5.6	4.7	3.9	3.1	2.5
1350	[10.1] 12.8 (11.9) [(9.5)]	[10.1] 10.3 [(9.5)]	8.6	7.0	5.9	5.0	4.2	3.4	2.8	2.1	1.8
1400	[9.0] 11.3 (10.5) [(8.4)]	8.2	6.7	5.4	4.5	3.8	3.1	2.5	2.0	1.5	1.2
1450	[7.8] 9.7 (9.0) [(7.3)]	6.4	5.1	4.1	3.4	2.9	2.2	1.7	1.4	1.0	0.9
1500	[6.2] 7.8 (7.7) [(5.6)]	4.9	3.9	3.2	2.6	2.1	1.6	1.2	0.9	0.65	0.5

NOTE:

(1) Values in square parentheses [ ] reflect the effects of service at the indicated temperature for 300,000 hr.

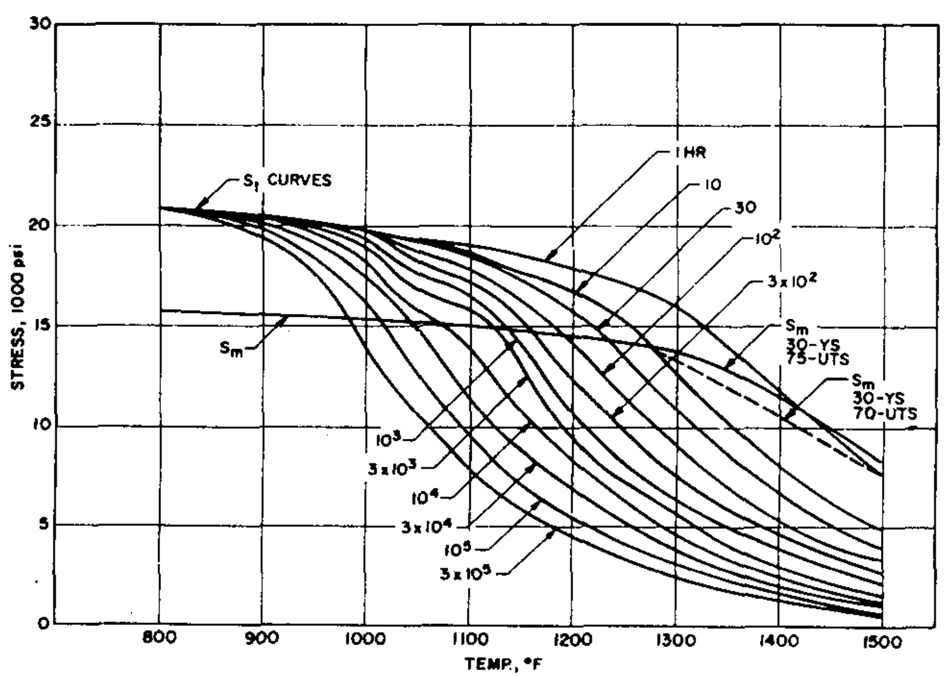


TABLE I-14.4B
S_t — ALLOWABLE STRESS INTENSITY VALUES, 1000 psi TYPE 316 SS

Temp. °F	1 hr	10 hr	30 hr	10^2 hr	3×10^2 hr	10^3 hr	3×10^3 hr	10^4 hr	3×10^4 hr	10^5 hr	3×10^5 hr
800	20.8	20.8	20.8	20.8	20.8	20.8	20.8	20.8	20.8	20.8	20.8
850	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.6	20.3
900	20.4	20.4	20.4	20.4	20.4	20.4	20.4	20.4	20.2	19.9	19.3
950	20.1	20.1	20.1	20.1	20.1	20.0	20.0	19.7	19.2	18.4	17.6
1000	19.8	19.8	19.8	19.8	19.8	19.5	19.0	18.2	17.5	16.2	14.0
1050	19.4	19.4	19.2	18.7	18.3	17.6	16.8	15.9	14.9	12.5	10.7
1100	19.1	19.0	18.5	17.8	17.3	16.6	15.9	13.9	11.5	9.5	7.8
1150	18.5	17.7	17.3	16.4	15.4	14.2	13.0	10.9	8.9	7.2	5.9
1200	17.8	16.8	15.8	14.2	12.4	10.6	9.4	8.3	6.9	5.5	4.5
1250	17.1	15.2	13.5	11.5	9.8	8.3	7.3	6.3	5.4	4.2	3.3
1300	16.1	12.8	10.9	9.1	7.5	6.4	5.6	4.7	3.9	3.1	2.5
1350	14.2	10.3	8.6	7.0	5.9	5.0	4.2	3.4	2.8	2.1	1.8
1400	12.0	8.2	6.7	5.4	4.5	3.8	3.1	2.5	2.0	1.5	1.2
1450	9.7	6.4	5.1	4.1	3.4	2.9	2.2	1.7	1.4	1.0	0.8
1500	7.8	4.9	3.9	3.2	2.6	2.1	1.6	1.2	0.9	0.65	0.5

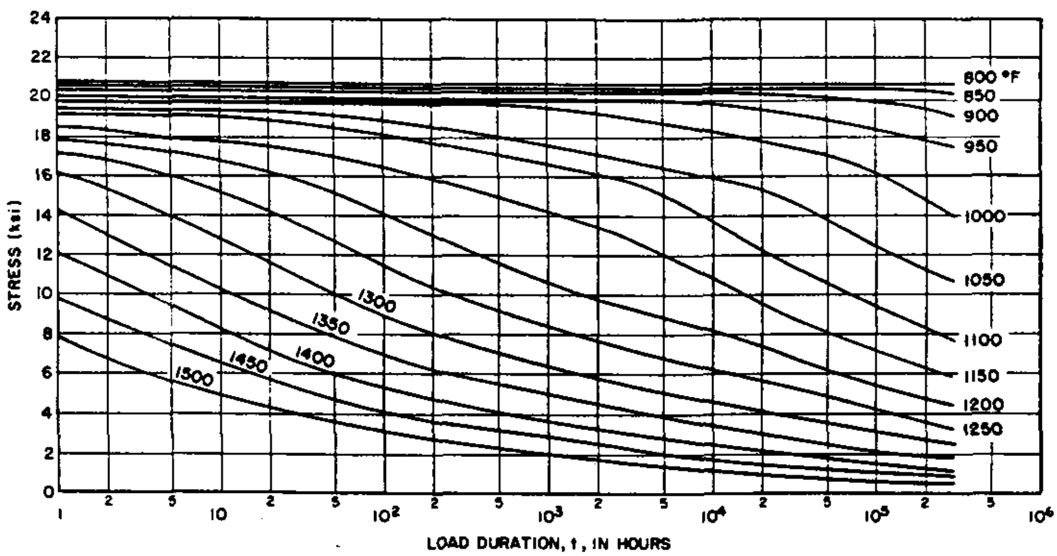


FIG. I-14.4B S_t — TYPE 316 SS

TABLE I-14.5
YIELD STRENGTH VALUES, [1]S_y, VS. TEMPERATURE

Temp., F	304 SS	316 SS	Ni-Fe-Cr Alloy 800H (Stresses in ksi Units)	2¼ Cr-1 Mo	Ni-Cr-Fe-Mo-Cb Alloy 718
RT	30.0	30.0	25.0	30.0	150.0
100	30.0	30.0	24.3	30.0	148.4
200	25.0	25.8	22.5	27.8	143.9
300	22.5	23.3	21.1	27.1	140.7
400	20.7	21.4	20.0	26.9	138.3
500	19.4	19.9	19.0	26.9	136.7
600	18.2	18.8	18.3	26.9	135.4
700	17.7	18.1	17.5	26.9	134.3
750	17.3	17.8	17.2	26.9	133.7
800	16.8	17.6	17.0	26.7	133.1
850	16.5	17.4	16.6	26.2	132.4
900	16.2	17.3	16.5	25.7	131.5
950	15.9	17.1	16.2	24.8	130.5
1000	15.6	17.0	16.0	23.7	129.4
1050	15.2	16.7	15.8	22.4	128.0
1100	14.7	16.5	15.6	20.6	
1150	14.4	16.4	15.5	18.5	
1200	14.1	16.2	15.3	16.2	
1250	13.7	15.8	15.1		
1300	13.2	15.3	14.7		
1350	12.5	14.9	14.5		
1400	11.6	14.4	14.0		
1450	10.6	13.8	13.5		
1500	9.5	13.1	13.0		
1550			12.0		
1600			11.2		

[1]The tabulated values of yield strength are those which the Committee believes are suitable for use in design calculations required by this Case. At temperatures above room temperature the yield strength values correspond to the yield strength trend curve adjusted to the minimum specified room temperature yield strength. The yield strength values do not correspond exactly to either "average" or "minimum" as these terms are applied to a statistical treatment of a homogeneous set of data.

Neither the ASME Materials Specifications nor the rules of this Case require elevated temperature testing for yield strengths of production material for use in Code components. It is not intended that results of such tests, if performed, be compared with these tabulated yield strength values for ASME Code acceptance/rejection purposes for materials. If some elevated temperature test results on production material appear lower than the tabulated values by a large amount (more than the typical variability of material and suggesting the possibility of some error) further investigation by retests or other means should be considered.

TABLE I-14.6B
EXPECTED MINIMUM STRESS-TO-RUPTURE VALUES, 1000 psi TYPE 316 SS

Temp., °F	1 hr	10 hr	30 hr	10^2 hr	3×10^2 hr	10^3 hr	3×10^3 hr	10^4 hr	3×10^4 hr	10^5 hr	3×10^5 hr
800	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.5
850	63.3	63.3	63.3	63.3	63.3	63.3	63.3	63.3	60	56	52
900	62.2	62.2	62.2	62.2	62.1	62	58	54.1	48	42.6	38
950	60	60	60	60	56	51.6	46.5	42.6	37.5	32.4	28.3
1000	58.5	58.5	55	51.7	47	42.1	37.5	33.6	28.8	24.6	21
1050	56	52.9	47.5	43.4	38.2	34.4	30.2	26.4	22.3	18.8	16
1100	53.5	45.1	40	36.4	32.2	28.1	24.2	20.8	17.3	14.3	11.7
1150	46.5	38.4	34	30.5	26.6	23.0	19.5	16.4	13.4	10.9	8.8
1200	40	32.7	29	25.6	22	18.8	15.6	12.9	10.3	8.3	6.7
1250	35	27.8	24.3	21.4	18.1	15.4	12.7	10.2	8.1	6.3	4.9
1300	30	23.7	20.8	18.0	15	12.5	10.0	8.0	6.2	4.8	3.7
1350	26	20.0	17.5	15.0	12.7	10.4	8.2	6.4	4.9	3.6	2.7
1400	22.5	17.1	14.8	12.4	10.2	8.4	6.6	5.0	3.8	2.8	2.1
1450	19.5	14.6	12.6	10.5	8.6	6.8	5.2	3.9	2.9	2.1	1.5
1500	17	12.5	10.6	8.8	7.2	5.6	4.2	3.1	2.3	1.6	1.2

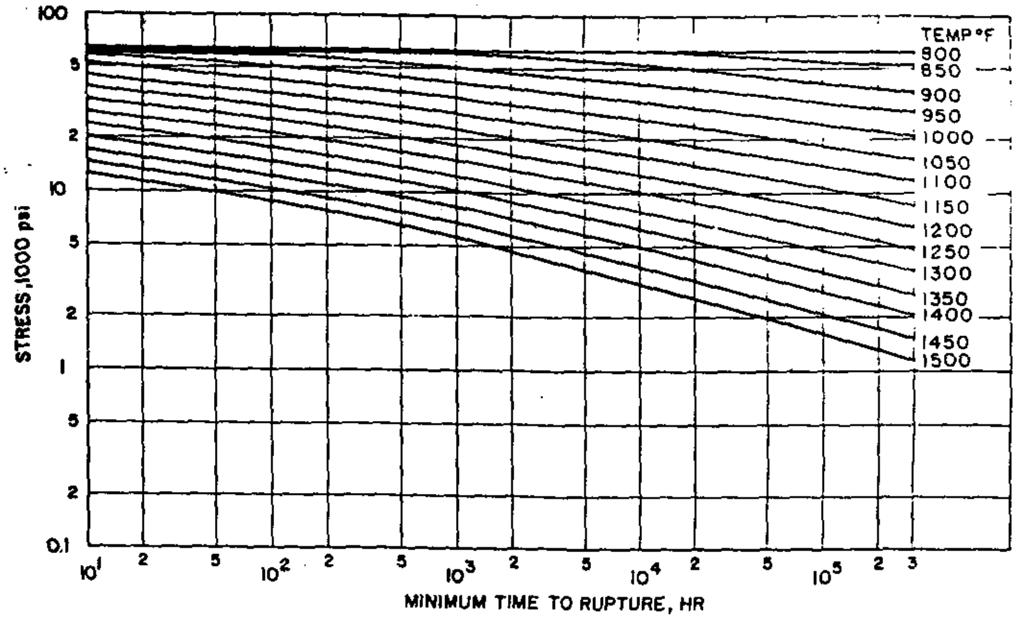


FIG. I-14.6B STRESS-TO-RUPTURE (MINIMUM)

TABLE I-14.7
MODULUS OF ELASTICITY VS. TEMPERATURE

	(Static) Modulus of Elasticity, psi × 10^{-6}			
Temp., °F	304 SS and 316 SS	Ni-Fe-Cr Alloy 800H	2¼ Cr - 1 Mo	Ni-Cr-Fe-Mo-Cb Alloy 718
70	28.3	28.5	30.6	29.0
100	27.9	28.4	30.4	28.9
200	27.7	27.8	29.8	28.3
300	27.1	27.4	29.4	27.8
400	26.6	27.1	28.8	27.6
500	26.1	26.6	28.3	27.1
600	25.4	26.4	27.7	26.8
700	24.8	25.9	27.1	26.4
750	24.3	25.7	26.6	26.1
800	24.1	25.4	26.3	25.8
850	23.8	25.1	25.9	25.5
900	23.5	24.8	25.6	25.2
950	23.2	24.5	25.1	24.9
1000	22.8	24.2	24.6	24.7
1050	22.5	24.1	24.2	24.5
1100	22.1	23.8	23.7	
1150	21.6	23.5	23.1	
1200	21.2	23.2	22.5	
1250	20.8	22.9		
1300	20.2	22.7		
1350	19.8	22.2		
1400	19.2	21.9		
1450	18.7	21.7		
1500	18.1	21.2		

TABLE I-14.8
INSTANTANEOUS COEFFICIENT OF THERMAL EXPANSION VS TEMPERATURE

	Instantaneous Coefficient of Thermal Expansion, in./in. – °F × 10⁶				
Temp., °F	304 SS	316 SS	Ni-Fe-Cr Alloy 800H	2¼ Cr - 1 Mo	Ni-Cr-Fe-Mo-Cb Alloy 718
70	8.46	8.42	7.75	6.45	7.05
100	8.63	8.59	8.05	6.60	7.12
200	9.08	9.09	8.53	6.90	7.39
300	9.46	9.56	8.80	7.35	7.62
400	9.80	9.95	8.98	7.65	7.84
500	10.10	10.25	9.12	7.90	8.04
600	10.38	10.51	9.20	8.10	8.20
700	10.60	10.76	9.32	8.25	8.38
750	10.70	10.87	9.42	8.32	8.46
800	10.79	10.98	9.52	8.40	8.55
850	10.87	11.09	9.65	8.45	8.68
900	10.97	11.20	9.80	8.50	8.82
950	11.06	11.31	9.97	8.55	8.95
1000	11.14	11.40	10.16	8.60	9.11
1050	11.23	11.49	10.37	8.63	9.30
1100	11.31	11.58	10.60	8.65	9.49
1150	11.38	11.65	10.80	8.68	
1200	11.47	11.72	11.00	8.70	
1250	11.55	11.78	11.20		
1300	11.63	11.82	11.37		
1350	11.71	11.86	11.54		
1400	11.78	11.90	11.68		
1450	11.86	11.94	11.80		
1500	11.94	11.97	11.92		
1550		12.00	12.00		
1600		12.03	12.10		

APPENDIX T

RULES FOR STRAIN, DEFORMATION, AND FATIGUE LIMITS AT ELEVATED TEMPERATURES

T-1100 INTRODUCTION

T-1110 Objective

The objective of this Appendix is to provide rules which may be used by Owners and N Certificate Holders with respect to evaluation by analysis of strain, deformation, and fatigue limits for components whose load-controlled stresses are evaluated by the rules of this Case.

T-1120 General Requirements

T-1121 Type of Analysis. Where creep effects are presumed significant, inelastic analysis is generally required to provide a quantitative assessment of deformations and strains. However, elastic and simplified inelastic methods of analysis may sometimes be justified and used to establish conservative bounds for deformations, strains, strain ranges, and maximum stress in order to reduce the number of locations in a structure requiring detailed inelastic analysis.

T-1122 Analysis Required. The rules for design against gross distortion and fatigue are illustrated in Fig. 3220-1. The Design Loadings and Level D Service Loadings are exempted from strain and deformation limits as summarized below.

Loadings	Requirement
Design	— No deformation analysis required.
Service Levels A, B, and C	Apply the strain and deformation limits of Appendix T. Regions not expecting any service time under elevated temperatures may use the secondary stress and fatigue limits of NB-3222.2 and NB-3222.4 in place of the rules in T-1300, T-1400 and T-1700.
Service Level D	— Strain and deformation limits not applicable except as necessary to satisfy Level D Service Loadings functional requirements.
Test	— Consider as additional Level B Service Loadings.

T-1200 DEFORMATION LIMITS FOR FUNCTIONAL REQUIREMENTS

T-1210 Statement in Design Specification

Deformation limits to ensure proper component functioning shall be specified in the Design Specification (NCA-3250) for the component or shall be established by the N Certificate Holder for the proper performance of the component. Any such limits may restrict the design more severely than those specified for load-controlled stresses in -3220.

T-1220 Elastic Analysis Method

The limitations on loads from the rules and the other limits contained in -3200 are intended to restrict the accumulated inelastic strain (averaged across a wall thickness) to 1% or less. However, when elastic analysis is used, the occurrence of inelastic strains of this magnitude may not be apparent. If functional deformation requirements are specified, the designer shall ensure that they are not violated by assuming that strains of 1% occur within the structure in that distribution which leads to the worst possible deformation state consistent with the directions of loading. If this deformation state does not lead to deformations greater than the specified limits, then all functional requirements shall be considered as demonstrated for the design.

T-1230 Use of Inelastic Analysis

Inelastic analysis of deformations shall be used to demonstrate that deformations do not exceed specified limits, unless the elastic method of T-1220 has demonstrated compliance.

T-1300 DEFORMATION AND STRAIN LIMITS FOR STRUCTURAL INTEGRITY

T-1310 Limits for Inelastic Strains

In regions expecting elevated temperatures the maximum accumulated inelastic strain shall not exceed the following values.

(a) Strains averaged through the thickness, 1%.

(b) Strains at the surface, due to an equivalent linear distribution of strain through the thickness, 2%.

(c) Local strains at any point, 5%.

The above limits apply to computed strains accumulated over the expected operating lifetime of the element under consideration, and computed for some steady-state period at the end of this time during which significant transients are not occurring. These limits apply to the maximum positive value of the three principal strains. A positive strain is defined as one for which the length of the element in the direction of the strain is increased. The principal strains are computed for the strain components (ϵ_x, ϵ_y, ϵ_z, ϵ_{xy}, ϵ_{xz}, ϵ_{yz}). When the strain is computed at several locations through the thickness, the strains are first averaged and linearized on a component level and then combined to determine the principal strains for comparison to the limits on average and surface strains defined above. The limits for local strains are based on the computed strains at the point of interest.

T-1320 Satisfaction of Strain Limits Using Elastic Analysis

T-1321 General Requirements. The strain limits of T-1310 are considered to have been satisfied if the limits of any one of T-1322, T-1323, or T-1324 are satisfied. The guidelines of (a) through (d) below should be used in establishing the appropriate cycle to be evaluated in T-1322 and T-1323.

(a) An individual cycle, as defined in the Design Specification cannot be split into subcycles to satisfy these requirements.

(b) At least one cycle must be defined that includes the maximum secondary stress intensity range, Q_R, and the maximum value of $(P_L + P_b/K_t)$ which occur during *all* Level A, B, and C Service Loadings. The value of K_t may be determined using Eq. (6) of -3223.

(c) Any number of cycles can be grouped together and evaluated according to the conditions of T-1322 or T-1323, whichever is applicable.

E *(d)* The following definitions apply to T-1322 and T-1323:

$$X \equiv \left(P_L + \frac{P_b}{K_t}\right)_{max} \div S_y$$

where S_y is the average of the S_y values at the maximum and minimum wall-averaged temperatures during the cycle being evaluated and $(P_L + P_b/K_t)_{max}$ is the maximum value of the primary stress intensity, adjusted for bending via K_t, during the cycle being evaluated.

$$Y \equiv \frac{(Q_R)_{max}}{S_y}$$

where $(Q_R)_{max}$ is the maximum range of the secondary stress intensity during the cycle being considered and S_y is the average of the S_y values at the maximum and minimum wall-averaged temperatures during the cycle.

TABLE T-1323
TEMPERATURES AT WHICH $S_m = S_t 10^5$

Material	Temperature, °F
Type 304 SS	948
Type 316 SS	1011
Alloy 800H	1064
$2\frac{1}{4}$Cr-1Mo	801

T-1322 Test No. A-1. For Test Number A-1,

$$X + Y \leq S_a/S_y \qquad (1)$$

where S_a is the lesser of:

(a) 1.25 S_t using the highest wall-averaged temperature during the cycle and a time value of 10^4 hr; and

(b) The average of the two S_y values associated with the maximum and minimum wall-averaged temperatures during the cycle.

T-1323 Test No. A-2. For Test Number A-2,

$$X + Y \leq 1 \qquad (2)$$

for those cycles during which the average wall temperature at one of the stress extremes defining the maximum secondary stress range $(Q_R)_{max}$ is below the applicable temperature of Table T-1323.

T-1324 Test No. A-3. For Test Number A-3, the limits of NB-3222.2, NB-3222.3, and NB-3222.5 shall be met and, in addition, the requirements of (a) through (e) below shall be satisfied. E

(a) $\sum_i \frac{t_i}{t_{id}} \leq 0.1$

where

t_i = total duration of time during the service lifetime that the metal is at temperature, T_i. Note that the service lifetime shall never be greater than the sum of all t_i.

t_{id} = maximum allowable time as determined by entering Fig. I-14.6 at temperature T_i and a stress value of 1.5 times the S_y associated with T_i, denoted as 1.5 $S_y|_{Ti}$. If 1.5 $S_y|_{Ti}$ is above the stress values provided in Fig. I-14.6, this test cannot be satisfied. When 1.5 $S_y|_{Ti}$ is below the lowest stress value provided in Fig. I-14.6, the constant temperature line may be extrapolated to larger t_{id} values using the steepest slope on Fig. I-14.6 for that material.

(b) $\sum_i \epsilon_i \leq 0.2\%$

where ϵ_i is the creep strain that would be expected from a stress level of 1.25 $S_y|_{T_i}$ applied for the total duration of time during the service lifetime that the metal is at T_i. When the design lifetime is separated into several time periods, then the service lifetime shall not be greater than the sum of all the time periods. That is:

$$\sum_i t_i|T_i \geq \text{service lifetime}$$

(c) For the $3S_m$ limit in NB-3222.2 and NB-3222.3, use the lesser of $3S_m$ and $3\overline{S}_m$, where

$3\overline{S}_m$ = $(1.5\ S_m + S_{rH})$ when only one extreme of the stress difference [that produces the maximum range of the primary plus – secondary stress intensity, $P + Q$] occurs at a temperature above those covered by Subsection NB rules;

$3\overline{S}_m$ = $(S_{rH} + S_{rL})$ when both extremes of the stress differences (that define the maximum range of $P + Q$) occur at temperatures above those covered by Subsection NB rules;

S_{rH}, S_{rL} = relaxation strengths associated with the temperatures at the *hot* and *cold* extremes of the stress cycle. The *hot* temperature condition is defined as the maximum operating temperature of the stress cycle. The *hot* time is equal to the portion of service life when wall-averaged temperatures exceed 800°F (700°F for 2¼Cr-1Mo). The *cold* temperature is defined as the colder of the two temperatures corresponding to the two stress extremes in the stress cycle. The *cold* time is again equal to the portion of service life when wall-averaged temperatures exceed 800°F (700°F for 2¼Cr-1Mo).

In this criterion, total service life may *not* be further subdivided into temperature-time blocks. The two relaxation strengths, S_{rH} and S_{rL}, may be determined by performing a pure uniaxial relaxation analysis starting with an initial stress of 1.5 S_m and holding the initial strain throughout the time interval equal to the time of service above 800°F (700°F for 2¼Cr-1Mo).

(d) The reference to the endurance limit NB-3222.5(b) is not applicable to the materials in this Case.

(e) The material is one of the following alloys: 304SS; 316SS; Ni-Fe-Cr, Alloy 800H.

T-1325 Special Requirements for Piping Components

(a) Piping evaluations using the provisions of -3651(b) to satisfy the limits of T-1322, T-1323, or T-1330 shall include the stress term

$$\frac{E\ \alpha\ |\Delta T_1|}{2(1 - \nu)}$$

when computing the secondary stress intensity range, Q_R. The definitions of E, α, ΔT, and ν are as given in NB-3650.

(b) For purposes of applying the limits of T-1324 to piping components, satisfaction of the NB-3650 requirements may be used in lieu of meeting NB-3222.2, NB-3222.3, and NB-3222.5, provided that S_m is replaced by $\overline{S}_m$ and the ratchet check of NB-3653.7 is satisfied whenever

$$S_n > 3\overline{S}_m - \frac{E\ \alpha\ |\Delta T_1|}{2(1 - \nu)}$$

S_n, E, α, ΔT, and ν are defined in NB-3650, and $\overline{S}_m$ is the lesser of S_m or $(3\overline{S}_m) \div 3$, with $3\overline{S}_m$ as defined in T-1324(c).

T-1330 Satisfaction of Strain Limits Using Simplified Inelastic Analysis

T-1331 General Requirements. The strain limits of T-1310 are considered to have been satisfied if the limits of T-1332 are satisfied in addition to (a) through (g) below.

(a) T-1332 contains two tests, B-1 and B-2. Test B-1 can be used only for

(1) axisymmetric structures subjected to axisymmetric loadings and away from local structural discontinuities, or

(2) general structures in which the peak through-the-wall thermal stress is negligible (i.e., the thermal stress distribution is linear through the wall).

Test B-2, which is more conservative, is applicable to any structure and loading.

(b) The individual cycle as defined in the design specification cannot be split into subcycles. Unless otherwise specified (see -3114) earthquakes and other transient conditions should be uniformly distributed over the lifetime of the plant for this strain evaluation.

(c) As an alternate to the use of T-1332, the inelastic strains due to any number of selected operational cycles may be evaluated separately by T-1333 or using detailed inelastic analysis. The resulting sum of the inelastic strains must satisfy the limits of T-1310. T-1333 is applicable only to axisymmetric structures subjected to axisymmetric loadings and away from local structural discontinuities.

(d) Secondary stresses with elastic followup (i.e., pressure-induced membrane and bending stresses and thermal-induced membrane stresses) are classified as primary stresses for purposes of this evaluation. Alternatively, the strains due to such stresses may be calculated separately and added to the strains

the increase of σ_c stress for cycles evaluated using T-1333 and detailed inelastic analyses.

$\Sigma\eta$ = the plastic ratchet strain increments for cycles in R_1 and R_2 regimes. obtained as explained in T-1333(b)

E $\Sigma\delta$ = the enhanced creep strain increments due to relaxation of the $[\sigma_c]$ stresses, obtained as explained in T-1333(c).

E (*b*) Plastic ratcheting occurs in cycles when $[\sigma_{cL}] \geq S_{yH}$. The increment of plastic ratchet strain within this cycle is bounded by:

$$\eta_{(n)} = \frac{1}{E_H}\left[([\sigma_{cL}] - S_{yH}) + ([\sigma_{cH}] - S_{yL})\right] \qquad (6)$$

for $Z_L \leqslant 1.0$; or

$$\eta_{(n)} = \frac{1}{E_L}([\sigma_{cL}] - S_{yL}) + \frac{1}{E_H}([\sigma_{cH}] - S_{yH}) \qquad (7)$$

for $Z_L > 1.0$. $[\sigma_{cL}]$ and $[\sigma_{cH}]$ are the effective stresses for the cold and hot extremes of the cycles as given by $[\sigma_{cL}] = Z_L S_{yL}$ and $[\sigma_{cH}] = Z_H S_{yH}$ respectively.

The effective creep stress parameter Z is obtained from Eq. (3) for regimes S_2, P, and R_2. Equation (4) is for regimes S_1 and R_1. Curves resulting from Eqs. (3) and (4) are shown in Fig. T-1330-1. Note that braces indicate $[\sigma_c]$ stress calculated for T-1333 evaluations. E_L and E_H are the elastic moduli at the cold and hot ends of the cycle.

Note that all values in Eqs. (6) and (7) are related to the load cycle (n).

E (*c*) For cycles where $[\sigma_{cL}] \geq S_{yH}$, the enhanced creep strain increment due to stress relaxation is given by:

$$\delta_{(n)} = \frac{1}{E_H}\frac{S_{yH}^2 - \sigma_c^2}{\sigma_c} \qquad (8)$$

For cycles where $[\sigma_{cL}] < S_{yH}$, the enhanced creep strain increment due to $[\sigma_{cL}]$ stress relaxation is given by:

$$\delta_{(n)} = \frac{1}{E_H}\frac{[\sigma_{cL}]^2 - \sigma_c^2}{\sigma_c} \qquad (9)$$

σ_c is the effective creep stress from T-1332 for the next cycle when sequence of loading is specified. Otherwise the lowest σ_c stress used in the T-1332 evaluation should be used in Eqs. (8) and (9).

Note that all values in Eqs. (8) and (9) are related to the load cycle (n). Only positive $\delta_{(n)}$ increments should be considered.

T-1400 CREEP-FATIGUE EVALUATION

T-1410 General Requirements

T-1411 Damage Equation. The combination of Levels A, B, and C Service Loadings shall be evaluated for accumulated creep and fatigue damage, including hold time and strain rate effects. For a design to be acceptable, the creep and fatigue damage shall satisfy the following relation:

$$\sum_{j=1}^{P}\left(\frac{n}{N_d}\right)_j + \sum_{k=1}^{q}\left(\frac{\Delta t}{T_d}\right)_k \leqslant D \qquad (10)$$

where

D = total creep-fatigue damage

P = number of different cycle types required to define the cyclic strain history for the specified service life. Each cycle type is uniquely defined by its strain range (ϵ_t) and the maximum metal temperature occurring during the cycle.

$(n)_j$ = number of applied repetitions of cycle type, j

$(N_d)_j$ = number of design allowable cycles for cycle type, j, determined from one of design fatigue curves (Figs. T-1420 corresponding to the maximum metal temperature occurring during the cycle. The design fatigue curves were determined from completely reversed loading conditions at strain rates greater than, or equal to, those noted on the curves.

q = number of time intervals (each with a unique stress-temperature combination) needed to represent the specified elevated temperature service life at the point of interest for the creep damage calculation

$(T_d)_k$ = allowable time duration determined from Fig. I-14.6 (stress-to-rupture curves) for a given stress and the maximum temperature at the point of interest and occurring during the time interval, k. For elastic analysis the appropriate stress measure is defined in T-1433. For inelastic analysis, the following equivalent stress quantity should be used:

$$\sigma_e = \bar{\sigma}\exp\left[C\left(\frac{J_1}{S_s} - 1\right)\right]$$

where

$$J_1 = \sigma_1 + \sigma_2 + \sigma_3$$

$$S_s = [\sigma_1^2 + \sigma_2^2 + \sigma_3^2]^{1/2}$$

$$\sigma_{eff} = \frac{1}{\sqrt{2}}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/2}$$

and σ_i are the principal stresses. The constant C is equal to 0.24 for types 304 and 316 stainless steels; for Alloy 800H and 2-1/4 Cr–1 Mo steel, the value is 0.0. For both types of analysis, the allowable time duration is determined by entering Fig. I-14.6 at that stress value determined by dividing the maximum stress (at the point of interest during the time interval, k) by the factor, K' (Table T-1411-1).

$(\Delta t)_k$ = duration of the time interval, k.

Note that the sum of the "q" time intervals must equal or exceed the total specified elevated temperature service life.

T-1412 Exemption from Fatigue Analysis. The rules in NB-3222.4(d) which permit exemption from fatigue analysis do not apply to temperatures above the limits of Subsection NB except where the service loadings have been qualified as not introducing significant time-dependent effects under the procedure of -3211(c).

T-1413 Equivalent Strain Range. An equivalent *strain range* is used to evaluate the fatigue damage sum for both elastic and inelastic analysis. When the Design Specification contains a histogram delineating a specific loading sequence, the strain range shall be calculated for the cycles described by the histogram. If the sequence of loading is not defined by the Design Specification, then the method of combining cycles described in NB-3222.4(e)(5) shall be applied. The equivalent strain range is computed as follows.

Step 1. Calculate all strain components for each point, i, in time (ϵ_{xi}, ϵ_{yi}, ϵ_{zi}, γ_{xyi}, γ_{yzi}, γ_{zxi}) for the complete cycle. When conducting inelastic analysis, the stress and strain concentration effects of local geometric discontinuities are included in this step. When conducting elastic analysis, peak strains arising from geometric discontinuities are not included, since these effects are added in the procedures of T-1432.

Step 2. Select a point when conditions are at an extreme for the cycle, either maximum or minimum. Refer to this time point by a subscript o.

TABLE T-1411-1

Material	K'
Austenitic Stainless Steel	0.67
Ni-Fe-Cr (Alloy 800H)	0.67
2¹/₄Cr-1Mo	0.67

Step 3. Calculate the history of the change in *strain components* by subtracting the values at the time, o, from the corresponding components at each point in time, i, during the cycle.

$$\Delta\epsilon_{xi} = \epsilon_{xi} - \epsilon_{xo}$$
$$\Delta\epsilon_{yi} = \epsilon_{yi} - \epsilon_{yo}$$
etc;

Step 4. Calculate the equivalent strain range for each point in time as:

$$\Delta\epsilon_{equiv,i} = \frac{\sqrt{2}}{2(1+\nu^*)}\left[(\Delta\epsilon_{xi} - \Delta\epsilon_{yi})^2 + (\Delta\epsilon_{yi} - \Delta\epsilon_{zi})^2 + (\Delta\epsilon_{zi} - \Delta\epsilon_{xi})^2 + \frac{3}{2}(\Delta\gamma_{xyi}^2 + \Delta\gamma_{yzi}^2 + \Delta\gamma_{zxi}^2)\right]^{1/2} \quad (11)$$

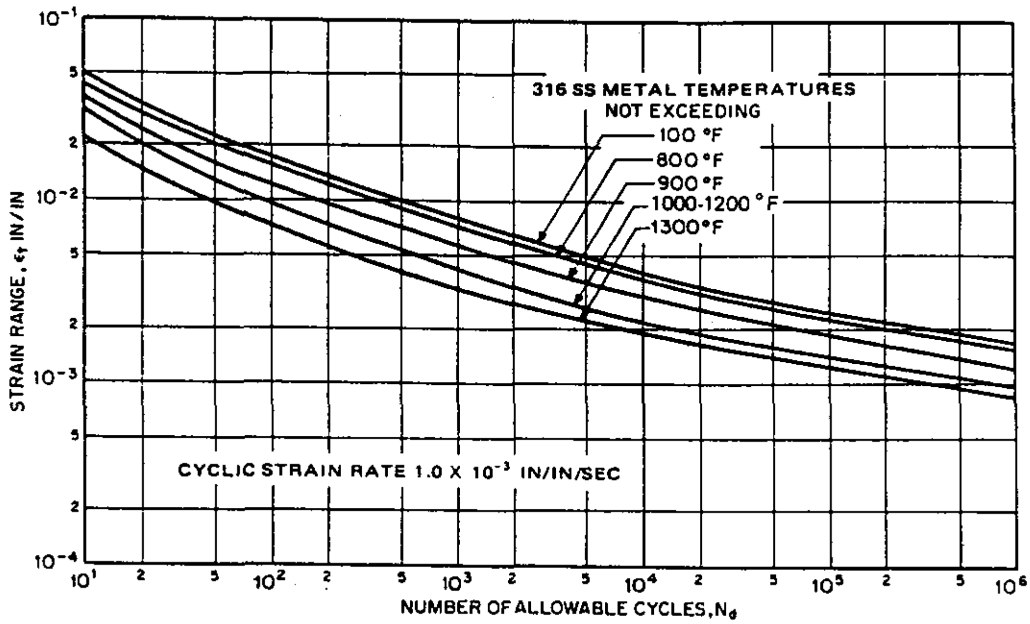
where

ν^* = 0.5 when using the rules of T-1420.
ν^* = 0.3 when using the rules of T-1430.

Step 5. *Define* $\Delta\epsilon_{max}$ as the maximum value of the above calculated equivalent strain ranges, $\Delta\epsilon_{equiv,i}$.

The above five step procedure may be used regardless of whether principal strains change directions or not. When principal strains do not rotate, an alternative to the above sequence is given in T-1414.

T-1414 Alternative Calculation Method – Equivalent Strain Range. An alternative calculational method for equivalent strain range determination –



N_d Number of Cycles*	ϵ_t, Strain Range (in./in.) at Temperature				
	100 F	800 F	900 F	1000–1200 F	1300 F
10^1	.0507	.0438	.0378	.0318	.0214
2×10^1	.0357	.0318	.0251	.0208	.0149
4×10^1	.026	.0233	.0181	.0148	.0105
10^2	.0177	.0159	.0123	.00974	.00711
2×10^2	.0139	.0125	.00961	.00744	.00551
4×10^2	.0110	.00956	.00761	.00574	.00431
10^3	.00818	.00716	.00571	.00424	.00328
2×10^3	.00643	.00581	.00466	.00339	.00268
4×10^3	.00518	.00476	.00381	.00279	.00226
10^4	.00403	.00376	.00301	.00221	.00186
2×10^4	.00343	.00316	.00256	.00186	.00162
4×10^4	.00293	.00273	.00221	.00161	.00144
10^5	.00245	.00226	.00182	.00136	.00121
2×10^5	.00213	.00196	.00159	.00121	.00108
4×10^5	.00188	.00173	.00139	.00109	.000954
10^6	.00163	.00151	.00118	.000963	.000834

*Cyclic strain rate: 1×10^{-3} in./in./sec.

FIG. T-1420-1B DESIGN FATIGUE STRAIN RANGE, ϵ_t, FOR 316 SS applicable only when principal strains do not rotate — is as follows:

Step 1. No change from Step 1 of T-1413.

Step 2. Determine the principal strains versus time for the cycle.

Step 3. At each time interval of Step 2, determine the strain differences $\epsilon_1 - \epsilon_2$, $\epsilon_2 - \epsilon_3$, $\epsilon_3 - \epsilon_1$

Step 4. Select a point when conditions are at an extreme for the cycle, either maximum or minimum. Refer to this time point by a subscript *o*.

Step 5. Determine the history of the change in strain differences by subtracting the values at the time, *o*, from the corresponding values at each point in time, *i*, during the cycle. Designate these strain difference changes as

$$\Delta(\epsilon_1 - \epsilon_2)_i = (\epsilon_1 - \epsilon_2)_i - (\epsilon_1 - \epsilon_2)_o$$
$$\Delta(\epsilon_2 - \epsilon_3)_i = (\epsilon_2 - \epsilon_3)_i - (\epsilon_2 - \epsilon_3)_o$$
$$\Delta(\epsilon_3 - \epsilon_1)_i = (\epsilon_3 - \epsilon_1)_i - (\epsilon_3 - \epsilon_1)_o$$

Step 6. For each time point, *i*, calculate the equivalent strain range as

$$\Delta\epsilon_{equiv,i} = \frac{\sqrt{2}}{2(1+\nu^*)}\left\{[\Delta(\epsilon_1 - \epsilon_2)_i]^2 + [\Delta(\epsilon_2 - \epsilon_3)_i]^2 + [\Delta(\epsilon_3 - \epsilon_1)_i]^2\right\}^{1/2}$$

where ν^* is defined as in T-1413.

Step 7. Define $\Delta\epsilon_{max}$ as the maximum value of the above calculated equivalent strain ranges, $\Delta\epsilon_{equiv,i}$.

T-1420 Limits Using Inelastic Analysis

When inelastic analysis is used to satisfy the requirements of T-1411, the rules of (a), (b) and (c) below apply.

(a) The creep damage term of Eq. (10) may also be calculated by using the integral form

E

$$\int_o^t \frac{dt}{T_d}$$

TABLE T-1420-1D
DESIGN FATIGUE STRAIN RANGE
FOR 2¼Cr-1Mo STEEL

N_d, Number of Cycles [Note (1)]	ϵ_t, Strain Range (in./in.) at Temperature 800°F	900–1100°F
10^1	0.056	0.040
4×10^1	0.023	0.0163
10^2	0.013	0.0097
2×10^2	0.0094	0.0070
4×10^2	0.0070	0.0056
10^3	0.0052	0.0042
2×10^3	0.0044	0.0039
4×10^3	0.0040	0.0035
10^4	0.0032	0.00265
2×10^4	0.0026	0.00215
4×10^4	0.0023	0.00182
10^5	0.00195	0.00158
2×10^5	0.00173	0.00142
4×10^5	0.00155	0.00130
10^6	0.00137	0.00118

NOTE:
(1) Cycle strain rate: 4×10^{-3} in./in./sec.

(b) The fatigue damage term of Eq. (10) is evaluated by entering a design fatigue curve at the strain range ϵ_t. The strain range ϵ_t is defined as $\epsilon_t = \Delta\epsilon_{max}$; where $\Delta\epsilon_{max}$ is the value calculated in either T-1413 or T-1414. The appropriate design fatigue curve is selected from Figs. T-1420-1 and corresponds to the maximum metal temperature experienced during the cycle.

(c) The total damage, *D*, shall not exceed the creep-fatigue damage envelope of Fig. T-1420-2.

T-1430 Limits Using Elastic Analysis

T-1431 General Requirements

(a) The elastic analysis rules in this paragraph may be used only when

(1) the elastic ratchetting rules of T-1320 or T-1330 with *Z* less than, or equal to, 1.0 have been satisfied;

(2) the $3S_m$ limit in NB-3222.2 is met using for $3S_m$ the lesser of $3S_m$ and $3\overline{S}_m$ as defined in T-1324; and

(3) pressure-induced membrane and bending stresses and thermal-induced membrane stresses are classified as primary (load-controlled) stresses.

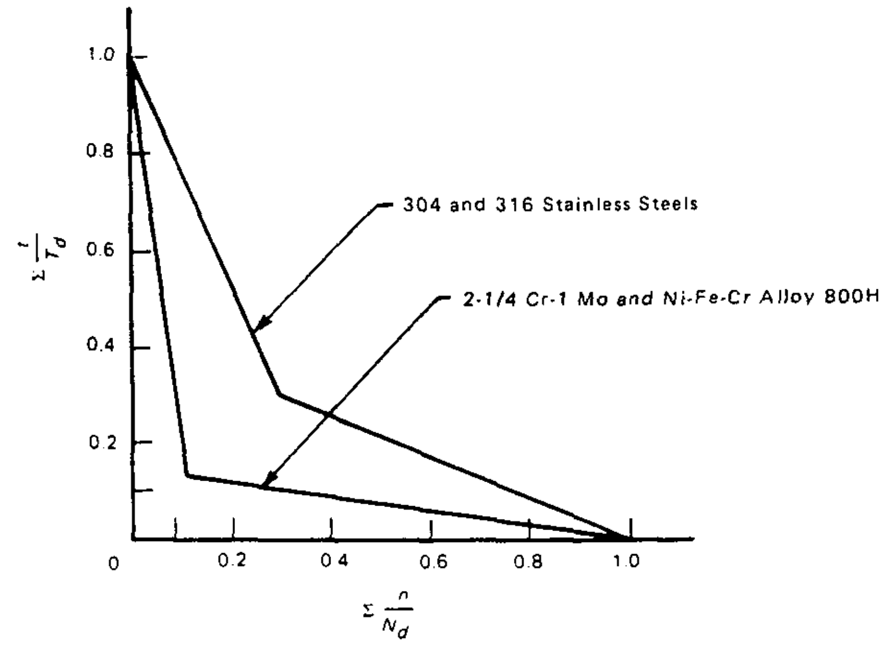


FIG. T-1420-2 CREEP-FATIGUE DAMAGE ENVELOPE

The secondary stress range due to radial thermal gradients may be excluded from $(Q_R)_{max}$ in either T-1322 or T-1323 in determining the applicability of elastic creep-fatigue rules.

(b) Linearly elastic analysis methods may significantly underestimate the actual strain range incurred during plastic or creep deformation. The method of T-1432 may be used to account for these increased strain ranges due to inelastic behavior in the region under consideration. The resulting strain range, ϵ_t, is used to enter a design fatigue curve to evaluate the fatigue damage term of Eq. (10). The appropriate design fatigue curve is selected from Fig. T-1420-1 and corresponds to the maximum metal temperature occuring during the cycle.

(c) The creep damage term of Eq. (10) is evaluated using the procedure of T-1433.

(d) The total damage, D, shall not exceed the creep-fatigue damage envelope of Fig. T-1420-2.

T-1432 Strain Range Determination

(a) Calculate $\Delta\epsilon_{max}$ using T-1413 or T-1414. The strain components to be used in T-1413 or T-1414 are elastically calculated and do not include local geometric stress concentration effects. Alternatively, calculate $\Delta\epsilon_{max}$ using the stress difference procedure described in NB-3216. However, for the purpose of calculating $\Delta\epsilon_{max}$ the effects of local geometric stress concentrations are omitted. The strain range $\Delta\epsilon_{max}$ is defined as equal to $2S_{alt}/E$, where E equals the modulus of elasticity at the maximum metal temperature experienced during the cycle.

(b) Calculate the modified maximum equivalent strain range, $\Delta\epsilon_{mod}$, using the procedure specified in any one of (c), (d), or (e).

(c) The modified maximum equivalent strain range, $\Delta\epsilon_{mod}$, may be calculated as

$$\Delta\epsilon_{mod} = \left(\frac{S^*}{S}\right) K^2 \, \Delta\epsilon_{max} \tag{12}$$

where (see Fig. T-1430-1)

$\Delta\epsilon_{mod}$ = the modified maximum equivalent strain range that accounts for the effects of local plasticity and creep

$\Delta\epsilon_{max}$ = the maximum equivalent strain range as determined above in (a)

K = either the equivalent stress concentration factor, as determined by test or analysis, or, the maximum value of the theoretical elastic E stress concentration factor in any direction for the local area under consideration. The equivalent stress concentration factor is defined as the effective (von Mises) primary plus secondary plus peak stress divided by the effective primary plus secondary stress. Note that fatigue strength reduction factors developed from low temperature continuous cycling fatigue tests may not be acceptable for defining K when creep effects are not negligible.

S^* = the stress indicator determined by entering the stress-strain curve of Fig. T-1430-1 at a strain range of $\Delta\epsilon_{max}$

$\bar{S}$ = the stress indicator determined by entering the stress-strain curve of Fig. T-1430-1 at a strain range of $K\Delta\epsilon_{max}$

The composite stress-strain curve used for this analysis is shown in Fig. T-1430-1, and it is constructed by adding the elastic stress-strain curve for the stress range, S_{rH}, to the appropriate time-independent isochronous stress-strain curve (σ', ϵ') from Fig. T-1800. The appropriate curve of Fig. T-1800 corresponds to the maximum metal temperature occurring during the cycle.

σ' = stress ordinate of the time-independent isochronous stress-strain curve of Fig. T-1800

ϵ' = strain abscissa of the time-independent isochronous stress-strain curve of Fig. T-1800

O' = origin of the time-independent isochronous stress-strain curve of Fig. T-1800

O = origin of the composite isochronous stress-strain curve (Fig. T-1430-1) used in this analysis

S_{rH} = a relaxation strength defined in T-1324

(d) Equation (12) results in a conservative determination of the modified maximum equivalent strain range, $\Delta\epsilon_{mod}$, relative to the maximum equivalent strain range, $\Delta\epsilon_{max}$. A more accurate and less conservative determination of the modified maximum equivalent strain range, $\Delta\epsilon_{mod}$, may then be obtained by use of Eq. (13).

$$\Delta\epsilon_{mod} = \frac{K^2 S^* \Delta\epsilon_{max}}{\Delta\sigma_{mod}} \tag{13}$$

where (see Fig. T-1430-1) $\Delta\epsilon_{mod}$, $\Delta\epsilon_{max}$, K, and S^* are as defined in (c) above, and $\Delta\sigma_{mod}$ = the range of effective stress that corresponds to the strain range, $\Delta\epsilon_{mod}$, in the composite stress-strain curve of Fig. T-1430-1. The unknowns of Eq. (13) (i.e., $\Delta\sigma_{mod}$ and $\Delta\epsilon_{mod}$) can be solved graphically, or analytically, by curve fitting the appropriate composite stress-strain curve. Note that the appropriate composite stress-strain curve is constructed as described above in (c).

(e) The most conservative estimate of the modified maximum equivalent strain range, $\Delta\epsilon_{mod}$, may be obtained as E

$$\Delta\epsilon_{mod} = K_e K \Delta\epsilon_{max} \tag{14}$$

where $\Delta\epsilon_{mod}$, K, and $\Delta\epsilon_{max}$ are defined in (c) above, and

$K_e = 1$ if $K\Delta\epsilon_{max} \leq 3\bar{S}_m/E$

$K_e = K\Delta\epsilon_{max}E/3\bar{S}_m$ for $K\Delta\epsilon_{max} > 3\bar{S}_m/E$

(f) Determine the multiaxial plasticity and Poisson ratio adjustment factor, K_ν, defined in Eq. (15)

$$K_\nu = 1.0 + f(K_\nu' - 1.0), \text{ but not less than } 1.0 \tag{15}$$

where

f = factor determined by entering Fig. T-1430-2 at the Triaxiality Factor, T.F., for the stress state at each of the two extremes of the stress cycle. The larger magnitude of f shall be used in Eq. (15).

K_ν' = plastic Poisson ratio adjustment factor determined by entering Fig. T-1430-3 at the ratio of $K_e K\Delta\epsilon_{max}E/3\bar{S}_M$ with the terms as defined in Eq. (14).

(g) Determine the creep strain increment $\Delta\epsilon_c$ for the stress cycle due to load-controlled stresses by using a stress intensity equal to 1.25 times the effective creep stress $\sigma_c = Z \cdot S_y$ as defined in T-1332. The rules of T-1321, T-1331, and T-1332 apply to determining $\Delta\epsilon_c$ except that the stress cycle time, including hold time between transients, shall be used instead of the entire service life. The resriction on Q_R in T-1323 relative to Table T-1323 does not apply to determining $\Delta\epsilon_c$. Enter the isochronous stress-strain curve (Fig. T-1800) for the maximum metal temperature during the stress cycle time-temperature block with the 1.25 σ_c stress held constant throughout each temperature-time block of the stress cycle. The $\Delta\epsilon_c$ equals the sum of the creep strain increment accumulated in one stress cycle time. Alternatively, the creep strain accumulated during the entire service life divided by the number of stress cycles during the entire service life may be used for the creep strain increment $\Delta\epsilon_c$. Based on satisfaction of T-1320 and the T-1431(a) rules, the $\Delta\epsilon_c$ value used need not exceed 1% divided by the total number of stress cycles $(n \times P)$. E

TABLE I-14.3B (1)
S_{mt} — ALLOWABLE STRESS INTENSITY VALUES, 1000 PSI TYPE 316 SS - 30-YS, 75-UTS (30-YS, 70-UTS)

Temp.°F	1 hr	10 hr	30 hr	10^2 hr	3×10^2 hr	10^3 hr	3×10^3 hr	10^4 hr	3×10^4 hr	10^5 hr	3×10^5 hr
800	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9
850	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7	15.7
900	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
950	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5
1000	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4	14.0
1050	15.1	15.1	15.1	15.1	15.1	15.1	15.1	15.1	14.9	12.5	10.7
1100	14.8	14.8	14.8	14.8	14.8	14.8	14.8	13.9	11.5	9.5	7.8
1150	14.7 [(14.6)]	14.7 [(14.6)]	14.7 [(14.6)]	14.7 [(14.6)]	14.7 [(14.6)]	14.2	13.0	10.9	8.9	7.2	5.9
1200	[13.6] 14.6 [(12.7)]	[13.6] 14.6 [(12.7)]	[13.6] 14.6 [(12.7)]	[13.6] 14.2 [(12.7)]	12.4	10.6	9.4	8.3	6.9	5.5	4.5
1250	[12.2] 14.2 [(11.7)]	[12.2] 14.2 [(11.7)]	[12.2] 14.2 [(11.7)]	11.5	9.8	8.3	7.3	6.3	5.4	4.2	3.3
1300	[11.4] 13.8 (13.4) [(10.7)]	[11.4] 12.8 [(10.7)]	10.9 [(10.7)]	9.1	7.5	6.4	5.6	4.7	3.9	3.1	2.5
1350	[10.1] 12.8 (11.9) [(9.5)]	[10.1] 10.3 [(9.5)]	8.6	7.0	5.9	5.0	4.2	3.4	2.8	2.1	1.8
1400	[9.0] 11.3 (10.5) [(8.4)]	8.2	6.7	5.4	4.5	3.8	3.1	2.5	2.0	1.5	1.2
1450	[7.8] 9.7 (9.0) [(7.3)]	6.4	5.1	4.1	3.4	2.9	2.2	1.7	1.4	1.0	0.9
1500	[6.2] 7.8 (7.7) [(5.6)]	4.9	3.9	3.2	2.6	2.1	1.6	1.2	0.9	0.65	0.5

NOTE:
(1) Values in square parentheses [ ] reflect the effects of service at the indicated temperature for 300,000 hr.