WB-3222.6 Primary Plus Secondary Stress Intensity. [Derived from \((P_m \text{ or } P_1) + P_h + Q\) in Figure WB-3222-1]. This stress intensity is derived from the highest value at any point across the thickness of a section of the general or local primary membrane stresses, plus primary bending stresses plus secondary stresses, produced by normal loads. The allowable value of the maximum range of this stress intensity is \(3S_m\).

NOTE: The concept of stress differences discussed in WB-3216 is essential to determination of the maximum range, since algebraic signs must be retained in the computation. This limitation on range is applicable to the entire history of normal loadings, not just to the stresses resulting from each individual transient.

WB-3222.9 Analysis for Cyclic Operation.

(a) Suitability for Cyclic Operation. The suitability of a component for specified normal loadings and Test Loadings [if required by WB-3225(d)] involving cyclic application of loads and thermal conditions shall be determined by the methods described herein, except that the suitability of high strength bolts shall be determined by the methods of WB-3232.4(b), and the possibility of thermal stress ratcheting shall be investigated in accordance with WB-3222.11. If the specified normal loads of the component meet all of the conditions of (d) below, no analysis for cyclic operation is required, and it may be assumed that the limits on peak stress intensities, as governed by fatigue, have been satisfied by compliance with the applicable requirements for material, design, fabrication, examination, and testing of this Subsection. If the normal loads do not meet all the conditions of (d) below, a fatigue analysis shall be made in accordance with (e) below or a fatigue test shall be made in accordance with Section III Appendices, Mandatory Appendix I, for the total specified number of significant pressure fluctuations during normal conditions by more than the quantity \(1/3 \times S_m\), where \(S_m\) is the allowable design fatigue curve for the maximum number of cycles defined on the curve may be used. Significant pressure fluctuations are those for which the total excursion exceeds one-third of the Design Pressure multiplied by \(S_m\) where \(S\) is defined as follows:

\[-(a)\text{ If the total specified number of cycles is }10^6\text{ cycles or less, }S\text{ is the value obtained from the applicable design fatigue curve for }10^6\text{ cycles.}\]

\[-(b)\text{ If the total specified number of cycles exceeds }10^6\text{ cycles, }S\text{ is the value of }S_m\text{ obtained from the applicable design fatigue curve for the maximum number of cycles defined on the curve.}\]

(3) Temperature Difference — Normal Condition. The total algebraic range of temperature difference, °F (°C), between any two adjacent points does not change during normal conditions by more than the quantity \(S_a/2EA\alpha\), where \(S_a\) is the value obtained from the applicable design fatigue curve of Section III Appendices, Mandatory Appendix I, for the total specified number of significant temperature difference fluctuations, \(\alpha\) is the value of the instantaneous coefficient of thermal expansion, and
E at the mean value of the temperatures at the two points as given by Section II, Part D, Subpart 2, Tables TE and TM. A temperature difference fluctuation shall be considered to be significant if its total algebraic range exceeds the quantity \( S/2E\alpha \), where \( S \) is defined as follows:

(-a) If the total specified number of cycles is \( 10^6 \) cycles or less, \( S \) is the value of \( S_o \) obtained from the applicable design fatigue curve for \( 10^6 \) cycles.

(-b) If the total specified number of cycles exceeds \( 10^6 \) cycles, \( S \) is the value of \( S_o \) obtained from the applicable design fatigue curve for the maximum number of cycles defined on the curve.

(4) Temperature Difference — Dissimilar Materials. For components fabricated from materials of differing moduli of elasticity or coefficients of thermal expansion, the total algebraic range of temperature fluctuation, °F (°C), experienced by the component during normal conditions does not exceed the magnitude \( S_o/2(E_1\alpha_1 - E_2\alpha_2) \), where \( S_o \) is the value obtained from the applicable design fatigue curve for the total specified number of significant temperature fluctuations, \( E_1 \) and \( E_2 \) are the moduli of elasticity (Section II, Part D, Subpart 2, Tables TM), and \( \alpha_1 \) and \( \alpha_2 \) are the values of the instantaneous coefficients of thermal expansion (Section II, Part D, Subpart 2, Tables TE) at the mean temperature value involved for the two materials of construction. A temperature fluctuation shall be considered to be significant if its total excursion exceeds the quantity \( S/2(E_1\alpha_1 - E_2\alpha_2) \), where \( S \) is defined as follows:

(-a) If the total specified number of cycles is \( 10^6 \) cycles or less, \( S \) is the value of \( S_o \) obtained from the applicable design fatigue curve for \( 10^6 \) cycles.

(-b) If the total specified number of cycles exceeds \( 10^6 \) cycles, \( S \) is the value of \( S_o \) obtained from the applicable design fatigue curve for the maximum number of cycles defined on the curve. If the two materials used have different applicable design fatigue curves, the lower value of \( S_o \) shall be used in applying the rules of this paragraph.

(5) Mechanical Loads. The specified full range of mechanical loads, excluding pressure but including support reactions, handling and transportation loads, and assembly/disassembly loads, does not result in load stresses whose range exceeds the \( S_o \) value obtained from the applicable design fatigue curve of Section III Appendices, Mandatory Appendix I, for the total specified number of significant load fluctuations. If the total specified number of significant load fluctuations exceeds the maximum number of cycles defined on the applicable design fatigue curve, the \( S_o \) value corresponding to the maximum number of cycles defined on the curve may be used. A load fluctuation shall be considered to be significant if the total excursion of load stress exceeds the quantity \( S \), where \( S \) is defined as follows:

(-a) If the total specified number of cycles is \( 10^6 \) cycles or less, \( S \) is the value of \( S_o \) obtained from the applicable design fatigue curve for \( 10^6 \) cycles.

(-b) If the total specified number of cycles exceeds \( 10^6 \) cycles, \( S \) is the value of \( S_o \) obtained from the applicable design fatigue curve for the maximum number of cycles defined on the curve.

(e) Procedure for Analysis for Cyclic Loading. If the specified normal loads for the component do not meet the conditions of (d), the ability of the component to withstand the specified cyclic operation without fatigue failure shall be determined as provided in this subsubparagraph. The determination shall be made on the basis of the stresses at a point, and the allowable stress cycles shall be adequate for the specified normal loads at every point. Only the stress differences due to operation cycles as specified in the Design Specifications need be considered. Compliance with these requirements means only that the component is suitable from the standpoint of possible fatigue failure; complete suitability for the specified normal loads is also dependent on meeting the general stress limits of WB-3222 and any applicable special stress limits of WB-3227.

(1) Stress Differences. For each normal load, determine the stress differences and the alternating stress intensity \( S_{alt} \), in accordance with WB-3216.

(2) Local Structural Discontinuities. These effects shall be evaluated for all conditions using stress concentration factors determined from theoretical, experimental, or photoelastic studies, or numerical stress analysis techniques. Experimentally determined fatigue strength reduction factors may be used when determined in accordance with the procedures of Section III Appendices, Mandatory Appendix II, II-1600, except for high strength alloy steel bolting for which the requirements of WB-3232.4(c) shall apply when using the design fatigue curve of Section III Appendices, Mandatory Appendix I, Figure I-9.4. No fatigue strength reduction factor greater than five need be used.

(3) Design Fatigue Curves. Section III Appendices, Mandatory Appendix I, contains the applicable fatigue design curves for the materials permitted by this Subsection. When more than one curve is presented for a given material, the applicability of each is identified. Where curves for various strength levels of a material are given, linear interpolation may be used for intermediate strength levels of these materials. The strength level is the specified minimum room temperature value.

(4) Effect of Elastic Modulus. Multiply \( S_{alt} \) (as determined in WB-3216.1 or WB-3216.2) by the ratio of the modulus of elasticity given on the design fatigue curve to the value of the modulus of elasticity used in the analysis. Enter the applicable design fatigue curve of Section III Appendices, Mandatory Appendix I at this value on the ordinate axis and find the corresponding number of cycles on the abscissa. If the operating cycle being considered is the only one which produces significant fluctuating stresses, this is the allowable number of cycles.
**WD-3222.4 Primary Plus Secondary Stress Intensity.** This stress intensity [derived from \( (P_m \text{ or } P_L) + P_b + Q \) in Figure WD-3222-1] is derived from the highest value at any point across the thickness of a section of the general or local primary membrane stresses, plus primary bending stresses, plus secondary stresses, produced by the specified mechanical loads and by general thermal effects associated with normal loadings. The effects of gross structural discontinuities but not of local structural discontinuities (stress concentrations) shall be included.

NOTE: The concept of stress differences discussed in WD-3216 is essential to determination of the maximum range, since algebraic signs must be retained in the computation. Note that this limitation on range is applicable to the entire history of normal loadings, not just to the stresses resulting from each individual transient.

The allowable value for the maximum range of this stress intensity is \( 3S_m \) [Figure WD-3222-1, Note (6)], except for certain cyclic events that may exceed the \( 3S_m \) limit. For this exception, in lieu of meeting the \( 3S_m \) limit, an elastic–plastic fatigue analysis in accordance with WD-3228 may be performed to demonstrate that the cumulative fatigue usage attributable to the combination of these low cycle events plus all other cyclic events does not exceed a value of 1.0 when calculated in accordance with WD-3222.5.

**WD-3222.5 Analysis for Cyclic Operation.**

(a) Suitability for Cyclic Operation. The suitability of an internal support structure for specified operating loadings involving cyclic application of loads and thermal conditions shall be determined by the methods described herein, except that the suitability of high strength bolts shall be determined by the methods of WD-3235 and the possibility of thermal stress ratcheting shall be investigated in accordance with WD-3222.6. If the specified normal loadings of the structure meet all of the conditions of (d) below, no analysis for cyclic operation is required, and it may be assumed that the limits on peak stress intensities, as governed by fatigue, have been satisfied for a structure by compliance with the applicable requirements for material, design, fabrication, and examination of this Subsection, provided the specified normal loadings of the structure, or portion thereof, meets all the conditions stipulated in (1) through (4) below.

(b) Peak Stress Intensity. This stress intensity is derived from the highest value at any point across the thickness of a section of the combination of all primary, secondary, and peak stresses produced by specified mechanical loads, and by general and local thermal effects associated with normal conditions and including the effects of gross and local structural discontinuities.

(c) Conditions and Procedures. The conditions and procedures of WD-3222.5 are based on a comparison of peak stresses with strain cycling fatigue data. The strain cycling fatigue data are represented by design fatigue strength curves of Section III Appendices, Mandatory Appendix I. These curves show the allowable amplitude \( S_a \) of the alternating stress intensity component (one-half of the alternating stress intensity range) plotted against the number of cycles. This stress intensity amplitude is calculated on the assumption of elastic behavior and, hence, has the dimensions of stress, but it does not represent a real stress when the elastic range is exceeded. The fatigue curves in Section III Appendices, Mandatory Appendix I are obtained from uniaxial strain cycling data in which the imposed strains have been multiplied by the elastic modulus and a design margin has been provided so as to make the calculated stress intensity amplitude and the allowable value of the stress intensity amplitude directly comparable. Where necessary, the curves have been adjusted to include the maximum effects of mean stress, which is the condition where the stress fluctuates about a mean value that is different from zero. As a consequence of this procedure, it is essential that the requirements of WD-3222.4 be satisfied at all times with transient stresses included, and that the calculated value of the alternating stress intensity be proportional to the actual strain amplitude. To evaluate the effect of alternating stresses of varying amplitudes, a linear damage relation is assumed in (e)(5) below.

(d) Structures Not Requiring Analysis for Cyclic Operation. An analysis for cyclic operation is not required, and it may be assumed that the limits on peak stress intensities, as governed by fatigue, have been satisfied for a structure by compliance with the applicable requirements for material, design, fabrication, and examination of this Subsection, provided the specified normal loadings of the structure, or portion thereof, meets all the conditions stipulated in (1) through (4) below.

1. **Temperature Difference – Loading and Unloading of Contents.** The temperature difference in °F (°C) between any two adjacent points does not exceed \( S_a/(2E\alpha) \), where \( S_a \) is the value obtained from the applicable design fatigue curves of Section III Appendices, Mandatory Appendix I for the specified number of load and unload cycles, \( \alpha \) is the value of the instantaneous coefficient of thermal expansion at the mean value of the temperatures at the two points as given by Section II, Part D, Subpart 2, Table TE, and \( E \) is taken from Section II, Part D, Subpart 2, Table TM at the mean value of the temperatures at the two points.

2. **Temperature Difference – Normal Conditions.** The temperature difference in °F (°C) between any two adjacent points does not change (the algebraic range of the difference shall be used) during normal conditions by more than the quantity \( S_a/(2E\alpha) \), where \( S_a \) is the value obtained from the applicable design fatigue curve of Section III Appendices, Mandatory Appendix I for the total specified number of significant temperature difference fluctuations. A temperature difference fluctuation shall
be considered to be significant if its total algebraic range exceeds the quantity $S/(2Ea)$ where $S$ is defined as follows:

(a) If the total specified number of cycles is $10^6$ cycles or less, $S$ is the value of $S_a$ obtained from the applicable design fatigue curve for $10^6$ cycles.

(b) If the total specified number of cycles exceeds $10^6$ cycles, $S$ is the value of $S_a$ obtained from the applicable design fatigue curve for the maximum number of cycles defined on the curve.

(3) Temperature Difference – Dissimilar Materials. For internal support structures fabricated from materials of differing moduli of elasticity or coefficients of thermal expansion, or both, the total algebraic range of temperature fluctuation in °F (°C) experienced by the structure during normal conditions does not exceed the magnitude $S_a/2 (E_1 \alpha_1 - E_2 \alpha_2)$, where $S_a$ is the value obtained from the applicable design fatigue curve of Section III Appendices, Mandatory Appendix I for the total specified number of significant temperature fluctuations, $E_1$ and $E_2$ are the moduli of elasticity, and $\alpha_1$ and $\alpha_2$ are the values of the instantaneous coefficients of thermal expansion at the mean temperature value involved for the two materials of construction (Section II, Part D, Subpart 2, Tables TE and TM). A temperature fluctuation shall be considered to be significant if its total excursion exceeds the quantity $S_a/2 (E_1 \alpha_1 - E_2 \alpha_2)$, where $S$ is defined as follows:

(a) If the total specified number of cycles is $10^6$ cycles or less, $S$ is the value of $S_a$ obtained from the applicable design fatigue curve for $10^6$ cycles.

(b) If the total specified number of cycles exceeds $10^6$ cycles, $S$ is the value of $S_a$ obtained from the applicable design fatigue curve for the maximum number of cycles defined on the curve.

(4) Mechanical Loads. The specified full range of mechanical loads does not result in load stresses whose range exceeds the $S_a$ value obtained from the applicable design fatigue curve of Section III Appendices, Mandatory Appendix I for the total specified number of significant load fluctuations. If the total specified number of significant load fluctuations exceeds the maximum number of cycles defined on the applicable design fatigue curve, the $S_a$ value corresponding to the maximum number of cycles defined on the curve may be used. A load fluctuation shall be considered to be significant if the total excursion of load stress exceeds the quantity of $S$, where $S$ is defined as follows:

(a) If the total specified number of cycles is $10^6$ cycles or less, $S$ is the value of $S_a$ obtained from the applicable design fatigue curve for $10^6$ cycles.

(b) If the total specified number of cycles exceeds $10^6$ cycles, $S$ is the value of $S_a$ obtained from the applicable design fatigue curve for the maximum number of cycles defined on the curve.

(e) Procedure for Analysis for Cyclic Loading. If the specified normal loadings for the structure do not meet the conditions of (d) above, the ability of the internal support structure to withstand the specified cyclic operation without fatigue failure shall be determined as provided herein. The determination shall be made on the basis of the stresses at a point and the allowable stress cycles shall be adequate for the specified normal loadings at every point. Only the stress differences due to cycles as specified in the Design Specification need be considered. Compliance with these requirements means only that the structure is suitable from the standpoint of possible fatigue failure; complete suitability for the specified normal loadings is also dependent on meeting the general stress limits of WD-3222 and any applicable special stress limits of WD-3227 and WD-3229.

(1) Stress Differences. For each normal condition, determine the stress differences and the alternating stress intensity $S_{alt}$ in accordance with WD-3216.

(2) Local Structural Discontinuities. These effects shall be evaluated for all normal conditions using stress concentration factors determined from theoretical, experimental, or photoelastic studies, or numerical stress analysis techniques. Experimentally determined fatigue strength reduction factors may be used when stated herein or when determined in accordance with the procedures of Section III Appendices, Mandatory Appendix II, II-1600. Except for the case of crack-like defects, no fatigue strength reduction factor greater than five need be used.

(3) Design Fatigue Curves. Section III Appendices, Mandatory Appendix I contain the applicable fatigue design curves for the materials permitted by this Subsection. When more than one curve is presented for a given material, the applicability of each curve to material of various strength levels is identified. Linear interpolation may be used for intermediate strength levels of these materials. As used herein, the strength level is the specified minimum room temperature value.

(4) Effect of Elastic Modulus. Multiply $S_{alt}$ (WD-3216.1 or WD-3216.2) by the ratio of the modulus of elasticity given on the design fatigue curve to the value of the modulus of elasticity used in the analysis. Enter the applicable design fatigue curve of Section III Appendices, Mandatory Appendix I at this value on the ordinate axis and find the corresponding number of cycles on the abscissa. If the operating cycle being considered is the only one that produces significant fluctuating stresses, this is the allowable number of cycles.

(5) Cumulative Damage. If there are two or more types of stress cycle that produce significant stresses, their cumulative effect shall be evaluated as stipulated in Steps 1 through 6 below.

Step 1. Designate the specified number of times each type of stress cycle of Types 1, 2, 3, etc., will be repeated during the life of the structure as $n_1, n_2, n_3, \ldots, n_n$, respectively.