WA-3357 Review of Design Report

(a) A review of the Design Report shall be made by the N3 Certificate Holder certifying the Design Specification to determine that all the design and loading conditions identified in the Design Specification have been considered, and that the acceptance criteria established in the Design Specification and this Division have been met. This review shall be made by individuals who did not prepare the Certified Design Report.

(b) Documentation shall be provided to the Owner to indicate that the review required by (a) above has been completed.

(c) A copy of the documentation required by (b) above shall be attached to, and become part of, the Design Report.

WA-3358 Availability of Design Reports

The N3 Certificate Holder shall make a copy of the completed Certified Design Report, including documentation of the review when required (WA-3357), and drawings used for construction available to the Inspector.

WA-3360 FABRICATION SPECIFICATION

WA-3361 Provisions of the Fabrication Specification

WA-3361.1 Responsibility. It is the responsibility of the N3 Certificate Holder to prepare, certify, and issue the Fabrication Specification for components. The N3 Certificate Holder shall be responsible for the correlation of all Data Reports for the component. Separate Fabrication Specifications are not required for parts when they are included in the Fabrication Specification for the component.

WA-3361.2 Contents of the Fabrication Specification. The Fabrication Specification shall be based upon the Design Specification and the Design Output Documents, and shall contain sufficient detail, including forming and fabrication tolerances, to provide a complete basis for fabrication in accordance with this Division. Fabrication Specifications for components shall include the examination and testing requirements for closure welds. Such requirements shall not result in fabrication that fails to conform with the Design Specification, Design Documents and the rules of this Division.

WA-3361.3 Certification of the Fabrication Specification. The Fabrication Specification shall be certified to be correct and complete and to be in compliance with the requirements of WA-3361.2 by one or more Certifying Engineers, competent in the requirements of this Division and the field of Division 3 component fabrication and qualified in accordance with the requirements of Section III Appendices, Mandatory Appendix XXIII. Such Registered Professional Engineers are not required to be independent of the organization preparing the Fabrication Specification.

WA-3361.4 Filing the Fabrication Specification. Fabrication Specification in its entirety shall become the principal document governing fabrication and shall be available at the location of fabrication during the complete fabrication process.

WA-3361.5 Availability of the Fabrication Specification. The N3 Certificate Holder shall make a copy of the completed Fabrication Specification used for fabrication available to the Inspector and the Owner.

WA-3370 RESPONSIBILITY FOR QUALITY ASSURANCE

WA-3371 Scope of Responsibilities

The N3 Certificate Holder shall be responsible for surveying, qualifying, and auditing suppliers of subcontracted services (WA-3122), including nondestructive examination contractors and Material Organizations. Material Organizations holding Quality System Certificates (Materials), and Certificate Holders whose scope includes the supply or manufacture of materials, need not be surveyed or audited for work or material covered by the scope of their Certificate. Subcontractors holding an appropriate Certificate of Authorization need not be surveyed nor audited for work within the scope of the subcontractor’s Certificate.

An N3 Certificate Holder may qualify vendors of subcontracted services (WA-3122) other than those requiring a Certificate of Authorization for another Certificate Holder doing work for that N3 Certificate Holder. The qualification documentation shall be supplied to the other Certificate Holder prior to their use of the subcontracted service.

WA-3372 Documentation of Quality Assurance Program

The N3 Certificate Holder shall be responsible for documenting its Quality Assurance Program (WA-4134).

WA-3373 Filing of Quality Assurance Manual

The N3 Certificate Holder shall file with the Authorized Inspection Agency (WA-5121) copies of the Quality Assurance Manual. The N3 Certificate Holder shall keep a copy on file available to the Inspector (WA-5123).

WA-3380 DATA REPORTS

The N3 Certificate Holder shall certify compliance with this Division by signing the appropriate Data Report and application of the Certification Mark (Article WA-8000).
(b) Approved suppliers may adopt a limited scope quality system program as approved by the Certificate Holder or Material Organization [NCA-4255.3(b)].

WA-3812 Exclusions

Material falling within the small products exclusion of WB-2610, WC-2610, or WD-2610, as appropriate or material that is allowed by this Section to be furnished with a Certificate of Compliance, is exempted from the requirements of WA-3800, except:

(a) Certified Material Test Reports or Certificates of Compliance shall meet the requirements of NCA-3862.1.
(b) For construction of components meeting the requirements of this Division, material identification and marking shall meet the requirements of NCA-4256.3.

WA-3820 MATERIAL ORGANIZATIONS

A Material Organization shall be certified or qualified in accordance with NCA-3820 through NCA-3842.2, and NCA-4250 through NCA-4259.2. Material Certification shall be in accordance with NCA-3860.
ARTICLE WA-7000
REFERENCE STANDARDS

WA-7100  GENERAL REQUIREMENTS

Dimensions of standard products shall comply with the dimensional standards listed in Table WA-7100-1 when the standard is referenced in the Division 3 Subsection. However, compliance with these standards does not replace or eliminate the requirements for stress analysis when called for by Article WB-3000, Article WC-3000, or Article WD-3000 for a specific component.

The standards and specifications referenced in the text of each Subsection are listed in Table WA-7100-2. Where reference is made within Division 3 to requirements that are part of the ASME Boiler and Pressure Vessel Code, they are not included in this Table.

<table>
<thead>
<tr>
<th>Standard ID</th>
<th>Published Title</th>
<th>Section III Referenced Edition</th>
<th>Other Acceptable Editions</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASME B16.21</td>
<td>Nonmetallic Flat Gaskets for Pipe Flanges</td>
<td>2005</td>
<td>1992</td>
</tr>
<tr>
<td>ASME B16.47</td>
<td>Large Diameter Steel Flanges</td>
<td>2006</td>
<td>1998</td>
</tr>
<tr>
<td>ASME B18.2.2 [Note (2)]</td>
<td>Square, Hex, Heavy Hex, and Skew Head Bolts and Hex, Hex Flange, Lobed Head and Lag Screws</td>
<td>2010</td>
<td>1999, 1981</td>
</tr>
<tr>
<td>ASME/ANSI B18.2.2 [Note (2)]</td>
<td>Square and Hex Nuts (Inch Series)</td>
<td>1987 (R1999)</td>
<td>1987, 1972 (R1983)</td>
</tr>
</tbody>
</table>

NOTES:
(1) Analysis per ASME B16.9, para. 2.2, is acceptable only for caps and reducers.
(2) These standards are referenced for dimensional purposes only. Any manufacturing or inspection requirements contained in item are not mandatory. The SA or SB Material Specification specifies the applicable manufacturing and inspection requirements.
the orientation and location of all tests performed to meet the requirements of WB-2330 shall be reported in the Certified Material Test Report.

(17) **WB-2321.3 Fracture Toughness Tests.** Fracture toughness tests, when required, shall be performed in accordance with ASTM E399. The tests shall be performed at the lowest service temperature (LST). A test shall consist of two test specimens.

(17) **WB-2321.4 Dynamic Tear Test.** The dynamic tear tests, when required, shall be performed in accordance with ASTM E604. The tests shall be performed at the LST. A test shall consist of two test specimens.

**WB-2322 Test Specimens**

**WB-2322.1 Location of Test Specimens.**

(a) Toughness test specimens for quenched and tempered material shall be removed from the locations in each product form specified in WB-2220 for tensile test specimens. For material in other heat-treated conditions, toughness test specimens shall be removed from the locations specified for tensile test specimens in the material specification. For all material, the number of tests shall be in accordance with WB-2340. For bolting, the C_{eq} toughness test specimen shall be taken with the longitudinal axis of the specimen located at least one-half radius or 1 in. (25 mm) below the surface plus the machining allowance per side, whichever is less. The fracture plane of the specimens shall be at least one diameter or thickness from the heat-treated end. When the studs, nuts, or bolts are not of sufficient length, the midlength of the specimen shall be at the midlength of the studs, nuts, or bolts. The studs, nuts, or bolts selected to provide test coupon material shall be identical with respect to the quenched contour and size except for length, which shall equal or exceed the length of the represented studs, nuts, or bolts.

(b) For fracture toughness requirements, toughness test specimens for ductile cast iron shall be taken from each containment casting or its excess length part. The location shall be the same as that for the tensile specimens.

**WB-2322.2 Orientation of Toughness Test Specimens.**

(a) Toughness test specimens shall be oriented as follows:

(1) Specimens for forgings, other than bolting and bars used for containments, shall be oriented in a direction normal to the principal direction in which the material was worked. Specimens are neither required nor prohibited from the thickness direction.

(2) Specimens from material for pipe, tube, and fittings, except for those made from plate and castings, shall be oriented in the axial direction.

(3) Specimens from bolting material and bars shall be oriented in the axial direction.

(4) Specimens for all plate material, including that used for pipe, tube, and fittings, shall be oriented in a direction normal to the principal rolling direction, other than thickness direction.

(5) Specimens for cast material shall have their axes oriented the same as the axes of the tensile specimens (WB-2226).

(6) The plane of the toughness test specimen notch shall be normal to the surface of the material. However, for ductile cast iron, the fracture toughness specimen orientation shall be L-R, as identified in ASTM E399, Fig. 1 (Crack Plane Identifications for Cylindrical Bars and Tubes).

(b) Specimens for drop weight tests may have their axes oriented in any direction. The orientation used shall be reported in the Certified Material Test Report.

**WB-2330 TEST REQUIREMENTS AND ACCEPTANCE STANDARDS**

**WB-2331 Material for Containments**

**WB-2331.1 Test Requirements for Ferritic Steel Material for Containments.** Ferritic steel material for containments, other than bolting, shall be tested in accordance with (a) and (b), (c), or (d) below. Consideration shall be given to the test temperature requirements of leak testing and hydrostatic testing of the containment (WB-6212).

(a) For material with a nominal section between \(\frac{3}{16}\) in. (5 mm) and \(\frac{3}{8}\) in. (16 mm) thick, the dynamic tear test shall exhibit at least 80% shear fracture at the LST. For material of \(\frac{3}{8}\) in. (16 mm) and more but not exceeding 12 in. (300 mm) thick, the reference temperature, \(R_{NDT}\), shall be established as follows:

(1) Determine a temperature \(T_{NDT}\) that is at or above the nil-ductility transition temperature by drop weight tests.

(2) At a temperature not greater than \(T_{NDT} + 60^\circ\text{F}\) \((T_{NDT} + 33^\circ\text{C})\), each specimen of the \(C_v\) test (WB-2321.2) shall exhibit at least 35 mils (0.89 mm) lateral expansion and not less than 50 ft-lb (68 J) absorbed energy. Retesting in accordance with WB-2350 is permitted. When these requirements are met, \(T_{NDT}\) is the reference temperature \(R_{NDT}\).

(3) In the event that the requirements of (2) above are not met, conduct additional \(C_v\) tests in groups of three specimens (WB-2321.2) to determine the temperature \(T_c\) at which they are met. In this case the reference temperature \(R_{NDT} = T_c - 60^\circ\text{F}\) \((R_{NDT} = T_c - 33^\circ\text{C})\). Thus, the reference temperature for \(R_{NDT}\) is the higher of \(T_{NDT}\) and \((T_c - 60^\circ\text{F})\) \((T_c - 33^\circ\text{C})\).

(4) When a \(C_v\) test has not been performed at \(T_{NDT} + 60^\circ\text{F}\) \((T_{NDT} + 33^\circ\text{C})\), or when the \(C_v\) test at \(T_{NDT} + 60^\circ\text{F}\) \((T_{NDT} + 33^\circ\text{C})\), does not exhibit a minimum of 50 ft-lb (68 J) and 35 mils (0.89 mm) lateral expansion, a temperature representing a minimum of 50 ft-lb (68 J)
and 35 mils (0.89 mm) lateral expansion may be obtained from a full $C_n$ impact curve developed from the minimum data points of all the $C_n$ tests performed.

(b) Apply the procedures of (a) above to (1), (2), and (3) below.

(1) the containment base materials,

(2) the base metal, the heat-affected zone, and weld metal from the weld procedure qualification tests in accordance with WB-4330;

(3) the weld metal of WB-2431.

(c) For materials where fracture toughness values are determined in accordance with WB-2321.3 the measured fracture toughness shall be reported in the Certified Material Test Report.

(d) Bars having a width or diameter of 2 in. (50 mm) and less which prohibit obtaining drop weight test specimens shall be tested in accordance with WB-2332.

(17) WB-2331.2 Acceptance Standards for Ferritic Steel Material for Containments. Except as limited in WB-4330, the reference temperature $R_{NDT}$ shall be the highest value of the individual $R_{NDT}$ values determined in accordance with WB-2331.1(a) and WB-2331.1(b). If applicable, the containment base materials shall be tested to determine the fracture toughness in accordance with WB-2321.3. The results shall meet the acceptance standards of either (a) or (b) below.

(a) For materials not exceeding 12 in. (305 mm), the reference temperature $R_{NDT}$ shall be the required value in Table WB-2331.2-1 where $A=LST - R_{NDT}$.

(b) For materials not exceeding 4 in. (100 mm), the nominal wall thickness shall satisfy the required value in Table WB-2331.2-2, and

(1) All full penetrations fabrication welds are ultrasonically examined in accordance with WB-5110 and meet the ultrasonic acceptance standards of WB-5330.

(a) Rules for fracture toughness requirements based on fracture mechanics methodology are in preparation.

### Table WB-2331.2-1
Required LST-$R_{NDT}$ Values for Ferritic Steel Material for Containment Material

<table>
<thead>
<tr>
<th>Nominal Wall Thickness, in. (mm)</th>
<th>$A = LST - R_{NDT}$, °F (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{3}{4}$ (16)</td>
<td>25 (14)</td>
</tr>
<tr>
<td>1 (25)</td>
<td>45 (25)</td>
</tr>
<tr>
<td>2 (50)</td>
<td>75 (42)</td>
</tr>
<tr>
<td>3 (75)</td>
<td>90 (50)</td>
</tr>
<tr>
<td>4 (100)</td>
<td>125 (57)</td>
</tr>
<tr>
<td>8 (200)</td>
<td>220 (64)</td>
</tr>
<tr>
<td>12 (300)</td>
<td>250 (77)</td>
</tr>
</tbody>
</table>

GENERAL NOTE: Linear interpolation is permissible.

### Table WB-2331.2-2
Required Fracture Toughness Values for Ferritic Steel Material for Containments Having a Specified Yield Strength of 50 ksi (350 000 kPa) or Less at 100°F (38°C)

<table>
<thead>
<tr>
<th>Nominal Wall Thickness, in. (mm)</th>
<th>Rapid Load Fracture Toughness, ksi-in. (MPa-m) (Note 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{3}{4}$ (16)</td>
<td>50 (55)</td>
</tr>
<tr>
<td>1 (25)</td>
<td>65 (70)</td>
</tr>
<tr>
<td>2 (50)</td>
<td>94 (83)</td>
</tr>
<tr>
<td>3 (75)</td>
<td>112 (101)</td>
</tr>
<tr>
<td>4 (100)</td>
<td>130 (119)</td>
</tr>
</tbody>
</table>

GENERAL NOTE: Linear interpolation is permissible.

### Table WB-2332
Material for Piping, Excluding Bolting Material

(a) Containment boundary material, other than bolting, with nominal wall thickness 2\(\frac{1}{2}\) in. (64 mm) and less for piping (pipe and tubes) and fittings with all pipe connections of nominal wall thickness 2\(\frac{1}{2}\) in. (64 mm) and less shall be tested as required in (1) and (2) below.

(1) Test three $C_n$ specimens at a temperature lower than or equal to the LST. All three specimens shall meet the requirements of Table WB-2332(a)-1.

(2) Apply the procedures of (1) above to:

(a) the base material;
blend, or chemically controlled mixes of flux or core materials. Alternatively, a lot of covered, flux cored, or fabricated electrodes may be considered one type and size of electrode, produced in a continuous period, not to exceed 24 hr and not to exceed 100,000 lb (45 000 kg), from chemically controlled tube, wire, or strip and a dry batch, a dry blend, or chemically controlled mixes of flux, provided each container of welding material is coded for identification and traceable to the production period, the shift, line, and the analysis range both of the mix and the rod, tube, or strip used to make the electrode.

(1) Chemically controlled tube, wire, or strip is defined as consumable tube, wire, or strip material supplied on coils with a maximum of one spool per coil that has been chemically analyzed to ensure that the material conforms to the electrode manufacturer's chemical control limits for the specific type of electrode. Both ends of each coil shall be chemically analyzed, except that those coils which are splice free need only be analyzed on one end of the coil.

(2) Chemically controlled mixes of flux are defined as flux material that has been chemically analyzed to ensure that it conforms to the percent allowable variation from the electrode manufacturer's standard for each chemical element for that type electrode. A chemical analysis shall be made on each mix made in an individual mixing vessel after blending.

(e) A heat of bare electrode, rod, wire, or consumable insert is defined as the material produced from the same melt of metal.

(f) Alternatively, for carbon and low alloy steel bare electrode, rod, wire, or consumable inserts for use with SAW, OFW, GMAW, GTAW, and PAW processes, a heat may be defined as either the material produced from the same melt of metal or the material produced from one type and size of wire when produced in a continuous period [not to exceed 24 hr and not to exceed 100,000 lb (45 000 kg)] from chemically controlled wire, subject to requirements of (1), (2), and (3) below.

(1) For the chemical control of the product of the rod mill, coils shall be limited to a maximum of one splice prior to processing the wire. Chemical analysis shall be made from a sample taken from both ends of each coil of mill coiled rod furnished by mills permitting spliced coil practice of one splice maximum per coil. A chemical analysis need be taken from only one end of rod coils furnished by mills prohibiting spliced coil practice.

(2) Carbon, manganese, silicon, and other intentionally added elements shall be identified to ensure that the material conforms to the SFA or user's material specification.

(3) Each container of wire shall be coded for identification and traceability to the lot, production period, shift, line, and analysis of rod used to make the wire.

(g) A lot of submerged arc flux is defined as the quantity of flux produced from the same combination of raw materials under one production schedule.

(h) A dry blend of supplementary powdered filler metal is defined as one or more mixes of material produced in a continuous period, not to exceed 24 hr and not to exceed 20,000 lb (9 000 kg) from chemically controlled mixes of powdered filler metal, provided each container of powdered metal is coded for identification and traceable to the production period, the shift, and the mixing vessel. A chemically controlled mix of powdered filler metal is defined as powdered filler metal material that has been chemically analyzed to assure that it conforms to the percent allowable variation from the powdered filler metal manufacturer's standard, for each chemical element, for that type of powdered filler metal. A chemical analysis shall be made on each mix made in an individual mixing vessel after blending. The chemical analysis range of the supplemental powdered filler shall be the same as that of the welding electrode, and the ratio of powder to electrode used to make the test coupon shall be the maximum permitted for production welding.

**WB-2430 WELD METAL TESTS**

**WB-2431 Mechanical Properties Test**

Tensile and toughness tests shall be made, in accordance with this paragraph, of welding materials which are used to join P-Nos. 1 and 3 base materials in any combination, with the exceptions listed in (a) through (d) below.

(a) Austenitic stainless steel and nonferrous welding material used to join the listed P-Nos.

(b) Consumable inserts (backing filler material);

(c) Welding material used for GTAW root deposits with a maximum of two layers;

(d) Welding material to be used for the welding of base material exempted from toughness testing by WB-2311 shall likewise be exempted from the impact testing required by WB-2330 and this paragraph.

**WB-2431.1 General Test Requirements.** The welding test coupon shall be made in accordance with (a) through (f) below, using each process with which the weld material will be used in production welding.

(a) Test coupons shall be of sufficient size and thickness such that the test specimens required herein can be removed.

(b) The weld metal to be tested for all processes shall be deposited in such a manner as to eliminate substantially the influence of the base material on the results of the tests. Weld metal to be used with the electroslag process shall be deposited in such a manner as to conform to one of the applicable Welding Procedure Specifications (WPS) for production welding, Section IX. The base material shall conform to the requirements of Section IX, QW-403.1 or QW-403.4, as applicable.

(c) The welding of the test coupon shall be performed within the range of preheat and interpass temperatures that will be used in production welding. Coupons shall be tested in the as-welded condition, or they shall be
WB-2520  EXAMINATION AFTER QUENCHING AND TEMPERING

Ferritic steel products that have their properties enhanced by quenching and tempering shall be examined by the methods specified in this subarticle for each product form after the quenching and tempering phase of the heat treatment.

WB-2530  EXAMINATION AND REPAIR OF PLATE
WB-2531  Required Examination

All plates 2 in. (50 mm) nominal thickness and less shall be examined by the angle beam ultrasonic method in accordance with WB-2532.2. All plates greater than 2 in. (50 mm) thickness shall be examined by the straight beam ultrasonic method in accordance with WB-2532.1.

WB-2532  Examination Procedures
WB-2532.1  Straight Beam Examination. The requirements for straight beam examination shall be in accordance with SA-578, Specification for Straight Beam Wave Ultrasonic Testing and Inspection of Plain and Clad Steel Plates for Special Applications, as shown in Section V, except that the extent of examination and the acceptance standards to be applied are given in (a) and (b) below.

(a) Extent of Examination. One hundred percent of one major plate surface shall be covered by moving the search unit in parallel paths with not less than a 10% overlap.

(b) Acceptance Standards

(1) Any area where one or more imperfections produce a continuous total loss of back reflection accompanied by continuous indications on the same plane that cannot be encompassed within a circle whose diameter is 3 in. (75 mm) or one-half of the plate thickness, whichever is greater, is unacceptable.

(2) In addition, two or more imperfections smaller than described in (1) above shall be unacceptable unless separated by a minimum distance equal to the greatest diameter of the larger imperfection, or unless they may be collectively encompassed by the circle described in (1) above.

WB-2532.2  Angle Beam Examination. The requirements for angle beam examination shall be in accordance with SA-577, Specification for Ultrasonic Beam Wave Inspection of Steel Plates, as shown in Section V and supplemented by (a) and (b) below. The calibration notch, extent of examination, and acceptance standards to be applied are given in (a) through (c) below.

(a) Calibration. Angle beam examination shall be calibrated from a notch.

(b) Extent of Examination. One hundred percent of one major plate surface shall be covered by moving the search unit in parallel paths with not less than 10% overlap.

(c) Acceptance Standards. Material that shows one or more imperfections which produce indications exceeding in amplitude the indication from the calibration notch is unacceptable unless additional exploration by the straight beam method shows the imperfections are laminar in nature and are acceptable in accordance with WB-2532.1(b).

WB-2537  Time of Examination

Acceptance examinations shall be performed at the time of manufacture as required in (a) through (c) below.

(a) Ultrasonic examination shall be performed after rolling to size and after heat treatment, except for post-weld heat treatment.

(b) Radiographic examination of repair welds, when required, may be performed prior to any required postweld heat treatment.

(c) Magnetic particle or liquid penetrant examination of repair welds shall be performed after final heat treatment, except that the examination may be performed prior to postweld heat treatment of P-No.1 material 2 in. (51 mm) and less nominal thickness.

WB-2538  Elimination of Surface Defects

Surface defects shall be removed by grinding or machining, provided the requirements of (a) through (d) below are met.

(a) The depression, after defect elimination, is blended uniformly into the surrounding surface.

(b) After defect elimination, the area is examined by the magnetic particle method in accordance with WB-2545 or the liquid penetrant method in accordance with WB-2546 to ensure that the defect has been removed or reduced to an imperfection of acceptable size.

(c) Areas ground to remove oxide scale or other mechanically caused impressions for appearance or to facilitate proper ultrasonic testing need not be examined by the magnetic particle or liquid penetrant test method.

(d) When the elimination of the defect reduces the thickness of the section below the minimum required to satisfy Article WB-3000, the product shall be repaired in accordance with WB-2539.

WB-2539  Repair by Welding

The Material Organization may repair by welding material from which defects have been removed, provided the depth of the repair cavity does not exceed one-third the nominal thickness and the requirements of the following subparagraphs are met. Prior approval of the Certificate Holder shall be obtained for the repair of plates to be used in the manufacture of a containment.

WB-2539.1  Defect Removal. The defect shall be removed by suitable mechanical or thermal cutting or gouging methods and the cavity prepared for repair (WB-4211.1).
Figure WC-3225-3
Attachment of Flat Heads to Containment Shell

(a) $t_p$, $a + b$ not less than $2t_s$
$b + c$ not less than $t_s$
$C = 0.33m$ but not less than 0.20

(b) $t_s$, $a + b$ not less than $2t_s$
$C = 0.33m$ but not less than 0.20

(c) $t_s$, $a + b$ but not less than $3t_s$
$b + c$ not less than $t_s$

(d) $t_s$, $C = 0.33m$ but not less than 0.20

(e) $t_s$, $C = 0.33m$ but not less than 0.20

(f) $t_s$, $C = 0.33m$ but not less than 0.20

(g) $t_s$, $C = 0.33m$ but not less than 0.20

GENERAL NOTE: $C$ min. = 0.7$t_s$ or $\frac{1}{4}$ in. (6 mm), whichever is less; $b$ = the lesser of $t_s$ or $T/2$.

Small $C$ since it is the dimension, not the factor.
(b) Specimens shall be taken in accordance with the requirements of Article WC-2000 and shall be taken from the tension side of the strained material.

(c) The percent strain shall be established by the following equations:

(1) For cylinders
\[
\% \text{ strain} = \frac{500}{R_f} \left( 1 - \frac{R_f}{R_o} \right)
\]

(2) For spherical or dished surfaces
\[
\% \text{ strain} = \frac{75r}{R_f} \left( 1 - \frac{R_f}{R_o} \right)
\]

(3) For pipe
\[
\% \text{ strain} = \frac{100r}{R}
\]

where
\[
R = \text{nominal bending radius to the center line of the pipe}\]
\[
R_f = \text{final radius to center line of shell}\]
\[
R_o = \text{original radius (equal to infinity for a flat part)}\]
\[
r = \text{nominal radius of the pipe}\]
\[
t = \text{nominal thickness}\]

(d) The procedure qualification shall simulate the maximum percent surface strain, employing a bending process similar to that used in the fabrication of the material or by direct tension on the specimen.

(e) Sufficient CV test specimens shall be taken from each of the three heats of material to establish a transition curve showing both the upper and lower shelves. On each of the three heats, tests consisting of three impact specimens shall be conducted at a minimum of five different temperatures distributed throughout the transition region. The upper and lower shelves may be established by the use of one test specimen for each shelf. Depending on the product form, it may be necessary to plot the transition curves using both the lateral expansion and energy level data (WC-2300). In addition, drop weight tests shall be made when required by WC-2300.

(f) Using the results of the impact test data from each of these heats, taken both before and after straining, determine either:

(1) the maximum change in NDT temperature along with:
   
   (a) the maximum change of lateral expansion and energy at the temperature under consideration; or
   
   (b) the maximum change in temperature at the lateral expansion and energy levels under consideration; or
   
   (2) where lateral expansion is the acceptance criteria (WC-2300), either the maximum change in temperature or the maximum change in lateral expansion.

WC-4213.3 Acceptance Criteria for Formed Material. To be acceptable, the formed material used in the component shall have impact properties, before forming, sufficient to compensate for the maximum loss of impact properties due to the qualified forming procedure used.

WC-4213.4 Requalification. A new procedure qualification test is required when any of the changes in (a), (b), or (c) below are made.

(a) The actual postweld heat treatment time at temperature is greater than previously qualified considering WC-2211. If the material is not postweld heat treated, the procedure must be qualified without postweld heat treatment.

(b) The maximum calculated strain of the material exceeds the previously qualified strain by more than 0.5%.

(c) Where preheat over 250°F (120°C) is used in the forming or bending operation but not followed by a subsequent postweld heat treatment.

WC-4214 Minimum Thickness of Fabricated Material

If any fabrication operation reduces the thickness below the minimum required to satisfy the rules of WC-2124 and Article WC-3000, the material may be repaired in accordance with WC-4130.

WC-4220 FORMING TOLERANCES

WC-4221 Tolerance for Containment Shells

Cylindrical, conical, or spherical shells of a completed containment, except formed heads covered by WC-4222, shall meet the requirements of the following subparagraphs at all cross sections.

WC-4221.1 Maximum Difference in Cross-Sectional

Diameters. The difference in inches (mm) between the maximum and minimum diameters at any cross-section shall not exceed the smaller of

(U.S. Customary Units)
\[
\frac{D}{200} = \frac{50}{100}
\]

(SI Units)
\[
\frac{D}{200} = \frac{1250}{100}
\]

where D is the nominal inside diameter, in. (mm), at the cross section under consideration. The diameters may be measured on the inside or outside of the containment. If measured on the outside, the diameters shall be corrected for the plate thickness at the cross section under consideration (Figure WC-4221.1-1). When the cross section passes through an opening, the permissible difference in inside diameters given herein may be increased by 2% of the inside diameter of the opening.
temperature \( R_{NTD} = T_{C_v} - 60^\circ F \) (33°C). Thus, the reference temperature \( R_{NTD} \) is the higher of \( T_{NDT} \) or \([ T_{C_v} - 60^\circ F \) (33°C)]).

(4) When a \( C_v \) test has not been performed \([ T_{NDT} + 60^\circ F \) (33°C)] or when the \( C_v \) test at \([ T_{NDT} + 60^\circ F \) (33°C)] does not exhibit a minimum of 50 ft-lb (68 J) energy absorption and 35 mils (0.89 mm) lateral expansion, a temperature representing a minimum of 50 ft-lb (68 J) energy absorption and 35 mils (0.89 mm) lateral expansion may be obtained from a full \( C_v \) impact curve developed from the minimum data points of all the \( C_v \) tests performed.

(5) The lowest service temperature shall be not lower than \( R_{NTD} + 100^\circ F \) (56°C) unless a lower temperature is justified by using methods similar to those contained in Section III Appendices, Nonmandatory Appendix G.

(b) Apply the procedures of (a) above to

(1) the base material

(2) the base material, the heat-affected zone, and weld metal from the weld procedure qualification tests in accordance with WD-4330

(3) the weld metal of WD-2431

(c) Product forms having dimensions that prohibit obtaining drop weight test specimens shall be tested in accordance with WD-2331.

(d) Consideration shall be given to the effects of irradiation on material toughness properties. The Design Specification shall include additional requirements, as necessary, to assure adequate fracture toughness for the service lifetime of the integral support structures. The toughness properties may be verified in service periodically by a material surveillance program using the methods of ASTM E185 and the material conditions monitored by the inservice inspection requirements of Section XI.

WD-2340 NUMBER OF IMPACT TESTS REQUIRED

WD-2341 Plates

One test shall be made from each plate as heat treated. Where plates are furnished in the nonheat-treated condition and qualified by heat treated test specimens, one test shall be made for each plate as-rolled. The term as-rolled refers to the plate rolled from a slab or directly from an ingot, not to its heat treated condition.

WD-2342 Forgings

(a) Where the weight of an individual forging is less than 1,000 lb (450 kg), one test shall be made to represent each heat in each heat treatment lot.

(b) When heat treatment is performed in a continuous type furnace with suitable temperature controls and equipped with recording pyrometers so that complete heat treatment records are available, a heat treatment charge shall be considered as the lesser of a continuous run not exceeding 8 hr duration or a total weight, so treated, not exceeding 2,000 lb (900 kg).

(c) One test shall be made for each forging of 1,000 lb to 10,000 lb (450 kg to 4,500 kg) in weight.

(d) As an alternative to (c) above, a separate test forging may be used to represent forgings of different sizes in one heat and heat treat lot, provided the test piece is a representation of the greatest thickness in the heat treat lot. In addition, test forgings shall have been subjected to substantially the same reduction and working as the forgings represented.

(e) Forgings larger than 10,000 lb (4,500 kg) shall have two tests per part for Charpy V-notch and one test for drop weights. The location of drop weight or \( C_v \) impact test specimens shall be selected so that an equal number of specimens is obtained from positions in the forging 180 deg apart.

WD-2343 Bars

One test shall be made for each diameter or size having a nominal cross-sectional area greater than 1 in.\(^2\) in each lot, where a lot is defined as one heat of material heat treated in one charge or as one continuous operation, not to exceed 6,000 lb (2,700 kg).

WD-2344 Tubular Products and Fittings

On products that are seamless or welded without filler metal, one test shall be made from each lot. On products that are welded with filler metal, one additional test with the specimens taken from the weld area shall also be made on each lot. A lot shall be defined as stated in the applicable material specification but in no case shall a lot consist of products from more than one heat of material and of more than one diameter, with the nominal thickness of any product included not exceeding that to be impact tested by more than \( 1/4 \) in. (6 mm); a such lot shall be in a single heat treatment load or in the same

---

### Table WD-2333-1

<table>
<thead>
<tr>
<th>Nominal Diameter, in. (mm)</th>
<th>Lateral Expansion, mils (mm)</th>
<th>Absorbed Energy, ft-lb (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (25) or less</td>
<td>No test required</td>
<td>No test required</td>
</tr>
<tr>
<td>1 (25) through 4 (100)</td>
<td>25 (0.64)</td>
<td>No requirements</td>
</tr>
<tr>
<td>Over 4 (100)</td>
<td>25 (0.64)</td>
<td>45 (61)</td>
</tr>
</tbody>
</table>
continuous run in a continuous furnace controlled within a 50°F (28°C) range and equipped with recording pyrometers.

**WD-2345 Bolting Material**

One test shall be made for each lot of material where a lot is defined as one heat of material heat treated in one charge or as one continuous operation, not to exceed in weight the following:

<table>
<thead>
<tr>
<th>Diameter, in. (mm)</th>
<th>Weight, lb (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4 (6) and less</td>
<td>1,500 (700)</td>
</tr>
<tr>
<td>Over 1/4 to 2/3 (45 to 64)</td>
<td>3,000 (1,350)</td>
</tr>
<tr>
<td>Over 2/3 to 5 (64 to 125)</td>
<td>6,000 (2,700)</td>
</tr>
<tr>
<td>Over 5 (125)</td>
<td>10,000 (4,500)</td>
</tr>
</tbody>
</table>

**WD-2346 Test Definition**

Unless otherwise stated in **WD-2345** through **WD-2345**, the term **one test** is defined to include the combination of the drop weight test and the Cₚ test when RTₕNTD is required (**WD-2332**) and only the Cₚ test when determination of RTₕNTD is not required (**WD-2331**).

**WD-2350 RETESTS**

(a) For Cₚ tests required by **WD-2330**, one retest at the same temperature may be conducted, provided:

(1) the average value of the test results meets the minimum requirements,
(2) not more than one specimen per test is below the minimum requirements,
(3) the specimen not meeting the minimum requirements is not lower than 10 ft-lb (13.6 J) or 5 mils (0.13 mm) below the specified requirements.

(b) A retest consists of two additional specimens taken as near as practicable to the failed specimens. For acceptance of the retest, both specimens shall meet the minimum requirements.

**WD-2360 CALIBRATION OF INSTRUMENTS AND EQUIPMENT**

Calibration of temperature instruments and Cₚ impact test machines used in impact testing shall be performed at the frequency specified in the following:

(a) Temperature instruments used to control test temperature of specimens shall be calibrated and the results recorded to meet the requirements of NCA-4258.2 at least once in each 3-month interval.

(b) Cₚ test machines shall be calibrated and the results recorded to meet the requirements of NCA-4258.2. The calibrations shall be performed using the frequency and methods outlined in ASTM E23 and employing standard specimens obtained from the National Institute of Standards and Technology, or any supplier of subcontracted calibration services accredited in accordance with the requirements of WA-3123 and NCA-4258.2(c).

**WD-2400 WELDING MATERIAL**

**WD-2410 GENERAL REQUIREMENTS**

(a) All welding material used in the construction and repair of components or material, except welding material used for hard surfacing, shall conform to the requirements of the material specification or to the requirements for other welding material as permitted in Section IX. In addition, welding material shall conform to the requirements stated in this subarticle and to the rules covering identification in **WD-2150**.

(b) The Certificate Holder shall provide the organization performing the testing with the following information, as applicable:

(1) welding process,
(2) SFA Specification and classification,
(3) other identification if no SFA Specification applies,
(4) minimum tensile strength [**WD-2431.1(c)**] in either the as-welded or heat-treated condition or both [**WD-2431.1(c)**],
(5) drop weight test for material as-welded or heat treated or both (**WD-2332**),
(6) Charpy V-notch test for material as-welded or heat treated or both (**WD-2331**); the test temperature, and the lateral expansion or the absorbed energy, shall be provided,
(7) the preheat and interpass temperatures to be used during welding of the test coupon (**WD-2431.1(c)**),
(8) postweld heat treatment time, temperature range, and maximum cooling rate, if the production weld will be heat treated (**WD-2431.1(c)**),
(9) elements for which chemical analysis is required per the SFA Specification or WPS, and **WD-2432**
(10) minimum delta ferrite (**WD-2433**)

**WD-2420 REQUIRED TESTS**

The required tests shall be conducted for each lot of covered, flux cored, or fabricated electrodes; for each heat of bare electrodes, rod, or wire for use with the OFW, GMAW, GTAW, and PAW processes (Section IX); for each heat of consumable inserts; for each combination of heat of bare electrodes and lot of submerged arc flux; for each combination of lot of fabricated electrodes and lot of submerged arc flux; or for each combination of heat of bare electrodes or lot of fabricated electrodes and dry blend of supplementary powdered filler metal and lot of submerged arc flux. Tests performed on welding material in the qualification of weld procedures will satisfy the testing requirements for the lot, heat, or combination of heat and batch of welding material used, provided the tests required by Article **WD-4000** and this subarticle are made and the results conform to the requirements of this Article. The following definitions apply:

(c) dry batch of covering mixture: the quantity of dry covering ingredients mixed at one time in one mixing vessel; a dry batch may be used singly or may be
The deformations of an ideally plastic structure increase without bound at this load, which is termed the collapse load. Among the methods used in limit analysis is a technique that assumes elastic, perfectly plastic, material behavior and a constant level of moment or force in those redundant structural elements in which membrane yield, plastic hinge, or critical buckling load has been reached. Any increase in load must be accompanied by a stable primary structure until a failure mechanism defined by the lower bound theorem of limit analysis is reached in the primary structure.

**WD-3213.16 Collapse Load — Lower Bound.** If, for a given load, any system of stresses can be found that 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 that permits calculations of a lower bound to the collapse load.

**WD-3213.17 Critical Buckling.** Critical buckling occurs when an internal support structure is loaded to a state at which an infinitesimal additional load or disturbance causes the internal support structure to change from an equilibrium condition to one of instability.

**WD-3213.18 Operational Cycle.** Operational cycle is defined as the initiation and establishment of new conditions followed by a return to the conditions that prevailed at the beginning of the cycle. The types of operating conditions that may occur are further defined in **WD-3113**.

**WD-3213.19 Stress Cycle.** Stress cycle is a condition in which the alternating stress difference goes from an initial value through an algebraic maximum value to an algebraic minimum value and then returns to the initial value. A single operational cycle may result in one or more stress cycles. Dynamic effects shall also be considered as stress cycles.

**WD-3213.20 Fatigue Strength Reduction Factor.** Fatigue strength reduction factor is a stress concentration factor that accounts for the effect of a local structural discontinuity (stress concentration) on the fatigue strength. In the absence of experimental data, the theoretical stress concentration factor may be used.

**WD-3213.21 Deformation.** Deformation of a component is an alteration of its shape or size.

**WD-3213.22 Ratcheting.** Ratcheting is a progressive incremental inelastic deformation or strain that can occur in a component that is subjected to variations of mechanical stress, thermal stress, or both.

**WD-3213.23 Shakedown.** Shakedown of a structure occurs if, after a few cycles of load application, ratcheting ceases. The subsequent structural response is elastic, or elastic-plastic, and progressive incremental inelastic deformation is absent. Elastic shakedown is the case in which the subsequent response is elastic.

**WD-3214 Stress Analysis**

A detailed stress analysis of the internal support structure shall be prepared in sufficient detail to show that each of the stress limitations of **WD-3220**, **WD-3230**, and **WD-3240** are satisfied when the internal support structure is subjected to the loadings of **WD-3110**.

**WD-3215 Derivation of Stress Intensities**

One requirement for the acceptability of a design (**WD-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 that are subject to the specified limits. The steps in the procedure are stipulated in (a) through (e) below.

(a) At the point on the structure that 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 \( \sigma_t \), \( \sigma_l \), and \( \sigma_r \) for normal stresses and \( \tau_{tl} \), \( \tau_{tr} \), and \( \tau_{rl} \) for shear 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 [see **Table WD-3217-1** and Figure **WD-3222-1**,

(c) For each category, calculate the algebraic sum of the values for each direction yielding principal stresses \( \sigma_1 \), \( \sigma_2 \), and \( \sigma_3 \). In many structural calculations, the \( t \), \( l \), and \( r \) directions may be so chosen that the shear stress components are zero and \( \sigma_1 \), \( \sigma_2 \), and \( \sigma_3 \) are identical to \( \sigma_t \), \( \sigma_l \), and \( \sigma_r \).

(d) 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 $S_{31}$.

NOTE: Membrane stress intensity is derived from the stress components averaged across the thickness of the section. The averaging shall be performed at the component level in (b) or (c) above.

**WD-3216 Derivation of Stress Differences and Alternating Stress Intensities**

If the specified operation of the internal support structure does not meet the conditions of WD-3222.5(d), the ability of the structure to withstand the specified cyclic operation without fatigue failure shall be determined as provided in WD-3222.5(e). The determination shall be made on the basis of the stresses at a point throughout the structure, and the allowable stress cycles shall be adequate for the specified service at every point. Only the stress differences due to cyclic operating loads as specified in the Design Specification need be considered.

**WD-3216.1 Constant Principal Stress Direction**

For any case in which the directions of the principal stresses at the point being considered do not change during the cycle, the steps stipulated in (a) through (c) shall be taken to determine the alternating stress intensity.

(a) **Principal Stresses.** Consider the values of the three principal stresses at the point versus time for the complete stress cycle, taking into account both the gross and local structural discontinuities and the thermal effects that vary during the cycle. These are designated as $\sigma_1$, $\sigma_2$, and $\sigma_3$ for later identification.

(b) **Stress Differences.** Determine the stress differences $\Delta\sigma_1 = \sigma_1 - \sigma_2$, $\Delta\sigma_2 = \sigma_2 - \sigma_3$, $\Delta\sigma_3 = \sigma_3 - \sigma_1$ versus time for the complete cycle. In what follows, the symbol $\Delta\sigma_{ij}$ is used to represent any one of these three stress differences.

(c) **Alternating Stress Intensity.** Determine the extremes of the range through which each stress difference $\Delta\sigma_{ij}$ fluctuates and find the absolute magnitude of this range for each $\Delta\sigma_{ij}$. Call this magnitude $S_{ij}$, and let $S_{alt ij} = 0.5 S_{ij}$. The alternating stress intensity $S_{alt}$ is the largest of the $S_{alt ij}$ values.

**WD-3216.2 Varying Principal Stress Direction.**

For any case in which the directions of the principal stresses at the point being considered do change during the stress cycle, it is necessary to use the more general procedure of (a) through (e) below.

(a) Consider the values of the six stress components $\sigma_1$, $\sigma_2$, $\tau_{11}$, $\tau_{22}$, $\tau_{12}$, which versus time for the complete stress cycle, taking into account both the gross and local structural discontinuities and the thermal effects that vary during the cycle.

(b) Choose a point in time when the conditions are one of the extremes for the cycle (either maximum or minimum, algebraically) and identify the stress components at this time by the subscript $i$. In most cases it will be possible to choose at least one time during the cycle when the conditions are known to be extreme. In some cases, it may be necessary to try different points in time to find the one that results in the largest value of alternating stress intensity.

(c) Subtract each of the six stress components $\sigma_i$, $\tau_{ij}$, etc., from the corresponding stress components $\sigma_{i}'$, $\tau_{ij}'$, etc., at each point in time during the cycle and call the resulting components $\sigma_{i}'$, $\tau_{ij}'$, etc.

(d) At each point in time during the cycle, calculate the principal stresses $\sigma_{i}'$, $\sigma_{j}'$, $\sigma_{k}'$ derived from the six stress components $\sigma_{i}'$, $\tau_{ij}'$, etc. Note that the directions of the principal stresses may change during the cycle but each principal stress retains its identity as it rotates.

(e) Determine the stress differences $S_{12}' = \sigma_{1}' - \sigma_{2}'$, $S_{23}' = \sigma_{2}' - \sigma_{3}'$, $S_{31}' = \sigma_{3}' - \sigma_{1}'$ versus time for the complete cycle and find the largest absolute magnitude of any stress difference at any time. The alternating stress intensity $S_{alt}'$ is one-half of this magnitude.

**WD-3217 Classification of Stress**

Table WD-3217-1 provides assistance in the determination of the category to which a stress should be assigned.

**WD-3220 DESIGN BY ANALYSIS REQUIREMENTS FOR PLATE- AND SHELL-TYPE INTERNAL SUPPORT STRUCTURE MEMBERS**

Plate- and shell-type internal support structures shall satisfy the stress intensity limits in WD-3220 and the acceptable deformation limits set forth in the Design Specification to ensure criticality control.

(a) To satisfy stress intensity limits, an elastic analysis shall be performed except as permitted by WD-3225.

(b) To satisfy deformation limits in those cases where stresses exceed $S_p$ at temperature, an analysis that maximizes deformations as discussed in WD-3125 shall be performed.

**WD-3221 Design Limits**

The stress intensity limits that shall be satisfied for the Design Loadings (WD-3112) stated in the Design Specification are the three limits of this paragraph and the special stress limits of WD-3227. The design stress intensity values $S_m$ at the Design Temperature are described in WD-3112-3. The limits are summarized by Figure WD-3221-1.

**WD-3221.1 General Primary Membrane Stress Intensity.** This stress intensity (derived from $P_m$ in Figure WD-3221-1) is derived from the average value across the thickness of a section of the general primary stresses (WD-3213.6) produced by specified Design Mechanical Loads, but excluding all secondary and peak stresses. Averaging is to be applied to the stress components prior to determination of the stress intensity values. The allowable value of the stress intensity is $S_m$ at the Design Temperature.
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 $S_u$ 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 $S_u$ 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 $S_u/E_1(\alpha_1 - \alpha_2)$, where $S_u$ 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 $S/(2E_1\alpha_1 - E_2\alpha_2)$, 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 $S_u$ 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 $S_u$ obtained from the applicable design fatigue curve for the maximum number of cycles defined on the curve. The two materials used have different applicable design fatigue curves, the lower value of $S_u$ shall be used in applying the rules of this paragraph.

(4) Mechanical Loads. The specified full range of mechanical loads does not result in load stresses whose range exceeds the $S_u$ 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 $S_u$ 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 $S_u$ 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 $S_u$ 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 curves 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 $S_u$ 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, 11-1600. 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 design fatigue 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 $n_1, n_2, n_3, ..., n_n$, respectively.
NOTE: In determining $n_1, n_2, n_3, ..., n_m$, consideration shall be given to the superposition of cycles of various origins that produce a total stress difference range greater than the stress difference ranges of the individual cycles. For example, if one type of stress cycle produces 1,000 cycles of a stress difference variation from zero to +60,000 psi and another type of stress cycle produces 10,000 cycles of a stress difference variation from zero to -50,000 psi, the two types of cycles to be considered are defined by the following parameters:

Type 1 cycle: $n_1 = 1,000,$
$S_{ait1} = (60,000 + 50,000)/2 = 55,000$ psi

Type 2 cycle: $n_2 = 9,000,$
$S_{ait2} = (50,000 + 0)/2 = 25,000$ psi

Step 2. For each type of stress cycle, determine the alternating stress intensity $S_{ait}$ by the procedures of WD-3216.1 or WD-3216.2 above. Call these quantities $S_{ait1}, S_{ait2}, S_{ait3}, ..., S_{aitn}$.

Step 3. For each value $S_{ait1}, S_{ait2}, S_{ait3}, ..., S_{aitn}$, use the applicable design fatigue curve (Section III Appendices, Mandatory Appendix I) to determine the maximum number of repetitions that would be allowable if this type of cycle were the only one acting. Call these values $N_1, N_2, N_3, ..., N_n$.

Step 4. For each type of stress cycle, calculate the usage factors $U_1, U_2, U_3, ..., U_n$, from $U_3 = n_3/N_3, U_2 = n_2/N_2, U_3 = n_3/N_3, ..., U_n = n_n/N_n$.

Step 5. Calculate the cumulative usage factor $U$ from $U = U_1 + U_2 + U_3 + ... + U_n$.

Step 6. The cumulative usage factor $U$ shall not exceed 1.0.

**WD-3222.6 Stress Ratcheting.** It should be noted that under certain combinations of steady-state and cyclic loadings, there is a possibility of large distortions developing as the result of ratcheting action; that is, the deformation increases by a nearly equal amount for each cycle. Ratcheting can occur in a structure that is subjected to variations of mechanical stress, thermal stress, or both. Examples of this phenomenon are treated in this subparagraph and in WD-3227.3.

(a) The limiting value of the maximum cyclic thermal stress permitted in a portion of an axisymmetric shell or plate with steady-state loading in order to prevent cyclic progressive distortion is determined as follows. Let

$y' = \max$ maximum allowable range of thermal stress computed on an elastic basis divided by the yield strength $S_y$, taken at the average temperature of the transient under consideration

$x = \max$ maximum general membrane stress divided by the yield strength $S_y$, taken at the average temperature of the transient under consideration

NOTE: For both $x$ and $y'$, it is permissible to use $1.5S_y$, whenever it is greater than $S_y$.

(1) Case 1: linear variation of temperature through the wall

$y' = 1/x$ for $0 < x < 0.5$

(2) Case 2: parabolic, constantly increasing or constantly decreasing, variation of temperature through the wall

$y' = 5.2(1 - x)$ for $0.615 < x < 1.0$ and, approximately, for $x < 0.615$ as follows:

$y' = 4.65, 3.55,$ and $2.70,$ for $x = 0.3, 0.4,$ and $0.5,$ respectively.

(b) Use of yield strength $S_y$ in the above relations instead of the proportional limit allows a small amount of growth during each cycle until strain hardening raises the proportional limit to $S_y$. If the yield strength of the material is higher than two times the $S_y$ value for the maximum number of cycles on the applicable fatigue curve of Section III Appendices, Mandatory Appendix I for the material, the latter value shall be used if there is to be a large number of cycles because strain softening may occur.

(c) Similar methodology shall be used for mechanical-applied ratcheting loads specified in the Design Specification. The Design Specification may prescribe specific methodology.

**WD-3222.7 Deformation Limits.** Any deformation limits prescribed by the Design Specification shall be satisfied. See WD-3125.

**WD-3224 Level C Service Limits**

The Level C Service Limits shall be satisfied for off-normal loadings for which they are designated by the Design Specification and are summarized by Figure WD-3224-1. Dynamic instability shall be considered in meeting the load, stress, and deformation limits.

**WD-3224.1 Primary Stress Intensity Limits.** The permissible values for Level C Service Limits shall be taken as 150% of the values given in WD-3221. See WD-3221.3 when evaluating other than solid rectangular sections.

**WD-3224.2 Special Stress Limits.** The permissible values for special stress limits shall be taken as 150% of the values given in WD-3227. The requirements of WD-3227.2(c) and WD-3227.3 need not be satisfied.

**WD-3224.3 Deformation Limits.** Any deformation limits prescribed by the Design Specification shall be satisfied. See WD-3125.

**WD-3225 Level D Service Limits**

If the Design Specification specifies any accident loadings for which Level D Service Limits are designated [WA-2123.4(b)], the rules contained in Section III
### Stress Categories and Limits of Stress Intensities for Off-Normal Loadings

<table>
<thead>
<tr>
<th>Stress Category</th>
<th>General Membrane</th>
<th>Primary [Notes (1), (2), and (3)]</th>
<th>Local Membrane</th>
<th>Bending</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description (for examples, see Table WD-3217-1)</td>
<td>Average primary stress across solid section. Excludes discontinuities and concentrations.</td>
<td>Average stress across any solid section. Considers discontinuities but not concentrations.</td>
<td>Component of primary stress proportional to distance from centroid of solid section. Excludes effects of discontinuities and concentrations.</td>
<td></td>
</tr>
<tr>
<td>Symbol</td>
<td>$P_m$</td>
<td>$P_t$</td>
<td>$P_b$</td>
<td></td>
</tr>
<tr>
<td>Combination of stress components and allowable limits of stress intensities.</td>
<td>1.5$S_m$ Elastic</td>
<td>2.25$S_m$ Elastic</td>
<td>(2$P_m$ or $P_t$) + $P_b$</td>
<td></td>
</tr>
<tr>
<td>Level C Service Limits</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Legend:
- $\circ$ = Allowable value
- $\square$ = Calculated Value

#### NOTES:
1. The symbols $P_m$, $P_t$, $P_b$ do not represent single quantities, but rather sets of six quantities representing the six stress components $\sigma_x$, $\sigma_y$, $\sigma_z$, $\tau_{xy}$, $\tau_{yz}$, and $\tau_{zx}$.
2. For configurations where compressive stresses occur, the stress limits shall be revised to take into account critical buckling stresses (WD-3229).
3. When loads are dynamically applied, consideration should be given to the use of dynamic load amplification.
4. Values shown are for a solid rectangular section. See WD-3224-1 for other than a solid rectangular section.

### WD-3227 Special Stress Limits

The following deviations from the basic stress limits are provided to cover special operating loadings or configurations. Some of these deviations are more restrictive, and some are less restrictive, than the basic stress limits. Rules governing application of these special stress limits for Level C and Level D Service Limit applications are contained in WD-3224.2 and WD-3225, respectively. In cases of conflict between these requirements and the basic stress limits, the rules of WD-3227 take precedence for the particular situations to which they apply. WD-3227 does not apply to bolted joints (WD-3230).

#### WD-3227.1 Bearing Loads.

(a) The average bearing stress for resistance to crushing under the maximum load, experienced as a result of Design Loadings or normal loadings for which Design or Level A Service Limits, respectively, are designated, shall be limited to $S_y$, at temperature, except that when the distance to a free edge is larger than the distance over which the bearing load is applied, a stress of 1.5$S_y$ at temperature is permitted. For clad surfaces, the strength 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.

(b) When bearing loads are applied near free edges, such as at a protruding ledge, the possibility of a shear failure shall be considered. In the case of load stress only, the average shear stress shall be limited to 0.6$S_y$. In the case of load stress plus secondary stress, the average shear stress shall not exceed (1) or (2) below:

1. For materials to which Section II, Part D, Subpart 1, Table 2A, Note G7 or Table 2B, Note G1, applies, the lower of 0.5$S_y$ at 100°F (38°C) and 0.67$S_y$ at temperature;
2. For all other material, 0.5$S_y$ at temperature.
(c) 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.

(d) When considering bearing stresses in pins and similar members, the $S_y$ at temperature value is applicable, except that a value of 1.5$S_y$ may be used if no credit is given to bearing area within one pin diameter from a plate edge.

**WD-3227.2** **Pure Shear.**

(a) The average primary shear stress across a section loaded in pure shear, experienced as a result of Design Loadings or normal loadings for which Design or Level A Service Limits, respectively, are designated (for example, keys, shear rings), shall be limited to 0.6$S_m$.

(b) The maximum primary shear, experienced as a result of Design Loadings or normal loadings for which Design or Level A Service Limits, respectively, are designated, exclusive of stress concentration at the peripheral of a solid circular section in torsion, shall be limited to 0.8$S_m$.

(c) Primary plus secondary and peak shear stresses shall be converted to stress intensities (equal to two times pure shear stress) and, as such, shall not exceed the basic stress limits of **WD-3222.4** and **WD-3222.5**.

**WD-3227.3** **Progressive Distortion of Nonintegral Connections.** Screwed-on caps, screwed-in plugs, shear ring closures, and breechlock closures are examples of nonintegral connections that are subject to failure by bell moutching 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 operating 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. Therefore, primary plus secondary stress intensities (**WD-3222.4**) that result in slippage between the parts of a nonintegral connection, in which disengagement could occur as a result of progressive distortion, shall be limited to the value $S_y$ (Section II, Part D, Subpart 1, Table Y-1) at the temperature under consideration.

**WD-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 $S_m$, except for Service Level D.

**WD-3227.5** **Applications of Elastic Analysis for Stresses Beyond the Yield Strength.** Certain of the allowable stresses permitted in the design criteria are such that the maximum stress calculated on an elastic basis may exceed the yield strength of the material. The limit on primary plus secondary stress intensity of $3S_m$ (**WD-3222.4**) has been placed at a level that assures shakedown to elastic action after a few repetitions of the stress cycle except in regions containing significant local structural discontinuities or local thermal stresses. These last two factors are considered only in the performance of a fatigue evaluation. Therefore

(a) in evaluating stresses for comparison with the stress limits on other than fatigue allowables, stresses shall be calculated on an elastic basis

(b) in evaluating stresses for comparison with fatigue allowables, all stresses except those that result from local thermal stresses [**WD-3215.12(b)**] shall be evaluated on an elastic basis. In evaluating local thermal stresses, the elastic equations shall be used, except that the numerical value substituted for Poisson’s ratio shall be determined from the expression

$$\nu = 0.5 - 0.2 \frac{S_y}{S_m},$$

but not less than 0.3

where

$S_n =$ alternating stress intensity determined in **WD-3222.5(e)** prior to the elastic modulus adjustment in **WD-3222.5(e)(4)**

$S_y =$ the yield strength of the material at the mean value of the temperature of the cycle

**WD-3228** **Simplified Elastic–Plastic Analysis**

The $3S_m$ limit on the range of primary plus secondary stress intensity (**WD-3222.4**) may be exceeded, provided that the requirements of (a) through (f) below are met.

(a) The range of primary plus secondary membrane plus bending stress intensity, excluding thermal bending stresses, shall be $\leq 3S_m$.

(b) The value of $S_n$ used for entering the design fatigue curve is multiplied by the factor $K_e$ where

$$K_e = \begin{cases} 1.0 & \text{for } S_n \leq 3S_m \\ 1.0 + \frac{[1-n]}{n(m-1)}\left(\frac{S_n}{3S_m} - 1\right) & \text{for } 3S_m < S_n < 3mS_m \\ 1/n & \text{for } S_n \geq 3mS_m \end{cases}$$

$S_n =$ range of primary plus secondary stress intensity
shall be plotted on a lateral expansion versus temperature graph. The difference in temperature between \( T_{\text{HAZ}} \) and \( T_{\text{UBM}} \), where the heat-affected zone and the unaffected base material average lateral expansion values are the same and not less than that specified in (2) above, shall be used to determine the adjustment temperature \( T_{\text{ADJ}} \), where

\[
T_{\text{ADJ}} = T_{\text{HAZ}} - T_{\text{UBM}}
\]

If \( T_{\text{ADJ}} \leq 0 \), then \( T_{\text{ADJ}} = 0 \).

(4) As an alternative to (3) above, if the average lateral expansion value of the heat-affected zone is no less than 35 mils (0.89 mm) and the average of the heat-affected zone specimens is not less than 5 mils (0.13 mm) below the average lateral expansion value of the unaffected base material, \( T_{\text{ADJ}} \) may be taken as 15°F (8°C).

(5) As a second alternative to (3) above, if the average lateral expansion value of the heat-affected zone specimens is no less than 35 mils (0.89 mm), the difference between the average lateral expansion of the heat-affected zone and the unaffected base material specimens shall be calculated and used as described in (e)(3) below.

(e) At least one of the following methods shall be used to compensate for the heat-affected zone toughness decrease due to the welding procedure effects:

(1) The \( RT_{\text{BDT}} \) temperature established in WD-2332 or the lowest service temperature specified in the Design Specification (WD-2331) for all of the material to be welded in production Welding Procedure Specifications supported by this Welding Procedure Qualification Record shall be increased by the adjustment temperature \( T_{\text{ADJ}} \).

(2) The specified testing temperature for the production material may be reduced by \( T_{\text{ADJ}} \).

(3) The materials to be welded may be welded using the Welding Procedure Specification provided they exhibit \( C_v \) values that are no less than the minimum required lateral expansion value required by WD-2300 plus the difference in average lateral expansion values established in (c)(7) or (d)(5) above.

(7) The \( C_v \) testing results shall be recorded on the Welding Procedure Qualification Record and any offsetting \( T_{\text{ADJ}} \) or increased toughness requirements shall be noted on the Welding Procedure Qualification Record and on the Welding Procedure Specification. More than one compensation method may be documented on the Welding Procedure Qualification Record.

(g) A Welding Procedure Specification qualified to the impact testing requirements of Subsection WB, WC, NW, NC, or NE may be accepted as an alternative to the Welding Procedure impact testing requirements of this Division.

WD-4336 Qualification Requirements for Built-Up Weld Deposits

Built-up weld deposits for base metal reinforcement shall be qualified in accordance with the requirements of WD-4331 to WD-4335, inclusive.

WD-4400 RULES GOVERNING MAKING, EXAMINING, AND REPAIRING WELDS

WD-4410 PRECAUTIONS TO BE TAKEN BEFORE WELDING

WD-4411 Identification, Storage, and Handling of Welding Material

Each Certificate Holder shall be responsible for control of the welding electrodes and other material that is used in the fabrication (WD-4120). Suitable identification, storage, and handling of electrodes, flux, and other welding material shall be maintained. Precautions shall be taken to minimize absorption of moisture by electrodes and flux.

WD-4412 Cleanliness and Protection of Welding Surfaces

The method used to prepare the base metal shall leave the weld preparation with reasonably smooth surfaces. The surfaces for welding shall be free of scale, rust, oil, grease, and other deleterious material. The work shall be protected from deleterious contamination and from rain, snow, and wind during welding. Welding shall not be performed on wet surfaces.

WD-4420 RULES FOR MAKING WELDED JOINTS

WD-4421 Backing Bars

Backing bars shall conform to the requirements of WD-3240. The material for backing bars, when used, shall be compatible with the base metal. Permanent backing bars, when permitted by WD-3240, shall be continuous, and any splices shall be made by full penetration welds. Spacer pins shall not be incorporated into the welds.

WD-4422 Peening

Controlled peening may be performed to minimize distortion. Peening shall not be used for stress mitigation. Peening shall not be used on the initial layer, root of the weld metal, or on the final layer unless the weld is post-weld heat treated.