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SECTION VIII

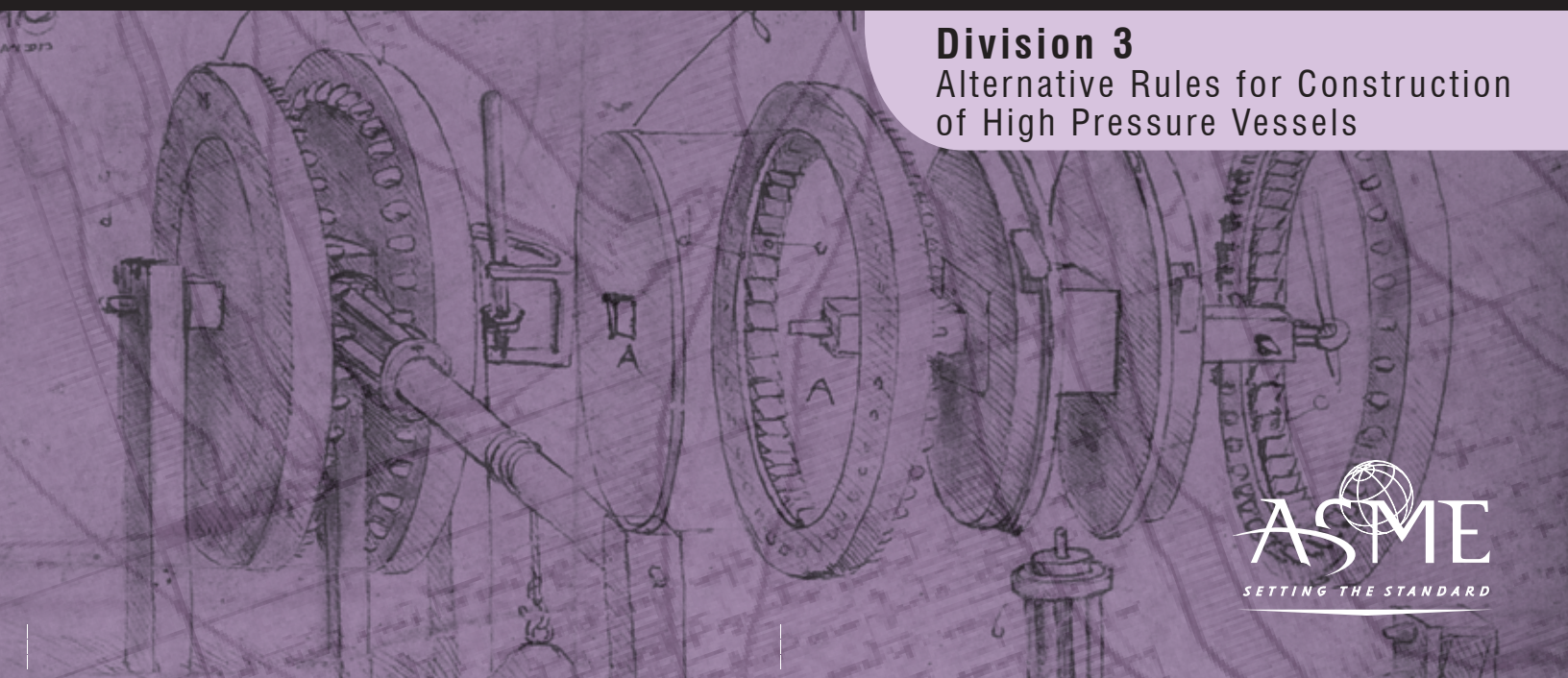
Rules for Construction of Pressure Vessels

2025 ASME Boiler and Pressure Vessel Code

An International Code

Division 3

Alternative Rules for Construction of High Pressure Vessels



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AN INTERNATIONAL CODE

2025 ASME Boiler & Pressure Vessel Code

2025 Edition July 1, 2025

VIII

RULES FOR CONSTRUCTION OF PRESSURE VESSELS

Division 3

Alternative Rules for Construction of High Pressure Vessels

ASME Boiler and Pressure Vessel Committee
on Pressure Vessels

The American Society of Mechanical Engineers
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FOREWORD*

In 1911, The American Society of Mechanical Engineers established the Boiler and Pressure Vessel Committee to formulate standard rules for the construction of steam boilers and other pressure vessels. In 2009, the Boiler and Pressure Vessel Committee was superseded by the following committees:

(a) Committee on Power Boilers (I)
(b) Committee on Materials (II)
(c) Committee on Construction of Nuclear Facility Components (III)
(d) Committee on Heating Boilers (IV)
(e) Committee on Nondestructive Examination (V)
(f) Committee on Pressure Vessels (VIII)
(g) Committee on Welding, Brazing, and Fusing (IX)
(h) Committee on Fiber-Reinforced Plastic Pressure Vessels (X)
(i) Committee on Nuclear Inservice Inspection (XI)
(j) Committee on Transport Tanks (XII)
(k) Committee on Overpressure Protection (XIII)
(l) Technical Oversight Management Committee (TOMC)

Where reference is made to "the Committee" in this Foreword, each of these committees is included individually and collectively.

The Committee's function is to establish rules of safety relating to pressure integrity. The rules govern the construction** of boilers, pressure vessels, transport tanks, and nuclear components, and the inservice inspection of nuclear components and transport tanks. For nuclear items other than pressure-retaining components, the Committee also establishes rules of safety related to structural integrity. The Committee also interprets these rules when questions arise regarding their intent. The technical consistency of the Sections of the Code and coordination of standards development activities of the Committees is supported and guided by the Technical Oversight Management Committee. The Code does not address other safety issues relating to the construction of boilers, pressure vessels, transport tanks, or nuclear components, or the inservice inspection of nuclear components or transport tanks. Users of the Code should refer to the pertinent codes, standards, laws, regulations, or other relevant documents for safety issues other than those relating to pressure integrity and, for nuclear items other than pressure-retaining components, structural integrity. Except for Sections XI and XII, and with a few other exceptions, the rules do not, of practical necessity, reflect the likelihood and consequences of deterioration in service related to specific service fluids or external operating environments. In formulating the rules, the Committee considers the needs of users, manufacturers, and inspectors of components addressed by the Code. The objective of the rules is to afford reasonably certain protection of life and property, and to provide a margin for deterioration in service to give a reasonably long, safe period of usefulness. Advancements in design and materials and evidence of experience have been recognized.

The Code contains mandatory requirements, specific prohibitions, and nonmandatory guidance for construction activities and inservice inspection and testing activities. The Code does not address all aspects of these activities and those aspects that are not specifically addressed should not be considered prohibited. The Code is not a handbook and cannot replace education, experience, and the use of engineering judgment. The phrase *engineering judgment* refers to technical judgments made by knowledgeable engineers experienced in the application of the Code. Engineering judgments must be consistent with Code philosophy, and such judgments must never be used to overrule mandatory requirements or specific prohibitions of the Code.

The Committee recognizes that tools and techniques used for design and analysis change as technology progresses and expects engineers to use good judgment in the application of these tools. The designer is responsible for complying with Code rules and demonstrating compliance with Code equations when such equations are mandatory. The Code neither requires nor prohibits the use of computers for the design or analysis of components constructed to the requirements of the Code. However, designers and engineers using computer programs for design or analysis are cautioned that they are

* The information contained in this Foreword is not part of this American National Standard (ANS) and has not been processed in accordance with ANSI's requirements for an ANS. Therefore, this Foreword may contain material that has not been subjected to public review or a consensus process. In addition, it does not contain requirements necessary for conformance to the Code.

** *Construction*, as used in this Foreword, is an all-inclusive term comprising materials, design, fabrication, examination, inspection, testing, certification, and overpressure protection.

responsible for all technical assumptions inherent in the programs they use and the application of these programs to their design.

The rules established by the Committee are not to be interpreted as approving, recommending, or endorsing any proprietary or specific design, or as limiting in any way the manufacturer's freedom to choose any method of design or any form of construction that conforms to the Code rules.

The Committee meets regularly to consider revisions of the rules, new rules as dictated by technological development, Code cases, and requests for interpretations. Only the Committee has the authority to provide official interpretations of the Code. Requests for revisions, new rules, Code cases, or interpretations shall be addressed to the staff secretary in writing and shall give full particulars in order to receive consideration and action (see the Correspondence With the Committee page). Proposed revisions to the Code resulting from inquiries will be presented to the Committee for appropriate action. The action of the Committee becomes effective only after confirmation by ballot of the Committee and approval by ASME. Proposed revisions to the Code approved by the Committee are submitted to the American National Standards Institute (ANSI) and published at http://go.asme.org/BPVCPublicReview to invite comments from all interested persons. After public review and final approval by ASME, revisions are published at regular intervals in Editions of the Code.

The Committee does not rule on whether a component shall or shall not be constructed to the provisions of the Code. The scope of each Section has been established to identify the components and parameters considered by the Committee in formulating the Code rules.

Questions or issues regarding compliance of a specific component with the Code rules are to be directed to the ASME Certificate Holder (Manufacturer). Inquiries concerning the interpretation of the Code are to be directed to the Committee. ASME is to be notified should questions arise concerning improper use of the ASME Single Certification Mark.

When required by context in the Code, the singular shall be interpreted as the plural, and vice versa.

The words "shall," "should," and "may" are used in the Code as follows:

- *Shall* is used to denote a requirement.
- *Should* is used to denote a recommendation.
- *May* is used to denote permission, neither a requirement nor a recommendation.

STATEMENT OF POLICY ON THE USE OF THE ASME SINGLE CERTIFICATION MARK AND CODE AUTHORIZATION IN ADVERTISING

ASME has established procedures to authorize qualified organizations to perform various activities in accordance with the requirements of the ASME Boiler and Pressure Vessel Code. It is the aim of the Society to provide recognition of organizations so authorized. An organization holding authorization to perform various activities in accordance with the requirements of the Code may state this capability in its advertising literature.

Organizations that are authorized to use the ASME Single Certification Mark for marking items or constructions that have been constructed and inspected in compliance with the ASME Boiler and Pressure Vessel Code are issued Certificates of Authorization. It is the aim of the Society to maintain the standing of the ASME Single Certification Mark for the benefit of the users, the enforcement jurisdictions, and the holders of the ASME Single Certification Mark who comply with all requirements.

Based on these objectives, the following policy has been established on the usage in advertising of facsimiles of the ASME Single Certification Mark, Certificates of Authorization, and reference to Code construction. The American Society of Mechanical Engineers does not "approve," "certify," "rate," or "endorse" any item, construction, or activity and there shall be no statements or implications that might so indicate. An organization holding the ASME Single Certification Mark and/or a Certificate of Authorization may state in advertising literature that items, constructions, or activities "are built (produced or performed) or activities conducted in accordance with the requirements of the ASME Boiler and Pressure Vessel Code," or "meet the requirements of the ASME Boiler and Pressure Vessel Code." An ASME corporate logo shall not be used by any organization other than ASME.

The ASME Single Certification Mark shall be used only for stamping and nameplates as specifically provided in the Code. However, facsimiles may be used for the purpose of fostering the use of such construction. Such usage may be by an association or a society, or by a holder of the ASME Single Certification Mark who may also use the facsimile in advertising to show that clearly specified items will carry the ASME Single Certification Mark.

STATEMENT OF POLICY ON THE USE OF ASME MARKING TO IDENTIFY MANUFACTURED ITEMS

The ASME Boiler and Pressure Vessel Code provides rules for the construction of boilers, pressure vessels, and nuclear components. This includes requirements for materials, design, fabrication, examination, inspection, and stamping. Items constructed in accordance with all of the applicable rules of the Code are identified with the ASME Single Certification Mark described in the governing Section of the Code.

Markings such as "ASME," "ASME Standard," or any other marking including "ASME" or the ASME Single Certification Mark shall not be used on any item that is not constructed in accordance with all of the applicable requirements of the Code.

Items shall not be described on ASME Data Report Forms nor on similar forms referring to ASME that tend to imply that all Code requirements have been met when, in fact, they have not been. Data Report Forms covering items not fully complying with ASME requirements should not refer to ASME or they should clearly identify all exceptions to the ASME requirements.

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January 1, 2025

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CORRESPONDENCE WITH THE COMMITTEE

General

ASME codes and standards are developed and maintained by committees with the intent to represent the consensus of concerned interests. Users of ASME codes and standards may correspond with the committees to propose revisions or cases, report errata, or request interpretations. Correspondence for this Section of the ASME Boiler and Pressure Vessel Code (BPVC) should be sent to the staff secretary noted on the Section's committee web page, accessible at https://go.asme.org/CSCommittees.

NOTE: See ASME BPVC Section II, Part D for guidelines on requesting approval of new materials. See Section II, Part C for guidelines on requesting approval of new welding and brazing materials ("consumables").

Revisions and Errata

The committee processes revisions to this Code on a continuous basis to incorporate changes that appear necessary or desirable as demonstrated by the experience gained from the application of the Code. Approved revisions will be published in the next edition of the Code.

In addition, the committee may post errata and Special Notices at http://go.asme.org/BPVCerrata. Errata and Special Notices become effective on the date posted. Users can register on the committee web page to receive email notifications of posted errata and Special Notices.

This Code is always open for comment, and the committee welcomes proposals for revisions. Such proposals should be as specific as possible, citing the paragraph number, the proposed wording, and a detailed description of the reasons for the proposal, including any pertinent background information and supporting documentation.

Cases

(a) The most common applications for cases are

(1) to permit early implementation of a revision based on an urgent need

(2) to provide alternative requirements

(3) to allow users to gain experience with alternative or potential additional requirements prior to incorporation directly into the Code

(4) to permit use of a new material or process

(b) Users are cautioned that not all jurisdictions or owners automatically accept cases. Cases are not to be considered as approving, recommending, certifying, or endorsing any proprietary or specific design, or as limiting in any way the freedom of manufacturers, constructors, or owners to choose any method of design or any form of construction that conforms to the Code.

(c) The committee will consider proposed cases concerning the following topics only:

(1) equipment to be marked with the ASME Single Certification Mark, or

(2) equipment to be constructed as a repair/replacement activity under the requirements of Section XI

(d) A proposed case shall be written as a question and reply in the same format as existing cases. The proposal shall also include the following information:

(1) a statement of need and background information

(2) the urgency of the case (e.g., the case concerns a project that is underway or imminent)

(3) the Code Section and the paragraph, figure, or table number to which the proposed case applies

(4) the editions of the Code to which the proposed case applies

(e) A case is effective for use when the public review process has been completed and it is approved by the cognizant supervisory board. Cases that have been approved will appear in the next edition or supplement of the Code Cases books, "Boilers and Pressure Vessels" or "Nuclear Components." Each Code Cases book is updated with seven Supplements.

Supplements will be sent or made available automatically to the purchasers of the Code Cases books until the next edition of the Code. Annulments of Code Cases become effective six months after the first announcement of the annulment in a Code Case Supplement or Edition of the appropriate Code Case book. The status of any case is available at http://go.asme.org/BPVCCDatabase. An index of the complete list of Boiler and Pressure Vessel Code Cases and Nuclear Code Cases is available at http://go.asme.org/BPVCC.

Interpretations

(a) Interpretations clarify existing Code requirements and are written as a question and reply. Interpretations do not introduce new requirements. If a revision to resolve conflicting or incorrect wording is required to support the interpretation, the committee will issue an intent interpretation in parallel with a revision to the Code.

(b) Upon request, the committee will render an interpretation of any requirement of the Code. An interpretation can be rendered only in response to a request submitted through the online Inquiry Submittal Form at http://go.asme.org/InterpretationRequest. Upon submitting the form, the inquirer will receive an automatic email confirming receipt.

(c) ASME does not act as a consultant for specific engineering problems or for the general application or understanding of the Code requirements. If, based on the information submitted, it is the opinion of the committee that the inquirer should seek assistance, the request will be returned with the recommendation that such assistance be obtained. Inquirers may track the status of their requests at http://go.asme.org/Interpretations.

(d) ASME procedures provide for reconsideration of any interpretation when or if additional information that might affect an interpretation is available. Further, persons aggrieved by an interpretation may appeal to the cognizant ASME committee or subcommittee. ASME does not "approve," "certify," "rate," or "endorse" any item, construction, proprietary device, or activity.

(e) Interpretations are published in the ASME Interpretations Database at http://go.asme.org/Interpretations as they are issued.

Committee Meetings

The ASME BPVC committees regularly hold meetings that are open to the public. Persons wishing to attend any meeting should contact the secretary of the applicable committee. Information on future committee meetings can be found at http://go.asme.org/BCW.

SUMMARY OF CHANGES

Changes listed below are identified on the pages by a margin note, **(25)**, placed next to the affected area.

Page	*Location*	*Change*
xvii	List of Sections	Title of Section XI, Division 1 revised
xviii	Foreword	Third, fourth, seventh, tenth, and eleventh paragraphs editorially revised
xxi	Personnel	Updated
2	KG-130	Subparagraph (c) revised
5	Table KG-141	Updated
6	Table KG-150	Under "U.S. Customary Units," all instances of "lb" revised to "lbf"
8	KG-300	Last sentence revised
8	KG-310	First sentence revised
9	KG-311.7	Subparagraph (c) revised
9	KG-311.11	First paragraph revised
10	KG-311.14	Endnote 1 and subpara. (b) revised
11	KG-311.15	Subparagraphs (b) and (e) revised
12	KG-323	First paragraph and subparas. (f) and (h) revised
12	KG-324	Subparagraph (b) revised
13	KG-324.1	Subparagraphs (b) and (e) revised
13	KG-330	Editorially revised
15	KG-412	Revised
15	KG-413.2	Revised
16	KG-420	Subparagraphs (d) and (d)(2) revised
16	KG-440	First paragraph and subpara. (l) revised
20	KG-613	Revised
25	KM-211.2	Subparagraph (b) revised
26	KM-211.3	Subparagraph (b) revised
26	KM-211.5	Added
26	KM-212.2	Title revised
30	Table KM-234.2(a)	General Note revised
31	KM-250	(1) First paragraph revised (2) Second through fourth paragraphs designated (a) through (d) and previously designated subparas. redesignated
32	KM-254	First sentence revised
32	KM-261	First paragraph revised
33	KM-270	In subpara. (c), definition of *P* revised
34	Figure KM-270.1M	Corrected by errata to the graphic displaying metric units
39	KM-400	In subpara. (a), second paragraph revised
40	Table KM-400-1	(1) Carbon steel, SA-354; 0.7Cr–1.5Si; 3½Ni–1½ Cr–½ Mo–½ Mn; and Notes (25) and (26) added (2) For 2¼Cr–1Mo, reference to Note (15) added (3) General Note (b) and Notes (3), (4), (8), (9), (11), (12), (14), (18), and (23) revised
48	Table KM-400-1M	(1) Carbon steel, SA-354; 0.7Cr–1.5Si; 3½Ni–1½ Cr–½ Mo–½ Mn; and Notes (25) and (26) added (2) For 2¼Cr–1Mo, reference to Note (15) added (3) General Note (b) and Notes (3), (4), (8), (9), (11), (12), (14), (18), and (23) revised

Page	*Location*	*Change*
57	Table KM-400-2	(1) For 15Cr–5Ni–3Cu, SA-564 and SA-705, conditions H1150M and H1150, Max. Design Temp. revised
		(2) General Note and Notes (3), (5), (6), and (10) revised
62	Table KM-400-2M	(1) For 15Cr–5Ni–3Cu, SA-564 and SA-705, conditions H1150M and H1150, Max. Design Temp. revised
		(2) General Note and Notes (3), (5), (6), and (10) revised
67	Table KM-400-3	General Note (b) revised
69	Table KM-400-3M	General Note (b) revised
71	Table KM-400-4	In Note (2), metric units deleted
72	Table KM-400-4M	In Note (2), U.S. customary units deleted
74	KM-610	First sentence editorially revised
82	Article KM-8	Added
84	KD-120	Subparagraph (c) revised
89	KD-221.1	Definition of K_{ut} revised
89	KD-221.2	Definition of K_{utj} revised
93	Table KD-230.4	In General Note (c), definitions of K_{ut} and K_{utj} revised
95	KD-236	Revised in its entirety
96	KD-240	Subparagraphs (d) and (e) revised
112	Table KD-320.1	In General Note (e)(4), second equation for N revised
116	Table KD-320.1M	In General Note (e)(4), second equation for N revised
135	KD-401	(1) In subpara. (a), last sentence deleted
		(2) Subparagraph (d) deleted
135	KD-411	Subparagraph (a) revised
136	KD-420	Subparagraphs (a) and (b) revised
136	KD-430	Subparagraph (a) revised
138	Table KD-430	(1) Row for cast high strength alloy steels added
		(2) Note (1) revised
138	Table KD-430M	(1) Row for cast high strength alloy steels added
		(2) Note (1) revised
139	Table KD-431	Former Table D-500 redesignated and moved
137	KD-450	Added
137	KD-451	Added
144	KD-620	Subparagraph (b) revised
169	KD-1043	Subparagraphs (a) and (d) revised
169	KD-1045	Subparagraph (d) deleted
170	KD-1048	Subparagraph designator (a) removed and subpara. (b) deleted
170	KD-1049	First sentence revised
188	KF-121.1	In subpara. (b), first sentence revised
190	KF-211	Second paragraph added
191	KF-216	Revised
192	KF-222.1	In sixth sentence, reference to Section IX revised
192	KF-226	Subparagraph (b) revised
193	KF-233	In subpara. (a), penultimate sentence revised
193	KF-236	First sentence revised
193	KF-238	Subparagraph (a) revised
204	KF-613.1	Last sentence revised
205	KF-615	Revised in its entirety
205	KF-620	In subpara. (b), second sentence revised
205	KF-630	Subparagraph (f) added
212	KF-825.2	Subparagraph (a) revised
212	KF-825.3	Subparagraphs (a) and (b) revised
213	KF-825.6	Revised

Page	*Location*	*Change*
213	KF-825.7	Subparagraph (a) revised
213	KF-825.8	First paragraph and subpara. (a) revised
217	KF-912	Second paragraph revised
220	KF-1130	Subparagraph (c) revised
221	KF-1160	Revised
224	KOP-100	(1) Subparagraph (a) revised
		(2) Subparagraph (c) deleted and subsequent subparagraph redesignated
224	KOP-120	Subparagraphs (a), (c), and (e) revised
225	KOP-130	Subparagraph (a) revised
225	KOP-140	First sentence revised
225	KOP-151	Revised
225	KOP-153	In subpara. (a), reference to Section XIII, Part 4 revised to Section XIII, Part 3
226	KOP-156	Revised in its entirety
228	KOP-200	Revised
228	KOP-210	Subparagraph (b) revised and subpara. (h) added
230	KOP-300	First paragraph and subparas. (a) and (b)(4) revised
231	KE-105	Added
231	KE-106	Former KE-105 redesignated
232	KE-112.1	First paragraph revised
233	KE-114	Revised
233	KE-115	Cross-reference updated
234	KE-211	Subparagraphs (a)(3) and (a)(4) revised
234	KE-212.1	Last sentence revised
234	KE-212.4	First sentence revised
235	KE-213	Subparagraphs (b) and (c) revised
235	KE-221	Subparagraph (c) revised
235	KE-230	Subparagraph (a) revised
235	KE-231	Subparagraph (c) revised
236	KE-233	Revised in its entirety
236	KE-233.1	Subparagraph (c) added and subsequent subparagraph redesignated
237	KE-241	Subparagraphs (b) and (c) revised
239	KE-251	Subparagraph (a) revised
239	KE-252	Subparagraph (c) revised
239	KE-263	First paragraph revised
240	KE-270	Added
241	KE-300	Subparagraphs (b), (c), (d), and (e) revised
241	KE-301	(1) Subparagraphs (c), (i)(2)(-a)(-2), and (i)(3)(-d) revised
		(2) Subparagraph (i)(3)(-e) added
244	KE-302	Subparagraphs (b) and (e) revised
253	KE-310	First paragraph revised
254	KE-322	Last sentence revised
254	KE-324	Revised
254	KE-325	Revised
254	KE-333	First paragraph and subparas. (a) and (a)(3) revised
255	KE-334	Revised in its entirety
261	KT-304	Added
261	KT-305	Added
261	KT-311	Revised
262	KT-312.1	Definition of K_{ut} revised
262	KT-312.2	Last paragraphs revised
262	KT-312.3	Subparagraph (b) revised

Page	*Location*	*Change*
268	KS-140	Revised
269	KS-250	Subparagraph (b) revised
269	KS-260	Revised
270	KS-300	Subparagraph (a)(2)(-b) revised
270	KS-301	Subparagraph (a) revised
270	KS-302	Revised
271	KS-320	Subparagraphs (d)(6) and (d)(10) revised
272	1-100	Definitions of a, K_{ub}, and K_{utj} revised
280	2-100	In second paragraph, first sentence revised
280	2-112	Second sentence revised
281	2-119	Second sentence revised
281	2-123	Subparagraph (d) revised
282	5-200	Subparagraph (c)(2) revised
297	9-400	Subparagraph (e) revised
299	Form K-1	On second page, “Certificate of Shop Inspection” and “Certificate of Field Assembly Inspection” revised
301	Form K-2	On second page, “Certificate of Shop Inspection” and “Certificate of Field Assembly Inspection” revised
306	Form CRPV-1A	On second page, “Certificate of Shop Inspection” revised
310	Form CRPV-2A	On second page, “Certification by Shop Inspector of Qualification ...” revised
313	Nonmandatory Appendix D	Deleted
339	I-300	In first column of in-text table, all instances of “lb” revised to “lbf”

CROSS-REFERENCING IN THE ASME BPVC

Paragraphs within the ASME BPVC may include subparagraph breakdowns, i.e., nested lists. The following is a guide to the designation and cross-referencing of subparagraph breakdowns:

(a) Hierarchy of Subparagraph Breakdowns

(1) First-level breakdowns are designated as (a), (b), (c), etc.

(2) Second-level breakdowns are designated as (1), (2), (3), etc.

(3) Third-level breakdowns are designated as (-a), (-b), (-c), etc.

(4) Fourth-level breakdowns are designated as (-1), (-2), (-3), etc.

(5) Fifth-level breakdowns are designated as (+a), (+b), (+c), etc.

(6) Sixth-level breakdowns are designated as (+1), (+2), etc.

(b) Cross-References to Subparagraph Breakdowns. Cross-references within an alphanumerically designated paragraph (e.g., PG-1, UIG-56.1, NCD-3223) do not include the alphanumerical designator of that paragraph. The cross-references to subparagraph breakdowns follow the hierarchy of the designators under which the breakdown appears. The following examples show the format:

(1) If X.1(c)(1)(-a) is referenced in X.1(c)(1), it will be referenced as (-a).

(2) If X.1(c)(1)(-a) is referenced in X.1(c)(2), it will be referenced as (1)(-a).

(3) If X.1(c)(1)(-a) is referenced in X.1(e)(1), it will be referenced as (c)(1)(-a).

(4) If X.1(c)(1)(-a) is referenced in X.2(c)(2), it will be referenced as X.1(c)(1)(-a).

PART KG
GENERAL REQUIREMENTS

ARTICLE KG-1
SCOPE AND JURISDICTION

KG-100 SCOPE

KG-101 INTENT

The rules of this Division constitute requirements for the design, construction, inspection, and overpressure protection of metallic pressure vessels with design pressures generally above 10 ksi (70 MPa). However, it is not the intent of this Division to establish maximum pressure limits for either Section VIII, Division 1 or 2, nor minimum pressure limits for this Division. Specific pressure limitations for vessels constructed to the rules of this Division may be imposed elsewhere in this Division for various types of fabrication. Whenever *Construction* appears in this document, it may be considered an all-inclusive term comprising materials, design, fabrication, examination, inspection, testing, certification, and pressure relief.

KG-102 DESCRIPTION

Pressure vessels within the scope of this Division are pressure containers for the retainment of fluids, gaseous or liquid, under pressure, either internal or external.

This pressure may be generated by

(a) an external source

(b) the application of heat from

(1) direct source

(2) indirect source

(c) a process reaction

(d) any combination thereof

KG-103 LAWS OR REGULATIONS

The scope of this Division has been established to identify components and parameters considered in formulating the rules given in this Division. Laws or regulations issued by municipal, state, provincial, federal, or other enforcement or regulatory bodies having jurisdiction at the location of an installation establish the mandatory applicability of the Code rules, in whole or in part, within the jurisdiction. Those laws or regulations may require the use of this Division for vessels or components not considered to be within its scope. These laws or regulations should be reviewed to determine size or service limitations of the coverage, which may be different or more restrictive than those of this Division.

KG-104 LOCATION

KG-104.1 Fixed Location. Except as provided in KG-104.2, these rules cover vessels to be installed at a fixed (stationary) location for a specific service where operation and maintenance control are maintained in conformance with the User's Design Specification and records retained during the life of the vessel by the User.

KG-104.2 Mobile Vessels. These rules also apply to pressure vessels that are relocated from work site to work site between pressurizations, and where operation and maintenance control are maintained in conformance with the User's Design Specification and records retained during the life of the vessel by the User.

KG-110 GEOMETRIC SCOPE OF THIS DIVISION

The scope of this Division includes only the vessel and integral communicating chambers and shall include the requirements specified in KG-111 through KG-117.

KG-111 EXTERNAL PIPING AND JACKETS

Where external piping is to be connected to the vessel (see Article KD-6):

(a) the first threaded joint for screwed connections

(b) the face of the first flange for flanged connections

(c) the first sealing surface for proprietary connections or fittings

(d) the welding end connection for the first circumferential joint for welded connections to external piping, valves, instruments, and the like

(e) the welding pad for attachment of an external jacket

KG-112 INTERNAL PRESSURE PIPING

Internal pressure piping, when failure of such piping will affect the integrity of the pressure boundary.

KG-113 NONPRESSURE PARTS

Nonpressure parts that are welded directly to the internal or external surface of a pressure vessel. For parts beyond this, and for stud-bolted attachments, see Articles KD-6 and KD-7.

KG-114 COVERS AND CLOSURES

Pressure-retaining permanent covers or closures, including seals and bolting, or other mechanical retainers, used in service for vessel openings (see Article KD-6).

KG-115 INSTRUMENT CONNECTIONS

The first sealing surface for small proprietary fittings or instrumentation, such as gages and instruments, for which rules are not provided by this Division (see Article KD-6).

KG-116 OVERPRESSURE PROTECTION

Overpressure protection shall satisfy the requirements of Part KOP.

KG-117 COMBINATION UNITS

When a pressure vessel unit consists of more than one independent pressure chamber, only the parts of chambers which are within the scope of this Division need to be constructed in compliance with its provisions (see Articles KD-1 and KG-3).

KG-120 CLASSIFICATIONS OUTSIDE THE SCOPE OF THIS DIVISION

The following pressure-containing components are not included in the scope of this Division:

(a) vessels and components exclusively within the scope of other Sections of the ASME Boiler and Pressure Vessel Code

(b) fired process tubular heaters and components (see API STD 560 or ISO 13705)

(c) pressure-containing equipment that is an integral part or component of a rotating or reciprocating mechanical device, such as

(1) pumps
(2) compressors
(3) turbines
(4) generators
(5) engines
(6) hydraulic or pneumatic cylinders

where the primary design considerations and/or stresses are derived from the functional requirements of the device

(d) piping and piping components covered in the scope of the ASME B31 Piping Codes

(e) components covered in the scope of other applicable ASME Codes and Standards

KG-121 STAMPING OF PRESSURE-CONTAINING COMPONENTS OUTSIDE THE SCOPE OF THIS DIVISION

Any pressure-containing component, with the exception of components that follow the rules of KG-120(a), which meets all applicable requirements of this Division may be stamped with the Certification Mark with U3 Designator.

The Certification Mark is an ASME symbol identifying a product as meeting Code requirements. The Designator is a symbol used in conjunction with the Certification Mark for the scope of activity described in a Manufacturer's Certificate of Authorization.

KG-130 ASSEMBLY AND TESTING OF VESSELS AT FIELD OR INTERMEDIATE SITES (25)

A field site is a location of final permanent installation of the pressure equipment. An intermediate site is a temporary location under the control of the Certificate Holder. The location of an intermediate site is other than that listed on the Certificate of Authorization and other than a field site. All Code activities may be performed at intermediate or field sites by the Certificate Holder provided they comply with all Code requirements, and control of those activities is described in the Certificate Holder's Quality Control System. Assembly and testing of vessels constructed to this Division at intermediate or field sites shall be performed using one of the following three alternatives:

(a) The Manufacturer of the vessel completes the vessel in the field or at an intermediate site.

(b) The Manufacturer of parts of a vessel to be completed in the field or at an intermediate site by some other party stamps these parts in accordance with Code rules and supplies the Manufacturer's Data Report Form K-2 to the other party. The other party, who shall also hold a valid U3 Certificate of Authorization, makes the final assembly, required nondestructive examination (NDE), and final pressure test; completes the Manufacturer's Data Report Form K-1; and stamps the vessel. The Certificate of Authorization is a document issued by the Society that authorizes the use of the ASME Certification Mark and appropriate Designator for a specified time and for a specified scope of activity.

(c) Code work at field or intermediate sites is completed by a Certificate Holder of a valid U3 Certificate of Authorization other than the Manufacturer. The Certificate Holder performing the work is required to supply a Manufacturer's Data Report Form K-2 covering the portion of the work completed by the Certificate Holder's organization (including data on the pressure test if conducted by the Certificate Holder performing the fieldwork) to the Manufacturer responsible for the Code vessel. The Manufacturer applies the ASME Certification Mark with U3 Designator in the presence of a representative

from the Manufacturer's Inspection Agency and completes the Manufacturer's Data Report Form K-1 with the Inspector.

In all three alternatives, the party completing and signing the Manufacturer's Data Report Form K-1 assumes full Code responsibility for the vessel. In all three cases, each Manufacturer's Quality Control System shall describe the controls to assure compliance for each Certificate holder.

KG-140 STANDARDS REFERENCED BY THIS DIVISION

KG-141 SECTIONS OF THE ASME CODE

(a) Sections of the ASME Boiler and Pressure Vessel Code referenced in this Division are

- Section I, Rules for Construction of Power Boilers
- Section II, Materials
  - Part A — Ferrous Material Specifications
  - Part B — Nonferrous Material Specifications
  - Part C — Specifications for Welding Rods, Electrodes, and Filler Metals
  - Part D — Properties
- Section V, Nondestructive Examination
- Section VIII, Division 1, Rules for Construction of Pressure Vessels
- Section VIII, Division 2, Alternative Rules for Construction of Pressure Vessels
- Section IX, Welding, Brazing, and Fusing Qualifications
- Section X, Fiber-Reinforced Plastic Pressure Vessels
- Section XIII, Rules for Overpressure Protection

(b) Throughout this Division references are made to various standards, such as ASME standards, that cover pressure–temperature rating, dimensional, or procedural standards for pressure vessel parts. Specific editions of standards referenced in this Division are shown in Table KG-141.

KG-142 STANDARD PARTS

Standard pressure parts which comply with an ASME product standard shall be made of materials permitted by this Division (see Part KM).

KG-150 UNITS OF MEASUREMENT

(a) Either U.S. Customary, SI, or any local customary units may be used to demonstrate compliance with requirements of this edition related to materials, fabrication, examination, inspection, testing, certification, and overpressure protection.

(b) A single system of units shall be used for all aspects of design except where otherwise permitted by this Division. When components are manufactured at different locations where local customary units are different than those used for the general design, the local units may be used for the design and documentation of that component, within the limitations given in (c). Similarly, for proprietary components or those uniquely associated with a system of units different than that used for the general design, the alternate units may be used for the design and documentation of that component, within the limitations given in (c).

(c) For any single equation, all variables shall be expressed in a single system of units. Calculations using any material data published in this Division or Section II, Part D (e.g., allowable stresses, physical properties, external pressure design factor B, etc.) shall be carried out in one of the standard units given in Table KG-150. When separate equations are provided for U.S. Customary and SI units, those equations must be executed using variables in the units associated with the specific equation. Data expressed in other units shall be converted to U.S. Customary or SI units for use in these equations. The result obtained from execution of these equations or any other calculations carried out in either U.S. Customary or SI units may be converted to other units.

(d) Production, measurement, and test equipment, drawings, welding procedure specifications, welding procedure and performance qualifications, and other fabrication documents may be in U.S. Customary, SI, or local customary units in accordance with the fabricator's practice. When values shown in calculations and analysis, fabrication documents, or measurement and test equipment are in different units, any conversions necessary for verification of Code compliance and to ensure that dimensional consistency is maintained shall be in accordance with the following:

(1) Conversion factors shall be accurate to at least four significant figures.

(2) The results of conversions of units shall be expressed to a minimum of three significant figures.

(e) Conversion of units, using the precision specified previously, shall be performed to ensure that dimensional consistency is maintained. Conversion factors between U.S. Customary and SI units may be found in the Nonmandatory Appendix I, Guidance for the Use of U.S. Customary and SI Units, in the ASME Boiler and Pressure Vessel Code. Whenever local customary units are used, the Manufacturer shall provide the source of the conversion factors which shall be subject to verification and acceptance by the Authorized Inspector.

(f) Dimensions shown in the text, tables, and figures, whether given as a decimal or a fraction, may be taken as a decimal or a fraction and do not imply any manufacturing precision or tolerance on the dimension.

(g) Material that has been manufactured and certified to either the U.S. Customary or SI material specification (e.g., SA-516M) may be used regardless of the unit system used in design. Standard fittings (e.g., flanges and elbows)

that have been certified to either U.S. Customary or SI units may be used regardless of the equations or any other calculations carried out in either U.S. Customary or SI units system used in design.

(h) All entries on a Manufacturer's Data Report and data for Code-required nameplate marking shall be in units consistent with the fabrication drawings for the component using U.S. Customary, SI, or local customary units. Units may be shown parenthetically (either primary or alternative). Users of this Code are cautioned that the receiving jurisdiction should be contacted to ensure the units are acceptable.

KG-160 TOLERANCES

The Code does not fully address tolerances. When dimensions, sizes, or other parameters are not specified with tolerances, the values of these parameters are considered nominal and allowable tolerances or local variances may be considered acceptable when based on engineering judgment and standard practices as determined by the designer.

Table KG-141
Referenced Standards in This Division and Year of Acceptable Edition

(25)

Title	Number	Year
Fitness-For-Service	API 579-1/ASME FFS-1	2021
Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Chemical Plants	API RP 941	2016, Addendum 1: 2020
Fired Heaters for General Refinery Service	API Standard 560	Latest Edition
Minimum Design Loads for Buildings and Other Structures	ASCE/SEI 7	2022
Unified Inch Screw Threads (UN and UNR Thread Form)	ASME B1.1	Latest edition
Pipe Flanges and Flanged Fittings, NPS ½ Through NPS 24 Metric/Inch Standard	ASME B16.5	2025 [Note (2)]
Nuts for General Applications: Machine Screw Nuts, Hex, Square, Hex Flange, and Coupling Nuts (Inch Series)	ASME B18.2.2	Latest edition
Metric Fasteners for Use in Structural Applications	ASME B18.2.6M	Latest edition
Process Piping	ASME B31.3	Latest edition
Surface Texture (Surface Roughness, Waviness and Lay)	ASME B46.1	Latest edition
Conformity Assessment Requirements	ASME CA-1	Latest edition
Inspection Planning Using Risk-Based Methods	ASME PCC-3	Latest edition
Qualifications for Authorized Inspection	ASME QAI-1	Latest edition [Note (1)]
Standard Test Method for Apparent Hoop Tensile Strength of Plastic or Reinforced Plastic Pipe	ASTM D2290	2019a
Standard Test Methods for Tension Testing of Metallic Materials	ASTM E8	Latest edition
Standard Test Methods for Notched Bar Impact Testing of Metallic Materials	ASTM E23	Latest edition
Standard Hardness Conversion Tables for Metals Relationship Among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Superficial Hardness, Knoop Hardness, and Scleroscope Hardness	ASTM E140	Latest edition
Standard Method for Linear-Elastic Plane-Strain Fracture Toughness of Metallic Materials	ASTM E399	2023
Standard Test Methods for Tension Testing Wrought and Cast Aluminum- and Magnesium-Alloy Products	ASTM B557	Latest Edition
Standard Test Method for Measurement of Fatigue Crack Growth Rates	ASTM E647	2024
Standard Practices for Cycle Counting in Fatigue Analysis	ASTM E1049	Latest edition
Standard Test Method for Determining Threshold Stress Intensity Factor for Environment-Assisted Cracking of Metallic Materials	ASTM E1681	2023ε1
Standard Test Method for Measurement of Fracture Toughness	ASTM E1820	2024
Standard Terminology Relating to Fatigue and Fracture Testing	ASTM E1823	2024a
Standard Test Method for Determination of Reference Temperature, T_o, for Ferritic Steels in the Transition Range	ASTM E1921	Latest edition
Marking and Labeling Systems	ANSI/UL-969	Latest edition
Guide to Methods for Assessing the Acceptability of Flaws in Metallic Structures	BS-7910	2019
Standard for Compressed Gas Cylinder Valve Outlet and Inlet Connections	CGA V-1	2021
Gas cylinders — 17E and 25E taper threads for connection of valves to gas cylinders — Part 1: Specifications	ISO 11363-1	2018
Petroleum, petrochemical and natural gas industries — Fired heaters for general refinery service	ISO 13705	Latest edition

GENERAL NOTE: For product standards, pressure–temperature ratings and cyclic analysis may limit application (see Part KD).

NOTES:
(1) See KG-411.
(2) The use of a flange or flanged fitting that relies on and meets the requirements of a B16 Case is not permitted.

(25)

Table KG-150
Standard Units for Use in Equations

Quantity	U.S. Customary Units	SI Units
Linear dimensions (e.g., length, height, thickness, radius, diameter)	inches (in.)	millimeters (mm)
Area	square inches ($in.^2$)	square millimeters (mm^2)
Volume	cubic inches ($in.^3$)	cubic millimeters (mm^3)
Section modulus	cubic inches ($in.^3$)	cubic millimeters (mm^3)
Moment of inertia of section	$inches^4$ ($in.^4$)	$millimeters^4$ (mm^4)
Mass (weight)	pounds mass (lbm)	kilograms (kg)
Force (load)	pounds force (lbf)	newtons (N)
Bending moment	inch-pounds (in.-lbf)	newton-millimeters (N·mm)
Pressure, stress, stress intensity, and modulus of elasticity	pounds per square inch (psi)	megapascals (MPa)
Energy (e.g., Charpy impact values)	foot-pounds (ft-lbf)	joules (J)
Temperature	degrees Fahrenheit (°F)	degrees Celsius (°C)
Absolute temperature	Rankine (°R)	kelvin (K)
Fracture toughness	ksi square root inches ($ksi\sqrt{in.}$)	MPa square root meters ($MPa\sqrt{m}$)
Angle	degrees or radians	degrees or radians
Boiler capacity	Btu/hr	watts (W)

ARTICLE KG-2
ORGANIZATION OF THIS DIVISION

KG-200 ORGANIZATION

KG-210 PARTS OF THIS DIVISION

This Division is divided into eight parts.

(a) Part KG contains the scope of the Division, establishes the extent of its coverage, and sets forth the responsibilities of the User and Manufacturer and the duties of the Inspectors of vessels constructed under these rules.

(b) Part KM contains

(1) the materials which may be utilized

(2) the permissible material specification identification numbers, special requirements, and limitations

(3) mechanical and physical properties upon which the design is based, and other necessary information concerning material properties (see Section II, Part D)

(c) Part KD contains requirements for the design of vessels and vessel parts.

(d) Part KF contains requirements for the fabrication of vessels and vessel parts.

(e) Part KOP contains rules for overpressure protection.

(f) Part KE contains requirements for nondestructive examination and repair of materials, vessels, and vessel parts.

(g) Part KT contains testing requirements and procedures.

(h) Part KS contains requirements for stamping and certifying vessels and vessel parts. It also gives requirements for Manufacturer's Data Reports and Records to be furnished to the User.

KG-220 APPENDICES

KG-221 Mandatory. The Mandatory Appendices address specific subjects not covered elsewhere in this Division. Their requirements are mandatory when applicable.

KG-222 Nonmandatory. The Nonmandatory Appendices provide information and suggested good practices.

KG-230 ARTICLES AND PARAGRAPHS

KG-231 Articles. The main divisions of the Parts of this Division are designated Articles. These are given numbers and titles such as Article KG-1, Scope and Jurisdiction.

KG-232 Paragraphs and Subparagraphs. The Articles are divided into paragraphs and subparagraphs which are given three-digit numbers, the first of which corresponds to the Article number. Each such paragraph or subparagraph number is prefixed with letters which, with the first digit (hundreds), indicate the Part and Article of this Division in which it is found, such as KD-140, which is a subparagraph of KD-100 in Article KD-1 of Part KD.

(a) Major subdivisions of paragraphs or subparagraphs are indicated by the basic paragraph number followed by a decimal point and one or two digits. Each of these subdivisions are titled and appear in the table of contents.

(b) Minor subdivisions of paragraphs are designated (a), (b), etc.

(c) Where further subdivisions are needed, they are designated by numbers in parentheses [e.g., KG-311.8(b)(1)].

KG-240 REFERENCES

When a Part, Article, or paragraph is referenced in this Division, the reference shall be taken to include all subdivisions under that Part, Article, or paragraph, including subparagraphs.

KG-250 TERMS AND DEFINITIONS

Terms and symbols used in this Division are defined in the various Parts, Articles, or paragraphs where they first apply or are of primary interest. A list of symbols is given in Mandatory Appendix 1.

ARTICLE KG-3
RESPONSIBILITIES AND DUTIES

(25) KG-300 GENERAL

The User, Manufacturer, and Inspector involved in the production and certification of vessels according to this Division have definite responsibilities and duties in meeting the requirements of this Division. The responsibilities and duties set forth in the following relate only to compliance with this Division, and are not to be construed as involving contractual relations or legal liabilities. Whenever *User* appears in this document, it may be considered to apply also to an agent (e.g., designee or licensor) acting on the User's behalf.

(25) KG-310 USER'S RESPONSIBILITY

It is the responsibility of the User or an agent acting on behalf of the User to provide a User's Design Specification for each pressure vessel to be constructed in accordance with this Division. The User's Design Specification shall contain sufficient detail to provide a complete basis for design and construction in accordance with this Division. It is the User's responsibility to specify, or cause to be specified, the effective Code Edition to be used for construction.

A single User's Design Specification may be prepared to support the design of more than one pressure vessel when all details of the construction are identical for each pressure vessel. The installation location for all vessels supported by a single User's Design Specification shall be defined in sufficient detail such that any jurisdictional, technical, and environmental requirements for the vessel are defined. The User's Design Specification shall include the most conservative state jurisdictional, technical, and environmental requirements to be considered during the design.

(a) The designated agent may be

(1) a design agency specifically engaged by the User

(2) the Manufacturer of a system for a specific service that includes a pressure vessel as a component that is purchased by the User, or

(3) an organization that offers pressure vessels for sale or lease for specific services

(b) The User may select more than one designated agent to obtain the most experience-based advice in several areas of expertise when needed (e.g., design, metallurgy, fabrication, pressure relief).

(c) A designated agent may be self-appointed as such by accepting certain responsibilities of a designated agent, as in the case of vessels designed, manufactured (built) for stock, and intended for operation in a specific application.

(d) The Design Specification shall contain sufficient detail to provide a complete basis for Division 3 design and construction. Such requirements shall not result in design or construction that fails to conform with the rules of this Division.

(e) Multiple Duplicate. A single User's Design Specification may be prepared to support the design of more than one pressure vessel that is to be located in a single, specific jurisdiction, provided that the environmental requirements and jurisdictional regulatory authority applied for each installation location are clearly specified and are the same or more conservative than required.

KG-311 USER'S DESIGN SPECIFICATION

The User's Design Specification shall include the specifications described in KG-311.1 through KG-311.15

KG-311.1 Vessel Identification.

(a) unique vessel serial number. However, the User may specify that the unique vessel serial number may be assigned by the Manufacturer for each vessel.

(b) name, function, purpose

(c) service fluid

KG-311.2 Vessel Configuration.

(a) shape

(b) vertical or horizontal

(c) nominal size or volume capacity

(d) support method and location, including the foundation type and allowable loading, if applicable (see KD-110 and Article KD-7). When the support method is unknown at the time of vessel manufacture, the User's Design Specification shall state that the Manufacturer is not responsible for the design of any supports or attachments not welded to the vessel (see Article KD-7) and that the User assumes the responsibility.

(e) construction type

(f) functions and boundaries of the items covered in KG-110

(g) items furnished by Manufacturer

(h) items furnished by User

KG-311.3 Controlling Dimensions.

(a) outline drawings
(b) openings, connections, closures
  (1) quantity of each
  (2) type and size
  (3) purpose
  (4) location, elevation, and orientation

KG-311.4 Design Criteria.

(a) Design Pressure. Design pressure is the pressure at the top of the vessel and which, together with the applicable coincident (metal) temperature, is stamped on the nameplate. The pressure at the top of the vessel is also the basis for the pressure setting of the pressure relief devices protecting the vessel.

(b) Design Temperature. The maximum mean metal temperature specified by the User, at design pressure. See KD-112. This is the design temperature that is to be stamped on the vessel.

(c) More than one combination of design pressure and temperature may be specified.

(d) Minimum Design Metal Temperature (MDMT). The MDMT is the lowest temperature to which the vessel will be exposed when the primary stresses at any location in the vessel are greater than 6 ksi (40 MPa)(see KM-234). This temperature shall be determined considering the lowest process temperature to which the vessel will normally be exposed in service, including process upsets, dumps, jet impingement, etc. Also, see KD-112 and KD-113.

(e) Thermal gradients across the vessel sections.

KG-311.5 Operating Conditions.

(a) operating pressure at coincident fluid temperature. The *operating pressure* is the maximum sustained process pressure that is expected in service. The operating pressure shall not exceed the design pressure. This pressure is expressed as a positive value, and may be internal or external to the vessel.

(b) upset and other combinations of operating pressures and coincident fluid temperature in sufficient detail to constitute an adequate basis for selecting materials

(c) proposed methods of heating and cooling, as well as those upset conditions that could lead to rapid heating or cooling of the vessel surfaces

(d) cyclic operating data and conditions

KG-311.6 Contained Fluid Data.

(a) phase (liquid, gaseous, dual)
(b) density
(c) unusual thermodynamic properties
(d) inlet and outlet fluid temperatures
(e) flow rates
(f) jet impingement streams
(g) statement if noxious, hazardous, or flammable

KG-311.7 Materials Selection. (25)

(a) appropriate materials for resistance to process corrosion (specific or generic).

(b) corrosion/erosion allowance.

(c) any information relating to possible deterioration of the selected construction materials due to environmental exposure. Examples of such concerns may be found in, but are not limited to, Section II, Part D, Nonmandatory Appendix A.

(d) if materials of construction include steels with a minimum specified yield strength greater than 120 ksi (827 MPa), state whether the material, when loaded, will be in contact with water or an aqueous environment at any time.

When additional requirements are appropriate for the intended service, see KG-311.12.

KG-311.8 Loadings.

(a) The User shall specify all expected combinations of coincident loading conditions as listed in KD-110. These shall include reaction load vectors.

(b) This loading data may be established by
  (1) calculation
  (2) experimental methods
  (3) actual measurement for similar conditions
  (4) computer analysis
  (5) published data

(c) For mobile vessels, loading conditions imposed by handling, transportation, or motion of the structure to which the vessel is fastened, including credible accidental loadings, shall be considered according to Article KD-1.

KG-311.9 Useful Operating Life Expected. State years, cycles, or both. It is permissible to state that the life is to be determined analytically during design.

KG-311.10 Fatigue Analysis.

(a) Fatigue analysis is mandatory for Division 3 vessels. It is the User's responsibility to provide, or cause to be provided, information in sufficient detail so an analysis for cyclic operation can be carried out in accordance with Articles KD-3 and KD-4.

(b) The User shall state if leak-before-burst can be established based on documented experience with similar designs, size, material properties, and operating conditions (see KD-141) or if leak-before-burst is to be established analytically. The number of design cycles shall be calculated by Article KD-4 if leak-before-burst cannot be established.

(c) The User shall state whether through-thickness leaks can be tolerated as a failure mode for protective liners and inner layers. See KD-103, KD-810(f), and KD-931.

KG-311.11 Overpressure Protection. The User or the (25) User's designated agent shall be responsible for the design, construction, and installation of the overpressure

protection system. This system shall meet the requirements of Part KOP. Calculations, test reports, and all other information used to justify the size, location, connection details, and flow capacity for the overpressure protection system shall be documented in the User Design Specification (see KOP-120). For a vessel built for stock by a Manufacturer, the Manufacturer shall fulfill all User's responsibilities as the User's designated agent in preparing the User's Design Specification's overpressure protection requirement. The only exception is that the Manufacturer shall not be required to document the relief system, if the relief system is provided by other than the vessel Manufacturer. The User's Design Specification shall state that the relief system is to be determined by others and state that the requirements of Part KOP are to be met prior to installation.

For vessels using power-actuated pressure relief systems following the rules of Article KOP-2, the User's Design Specification shall follow the requirements of KOP-201.

KG-311.12 Additional Requirements. The User shall state in the User's Design Specification what additional requirements are appropriate for the intended vessel service (see Part KE).

(a) For those services in which laminar discontinuities may be harmful, additional examination of materials prior to fabrication shall be specified by the User; for example, ultrasonic examination of plate in Section V, SA-435 and forgings in Section V, SA-388.

(b) State additional requirements such as nondestructive examinations, restricted chemistry, or heat treatments.

(c) The User shall state any nonmandatory or optional requirements of this Division that are considered to be mandatory for this vessel.

(d) The User shall state whether U.S. Customary or SI units are to be used in all certified documents, and on all marking and stamping required by this Division. The User shall also state if duplicate nameplates and certified documents in a second language are required, and if there are any other special requirements for markings and their locations. See also KG-150 and KS-130.

(e) The User shall state requirements for seals and bolting for closures and covers (see KD-660).

(f) Specific additional requirements relating to pressure testing shall be listed in the User's Design Specification, such as

(1) fluid and temperature range

(2) position of vessel

(3) location, Manufacturer's facility or on-site

(4) cleaning and drying

(g) The User shall state in the User's Design Specification what construction reports, records, or certifications, in addition to those listed in KS-320, the Manufacturer is required to provide to the User.

(h) See below.

(1) The User shall state in the User's Design Specification when the special requirements of Article KD-10 for vessels in high pressure hydrogen service shall be met.

(2) The User shall ensure that the requirements of KD-1001 are met.

(i) The User shall state considerations for limiting the potential for unsatisfactory performance when subjected to service or test loads, if applicable. Examples of such considerations may be found in, but are not limited to, KD-231.2(b).

KG-311.13 Installation Site.

(a) location

(b) jurisdictional authority (the User shall state the name and address of the jurisdictional authority that has jurisdiction at the site of installation of the vessel, and state any additional requirements or restrictions of that authority that pertain to the design, construction, or registration of this vessel). When preparing a User's Design Specification for a vessel design intended to be acceptable in multiple jurisdictions, the design shall be based on the most conservative requirements, including all technical, environmental, and jurisdictional requirements. The following information shall be provided:

(1) a listing of all jurisdictions considered in the design

(2) the governing parameters for all design inputs based on the stated installation locations

(c) environmental conditions

KG-311.14 Certification of User's Design Specification. (25) One or a combination of methods shown below shall be used to certify the User's Design Specification.

(a) One or more Professional Engineers,[1] registered in one or more of the states of the United States of America or the provinces of Canada and experienced in pressure vessel design, shall certify that the User's Design Specification meets the requirements in KG-311, and shall apply the Professional Engineer seal in accordance with the required procedures. In addition, the Registered Professional Engineer(s) shall prepare a statement to be affixed to the document attesting to compliance with the applicable requirements of the Code; see KG-311.15(e). This Professional Engineer shall be other than the Professional Engineer who certifies the Manufacturer's Design Report, although both may be employed by or affiliated with the same organization.

(b) One or more individual(s) in responsible charge of the specification of the vessel and the required design conditions shall certify that the User's Design Specification meets the requirements in KG-311. Such certification requires the signature(s) of one or more Engineers with requisite technical and legal stature, and jurisdictional authority needed for such a document. One or more individuals shall sign the documentation based on the information reviewed, and the knowledge and belief that the objectives of this Division have been

Form KG-311.15
Typical Certification of Compliance of the User's Design Specification

CERTIFICATION OF COMPLIANCE OF
THE USER'S DESIGN SPECIFICATION

I (We), the undersigned, being experienced and competent in the applicable field of design related to pressure vessel requirements relative to this User's Design Specification, certify that to the best of my knowledge and belief it is correct and complete with respect to the Design and Service Conditions given and provides a complete basis for construction in accordance with KG-311 and other applicable requirements of the ASME Section VIII, Division 3 Pressure Vessel Code, _____ Edition and Code Cases(s) _____ . This certification is made on behalf of the organization that will operate these vessels.

_____
company name
_____

Certified by: _____
Title and areas of responsibility: _____
Date: _____

Certified by: _____
Title and areas of responsibility: _____
Date: _____

Professional Engineer Seal: _____
as required
_____
Date: _____

satisfied. In addition, these individuals shall prepare a statement to be affixed to the document attesting to compliance with the applicable requirements of the Code; see KG-311.15(e).

(25) **KG-311.15 Requirements for Engineers Who Sign and Certify a User's Design Specification.** Any Engineer who signs and certifies a User's Design Specification shall meet one of the criteria shown in (a), (b), or (c) below and shall comply with the requirements of (d) and (e) below.

(a) A Registered Professional Engineer who is registered in one or more of the states of the United States of America or the provinces of Canada and experienced in pressure vessel design.

(b) An Engineer experienced in pressure vessel design who meets all required qualifications to perform engineering work and any supplemental requirements stipulated by the user and the licensing or registering authorities. The Engineer shall identify the location and the licensing or registering authorities under which the Engineer has received the authority to perform engineering work.

(c) An Engineer experienced in pressure vessel design who meets all required qualifications to perform engineering work and any supplemental requirements stipulated by the user. The Engineer shall be registered in the International Register of Professional Engineers of the Engineers Mobility Forum.

(d) The Engineer certifying the User's Design Specification shall comply with the requirements of the location to practice engineering where that Specification is prepared unless the jurisdiction where the vessel will be installed has different certification requirements.

(e) When more than one Engineer certifies and signs the User's Design Specification, the area of expertise shall be noted next to the signature of each Engineer under "areas of responsibilities" (e.g., design, metallurgy, pressure relief, fabrication, etc.). In addition, one of the Engineers signing the User's Design Specification shall certify that all elements required by this Division are included in the Specification.

(f) An example of a typical User's Design Specification Certification Form is shown in Form KG-311.15.

KG-311.16 Additional User's Design Specification Requirements for Composite Reinforced Pressure Vessels (CRPV). The User shall state in the User's Design Specification any provisions required for protection of the structural laminate layer from damage due to impact, ultraviolet radiation, or other environmental exposure; fire or abrasive conditions; and inservice degradation of the laminate for the life of the CRPV under the service conditions specified shall be stated in the User's Design Specification (see KG-522).

KG-320 MANUFACTURER'S RESPONSIBILITY

KG-321 STRUCTURAL AND PRESSURE-RETAINING INTEGRITY

The Manufacturer is responsible for the structural and pressure-retaining integrity of a vessel or part thereof, as established by conformance with all rules of this Division which are required to meet the conditions in the User's Design Specification and shown in the Manufacturer's Design Report.

KG-322 CODE COMPLIANCE

(a) The Manufacturer completing any vessel or part to be marked with the Certification Mark with U3 Designator or Certification Mark with the word "PART" (see KS-120) in accordance with this Division has the responsibility to comply with all the applicable requirements of this Division and, through proper certification, to ensure that any work done by others also complies with all requirements of this Division.

(b) The Manufacturer shall certify compliance with these requirements by the completion of the appropriate Manufacturer's Data Report, as described in KS-300.

(25) KG-323 MANUFACTURER'S DESIGN REPORT

As part of the Manufacturer's responsibility, the Manufacturer shall provide a Manufacturer's Design Report that includes

(a) design calculations and analysis that establish that the design as shown on the drawings, including as-built changes, complies with the requirements of this Division for the design conditions that have been specified in the User's Design Specification.

(b) final and as-built drawings.

(c) a single Manufacturer's Design Report may be completed and certified to document more than one pressure vessel when all details of construction are identical for each pressure vessel. The location of installation shall be a single, specific jurisdiction, provided that all technical requirements of the User's Design Specification are identical. When preparing a Manufacturer's Design Report for a vessel design intended to be acceptable in multiple jurisdictions, the design shall be based on the most conservative requirements, including all technical, environmental, and jurisdictional requirements. The following information shall be provided:

(1) a listing of all jurisdictions considered in the design

(2) the governing parameters for all design inputs based on the stated installation locations

A separate Manufacturer's Data Report shall be issued for each vessel.

(d) the results of the fatigue analysis according to Articles KD-3 and KD-4, and KD-1260, if applicable.

(e) documentation of the consideration of the effects of heating, or heat treatments during manufacturing, and similarly, the maximum metal temperature specified, to show that the material properties or prestress used in the design are not adversely affected (see Parts KD and KF).

(f) statement of any openings for which the Manufacturer has not installed closures such as the service cover, or closure or other connections.

(g) the limiting thermal gradients across the vessel section.

(h) all design information required for the User or the User's designated agent to design the vessel's support to meet the requirements of Article KD-7, when the support method is unknown at the time of vessel manufacture. This may include as a minimum

(1) vessel weight

(2) vessel loading considered in design

(3) vessel natural frequency

(i) Certification of the Design Report as provided in KG-324, which shall not relieve the Manufacturer of the responsibility for the structural integrity of the completed item for the conditions stated in the User's Design Specification.

KG-324 CERTIFICATION OF MANUFACTURER'S DESIGN REPORT (25)

One or a combination of methods shown below shall be used to certify the Manufacturer's Design Report.

(a) One of more Professional Engineers,[1] registered in one or more of the states of the United States of America or the provinces of Canada and experienced in pressure vessel design, shall certify the Manufacturer's Design Report meets the requirements in KG-323. The Registered Professional Engineer(s) shall apply the Professional Engineer seal in accordance with the required procedures. In addition, the Registered Professional Engineer(s) shall prepare a statement to be affixed to the document attesting to compliance with the applicable requirements of the Code; see KG-324.1(h). This Professional Engineer shall be other than the Professional Engineer who certifies the User's Design Specification, although both may be employed by or affiliated with the same organization.

(b) One or more individual(s), experienced in pressure vessel design shall certify that the Manufacturer's Design Report meets the requirements in KG-323. Such

certification requires the signature(s) of one or more Engineers with requisite technical and legal stature, and corporate authority needed for such a document. These responsible individuals shall sign the documentation based on the information reviewed, and the knowledge and belief that the objectives of this Division have been satisfied. In addition, these individuals shall prepare a statement to be affixed to the document attesting to compliance with the applicable requirements of the Code; see KG-324.1(i).

(25) **KG-324.1 Requirements for Signing and Certifying a Manufacturer's Design Report.** Any Engineer who signs and certifies a Manufacturer's Design Report shall meet one of the criteria shown in (a), (b), or (c) below and shall comply with the requirements of (d), (e), and (f) below.

(a) A Registered Professional Engineer who is registered in one or more of the states of the United States of America or the provinces of Canada and experienced in pressure vessel design.

(b) An Engineer experienced in pressure vessel design who meets all required qualifications to perform engineering work and any supplemental requirements stipulated by the user. The Engineer shall identify the location and the licensing or registering authorities under which the Engineer has received the authority to perform engineering work stipulated by the user in the Design Specification.

(c) An Engineer experienced in pressure vessel design who meets all required qualifications to perform engineering work and any supplemental requirements stipulated by the user. The Engineer shall be registered in the International Register of Professional Engineers of the Engineers Mobility Forum.

(d) The Engineer certifying the Manufacturer's Design Report shall comply with the requirements of the location to practice engineering where that Report is prepared unless the jurisdiction where the vessel will be installed has different certification requirements.

(e) When more than one Engineer certifies and signs the Manufacturer's Design Report, the area of expertise shall be noted next to the signature of each Engineer under "areas of responsibilities" (e.g., design, metallurgy, pressure relief, fabrication, etc.). In addition, one of the Engineers signing the Manufacturer's Design Report shall certify that all elements required by this Division are included in the Report.

(f) The manufacturer's Design Report shall be certified only after

(1) all design requirements of this Division and the User's Design Specification have been met.

(2) the Manufacturer's Construction Records are reconciled with the Manufacturer's Design Report and with the User's Design Specification.

(g) Certification of the Design Report shall not relieve the Manufacturer of the responsibility for the structural integrity of the completed item for the conditions stated in the User's Design Specification.

(h) The inspector shall review the Manufacturer's Design Report and ensure that the requirements of KG-440 have been satisfied.

(i) An example of a typical Manufacturer's Design Report Certification Form is shown in Form KG-324.1.

KG-325 MANUFACTURER'S CONSTRUCTION RECORDS (MCR)

The Manufacturer shall prepare, collect, and maintain construction records and documentation of NDE reports, repairs, and deviations from drawings, as production progresses, to show compliance with the Manufacturer's Design Report. An index to the construction records file shall be maintained current. See KS-320.

KG-330 DESIGNER (25)

The Designer is the individual engineer, or group of engineers, experienced in high pressure vessel design, who performs the required analysis of the vessel. The Designer may be an employee of the Manufacturer, or an agent acting in the Manufacturer's behalf.

Form KG-324.1
Typical Certification of Compliance of the Manufacturer's Design Report

CERTIFICATION OF COMPLIANCE OF
THE MANUFACTURER'S DESIGN REPORT

I (We), the undersigned, being experienced and competent in the applicable field of design related to pressure vessel construction relative to the certified User's Design Specification, certify that to the best of my knowledge and belief the Manufacturer's Design Report is complete, accurate, and complies with the User's Design Specification and with all the other applicable construction requirements of the ASME Section VIII, Division 3 Pressure Vessel Code, _____ Edition and Code Case(s) _____ . This certification is made on behalf of the Manufacturer _____
company name
_____

Certified by: _____
Title and areas of responsibility: _____
Date: _____

Certified by: _____
Title and areas of responsibility: _____
Date: _____

Professional Engineer Seal: _____
as required
_____
Date: _____

Authorized Inspector review: _____
Date: _____

ARTICLE KG-4
GENERAL RULES FOR INSPECTION

KG-400 GENERAL REQUIREMENTS FOR INSPECTION AND EXAMINATION

The inspection and examination of pressure vessels stamped with the Certification Mark with U3 Designator shall conform to the general requirements for inspection and examination in this Article and, in addition, to the specific requirements for inspection and examination given in the applicable paragraphs.

KG-410 MANUFACTURER'S RESPONSIBILITIES

KG-411 INSPECTION CONTRACT

The Manufacturer shall have in force, at all times, a valid inspection contract or agreement with an accredited Authorized Inspection Agency, employing Authorized Inspectors as defined in KG-431. A valid inspection contract or agreement is a written agreement between the Manufacturer and the Authorized Inspection Agency in which the terms and conditions for furnishing the service are specified and in which the mutual responsibilities of the Manufacturer and the Inspector are stated.

(25) KG-412 CERTIFICATION

The Manufacturer who completes any vessel to be marked with the Certification Mark with U3 Designator has the responsibility of complying with all the requirements of this Division and, through proper certification, of ensuring that work done by others also complies with all requirements of this Division, as indicated by the Manufacturer's signature on the Manufacturer's Data Report.

KG-413 PROVISIONS FOR INSPECTION

KG-413.1 Access. The Manufacturer of the vessel or part thereof shall arrange for the Inspector to have free access to such parts of all plants as are concerned with the supply or manufacture of materials for the vessel, at all times while work on the vessel is being performed, and to the site of field erected vessels during the period of assembly and testing of the vessel.

(25) **KG-413.2 Progress.** The Manufacturer shall keep the Inspector informed of the progress of the work and shall notify the Inspector reasonably in advance when the vessel or materials will be ready for any required tests or inspections.

KG-414 DOCUMENTATION FURNISHED TO INSPECTOR

The Manufacturer shall provide documentation and records, with ready and timely access for the Inspector, and perform the other actions as required by this Division. Some typical required documents, which are defined in the applicable rules, are summarized as follows:

(a) the Certificate of Authorization to use the Certification Mark with U3 Designator from the ASME Boiler and Pressure Vessel Committee (see Article KS-2)

(b) the drawings and design calculations for the vessel or part (see KG-323)

(c) the mill test report or material certification for all material used in the fabrication of the vessel or part including welding materials (see KM-101), and sample test coupons (see KT-110) when required

(d) any Partial Data Reports when required by KS-301

(e) reports of examination of all materials (except welding materials) before fabrication

(1) to make certain they have the required thickness in accordance with the Design Specification

(2) for detection of unacceptable defects

(3) to make certain the materials are permitted by this Division (see KM-100)

(4) and to make certain that the identification traceable to the mill test report or material certification has been maintained (see KF-112)

(f) documentation of impact tests when such tests are required [see KM-212, KM-230(a), and Article KT-2]

(g) obtain concurrence of the Inspector prior to any repairs when required by KF-113, KF-710 and 2-116 of Mandatory Appendix 2

(h) reports of examination of head and shell sections to confirm they have been properly formed to the specified shapes within permissible tolerances (see KF-120 and KF-130)

(i) qualification of the welding procedures before they are used in fabrication (see KF-210, KF-822, and KT-220)

(j) qualification of all Welders and Welding Operators before using Welders in production work (see KF-210 and KF-823)

(k) reports of examination of all parts prior to joining to make certain they have been properly fitted for welding and that the surfaces to be joined have been cleaned and the alignment tolerances are maintained (see KF-230)

(l) reports of examination of parts as fabrication progresses for material identification (see KG-413 and KS-301) that surface defects are not evident, and that dimensional geometries are maintained

(m) provision of controls to assure that all required heat treatments are performed (see Part KF)

(n) providing records of nondestructive examinations performed on the vessel or vessel parts. This shall include retaining the radiographic film

(o) making the required hydrostatic or pneumatic test and having the required examination performed during such test (see Article KT-3)

(p) applying the required stamping and/or nameplate to the vessel and making certain it is applied to the proper vessel (see Article KS-1)

(q) preparing the required Manufacturer's Data Report with the supplement, and having them certified by the Inspector (see Article KS-1)

(r) maintenance of records (see KS-310 and KS-320)

(25) KG-420 CERTIFICATION OF SUBCONTRACTED SERVICES

(a) The Quality Control Manual shall describe the manner in which the Manufacturer (Certificate Holder) controls and accepts the responsibility for the subcontracted activities (see KG-322). The Manufacturer shall ensure that all subcontracted activities meet the requirements of this Division. This section of the manual will be reviewed with the Inspector together with the entire Quality Control Manual.

(b) Work such as forming, nondestructive examination, heat treating, etc., may be performed by others. It is the vessel Manufacturer's responsibility to ensure that all work performed complies with all the applicable requirements of this Division. After ensuring compliance, and obtaining permission of the Inspector, the vessel may be stamped with the Certification Mark.

(c) Subcontracts that involve welding on the pressure boundary components for construction under the rules of this Division, other than repair welds permitted by the ASME material specifications, shall be made only to subcontractors holding a valid Certificate of Authorization with U, U2, or U3 Designators.

(d) A Manufacturer may engage individuals by contract for services as Welders or Welding Operators, at shop or site locations shown on the Manufacturer's Certificate of Authorization, provided all of the following conditions are met:

(1) The work to be done by Welders or Welding Operators is within the scope of the Certificate of Authorization.

(2) The use of such Welders or Welding Operators is described in the Quality Control Manual of the Manufacturer.

(3) The Welding Procedures have been properly qualified by the Manufacturer, according to Section IX.

(4) The Welders and Welding Operators are qualified by the Manufacturer according to Section IX to perform these procedures.

(5) Code responsibility and control is retained by the Manufacturer.

KG-430 THE INSPECTOR

KG-431 IDENTIFICATION OF INSPECTOR

All references to Inspectors throughout this Division mean the Authorized Inspector as defined in this paragraph. All inspections required by this Division shall be by an Inspector qualified according to KG-432 and regularly employed by

(a) an ASME accredited Authorized Inspection Agency, as defined in ASME QAI-1, Qualifications for Authorized Inspection, or

(b) a company that manufactures pressure vessels exclusively for its own use and not for resale which is defined as a User–Manufacturer. This is the only instance in which an Inspector may be in the employ of the Manufacturer.

KG-432 INSPECTOR QUALIFICATION

All Inspectors shall have been qualified in accordance with ASME QAI-1, Qualifications for Authorized Inspection.

KG-433 MONITOR QUALITY CONTROL SYSTEM

In addition to the duties specified, the Inspector has the duty to monitor the Manufacturer's Quality Control System as required in Mandatory Appendix 2.

KG-434 MAINTENANCE OF RECORDS

The Inspector shall verify that the Manufacturer has a system in place to maintain the documentation for the Manufacturer's Construction Records current with production, and to reconcile any deviations from the Manufacturer's Design Report.

KG-440 INSPECTOR'S DUTIES (25)

The Inspector of vessels to be marked with the Certification Mark with U3 Designator has the duty of making all required inspections and such other inspections considered necessary in order to satisfy the Inspector that all requirements have been met. Some typical required inspections and verifications, which are defined in the applicable rules, are summarized as follows:

(a) to verify that the Manufacturer has a valid Certificate of Authorization and is working according to an approved Quality Control System

(b) to verify that applicable Design Report, User's Design Specification, drawings, and related documents are available (see KG-414)

(c) to verify that materials used in the construction of the vessel comply with the requirements of Part KM

(d) to verify that all Welding Procedures have been qualified

(e) to verify that all Welders and Welding Operators have been qualified

(f) to verify that the heat treatments, including postweld heat treatment (PWHT), have been performed [see KG-414(m)]

(g) to verify that material imperfections repaired by welding are acceptably repaired and reexamined

(h) to verify that the required nondestructive examinations, impact tests, and other tests have been performed and that the results are acceptable

(i) to make a visual inspection of the vessel to confirm that the material numbers have been properly transferred (see KF-112)

(j) to perform internal and external inspections where applicable, and to witness the hydrostatic or pneumatic tests (see Article KT-3)

(k) to verify that the required marking is provided, including stamping, and that the nameplate has been permanently attached to the proper vessel or vessel chamber (see Article KS-1)

(l) to sign the Certificate of Inspection on the Manufacturer's Data Report when the vessel, to the best of the Inspector's knowledge and belief, is complete and in compliance with all the provisions of this Division (see Article KS-3)

(m) to verify that the Manufacturer has maintained proper records (see KS-320 and KG-320)

ARTICLE KG-5
ADDITIONAL GENERAL REQUIREMENTS FOR COMPOSITE REINFORCED PRESSURE VESSELS (CRPV)

KG-500 GENERAL REQUIREMENTS

The following Article provides additional general requirements for the manufacture of Composite Reinforced Pressure Vessels (CRPV).

KG-510 SCOPE

This construction method uses a laminate of continuous unidirectional filaments of a specified glass or carbon fiber with a specified resin that is circumferentially wound in a systematic manner under controlled tension over a cylindrical metallic layer and cured in place. Openings are not permitted in the laminate. Metallic ends and nozzles complete the construction; see Section X, Mandatory Appendix 10, Figures 10-201-1, 10-201-2, and 10-201-3.

KG-511 METALLIC LAYER

The outside diameter of the metallic layer in the reinforced area shall not exceed 60 in. (1.52 m). The thickness of the metallic layer shall not be less than 0.25 in. (6 mm).

KG-512 SERVICE LIFE

Service life for CRPV constructed under the rules of this Division shall be limited to twenty years from the date of manufacture as noted on Form CRPV-1A.

KG-513 APPLICATION SPECIFIC TESTS AND OTHER REQUIREMENTS

This Division does not include requirements or rules for tests that may be appropriate for certain applications (e.g., fire tests, drop tests, projectile impact tests). For some applications, it may be necessary to consider additional conditions such as exposure to fire and projectile impact damage.

KG-514 UPPER LIMIT OF DESIGN PRESSURE

The internal design pressure for CRPV shall not be greater than 15,000 psi (103 MPa).

KG-515 SERVICE PRESSURE AND WORKING PRESSURE

In some standards and regulations used in ambient temperature compressed gas transport service, the term “service pressure” is used to indicate the pressure in the vessel at a temperature of 68°F (20°C). In other standards and regulations, the term “working pressure” is used with the same definition. In these standards and regulations it is generally allowable for the service or working pressure to be exceeded as the gas is heated beyond 68°F (20°C) during filling or due to atmospheric heating. For pressure vessels to be used in transport service constructed to this Code, the service pressure and the working pressure shall be the maximum expected pressure at a temperature of 68°F (20°C). The service pressure or the working pressure or both shall be defined in the User’s Design Specification. The working pressure, service pressure, or the expected pressure due to heating during filling or atmospheric heating shall not exceed the design pressure of the vessel at the design temperature.

KG-516 PROTECTIVE LAYER

Additional requirements regarding specification of a protective layer for the CRPV in the User's Design Specification can be found in Section X, Mandatory Appendix 10, 10-202.

KG-517 REQUIREMENTS FOR CYCLIC PRESSURE QUALIFICATION TEST

In addition to the total number of operating cycles during the life of the CRPV, the User's Design Specification shall state if the temperature of the intended service will be controlled. If the intent is to control the temperature of service, the number of cycles colder than 30°F (0°C), the number of cycles between 30°F (0°C) and 110°F (45°C), and the number of cycles warmer than 110°F (45°C) shall be noted. If the service will be in ambient conditions with no intent to control the temperature, there is no requirement to report the number of cycles in the aforementioned temperature ranges.

KG-518 LAMINATE TENSILE STRENGTH AND ELASTIC MODULUS

The User's Design Specification shall state the required minimum tensile strength and the nominal elastic modulus for the laminate in the maximum property direction (parallel to the fiber direction).

KG-520 SUPPLEMENTAL GENERAL REQUIREMENTS FOR CRPV

KG-521 REQUIREMENTS FOR CRPV USED IN TRANSPORT SERVICE

(a) CRPV used in transport service shall conform to the regulatory requirements specific to the application in addition to this Division. Government regulatory agencies and other jurisdictions issue rules that may require compliance with additional Codes and Standards.)

(b) CRPV may be installed in ships, barges, container frames, rail cars, over-the-road trucks, and other craft, provided prior written agreement with the local jurisdictional authority is established covering operation and maintenance control for a specific service and where this operation and maintenance control is retained during the life of the CRPV by the User who prepares, or causes to be prepared, the User's Design Specification. See KG-310.

(c) CRPVs to be used in transport service as described above may be constructed and stamped within the scope of this Division as specified with the following additional provisions:

(1) The User's Design Specification shall include the requirements that provide for operation and maintenance control for the CRPV.

(2) For vessels to be used in transport service, the User's Design Specification shall specify the service pressure or the working pressure or both for the vessel (see KG-515).

(3) The Manufacturer's Data Report, as described in KS-300, shall include under "Remarks" one of the following statements:

(-a) "Constructed for transport service for use in (name of local jurisdictional authority in this space)."

(-b) "Constructed for service according to the requirements of (regulatory agency or additional code(s) in this space)."

(4) The loads on the CRPV imposed by the conditions of transport, including accident loads, relocation of the CRPV between sites, and cyclic loading and discharge shall be considered as part of KD-110.

(5) The CRPV shall not be used as structural support members in the transport vehicle or vessel structure.

KG-522 SUPPLEMENTARY MANUFACTURER'S RESPONSIBILITIES

Additional supplementary Manufacturer's requirements are found in Section X, Mandatory Appendix 10, 10-203.

ARTICLE KG-6
ADDITIONAL GENERAL REQUIREMENTS FOR IMPULSIVELY LOADED VESSELS

KG-600 GENERAL REQUIREMENTS

The following Article provides additional general requirements for the design and manufacture of impulsively loaded vessels.

KG-610 SCOPE

This Article applies to pressure vessels that are subjected to internal impulsive loadings that may consist of blast pressure from a detonation source and mechanical loadings caused by detonation fragments. Impulsive loading is defined in KD-210.

KG-611 CONSTRUCTION RULES

Each pressure vessel to which this Article applies shall comply with the existing rules of Section VIII, Division 3 and the additional requirements given in Article KM-7, KD-240, Article KOP-3, KT-350, and KS-102.

KG-612 MATERIALS AND COMBINATIONS OF MATERIALS

Each pressure vessel to which this Article applies shall comply with the requirements of KD-101, except as covered in Article KM-7.

KG-613 OVERPRESSURE PROTECTION (25)

In accordance with KG-311.11, the User or the User's designated agent shall be responsible for the provision in the Design Specification of the administrative or engineered controls that provide overpressure protection as specified in Article KOP-3.

KG-614 LOADINGS

The User's Design Specification (see KG-311) shall provide the following in addition to the required loadings specified in KG-311:

(a) the impulsive loading design basis.

(b) impulse source location within the vessel (i.e., vessel center, off-center, etc.).

(c) the basis for administrative controls limiting the impulse source.

(d) any protective liner requirements, such as for fragment shielding. For vessels without protective liners, such as single-use vessels, guidance for evaluation of postulated localized wall thinning from fragment partial penetration is provided in API-579-1/ASME FFS-1.

PART KM
MATERIAL REQUIREMENTS

ARTICLE KM-1
GENERAL REQUIREMENTS

KM-100 MATERIALS PERMITTED

(a) Materials that are to be used under the rules of this Division, except for integral cladding, welding filler metals, weld metal overlay, protective liner materials (see KD-103), laminate materials used for the wrapping of CRPV vessels (see Article KM-5), and inner layers of covers used on impulsively loaded vessels (see Article KM-7), shall conform to a material specification given in Section II, and shall be listed in Tables KM-400-1 through KM-400-4 (Tables KM-400-1M through KM-400-4M) The term *material specification* used in this Division shall be the referenced specification in Section II together with the supplemental requirements listed in the User's Design Specification (see KG-311.7).

(b) Materials that are outside the limits of size and/or thickness stipulated in the title or scope clause of the material specifications given in Section II and permitted by Part KM may be used if the materials are in compliance with the other requirements of the material specification and no size or thickness limitation is specified in this Division. In those specifications in which chemical composition or mechanical properties vary with size or thickness, materials outside the range shall be required to conform to the composition and mechanical properties shown for the nearest specified range.

(c) Except as provided in Articles KM-5, KM-7, and this paragraph, materials other than those allowed by this Division shall not be used for construction of the pressure-retaining component, including bolting and prestressed inner layer.

(1) Data on other materials may be submitted to and approved by the ASME Boiler and Pressure Vessel Committee in accordance with Section II, Part D, Mandatory Appendix 5.

(2) A vessel or part Manufacturer may certify materials identified with a specification not permitted by this Division, provided the following requirements are satisfied:

(-a) All requirements (including, but not limited to, melting method, melting practice, deoxidation, quality, and heat treatment) of a specification permitted by this Division to which the material is to be certified, including the requirements of this Division, have been demonstrated to have been met.

(-b) A certification that the material was manufactured and tested in accordance with the requirements of the specification to which the material is certified (a Certificate of Compliance), excluding the specific marking requirements, has been furnished to the vessel or part Manufacturer, together with copies of all documents and test reports pertinent to the demonstration of conformance to the requirements of the permitted specification.

(d) The bolt product form, as specified in Tables KM-400-1 through KM-400-3 (Tables KM-400-1M through KM-400-3M) shall not be used for applications other than bolting (see KM-300).

(e) Pressure vessel closure components, such as threaded bodies and main nuts, that have threaded sections for the purpose of engaging seals and/or retaining end loads may be manufactured from forging or bar product forms listed in Tables KM-400-1 through KM-400-3 (Tables KM-400-1M through KM-400-3M), provided that all other qualification and design requirements of this Division are met.

(f) The User shall confirm the coupling of dissimilar metals will have no harmful effect on the corrosion rate or life of the vessel for the service intended (see KG-311.7).

KM-101 CERTIFICATION BY MATERIALS MANUFACTURER

The Materials Manufacturer shall certify that all requirements of the applicable materials specifications in Section II (considering any exemptions allowed by KM-100), all special requirements of Part KM which are to be fulfilled by the Materials Manufacturer, and all supplementary material requirements specified by the User's Design Specification (see KG-311) have been complied with. The certification shall consist of a Materials Manufacturer's material test report showing numerical results of all required tests, and shall certify that all required examinations and repairs have been performed

on the materials. Also see KE-200. All conflicts between the materials specifications and the special requirements herein shall be noted and compliance with the special requirements stated (see KF-111).

KM-102 PREFABRICATED OR PREFORMED PRESSURE PARTS FURNISHED WITHOUT A CERTIFICATION MARK

(a) Prefabricated or preformed pressure parts for pressure vessels that are subject to stresses due to pressure and that are furnished by others or by the Manufacturer of the completed vessel shall conform to all applicable requirements of this Division except as permitted in (b), (c), (d), and (e) below. When the prefabricated or preformed parts are furnished with a nameplate that contains product-identifying marks and the nameplate interferes with further fabrication or service, and where stamping on the material is prohibited, the Manufacturer of the completed vessel, with the concurrence of the Authorized Inspector, may remove the nameplate. The removal of the nameplate shall be noted in the "Remarks" section of the vessel Manufacturer's Data Report. The nameplate shall be destroyed. The rules of (b), (c), (d), and (e) below shall not be applied to welded shells or heads.

Parts furnished under the provisions of (b), (c), and (d) need not be manufactured by a Certificate of Authorization Holder.

Prefabricated or preformed pressure parts may be supplied as follows:

(1) cast, forged, rolled, or die-formed nonstandard pressure parts

(2) cast, forged, rolled, or die-formed standard pressure parts that comply with an ASME product standard, either welded or nonwelded

(3) cast, forged, rolled, or die-formed standard pressure parts that comply with a standard other than an ASME product standard, either welded or nonwelded

(b) Cast, Forged, Rolled, or Die-Formed Nonstandard Pressure Parts. Pressure parts such as shells, heads, removable doors, and pipe coils that are wholly formed by casting, forging, rolling, or die forming may be supplied basically as materials. All such parts shall be made of materials permitted under this Division, and the Manufacturer of the part shall furnish identification in accordance with KM-101. Such parts shall be marked with the name or trademark of the parts manufacturer and with such other markings as will serve to identify the particular parts with accompanying material identification. The Manufacturer of the completed vessel shall be satisfied that the part is suitable for the design conditions specified for the completed vessel in accordance with the rules of this Division.

(c) Cast, Forged, Rolled, or Die-Formed Standard Pressure Parts That Comply With an ASME Product Standard, Either Welded or Nonwelded

(1) These are pressure parts that comply with an ASME product standard accepted by reference. The ASME product standard establishes the basis for the pressure–temperature rating and marking unless modified by this Division.

(2) Flanges and flanged fittings may be used at the pressure–temperature ratings specified in the appropriate standard listed in this Division.

(3) Materials for standard pressure parts shall be as permitted by this Division.

(4) Pressure parts such as welded standard pipe fittings, welding caps, and flanges that are fabricated by one of the welding processes recognized by this Division do not require inspection or identification in accordance with KM-101 except that certified reports of numerical results or certificates of compliance of the required Charpy V-notch impact testing of the parts shall be supplied to the Manufacturer of the completed vessel. Partial Data Reports are not required provided the requirements of KM-102(c) are met.

(5) If postweld heat treatment is required by the rules of this Division, it may be performed either in the location of the parts manufacturer or in the location of the Manufacturer of the vessel to be marked with the Certification Mark.

(6) If volumetric examination is required by the rules of this Division, it may be performed at one of the following locations:

(-a) the location of the Manufacturer of the completed vessel

(-b) the location of the pressure parts manufacturer

(7) Parts made to an ASME product standard shall be marked as required by the ASME product standard.

(8) The Manufacturer of the completed vessels shall have the following responsibilities when using standard pressure parts that comply with an ASME product standard:

(-a) ensure that all standard pressure parts comply with applicable rules of this Division

(-b) ensure that all standard pressure parts are suitable for the design conditions of the completed vessel

(-c) when volumetric examination is required by the rules of this Division, obtain the complete data set, properly identified, with an examination report, and any other applicable volumetric examination report

(9) The Manufacturer shall fulfill these responsibilities by obtaining, when necessary, documentation as provided below, providing for retention of this documentation, and having such documentation available for examination by the Inspector when requested. The documentation shall contain at a minimum

(-a) material used

(-b) the pressure–temperature rating of the part

(-c) the basis for establishing the pressure–temperature rating

(d) Cast, Forged, Rolled, or Die-Formed Standard Pressure Parts That Comply With a Standard Other Than an ASME Product Standard, Either Welded or Nonwelded

(1) Standard pressure parts that are either welded or nonwelded and comply with a manufacturer's proprietary standard or a standard other than an ASME product standard may be supplied by

(-a) a Certificate of Authorization holder

(-b) a pressure parts manufacturer

(2) Parts of small size falling within this category for which it is impossible to obtain identified material, or that may be stocked and for which identification in accordance with KM-101 cannot be obtained and are not customarily furnished, shall not be used.

(3) Materials for these parts shall be as permitted by this Division only.

(4) When welding is performed, it shall meet the requirements of this Division.

(5) Pressure parts such as welded standard pipe fittings, welding caps, and flanges that are fabricated by one of the welding processes recognized by this Division do not require inspection or identification in accordance with KM-101 except that certified reports of numerical results or certificates of compliance of the required Charpy V-notch impact testing of the parts shall be supplied to the Manufacturer of the completed vessel. Partial Data Reports are not required provided the requirements of KM-102(c) are met.

(6) If postweld heat treatment is required by the rules of this Division, it may be performed either in the location of the parts manufacturer or in the location of the Manufacturer of the completed vessel.

(7) If radiography or other volumetric examination is required by the rules of this Division, it may be performed at one of the following locations:

(-a) the location of the Manufacturer of the completed vessel

(-b) the location of the parts Manufacturer

(-c) the location of the pressure parts manufacturer

(8) Marking for these parts shall be as follows:

(-a) with the name or trademark of the Certificate Holder or the pressure part manufacturer and any other markings as required by the proprietary standard or other standard used for the pressure part

(-b) with a permanent or temporary marking that will serve to identify the part with the Certificate Holder or the pressure parts manufacturer's written documentation of the particular items, and that defines the pressure–temperature rating of the part

(9) The Manufacturer of the completed vessels shall have the following responsibilities when using standard pressure parts:

(-a) ensure that all standard pressure parts comply with applicable rules of this Division

(-b) ensure that all standard pressure parts are suitable for the design conditions of the completed vessel

(-c) when volumetric examination is required by the rules of this Division, obtain the complete data set, properly identified, with an examination report, and any other applicable volumetric examination report

(10) The Manufacturer of the completed vessel shall fulfill these responsibilities by one of the following methods:

(-a) Obtain, when necessary, documentation as described below, provide for retention of this documentation, and have such documentation available for examination by the Inspector when requested, or,

(-b) Perform an analysis of the pressure part in accordance with the rules of this Division. This analysis shall be included in the documentation and shall be made available for examination by the Inspector when requested.

(11) The documentation shall contain at a minimum

(-a) material used

(-b) the pressure–temperature rating of the part

(-c) the basis for establishing the pressure–temperature rating

(-d) a written certification by the pressure parts manufacturer that all welding complies with Code requirements

(e) The Code recognizes that a Certificate of Authorization Holder may fabricate parts in accordance with KM-102(d), and that are marked in accordance with KM-102(d)(8). In lieu of the requirements in KM-102(d)(4), the Certificate of Authorization Holder may subcontract to an individual or organization not holding an ASME Certificate of Authorization standard pressure parts that are fabricated to a standard other than an ASME product standard, provided all the following conditions are met:

(1) The activities to be performed by the subcontractor are included within the Certificate Holder's Quality Control System.

(2) The Certificate Holder's Quality Control System provides for the following activities associated with subcontracting of welding operations and these provisions shall be acceptable to the Manufacturer's Authorized Inspection Agency:

(-a) the welding processes permitted by this Division that are permitted to be subcontracted

(-b) welding operations

(-c) Authorized Inspection activities

(-d) placement of the Certificate of Authorization Holder's marking in accordance with KM-102(d)(8)

(3) The Certificate Holder's Quality Control System provides for the requirements of KG-413 to be met at the subcontractor's facility.

(4) The Certificate Holder shall be responsible for reviewing and accepting the Quality Control Programs of the subcontractor.

(5) The Certificate Holder shall ensure that the subcontractor uses written procedures and welding operations that have been qualified as required by this Division.

(6) The Certificate Holder shall ensure that the subcontractor uses personnel that have been qualified as required by this Division.

(7) The Certificate Holder and the subcontractor shall describe in their Quality Control Systems the operational control of procedure and personnel qualifications of the subcontracted welding operations.

(8) The Certificate Holder shall be responsible for controlling the quality and ensuring that all materials and parts that are welded by subcontractors and submitted to the Inspector for acceptance conform to all applicable requirements of this Division.

(9) The Certificate Holder shall describe in their Quality Control Systems the operational control for maintaining traceability of materials received from the subcontractor.

(10) The Certificate Holder shall receive approval for subcontracting from the Authorized Inspection Agency prior to the commencing of activities.

KM-103 BASE MATERIAL FOR INTEGRAL CLADDING, WELD METAL OVERLAY, AND OTHER PROTECTIVE LININGS

Base materials over which integral cladding or weld metal overlay materials are applied shall satisfy the requirements of Part KM. Base materials in which corrosion-resistant or abrasion-resistant liners are used shall also meet the requirements of Part KM.

KM-104 INTEGRAL CLADDING AND WELD METAL OVERLAY MATERIAL

Integral cladding and weld metal overlay materials may be any metallic material of weldable quality that meets the requirements of Article KF-3.

KM-105 PROTECTIVE LINER MATERIAL

Corrosion-resistant or abrasion-resistant liner materials may be any metallic or nonmetallic material suitable for the intended service conditions (see KG-311).

KM-106 REPETITION OF SPECIFIED EXAMINATIONS, TESTS, OR HEAT TREATMENTS

The requirements of Article KM-2 shall be met in addition to the examination, testing, and heat treating requirements for a given material that are stated in its material specification. No heat treatment need be repeated except in the case of quenched and tempered steel as required by KF-602.

ARTICLE KM-2
MECHANICAL PROPERTY TEST REQUIREMENTS FOR METALS

KM-200 GENERAL REQUIREMENTS

As permitted by KM-100, all forms of metal products may be used subject to meeting the requirements of the material specification as well as the mechanical test and examination requirements of this Division.

KM-201 DEFINITION OF THICKNESS

The requirements in this Article make reference to a thickness. For the purpose intended, the following definitions of thickness T at the time of heat treatment apply.

KM-201.1 Plates. The thickness is the dimension of the short transverse direction.

KM-201.2 Forgings. The thickness is the dimension defined as follows:

(a) for hollow forgings in which the axial length is greater than the radial thickness, the thickness is measured between the minimum inside and maximum outside surfaces (radial thickness), excluding flanges (protrusions) whose thicknesses are less than the wall thickness of the cylinder

(b) for disk forgings in which the axial length is less than or equal to outside diameter, the thickness is the axial length

(c) for ring forgings where the maximum axial length is less than the radial thickness, the maximum axial dimension is considered the thickness

(d) for rectangular solid forgings, the least rectangular dimension is the thickness

(e) for round, hexagonal, and octagonal solid forgings, the nominal thickness is the diameter or distance across the flats (axial length > diameter or distance across the flats)

KM-201.3 Bars and Bolting Materials. The thickness for bars and bolting material shall be the diameter for round bars, the lesser of the two cross-section dimensions for rectangular bars, and the distance across the flats for hexagonal bars; or the length of a given bar, whichever is less.

KM-201.4 Pipe. The thickness for pipe shall be the nominal wall thickness.

KM-210 PROCEDURE FOR OBTAINING TEST SPECIMENS AND COUPONS

For austenitic stainless steels and for nonferrous alloys, the procedure for obtaining test specimen coupons shall conform to the applicable material specification. These materials are exempt from the requirements of KM-211.

KM-211 PRODUCT FORMS

KM-211.1 Plates.

(a) For thicknesses less than 2 in. (50 mm), specimens shall be taken in accordance with the requirements of the applicable material specification.

(b) For thicknesses 2 in. (50 mm) and greater, the centerline of the test specimens shall be taken in accordance with the requirements of the applicable material specification, but not closer than T to any heat-treated edge and at a depth of $T/2$ from the plate surface.

(c) Where a separate test coupon is used to represent the vessel material, it shall be of sufficient size to ensure that the cooling rate of the region from which the test specimens are removed represents the cooling rate of the material at $T/2$ deep and at least T from any edge of the product. Unless cooling rates applicable to the bulk pieces or product are simulated in accordance with KM-220, the dimensions of the coupon shall be not less than $3T$ by $3T$ by T, where T is the maximum material thickness.

KM-211.2 Forgings. The datum point, defined as the midpoint of the gage length of tension test specimens or the area under the notch of impact test specimens, shall be located in accordance with one of the following methods. All testing shall be from integral prolongations of the forging, except as permitted in (d), and shall be performed after final heat treatment (see KT-111). In addition to the following, for quenched and tempered materials, the location of the datum point shall be equal to or farther from the nearest quenched surface than any pressurized surface or area of significant loading is from the quenched surface. The designer shall define the datum point locations within the forging relative to the rules of this Division. (25)

(a) For forgings having a maximum heat-treated thickness not exceeding 4 in. (100 mm), the datum points of the test specimens shall be located in the forging or test

forging at mid-thickness and at least $2T/3$ (T is the maximum heat-treated thickness) from the heat-treated end surface or nearest adjacent surfaces.

(b) For forgings having a maximum heat-treated thickness in excess of 4 in. (100 mm), the datum points of the test specimens shall be removed $T/4$ or deeper from the nearest heat-treated surface and at least $2T/3$ from the heat-treated end surface or nearest adjacent surfaces. $T/4$ from a heat-treated end or deeper may be used for precipitation hardening and age hardening materials listed in Table KM-400-2 (Table KM-400-2M) (UNS Nos. S13800, S15500, S17400, S17700, S45000, S45500, and S66286) that have been air cooled after aging.

(c) For forgings that are contour shaped or machined to essentially the finished product configuration prior to heat treatment, find the interior location that has the greatest distance to the nearest heat-treated surface. Designate this distance $t/2$. Test specimens shall be taken no closer to any heat-treated surface than one half of this distance ($\frac{1}{4}t$ location). The datum points of the specimen shall be a minimum of $t/2$ from any second heat-treated surface.

(d) With prior approval of the Manufacturer, test specimens may be taken from a separate test forging under the conditions described in KM-231(d), or removed from a location within the forging that has received substantially the same reduction and type of hot working as the main body of the forging for which the tests are being conducted, if permitted by the material specification. The dimensional requirements specified in (a), (b), (c), or (e) shall be met as applicable.

(e) For large forgings that require testing from each end in accordance with KM-231(b) or KM-231(c), test specimen locations according to (a), (b), (c), and (d) may be designated at each end independently based on the thickness at that end, provided at least one end represents the thickest dimension of the entire forging.

(25) **KM-211.3 Bars and Bolting Materials.**

(a) For diameters or thicknesses less than 2 in. (50 mm), the specimens shall be taken in accordance with the requirements of the applicable material specification.

(b) For diameters or thicknesses 2 in. (50 mm) and over, the datum point of the test specimen defined as the midpoint of the gage length of a tension test specimen or the area under the notch of the impact specimens shall be located at $T/4$ from the outside rolled surface or deeper and no closer than $2T/3$ from a heat-treated end. $T/4$ from a heat-treated end or deeper may be used for precipitation hardening and age hardening steels that have been air cooled after aging.

KM-211.4 Pipe.

(a) For thicknesses less than 2 in. (50 mm), specimens shall be taken in accordance with the requirements of the applicable material specification.

(b) For thicknesses 2 in. (50 mm) and over, specimens shall be taken in accordance with the requirements of the applicable material specification and at least $T/4$ from any heat-treated surface, where T is the maximum wall thickness of the pipe, and with the ends of the specimens no closer than T from a heat-treated end of the pipe. Test specimens shall be removed from integral prolongations from the pipe after completion of all heat treatment and forming operations.

KM-211.5 Castings. The datum point, defined as the midpoint of the gage length of tension test specimens or the area under the notch of impact test specimens, shall be located as defined in KM-211.2. Testing may be from prolongations or from cast test coupons. Where a single prolongation is required according to KM-231, it shall be taken from the feed-head end. Test coupons, cast with the vessel, shall be made from the same heat as the casting using a similar feed and head arrangement, shall be heat treated with the casting, and shall have a similar thickness to the casting at the time of heat treatment. The datum points of the test specimens for quenched and tempered materials shall be located at $T/4$ from the nearest quenched surface and T from the nearest quenched end. T is defined as twice the distance to the surface from the interior point that has the greatest distance to the test specimen's nearest quenched surface. (25)

KM-212 CHARPY IMPACT SPECIMENS

KM-212.1 Bolting Materials.

(a) Charpy V-notch impact test specimens shall be the standard 10 mm × 10 mm size and shall be oriented parallel to the axis of the bolt.

(b) Where Charpy V-notch impact testing is to be conducted and bolt diameter does not permit specimens in accordance with (a), subsize specimens may be used. Test temperature shall be reduced in accordance with Table KM-212.

(c) Where bolt diameter or length does not permit specimens in accordance with (a) or (b), impact testing is not required.

KM-212.2 Pressure-Retaining Component Materials, Other Than Bolting and Castings, Not Containing Welds. (25)

(a) The test coupons for Charpy specimens shall be oriented such that their major axes lie transverse to the direction of maximum elongation during rolling or to the direction of major working during forging. Examples of acceptable Charpy V-notch impact specimen orientations removed from plate and pipe are shown in

Table KM-212
Charpy Impact Test Temperature Reduction Below Minimum Design Metal Temperature

Actual Material Thickness or Charpy Impact Specimen Width Along the Notch, in. (mm) [Note (1)]	Temperature Reduction, °F (°C)
0.394 (10.00) (full-size standard bar)	0 (0)
0.354 (9.00)	0 (0)
0.315 (8.00)	0 (0)
0.295 (7.50) (3/4 size bar)	5 (3)
0.276 (7.00)	8 (4)
0.262 (6.67) (2/3 size bar)	10 (6)
0.236 (6.00)	15 (8)
0.197 (5.00) (1/2 size bar)	20 (11)
0.158 (4.00)	30 (17)
0.131 (3.33) (1/3 size bar)	35 (19)
0.118 (3.00)	40 (22)
0.098 (2.50) (1/4 size bar)	50 (28)

NOTE: (1) Straight line interpolation for intermediate values is permitted.

Figure KM-212 illustrations (a) and (b), respectively. Since the direction of major working in a forging can vary significantly depending upon its shape and the forging method used, a single, representative example of an acceptable Charpy specimen removed from such a forging cannot be shown. Corners of Charpy specimens parallel to and on the side opposite the notch may be as shown in Figure KM-212 illustration (b-2), if necessary, to maintain the standard 10 mm cross section at the notch.

(b) Where Charpy V-notch impact testing is to be conducted and material size or shape does not permit specimens in accordance with (a), longitudinal specimens with their major axes parallel to the direction of maximum elongation or major working may be used as shown in Figure KM-212 illustration (b-3).

(c) Where material size or shape does not permit Charpy V-notch specimens in accordance with (a) or (b), subsize longitudinal specimens may be used Test temperature shall be reduced in accordance with Table KM-212.

(d) Charpy V-notch impact testing is not required when the maximum obtainable subsize longitudinal specimen has a width along the notch of less than 0.099 in. (2.5 mm).

KM-212.3 Pressure-Retaining Component Materials Containing Welds.

(a) The test coupons for Charpy specimens shall be oriented such that their major axes lie transverse to the direction of the welded joint. Corners of Charpy specimens parallel to and on the side opposite the notch may be as shown in Figure KM-212, if necessary, to maintain the standard 10 mm cross section at the notch.

(b) Where Charpy V-notch impact testing is to be conducted and material size or shape does not permit specimens in accordance with (a), subsize specimens may be used. Test temperature shall be reduced in accordance with Table KM-212.

(c) Charpy V-notch impact testing is not required when the maximum obtainable subsize specimen has a width along the notch of less than 0.099 in. (2.5 mm).

KM-213 FRACTURE TOUGHNESS SPECIMENS

KM-213.1 Bolting Materials. If applicable, fracture toughness specimens shall be oriented such that the plane of the precrack is transverse to the axis of the bolt.

KM-213.2 Pressure-Retaining Component Materials, Other Than Bolting, Not Containing Welds. If applicable, fracture toughness specimens shall be oriented such that the plane of the precrack is parallel to the direction of maximum elongation during rolling or to the direction of major working during forging.

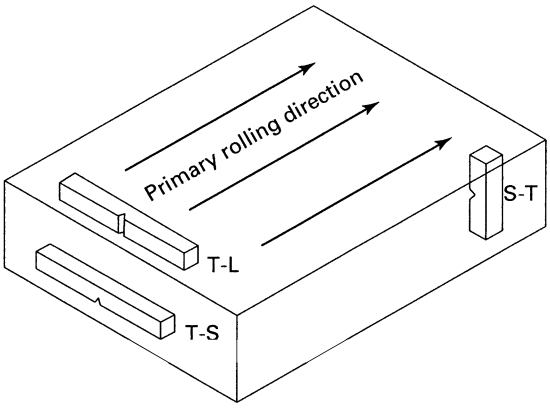
KM-213.3 Pressure-Retaining Component Materials Containing Welds. If applicable, fracture toughness specimens shall be oriented such that the plane of the precrack is parallel to the direction of the welded joint.

KM-220 PROCEDURE FOR HEAT TREATING SEPARATE TEST SPECIMENS

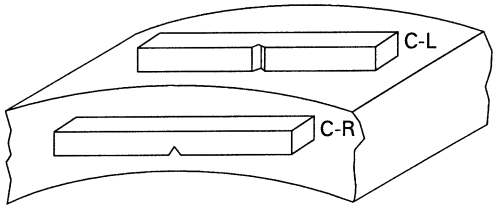
When metal products are to be heat treated and test specimens representing those products are removed prior to heat treatment, the test specimens shall be cooled at a rate similar to and no faster than the main body of the product. This rule shall apply for specimens taken directly from the product as well as those taken from separate test coupons representing the product. The following general techniques may be applied to all product forms, test specimens, or test coupons representing the product.

(a) Any procedure may be applied that can be demonstrated to produce a cooling rate in the test specimen that matches the cooling rate of the main body of the product at the region midway between mid-thickness and the surface ($T/4$) and no nearer to any heat-treated edge than a distance equal to the nominal thickness being cooled (T). The cooling rate of the test specimen shall replicate that of the actual part within a temperature of 25°F (14°C) at any given instant, and any given temperature shall be attained in both the actual part and test specimen within 20 sec at all temperatures after cooling begins from the heat treating temperature. Cooling rate can be determined by any method agreed upon between the manufacturer and purchaser, and can include, but is not limited to, theoretical calculations, experimental procedures, duplicate test forgings, or any combination thereof.

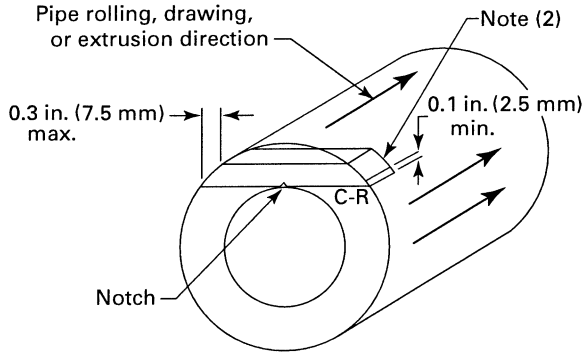
Figure KM-212
Examples of Acceptable Impact Test Specimens



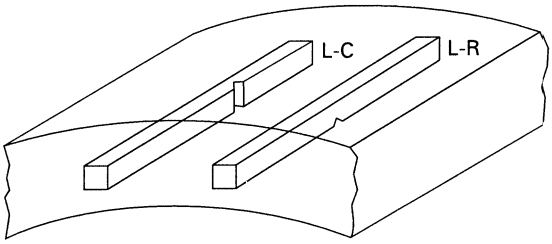
(a) Plate [Note (1)]



(b-1)



(b-2) [Note (3)]



(b-3)

(b) Charpy V-Notch Specimens From Pipe [Note (4)]

GENERAL NOTE: The Charpy impact specimen notch orientation codes shown are in accordance with ASTM E1823, Annex A2.

NOTES:

(1) For plate greater than 2.2 in. (55 mm) in thickness, short transverse (S-T orientation) Charpy V-notch impact specimens may also be used.

(2) Corners of the Charpy specimens may follow the contour of the component within the dimension limits shown.

(3) This Figure illustrates how an acceptable transverse Charpy specimen can be obtained from a cylindrical pipe too small for a full length standard specimen in accordance with ASME SA-370. The corners of longitudinal specimens parallel to and on the side opposite the notch may also be as shown.

(4) The transverse Charpy V-notch specimen orientation for pipe shall be as shown in illustration (b-1); either notch orientation (C-R or C-L) is acceptable. If the transverse orientation shown in illustration (b-1) cannot be accommodated by the pipe geometry, then the orientation shall be as shown in illustration (b-2). If the alternate transverse orientation shown in illustration (b-2) cannot be accommodated by the pipe geometry, then the orientation shall be as shown in illustration (b-3); either notch orientation (L-R or L-C) is acceptable.

(b) Faster cooling rates at product edges may be compensated for by

(1) taking the test specimens at least *T* from a quench edge, where *T* equals the product thickness

(2) attaching a similar alloy pad at least *T* wide by a partial penetration weld to the product edge where specimens are to be removed

(3) using thermal barriers or insulation at the product edge where specimens are to be removed

(c) If cooling rate data for the product and cooling rate-control devices for the test specimens are available, the test specimens may be heat treated in the device to represent the product provided that the provisions of (a) are met.

(d) When the material is clad or weld deposit overlaid by the producer prior to heat treatment, the full thickness samples shall be clad or weld deposit overlaid before such heat treatments.

KM-230 MECHANICAL TESTING REQUIREMENTS

(a) For materials listed in Tables KM-400-1 through KM-400-3 (Tables KM-400-1M through KM-400-3M), tensile and Charpy V-notch impact tests shall be conducted on representative samples of all materials used in the construction of pressure vessels, except that impact tests specified in Tables KM-234.2(a) and KM-234.2(b) are not required for nuts and washers, protective liner and inner layer materials, or for materials that do not contribute to the integrity of the pressure boundary. See also KM-250.

(b) For aluminum alloys listed in Table KM-400-4 (Table KM-400-4M), tensile and notch tensile tests shall be conducted. See also KM-270. Impact tests are not required.

KM-231 NUMBER OF TEST SPECIMENS REQUIRED

(a) Components or material weighing 1,000 lb (450 kg) or less at the time of heat treatment require at least one tension test and one set of three Charpy V-notch impact test specimens per heat, per heat treatment load.

(b) Components or material weighing between 1,000 lb and 5,000 lb (450 kg and 2 300 kg) at the time of heat treatment require at least one tension test and one set of three Charpy V-notch impact test specimens per component, plate, forging, or test forging [see (d)]. If the component or forging length, excluding test prolongation(s), exceeds 80 in. (2 000 mm), then one set of tests shall be taken at each end and they shall be spaced 180 deg apart. For plate with a length exceeding 80 in. (2 000 mm), one set of tests shall be taken at each end and they shall be removed from diagonally opposite corners.

(c) Components or material weighing over 5,000 lb (2 300 kg) at the time of heat treatment require at least two tension tests and two sets of three Charpy V-notch impact test specimens per component, plate, forging, or test forging [see (d)]. One set of tests shall be taken at each end and they shall be spaced 180 deg apart for a component, forging, or test forging [see (d)], and at diagonally opposite corners for plate. If the component or forging length, excluding test prolongation(s), exceeds 80 in. (2 000 mm), then two sets of tests shall be taken at each end and they shall be spaced 180 deg apart. The tests at one end shall be offset from the tests at the other end by 90 deg. For plate with a length exceeding 80 in. (2 000 mm), two sets of tests shall be taken at each end and they shall be removed from both corners.

(d) With prior approval of the Manufacturer, test specimens for forgings may be taken from a separate test forging that represents one or more production forgings under the following conditions:

(1) The separate test forging shall be of the same heat of material and shall be subjected to substantially the same reduction and working as the production forgings that it represents.

(2) The separate test forging shall be heat treated in a manner that produces a cooling rate similar to and no faster than the main body of the production forgings that it represents. The holding time at temperature and the heat-treating temperature for the separate forging shall be the same as for the production forgings that it represents.

(3) The separate test forging shall be of the same nominal thickness as the production forgings that it represents.

(4) Test specimen locations shall be as defined in KM-211.

(5) The separate test forging may be used to represent forgings of several thicknesses in lieu of (3) provided the following additional requirements are met:

(-a) the separate test forging shall have a weight equal to or greater than the weight of the heaviest forging in the batch to be represented

(-b) the separate test forging shall have a thickness equal to or greater than the thickness of the thickest forging in the batch to be represented

KM-232 TENSILE TEST PROCEDURE

Tensile testing of all materials except aluminum alloys shall be carried out in accordance with SA-370. Aluminum alloys shall be tested in accordance with ASTM B557.

KM-233 IMPACT TEST PROCEDURE

Charpy V-notch impact testing shall be carried out in accordance with SA-370 using the standard 10 mm × 10 mm specimens, except as permitted in KM-212.

(25) **Table KM-234.2(a)**
Minimum Required Charpy V-Notch Impact Values for Pressure-Retaining Component Materials

Specimen Orientation [Note (1)]	Number of Specimens [Note (2)]	Energy, ft-lbf (J) [Note (3)] for Specified Minimum Yield Strength, ksi (MPa)	
		Up to 135 (930), Incl.	Over 135 (930)
Transverse [Note (4)]	Average for 3	30 (41)	35 (47)
	Minimum for 1	24 (33)	28 (38)
Longitudinal [Note (5)]	Average for 3	50 (68)	60 (81)
	Minimum for 1	40 (54)	48 (65)

GENERAL NOTE: This table applies to all pressure-retaining materials, except castings (see Table KM-8-1), protective liners (see KD-103), inner layers of shrink-fit layered vessels and wire-wound vessels [see KD-810(f) and KD-931, respectively], bolting [see Table KM-234.2(b)], and aluminum alloys listed in Table KM-400-4 (Table KM-400-4M).

NOTES:
(1) Specimen orientation is relative to the direction of maximum elongation during rolling or to the direction of major working during forging, as applicable. See KM-212.
(2) See KM-260 for permissible retests.
(3) Energy values in this table are for standard size specimens. For subsize specimens, these values shall be multiplied by the ratio of the actual specimen width to that of a full-size specimen, 0.4 in. (10 mm).
(4) The acceptance criteria for all weld metal and heat-affected zone impact specimens shall be identical to those for transverse impact specimens.
(5) Except for components containing welds, longitudinal impact specimens may be tested only if component shape or size does not permit the removal of transverse specimens. See KM-212.

KM-234 CHARPY V-NOTCH IMPACT TEST REQUIREMENTS

KM-234.1 Impact Test Temperature.

(a) The impact test temperature shall not exceed the lower of 70°F (21°C) or the minimum design metal temperature specified in the User's Design Specification [see KG-311.4(d)] minus the appropriate temperature reduction value specified in Table KM-212, if applicable.

(b) For impulsively loaded ferritic vessels, the impact test temperature in (a) shall be reduced by 108°F (60°C) unless the designer can demonstrate by calculation or experiment that a higher temperature can be justified; any such justification shall be included in the User's Design Specification.

(c) The minimum design metal temperature for pressure-retaining component materials exempted from impact testing by KM-212.1(c), KM-212.2(d), or KM-212.3(c) shall not be lower than −325°F (−198°C) for fully austenitic stainless steels, or −55°F (−48°C) for other materials.

KM-234.2 Absorbed Energy Acceptance Criteria.

(a) Pressure-retaining component materials other than bolting shall meet the minimum Charpy V-notch impact value requirements specified in Table KM-234.2(a) unless exempted by KD-810(f) and KD-931.

(b) Bolting materials shall meet the minimum Charpy V-notch impact value requirements specified in Table KM-234.2(b).

KM-234.3 Lateral Expansion and Percentage Shear Reporting Requirements. The lateral expansion and percentage of shear fracture for all impact tests shall be measured in accordance with SA-370 and the results included in the test report.

KM-234.4 ADDITIONAL TOUGHNESS TESTING

Additional toughness testing in accordance with KM-250 is not required, provided that the toughness testing performed here is in the worst-case direction relative to the direction of maximum elongation during rolling or to the direction of major working during forging.

KM-240 HEAT TREATMENT CERTIFICATION/ VERIFICATION TESTS FOR FABRICATED COMPONENTS

Tests shall be made to verify that all heat treatments (i.e., quenching and tempering, solution annealing, aging, and any other subsequent thermal treatments that affect the material properties) as applicable have produced the required properties. Where verification tests shall be made from test specimens representative of the section being heat treated, the position and method of attachment of test coupons shall most nearly represent the entire item, taking into account its size and shape in accordance with testing requirements of the material specification. The requirements of KM-243 shall also apply.

KM-241 CERTIFICATION TEST PROCEDURE

(a) A sufficient number of test coupons to meet the requirements of KM-243 shall be provided from each lot of material in each vessel. These shall be quenched with the vessel or vessel component. If material from each lot is welded prior to heat treatment to material from the same or different lots in the part to be quenched, the test coupon shall be so proportioned that tensile and impact specimens may be taken from the same locations relative to thickness as are required by the applicable material specifications. Weld metal specimens shall be taken from the same locations relative to thickness as are required by the material specifications for plates

Table KM-234.2(b)
Minimum Required Charpy V-Notch Impact Values for Bolting Materials

ASME Materials Specification	Specimen Orientation [Note (2)]	Nominal Bolt Size, in. (mm)	Number of Specimens	Energy, ft-lbf (J) [Note (1)] for Specified Minimum Yield Strength, ksi (MPa)	
				Up to 135 (930), Incl.	Over 135 (930)
SA-320	Longitudinal	≤2 (50)	[Note (3)]	[Note (3)]	Not applicable
All others [Note (4)]	Longitudinal	All	Average for 3	30 (41)	35 (47)
			Minimum for 1 [Note (5)]	24 (33)	28 (38)

NOTES:
(1) Energy values in this table are for standard size specimens. For subsize specimens, these values shall be multiplied by the ratio of the actual specimen width to that of a full-size specimen, 0.4 in. (10 mm).
(2) Specimen orientation is relative to the axis of the bolt.
(3) The requirements of ASME SA-320, including the temperature to be used for impact testing, shall apply.
(4) Charpy V-notch impact testing is not required for nuts and washers.
(5) See KM-260 for permissible retests.

used in the component to be treated. If desired, the effect of this distance may be achieved by temporary attachment of suitable thermal buffers. The effectiveness of such buffers shall be demonstrated by tests.

(b) In cases where the test coupon is not attached to the part being treated, it shall be quenched from the same heat treatment charge and under the same conditions as the part which it represents. It shall be so proportioned that test specimens may be taken from the locations prescribed in (a).

KM-242 TEMPERING

KM-242.1 Attached Test Coupons. The test coupons shall remain attached to the vessel or vessel component during tempering, except that any thermal buffers may be removed after quenching. After the tempering operation and after removal from the component, the coupon shall be subjected to the same thermal treatment(s), if any, to which the vessel or vessel component will be later subjected. The holding time at temperature shall not be less than that applied to the vessel or vessel component (except that the total time at each temperature may be applied in one heating cycle) and the cooling rate shall not be faster.

KM-242.2 Separate Test Coupons. The coupons that are quenched separately, as described in KM-241(b), shall be tempered similarly and simultaneously with the vessel or component which they represent. The conditions for subjecting the test coupons to subsequent thermal treatment(s) shall be as described in KM-242.1.

KM-243 NUMBER OF TESTS

One tensile test and one impact test, consisting of three impact test specimens, shall be made on material from coupons representing each lot of material in each vessel or vessel component heat treated. A lot is defined as material from the same heat, heat treated simultaneously and having thicknesses within ±20% or $^1/_2$ in. (13 mm) of nominal thickness, whichever is smaller.

(a) Coupons not containing welds shall meet the complete tensile requirements of the material specification and impact requirements of this Part.

(b) Coupons containing weld metal shall be tested across the weld and shall meet the required mechanical property requirements of the material specification; in addition, the minimum impact requirements shall be met by samples with notches in the weld metal. The form and dimension of the tensile test specimen shall conform to Section IX, Figure QW-462.1(a) or Figure QW-462.1(d). Charpy impact testing shall be in accordance with the requirements of Article KT-2.

KM-250 ADDITIONAL TOUGHNESS REQUIREMENTS FOR PRESSURE-RETAINING COMPONENT MATERIALS (25)

Where a fracture mechanics evaluation in accordance with Article KD-4 is to be conducted, a value of K_{Ic} is required for the analysis. For aluminum alloys listed in Table KM-400-4 (Table KM-400-4M), the designer may use 23 ksi-in.$^{1/2}$ (25 MPa-m$^{1/2}$) as the value of K_{Ic} without additional testing. Otherwise, the designer shall specify the minimum value of K_{Ic} required and shall indicate which of the methods given in KM-251 through KM-254 are to be used to verify that the material meets this value.

(a) The designer shall specify the number, location, and orientation of the additional tests.

(b) The orientation of the direction of crack propagation for all test coupons shall be the same as the direction of crack propagation expected in the fracture mechanics analysis conducted in accordance with Article KD-4. Variation of fracture toughness through the thickness of a

component shall be considered to ensure the toughness used in Article KD-4 is representative of the material at the location being considered.

(c) Additional toughness testing, in addition to the required testing in KM-234, is not required, provided that the toughness testing performed is the worst-case direction relative to the direction of maximum elongation during rolling or to the direction of major working during forging.

(d) The fracture toughness used in Article KD-4 for each crack orientation shall be a correlated value from the testing performed in accordance with one of the methods in KM-251 through KM-254, provided:

(1) the testing is located at a depth equal to or greater than the depth of the critical flaw size in each location of the forging

(2) the testing is from a section of equal or greater thickness as the flaws being analyzed in Article KD-4

KM-251 CHARPY V-NOTCH IMPACT TESTING

The designer may require that the pressure-retaining component meet minimum Charpy V-notch absorbed energy values that are greater than those specified in KM-234.2 in order to verify compliance with the minimum K_{Ic} value. If additional impact testing is conducted, it shall be performed in accordance with SA-370 and be conducted at a temperature not exceeding the impact test temperature specified in KM-234.1. It shall be the designer's responsibility to determine and specify the appropriate K_{Ic}–CVN conversion equation, in compliance with API 579-1/ASME FFS-1, to be used to ascertain the Charpy V-notch acceptance criterion.

The Charpy V-notch impact values specified in KM-234.2 are established at upper shelf energy levels that are required for most high-strength, low-alloy steels. The designer does not need to provide any test information to use upper shelf correlations for these materials.

KM-252 CTOD FRACTURE TOUGHNESS TESTING

The designer may require that CTOD (crack tip opening displacement) testing of the high pressure-retaining component be conducted to determine the critical crack tip opening displacement CTOD or δ_{crit}, and to verify compliance with the minimum K_{Ic} value. If CTOD testing is required, it shall be performed in accordance with ASTM E1820, and be conducted at a temperature not exceeding the impact test temperature specified in KM-234.1. The temperature reduction values given in Table KM-212 do not apply. The equivalent K_{Ic} value (or $K_{c\delta}$) shall be computed from CTOD data using API 579-1/ASME FFS-1, Equation (9F.29).

KM-253 *J*-INTEGRAL FRACTURE TOUGHNESS TESTING

The designer may require that *J*-integral testing of the pressure-retaining component be conducted to determine the critical value of the *J*-integral or J_{crit}, and to verify compliance with the minimum K_{Ic} value. If *J*-integral testing is required, it shall be performed in accordance with ASTM E1820 and shall be conducted at a temperature not exceeding the impact test temperature specified in KM-234.1. The temperature reduction values given in Table KM-212 do not apply. The equivalent K_{Ic}, denoted as K_{Jc}, shall be computed from J_{crit} using API 579-1/ASME FFS-1, Equation (9F.27).

KM-254 K_{IC} FRACTURE TOUGHNESS TESTING (25)

The designer may require that direct K_{Ic} testing of the pressure-retaining component be conducted to verify compliance with the specified minimum K_{Ic} value. If such testing is required, it shall be performed in accordance with ASTM E399 and shall be conducted at a temperature not exceeding the impact test temperature specified in KM-234.1. The temperature reduction values given in Table KM-212 do not apply.

KM-260 RETESTS

KM-261 GENERAL RETEST REQUIREMENTS (25)

The following retest requirements apply to tension, Charpy V-notch impact, and notch tensile tests, and to CTOD, *J*-integral, and K_{Ic} fracture toughness tests.

(a) If any test specimen fails to meet the applicable acceptance criteria for mechanical reasons, such as test equipment malfunction or improper specimen preparation, the results may be discarded and another representative specimen may be substituted.

(b) If any test specimen fails to meet the applicable acceptance criteria for nonmechanical reasons, two representative specimens as close to the original specimen location as possible may be selected for retesting without reheat treatment, provided the failure was not caused by preexisting material defects such as ruptures, flakes, or cracks. Both of these specimens shall meet the applicable acceptance criteria (see KM-262 for Charpy V-notch impact retests).

(c) Only one retesting is permitted. If the material fails the retest, it may be retempered or reheat treated, as necessary.

KM-262 SPECIAL CHARPY V-NOTCH IMPACT RETEST REQUIREMENTS

(a) A Charpy V-notch impact retest is permitted if the average absorbed energy value meets the applicable acceptance criteria but the absorbed energy value for one specimen is below the specified minimum for

individual specimens. The retesting shall consist of two representative impact specimens removed from a location adjacent to and on either side, if possible, of the original specimen location. Each of the retest specimens shall exhibit an absorbed energy value equal to or greater than the minimum average value.

(b) Only one retesting is permitted. If the material fails the retest, it may be retempered or reheat treated, as necessary.

(25) KM-270 NOTCH TENSILE TESTING PROCEDURE AND ACCEPTANCE CRITERION

Material listed in Table KM-400-4 (Table KM-400-4M) shall be qualified by the following notch tensile test:

(a) The sharp-notch strength/yield strength ratio shall be determined for flat or round specimens specified below. Specimens shall be cut from a production vessel. Two specimens from a production vessel shall be tested to qualify a single heat of material. The specimen samples shall be obtained from the production vessel after all forming and heat treating is completed.

(b) The geometry of the specimen shall meet the dimensional requirements of Figure KM-270.1 (Figure KM-270.1M) for flat specimens or Figure KM-270.2 (Figure KM-270.2M) for round specimens. For Figure KM-270.1 (Figure KM-270.1M) specimen, head area may be reinforced using the plate dimensions shown in Figure KM-270.3 (Figure KM-270.3M). The specimen shall be cut so that the longitudinal axis of the specimen is parallel to the longitudinal axis of the vessel. The following exemptions to the dimensional requirements of the above specimens may be applied:

(1) For Figure KM-270.1 (Figure KM-270.1M) specimen, the test section width less than 2 in. (50 mm) may be used; however, the ratio of the notch depth to specimen net ligament width shall be not less than 0.25 in. (6.35 mm). The specimen thickness limitation in the test section need not be satisfied.

(2) For Figure KM-270.3 (Figure KM-270.3M) specimen, the test section diameter less than 0.5 in. (12.5 mm) may be used; however, the ratio of notch depth to the specimen net ligament diameter shall be not less than 0.25 in. (6.35 mm).

(c) The tensile test method specified in ASTM B557 shall be used in measuring the fracture load P of each specimen. Notch strength (NS) shall be calculated using the following equation:

$$\mathrm{NS} = P/A \qquad \text{(KM-270.1)}$$

where

A = net cross-section area at notch location, in.^{2} (mm^2)
NS = notch strength, psi (MPa)
P = minimum fracture load measured, lbf (N)

(d) Perform ASTM B557 tensile test to measure yield strength. Two specimens from a production vessel shall be tested to qualify a single heat of material. Test specimen geometry shall meet ASTM B557. The samples shall be obtained from the production vessel after all forming and heat treating are completed.

(e) Calculate notch strength ratio using the following equation:

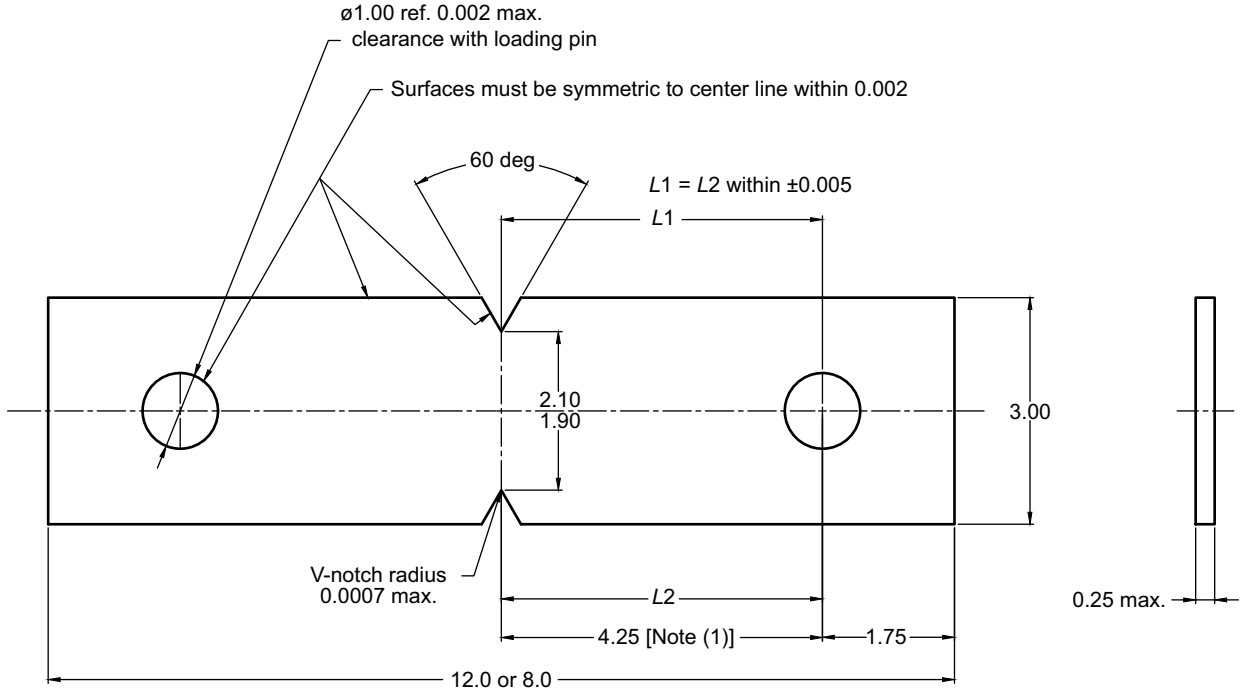
$$\mathrm{NSR} = \mathrm{NS}/\mathrm{YS} \qquad \text{(KM-270.2)}$$

where

NS = notch strength [see (c)], psi (MPa)
NSR = notch strength ratio
YS = minimum yield strength [see (d)], psi (MPa)

(f) Acceptance criterion: NSR shall be not less than 0.9.

Figure KM-270.1
Machine Sharp Edge-Notch Specimen



(25)

Figure KM-270.1M
Machine Sharp Edge-Notch Specimen

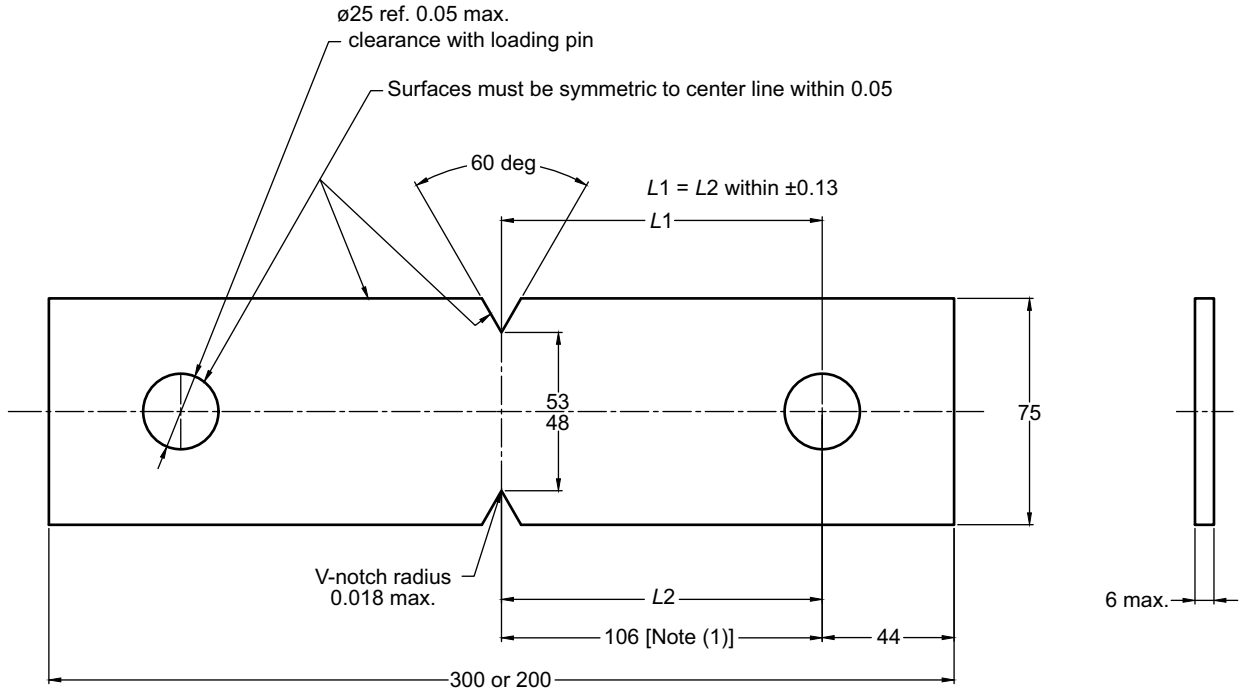


Figure KM-270.2
Reinforcing Plate for Specimen Head

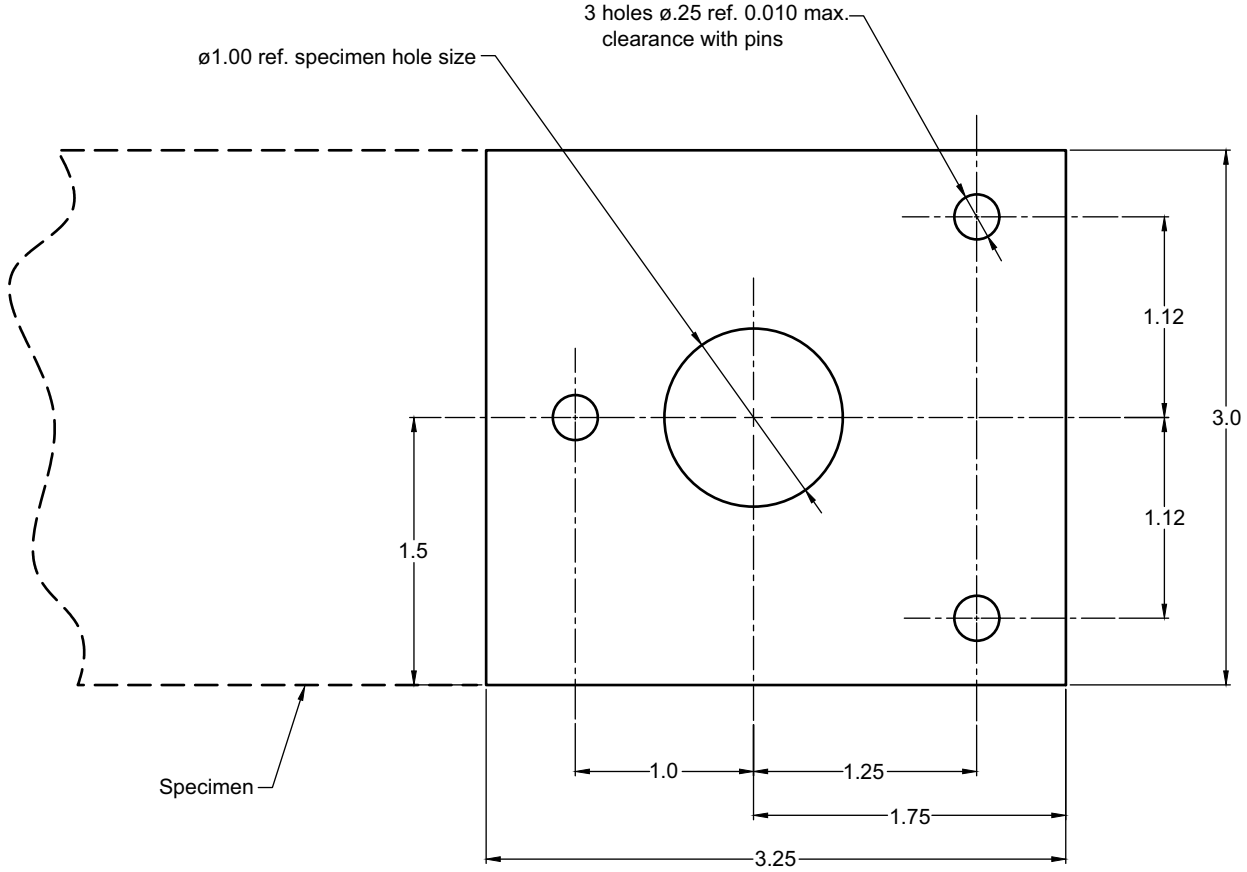


Figure KM-270.2M
Reinforcing Plate for Specimen Head

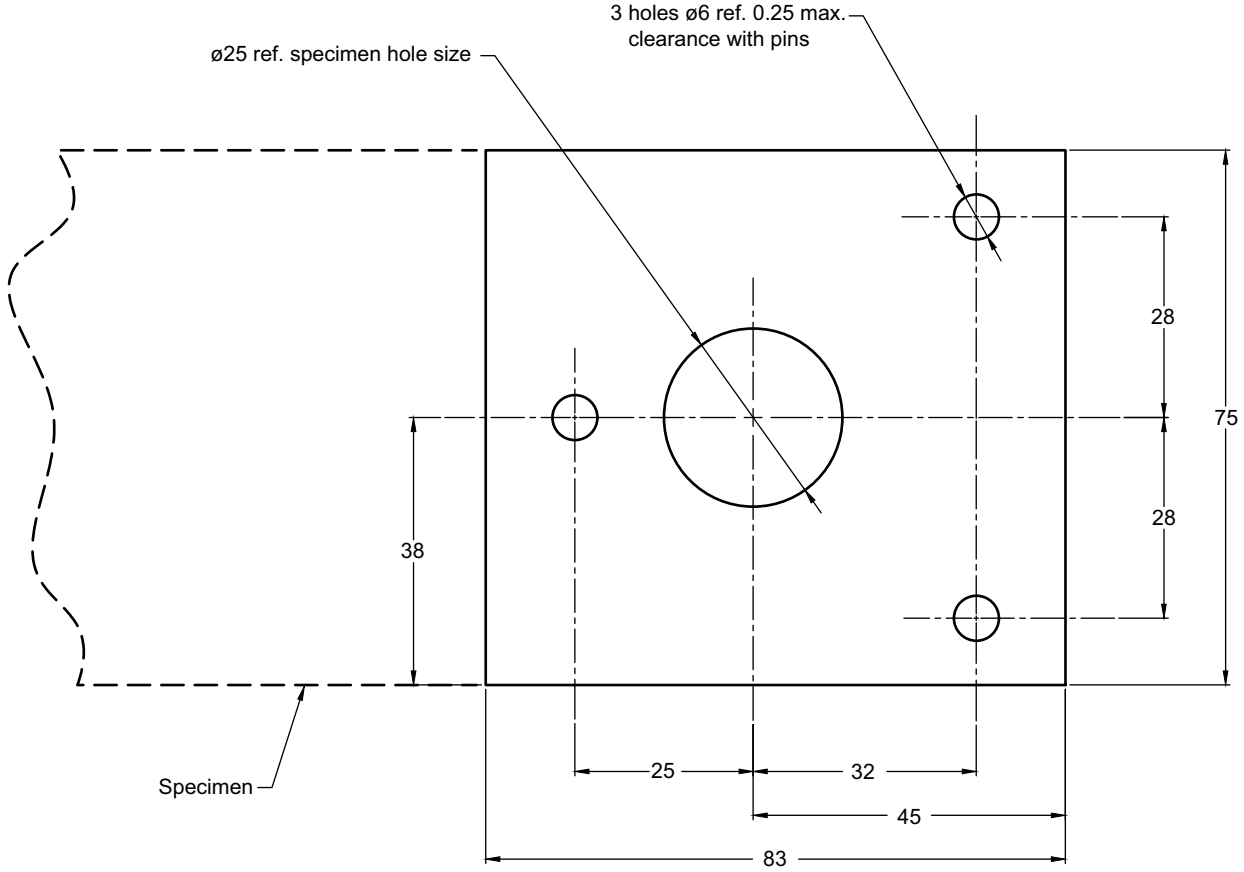


Figure KM-270.3
Standard Test Sections

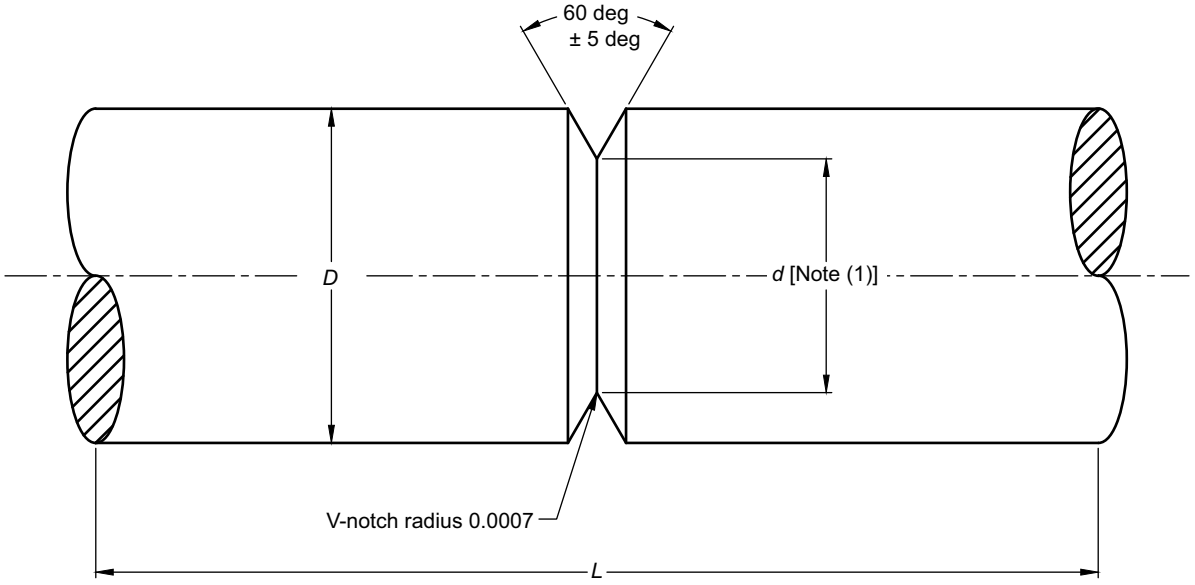
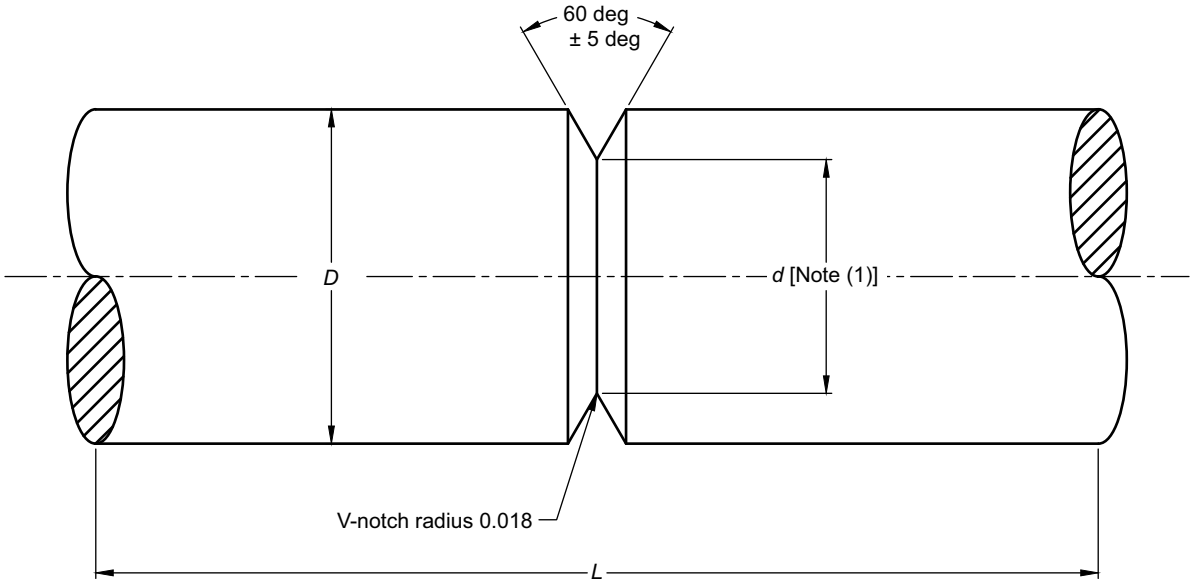


Figure KM-270.3M
Standard Test Sections



ARTICLE KM-3
SUPPLEMENTARY REQUIREMENTS FOR BOLTING

KM-300 REQUIREMENTS FOR ALL BOLTING MATERIALS

KM-301 SCOPE

In this Division, bolting includes the following metallic fasteners: bolts, stud bolts, studs, cap screws, nuts, and washers.

KM-302 MATERIAL SPECIFICATIONS AND YIELD STRENGTH VALUES

Specifications and supplementary rules for acceptable bolting materials are specified in Tables KM-400-1 through KM-400-3 (Tables KM-400-1M through KM-400-3M). Yield strengths at temperature for these bolting materials are specified in Section II, Part D, Subpart 1, Table Y-1. These product forms listed for bolting shall not be used for applications other than bolting (see KM-100).

KM-303 EXAMINATION OF BOLTS, STUDS, AND NUTS

Bolts, studs, and nuts shall be examined in accordance with KE-260.

KM-304 THREADING AND MACHINING OF STUDS

Threading and machining of studs shall meet the requirements of KD-624.

KM-305 USE OF WASHERS

The use of washers is optional. When used, they shall be of wrought material.

KM-306 MATERIALS FOR NUTS AND WASHERS

Materials for steel nuts and washers shall conform to SA-194 or to the requirements for nuts in the specification for the bolting material with which they are to be used.

KM-307 REQUIREMENTS FOR NUTS

Nuts shall be semifinished, chamfered, and trimmed. Nuts shall be threaded to Class 2B or finer tolerances according to ASME B1.1.

KM-307.1 Use With Flanges. For use with flanges, nuts shall conform at least to the dimensions specified in ASME B18.2.2 for Heavy Series Nuts.

KM-307.2 Use With Other Connections. For use with connections designed in accordance with the rules in Part KD, nuts may be of the Heavy Series or they may be of other dimensions provided their static and fatigue strengths are sufficient to maintain the integrity of the connection. Due consideration shall be given to bolt hole clearance, bearing area, thread form, class of fit, thread shear, and radial thrust from threads.

KM-307.3 Depth of Engagement. Nuts shall engage the threads for the full depth of the nut.

KM-307.4 Special Design. Nuts of special design may be used provided their strength meets the requirements of KM-307.2.

ARTICLE KM-4
MATERIAL DESIGN DATA

(25) KM-400 CONTENTS OF TABLES OF MATERIAL DESIGN DATA

(a) Vessels fabricated in accordance with the rules of this Division shall be built using the materials listed in the following tables unless specifically exempted by this Division:

(1) Table KM-400-1 (Table KM-400-1M)
(2) Table KM-400-2 (Table KM-400-2M)
(3) Table KM-400-3 (Table KM-400-3M)
(4) Table KM-400-4 (Table KM-400-4M)

The P-Numbers and Group Numbers listed for some of the materials in these tables are for information only. For welded construction in this Division, Section IX, Table QW/QB-422 shall be consulted for P-Numbers and Group Numbers. When there is a conflict in P-Number or Group Number, the numbers in Section IX shall govern.

(b) Limitations on the use of materials are contained in Notes to Tables KM-400-1 through KM-400-4 (Tables KM-400-1M through KM-400-4M).

(c) Material property data for all materials that may be used under the rules of this Division are specified in the following tables in Section II, Part D:

(1) Yield Strengths, S_y, are specified in Section II, Part D, Subpart 1, Table Y-1.

(2) Tensile Strengths, S_u, are specified in Section II, Part D, Subpart 1, Table U.

(3) Coefficients of thermal expansion are specified in Section II, Part D, Subpart 2, Tables TE-1 and TE-4.

(4) Moduli of elasticity are specified in Section II, Part D, Subpart 2, Tables TM-1 and TM-4.

(5) Coefficients of thermal diffusivity are specified in Section II, Part D, Subpart 2, Table TCD.

(d) With the publication of the 2004 Edition, Section II Part D is published as two separate publications. One publication contains values only in U.S. Customary units and the other contains values only in SI units. The selection of the version to use is dependent on the set of units selected for construction.

(e) Where specifications, grades, classes, and types are referenced, and where the material specification in Section II, Part A or Part B is a dual-unit specification (e.g., SA-516/SA-516M), the design values and rules shall be applicable to either the U.S. Customary version of the material specification or the SI unit version of the material specification. For example, when SA-516M Grade 485 is used in construction, the design values listed for its equivalent SA-516, Grade 70, in either the U.S. Customary or metric, Section II, Part D (as appropriate) shall be used.

(25)

Table KM-400-1
Carbon and Low Alloy Steels

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, in.	P-No.	Group No.	Specified Min. Tensile, ksi	Specified Min. Yield, ksi	Notes	Max. Design Temp., °F
Carbon steel	Pipe	SA-106	A	K02501	...	...	1	1	48	30	...	700
Carbon steel	Plate	SA-516	60	K02100	...	...	1	1	60	32	...	700
Carbon steel	Pipe	SA-106	B	K03006	...	...	1	1	60	35	...	700
Carbon steel	Smls. pipe	SA-333	6	K03006	...	...	1	1	60	35	...	700
Carbon steel	Plate	SA-516	65	K02403	...	...	1	1	65	35	...	700
Carbon steel	Plate	SA/EN 10025-2	S355J2+N	...	...	$2.48 < t \le 3.15$	...	...	68.2	47.1	(13)(24)	100
Carbon steel	Plate	SA/EN 10025-2	S355J2+N	...	...	$1.57 < t \le 2.48$	...	...	68.2	48.6	(13)(24)	100
Carbon steel	Plate	SA/EN 10025-2	S355J2+N	...	...	$0.63 < t \le 1.57$	...	...	68.2	50.0	(13)(24)	100
Carbon steel	Plate	SA/EN 10025-2	S355J2+N	...	...	$0.12 \le t \le 0.63$	...	...	68.2	51.5	(13)(24)	100
Carbon steel	Forgings	SA-350	LF2	K03011	...	...	1	2	70	36	...	700
Carbon steel	Forgings	SA-105	...	K03504	...	...	1	2	70	36	...	700
Carbon steel	Plate	SA-516	70	K02700	...	...	1	2	70	38	...	700
Carbon steel	Pipe	SA-106	C	K03501	...	...	1	2	70	40	...	700
Carbon steel	Forgings	SA-765	IV	K02009	...	...	1	3	80	50	...	600
Carbon steel	Plate	SA/EN 10025-2	S355J2+N	...	...	<0.12	...	...	74	51.5	(13)(24)	100
Carbon steel	Plate	SA-738	B	K12007	...	...	1	3	85	60	...	600
Carbon steel	Plate	SA-724	A	K11831	...	...	1	4	90	70	...	700
Carbon steel	Plate	SA-724	C	K12037	...	...	1	4	90	70	...	700
Carbon steel	Plate	SA-724	B	K12031	...	...	1	4	95	75	...	700
Carbon steel	Flat wire	SA-905	...	...	2	0.059	...	...	246	210	(1)(2)(16)	100
Carbon steel	Flat wire	SA-905	...	...	2	0.051	...	...	250	214	(1)(2)(16)	100
Carbon steel	Flat wire	SA-905	...	...	2	0.040	...	...	256	221	(1)(2)(16)	100
Carbon steel	Flat wire	SA-905	...	...	2	0.030	...	...	262	226	(1)(2)(16)	100
Carbon steel	Flat wire	SA-905	...	...	2	0.020	...	...	268	232	(1)(2)(16)	100
Carbon steel	Flat wire	SA-905	...	...	1	0.059	...	...	275	239	(1)(2)(16)	200
Carbon steel	Flat wire	SA-905	...	...	1	0.051	...	...	280	243	(1)(2)(16)	200
Carbon steel	Flat wire	SA-905	...	...	1	0.040	...	...	285	250	(1)(2)(16)	200

Table KM-400-1
Carbon and Low Alloy Steels (Cont'd)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, in.	P-No.	Group No.	Specified Min. Tensile, ksi	Specified Min. Yield, ksi	Notes	Max. Design Temp., °F
Carbon steel	Flat wire	SA-905	...	...	1	0.030	...	...	290	255	(1)(2)(16)	200
Carbon steel	Flat wire	SA-905	...	...	1	0.020	...	...	296	260	(1)(2)(16)	200
Carbon steel	Plate	SA-841	A	...	1	≤2.5	1	2	70	50	(23)	650
Carbon steel	Plate	SA-841	B	...	2	≤2.5	1	3	80	60	(23)	650
Carbon steel	Plate	SA-841	F	...	6	≤1¼	3	3	82	70	(23)	150
Carbon steel	Plate	SA-841	F	...	7	≤1	3	3	86	75	(23)	150
Carbon steel	Bolt	SA-354	BC	K04100	...	2½ < t ≤ 4	...	...	115	99	...	650
Carbon steel	Bolt	SA-354	BC	K04100	...	¼ < t ≤ 2½	...	...	125	109	...	650
Carbon steel	Bolt	SA-354	BD	K04100	...	2½ < t ≤ 4	...	...	140	115	...	650
Carbon steel	Bolt	SA-354	BD	K04100	...	¼ < t ≤ 2½	...	...	150	130	(16)	650
C–¼Mo	Bolt	SA-320	L7A	G40370	...	≤2½	...	...	125	105	...	100
C–½Mo	Pipe	SA-335	P1	K11522	...	...	3	1	55	30	...	700
½Cr–⅕Mo–V	Plate	SA-517	B	K11630	...	≤1¼	11B	4	115	100	(3)	700
½Cr–¼Mo–Si	Plate	SA-517	A	K11856	...	≤1¼	11B	1	115	100	(3)	700
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	0.032	...	...	300	...	(13)(19)(20)(21)(22)(25)	100
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	0.041	...	...	298	...	(13)(19)(20)(21)(22)(25)	100
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	0.054	...	...	292	...	(13)(19)(20)(21)(22)(25)	100
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	0.062	...	...	290	...	(13)(19)(20)(21)(22)(25)	100
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	0.080	...	...	285	...	(13)(19)(20)(21)(22)(25)	100
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	0.092	...	...	280	...	(13)(19)(20)(21)(22)(25)	100
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	0.120	...	...	275	...	(13)(19)(20)(21)(22)(25)	100
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	0.135	...	...	270	...	(13)(19)(20)(21)(22)(25)	100
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	0.162	...	...	265	...	(13)(19)(20)(21)(22)(25)	100

Table KM-400-1
Carbon and Low Alloy Steels (Cont'd)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, in.	P-No.	Group No.	Specified Min. Tensile, ksi	Specified Min. Yield, ksi	Notes	Max. Design Temp., °F
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	0.177	...	...	260	...	(13)(19)(20)(21)(22)(25)	100
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	0.192	...	...	260	...	(13)(19)(20)(21)(22)(25)	100
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	0.219	...	...	255	...	(13)(19)(20)(21)(22)(25)	100
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	0.250	...	...	250	...	(13)(19)(20)(21)(22)(25)	100
1Cr–1/5Mo	Bolt	SA-193	B7	G41400	...	$4 < t \le 7$	...	...	100	75	...	650
1Cr–1/5Mo	Bolt	SA-320	L7M	G41400	...	$\le 2\frac{1}{2}$	...	...	100	80	(4)	100
1Cr–1/5Mo	Bolt	SA-193	B7	G41400	...	$2\frac{1}{2} < t \le 4$	...	...	115	95	...	650
1Cr–1/5Mo	Forgings	SA-372	E	K13047	70	...	...	...	120	70	(5)(6)	700
1Cr–1/5Mo	Forgings	SA-372	F	G41350	70	...	...	...	120	70	(5)(6)(7)	700
1Cr–1/5Mo	Forgings	SA-372	J	K13548	70	...	...	...	120	70	(5)(6)(7)	650
1Cr–1/5Mo	Bolt	SA-193	B7	G41400	...	$\le 2\frac{1}{2}$	...	...	125	105	...	650
1Cr–1/5Mo	Bolt	SA-320	L7	G41400	...	$\le 2\frac{1}{2}$	...	...	125	105	(4)	650
1Cr–1/5Mo	Forgings	SA-372	J	G41370	110	...	...	...	135	110	(6)(7)(8)(16)	650
1Cr–1/5Mo	Bolt	SA-574	4137	G41370	...	$\ge \frac{5}{8}$	...	...	170	135	(13)(16)	550
1Cr–1/5Mo	Bolt	SA-574	4137	G41370	...	$\le \frac{1}{2}$	...	...	180	140	(13)(16)	550
1Cr–1/4Si–V	Wire	SA-231	...	...	Oil	0.500	...	...	190	...	(16)(19)(20)(21)(22)	100
1Cr–1/4Si–V	Wire	SA-232	...	...	Oil	0.500	...	...	190	...	(16)(19)(20)(21)(22)	100
1Cr–1/4Si–V	Wire	SA-231	...	...	Oil	0.438	...	...	195	...	(16)(19)(20)(21)(22)	100
1Cr–1/4Si–V	Wire	SA-232	...	...	Oil	0.438	...	...	195	...	(16)(19)(20)(21)(22)	100
1Cr–1/4Si–V	Wire	SA-231	...	...	Oil	0.375	...	...	200	...	(16)(19)(20)(21)(22)	100
1Cr–1/4Si–V	Wire	SA-232	...	...	Oil	0.375	...	...	200	...	(16)(19)(20)(21)(22)	100
1Cr–1/4Si–V	Wire	SA-231	...	...	Oil	0.312	...	...	203	...	(16)(19)(20)(21)(22)	100
1Cr–1/4Si–V	Wire	SA-232	...	...	Oil	0.312	...	...	203	...	(16)(19)(20)(21)(22)	100
1Cr–1/4Si–V	Wire	SA-231	...	...	Oil	0.283	...	...	205	...	(16)(19)(20)(21)(22)	100
1Cr–1/4Si–V	Wire	SA-232	...	...	Oil	0.283	...	...	205	...	(16)(19)(20)(21)(22)	100
1Cr–1/4Si–V	Wire	SA-231	...	...	Oil	0.244	...	...	210	...	(16)(19)(20)(21)(22)	100
1Cr–1/4Si–V	Wire	SA-232	...	...	Oil	0.244	...	...	210	...	(16)(19)(20)(21)(22)	100
1Cr–1/4Si–V	Wire	SA-231	...	...	Oil	0.192	...	...	220	...	(16)(19)(20)(21)(22)	100

Table KM-400-1
Carbon and Low Alloy Steels (Cont'd)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, in.	P-No.	Group No.	Specified Min. Tensile, ksi	Specified Min. Yield, ksi	Notes	Max. Design Temp., °F
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	0.192	...	...	220	...	(16)(19)(20)(21)(22)	100
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	0.162	...	...	225	...	(16)(19)(20)(21)(22)	100
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	0.162	...	...	225	...	(16)(19)(20)(21)(22)	100
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	0.135	...	...	235	...	(16)(19)(20)(21)(22)	100
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	0.135	...	...	235	...	(16)(19)(20)(21)(22)	100
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	0.105	...	...	245	...	(16)(19)(20)(21)(22)	100
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	0.105	...	...	245	...	(16)(19)(20)(21)(22)	100
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	0.080	...	...	255	...	(16)(19)(20)(21)(22)	100
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	0.080	...	...	255	...	(16)(19)(20)(21)(22)	100
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	0.062	...	...	265	...	(16)(19)(20)(21)(22)	100
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	0.062	...	...	265	...	(16)(19)(20)(21)(22)	100
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	0.054	...	...	270	...	(16)(19)(20)(21)(22)	100
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	0.054	...	...	270	...	(16)(19)(20)(21)(22)	100
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	0.041	...	...	280	...	(16)(19)(20)(21)(22)	100
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	0.041	...	...	280	...	(16)(19)(20)(21)(22)	100
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	0.032	...	...	290	...	(16)(19)(20)(21)(22)	100
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	0.032	...	...	290	...	(16)(19)(20)(21)(22)	100
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	0.020	...	...	300	...	(16)(19)(20)(21)(22)	100
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	0.020	...	...	300	...	(16)(19)(20)(21)(22)	100
1Cr–½Mo–V	Bolt	SA-193	B16	K14072	...	$4 < t \le 8$	...	...	100	85	...	700
1Cr–½Mo–V	Bolt	SA-193	B16	K14072	...	$2\frac{1}{2} < t \le 4$	...	...	110	95	...	700
1Cr–½Mo–V	Bolt	SA-193	B16	K14072	...	$\le 2\frac{1}{2}$	...	...	125	105	...	700
1¼Cr–½Mo–Si	Pipe	SA-335	P11	K11597	...	...	4	1	60	30	...	700
1¾Cr–½Mo–Ti	Plate	SA-517	E	K21604	...	$2\frac{1}{2} < t \le 6$	11B	2	105	90	(9)	700
1¾Cr–½Mo–Ti	Plate	SA-517	E	K21604	...	$\le 2\frac{1}{2}$	11B	2	115	100	...	700
2¼Cr–1Mo	Pipe	SA-335	P22	K21590	...	...	5A	1	60	30	(15)	700
2¼Cr–1Mo	Forgings	SA-336	F22	K21590	3	...	5A	1	75	45	(15)	700
2¼Cr–1Mo	Plate	SA-387	22	K21590	2	...	5A	1	75	45	(15)	700
2¼Cr–1Mo	Forgings	SA-508	22	K21590	3	...	5C	1	85	55	(15)	700
2¼Cr–1Mo–V	Forgings	SA-336	F22V	K31835	...	...	5C	1	85	60	(15)	700

Table KM-400-1
Carbon and Low Alloy Steels (Cont'd)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, in.	P-No.	Group No.	Specified Min. Tensile, ksi	Specified Min. Yield, ksi	Notes	Max. Design Temp., °F
2¼Cr–1Mo–V	Forgings	SA-182	F22V	K31835	...	...	5C	1	85	60	(15)	700
2¼Cr–1Mo–V	Forgings	SA-541	22V	K31835	...	...	5C	1	85	60	(15)	700
2¼Cr–1Mo–V	Plate	SA-542	D	K31835	4a	...	5C	1	85	60	(15)	700
2¼Cr–1Mo–V	Plate	SA-832	22V	K31835	...	...	5C	1	85	60	(15)	700
3Cr–1Mo–¼V–Ti–B	Forgings	SA-336	F3V	K31830	...	...	5C	1	85	60	(15)	700
3Cr–1Mo–¼V–Ti–B	Plate	SA-832	21V	K31830	...	...	5C	1	85	60	(15)	700
Mn–½Mo–¼Ni	Plate	SA-533	D	K12529	3	...	11A	4	100	83	...	700
Mn–½Mo–½Ni	Plate	SA-533	B	K12539	3	...	11A	4	100	83	...	700
Mn–½Mo–¾Ni	Plate	SA-533	C	K21554	2	...	3	3	90	70	...	700
Mn–½Ni–V	Plate	SA-225	C	K12524	...	...	10A	1	105	70	(11)	700
¾Ni–½Cr–½Mo–V	Plate	SA-517	F	K11576	...	≤2½	11B	3	115	100	(12)	700
¾Ni–½Mo–⅓Cr–V	Forgings	SA-508	2	K12766	1	...	3	3	80	50	...	700
¾Ni–½Mo–Cr–V	Forgings	SA-508	3	K12042	1	...	3	3	80	50	...	700
¾Ni–1Cu–¾Cr	Plate	SA-736	A	...	3	≤2	...	...	85	75	...	650
¾Ni–1Cu–¾Cr	Plate	SA-736	A	...	3	$2 < t \le 4$	...	...	75	65	...	650
1¼Ni–1Cr–½Mo	Plate	SA-517	P	K21650	...	$2½ < t \le 4$	11B	8	105	90	(9)	700
1¼Ni–1Cr–½Mo	Plate	SA-517	P	K21650	...	≤2½	11B	8	115	100	...	700
1¾ Ni–¾Cr–¼Mo	Bolt	SA-320	L43	G43400	...	≤4	...	...	125	105	...	700
1¾Ni-¾Cr-¼Mo	Bolt	SA-574	4340	G43400	...	≥⅝	...	...	170	135	(13)(16)	550
1¾Ni-¾Cr-¼Mo	Bolt	SA-574	4340	G43400	...	≤½	...	...	180	140	(13)(16)	550
2Ni–¾Cr–¼Mo	Bolt	SA-540	B23	H43400	5	$6 < t \le 9½$	...	...	115	100	...	700
2Ni–¾Cr–¼Mo	Bolt	SA-540	B23	H43400	5	≤6	...	...	120	105	...	700
2Ni–¾Cr–¼Mo	Bolt	SA-540	B23	H43400	4	≤9½	...	...	135	120	(16)	700
2Ni–¾Cr–¼Mo	Bolt	SA-540	B23	H43400	3	≤9½	...	...	145	130	(16)	700
2Ni–¾Cr–⅓Mo	Bolt	SA-540	B24	K24064	5	$6 < t \le 9½$	...	...	115	100	...	700
2Ni–¾Cr–⅓Mo	Bolt	SA-540	B24	K24064	5	≤6	...	...	120	105	...	700
2Ni–¾Cr–⅓Mo	Bolt	SA-540	B24	K24064	4	≤9½	...	...	135	120	(16)	700
2Ni–¾Cr–⅓Mo	Bolt	SA-540	B24	K24064	3	≤9½	...	...	145	130	(16)	700
2Ni–1½Cr–¼Mo–V	Forgings	SA-723	1	K23550	1	...	...	...	115	100	(13)(14)(18)	800
2Ni–1½Cr–¼Mo–V	Forgings	SA-723	1	K23550	2	...	...	...	135	120	(13)(14)(16)(18)	800

Table KM-400-1
Carbon and Low Alloy Steels (Cont'd)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, in.	P-No.	Group No.	Specified Min. Tensile, ksi	Specified Min. Yield, ksi	Notes	Max. Design Temp., °F
2Ni–1½Cr–¼Mo–V	Forgings	SA-723	1	K23550	2a	...	...	...	145	130	(13)(14)(16)(18)	800
2Ni–1½Cr–¼Mo–V	Forgings	SA-723	1	K23550	3	...	...	...	155	140	(13)(14)(16)(17)(18)	800
2Ni–1½Cr–¼Mo–V	Forgings	SA-723	1	K23550	4	...	...	...	175	160	(10)(13)(16)	700
2Ni–1½Cr–¼Mo–V	Forgings	SA-723	1	K23550	5	...	...	...	190	180	(10)(13)(16)	700
2¾Ni–1½Cr–½Mo	Plate	SA-543	C	K42338	1	...	11A	5	105	85	...	650
2¾Ni–1½Cr–½Mo	Plate	SA-543	C	K42338	2	...	11B	10	115	100	...	650
2¾Ni–1½Cr–½Mo–V	Forgings	SA-723	2	K34035	1	...	...	...	115	100	(13)(14)(18)	800
2¾Ni–1½Cr–½Mo–V	Forgings	SA-723	2	K34035	2	...	...	...	135	120	(13)(14)(16)(18)	800
2¾Ni–1½Cr–½Mo–V	Forgings	SA-723	2	K34035	2a	...	...	...	145	130	(13)(14)(16)(18)	800
2¾Ni–1½Cr–¼Mo–V	Forgings	SA-723	2	K34035	3	...	...	...	155	140	(13)(14)(16)(17)(18)	800
2¾Ni–1½Cr–½Mo–V	Forgings	SA-723	2	K34035	4	...	...	...	175	160	(10)(13)(16)	700
2¾Ni–1½Cr–½Mo–V	Forgings	SA-723	2	K34035	5	...	...	...	190	180	(10)(13)(16)	700
3Ni–1¾Cr–½Mo	Plate	SA-543	B	K42339	1	...	11A	5	105	85	...	650
3Ni–1¾Cr–½Mo	Plate	SA-543	B	K42339	2	...	11B	10	115	100	...	650
3½ Ni–1½ Cr–½ Mo– ½ Mn	Castings	SA-487	17	...	A	≤6	...	...	113	97	(13)(26)	100
3½ Ni–1½ Cr–½ Mo– ½ Mn	Castings	SA-487	17	...	A	$6 < t \leq 8$	...	...	110	94	(13)(26)	100
3½ Ni–1½ Cr–½ Mo– ½ Mn	Castings	SA-487	17	...	A	$8 < t \leq 12$	...	...	106	91	(13)(26)	100
3½ Ni–1½ Cr–½ Mo– ½ Mn	Castings	SA-487	17	...	A	$12 < t \leq 14$	...	...	102	88	(13)(26)	100
3½Ni–1¾Cr–½Mo	Forgings	SA-508	4N	K22375	3	...	3	3	90	70	...	700
3½Ni–1¾Cr–½Mo	Forgings	SA-508	4N	K22375	1	...	11A	5	105	85	...	700
3½Ni–1¾Cr–½Mo	Forgings	SA-508	4N	K22375	2	...	11B	10	115	100	...	650
3½Ni–1¾Cr–½Mo–V	Forgings	SA-541	4N	K42343	3	...	...	...	90	70	...	700
3½Ni–1¾Cr–½Mo–V	Forgings	SA-541	5	K42348	1	...	...	...	105	85	...	700
3½Ni–1¾Cr–½Mo–V	Forgings	SA-541	4N	K42343	2	...	...	...	115	100	...	700
3½Ni–1¾Cr–½Mo–V	Forgings	SA-541	5	K42348	2	...	...	...	115	100	...	700
4Ni–1½Cr–½Mo–V	Forgings	SA-723	3	K44045	1	...	...	...	115	100	(13)(14)(18)	800
4Ni–1½Cr–½Mo–V	Forgings	SA-723	3	K44045	2	...	...	...	135	120	(13)(14)(16)(18)	800
4Ni–1½Cr–½Mo–V	Forgings	SA-723	3	K44045	2a	...	...	...	145	130	(13)(14)(16)(18)	800
4Ni–1½Cr–½Mo–V	Forgings	SA-723	3	K44045	3	...	...	...	155	140	(13)(14)(16)(17)(18)	800
4Ni–1½Cr–½Mo–V	Forgings	SA-723	3	K44045	4	...	...	...	175	160	(10)(13)(16)	700
4Ni–1½Cr–½Mo–V	Forgings	SA-723	3	K44045	5	...	...	...	190	180	(10)(13)(16)	700

Table KM-400-1
Carbon and Low Alloy Steels (Cont'd)

GENERAL NOTES:

(a) The following abbreviation is used: Smls. = Seamless.

(b) The P-Numbers and Group Numbers listed for some of these materials are for information only. For welded construction in this Division, Section IX, Table QW/QB-422 shall be consulted for P-Numbers and Group Numbers. When there is a conflict in P-Number or Group Number, the numbers in Section IX govern.

NOTES:

(1) This material is permitted only in wire form when used for wire-wound vessels and wire-wound frames as described in Article KD-9.

(2) Strength values listed in Section II, Part D, Subpart 1, Table Y-1 for intermediate thickness may be interpolated.

(3) The maximum nominal plate thickness shall not exceed $1\frac{1}{4}$ in.

(4) The minimum tempering temperature shall be 800°F.

(5) This material is permitted in the liquid quenched and tempered condition only.

(6) Section IX, QW-250 Welding Variables, QW-404.12, QW-406.3, QW-407.2, and QW-409.1 shall also apply to this material. These variables shall be applied in accordance with the rules for welding of Part KF.

(7) Welding is not permitted when carbon content exceeds 0.35% by ladle analysis except as permitted in Article KF-7.

(8) The nominal wall thickness of the cylindrical shell of vessels constructed of SA-372 Grade J, Class 110 material shall not exceed 2 in.

(9) The maximum nominal plate thickness shall not exceed 6.00 in. for Grade E or 4.00 in. for Grade P.

(10) This material is permitted only when used as an inner layer in a vessel whose design meets the leak-before-burst criteria of KD-141.

(11) The maximum nominal plate thickness shall not exceed 0.58 in.

(12) The maximum nominal plate thickness shall not exceed 2.50 in.

(13) No welding is permitted on this material.

(14) Caution is advised when using this material above 700°F. After exposure to temperatures above 700°F, this material may exhibit temper embrittlement and stress relaxation effects. The designer shall consider these effects and their influence on the vessel.

(15) When this material is used in welded construction, the following additional requirements apply:

(a) In fulfilling the requirements of Articles KT-1 and KT-2, sufficient tensile tests shall be made to represent postweld heat treatment at both the minimum and maximum times at temperature, and impact tests shall be made to represent the minimum time at temperature. The results of the tensile tests shall meet the tensile requirements of the material specification. The number and orientation of the impact specimens, the testing temperature, and the acceptance criteria shall meet the impact test requirements of Part KM.

(b) Welding procedure qualification tensile tests shall meet both the minimum and maximum tensile strength requirements of the material specification.

(c) Each heat or lot of consumable welding electrodes and each heat or lot of filler wire and flux combination shall be tested to meet the requirements of (a) above.

(16) Caution is advised when using these materials as they are more susceptible than lower strength materials to environmental stress corrosion cracking and/or embrittlement due to hydrogen exposure. This susceptibility increases as material strength increases. The designer shall consider these effects and their influence on the vessel. See Section II, Part D, Nonmandatory Appendix A, A-701 and A-702.

(17) These materials shall not be used for applications when the material, when loaded, is in contact with water or an aqueous environment.

(a) This restriction does not apply to components that are in hydrostatic compression during all loading cycles. Hydrostatic compression is assumed to exist if the sum of the three principal stresses is negative (compressive) at all locations within the component.

(b) This restriction does not apply to inner layers in a vessel whose design meets the leak-before-burst criteria of KD-141.

(18) The actual measured yield strength for these materials shall not be greater than 25 ksi above the minimum specified value.

(19) These wire materials are suitable only for use in special closure parts designed in accordance with Article KD-6, for which it is impractical or impossible to obtain yield strength data. The materials shall not be used for fabrication of other pressure-retaining components, such as bolting, wire-wound vessels, or wire-wound frames.

(20) For these wire materials, the value shown in the "Thickness" column is the wire diameter. The wire may be reshaped for final use from a round to some other cross section, provided the processing does not adversely affect the tensile strength of the material.

(21) Tensile strength values for intermediate diameters shall be interpolated. The values at intermediate diameters shall be rounded to the same number of decimal places as the value at the lesser diameter between which values are being interpolated. The rounding rule is: when the next digit beyond the last place to be retained is less than 5, retain unchanged the digit in the last place retained; when the digit next beyond the last place to be retained is 5 or greater, increase by 1 the digit in the last place retained.

(22) These wire materials have maximum tensile strength requirements. See Section II, Part A, SA-231, SA-232, or SA-401, as applicable.

Table KM-400-1
Carbon and Low Alloy Steels (Cont'd)

NOTES: (Cont'd)

(23) Welding of this material by the electroslag or electrogas process is not permitted. Except for local heating such as cutting and welding, heating of this material above 1,200°F during fabrication is also not permitted.

(24) This material is permitted only when used in the fabrication of external yokes.

(25) The mechanical testing of the material shall be performed once it is in the final cross-sectional shape and heat treated in accordance with the specification prior to coiling into a helical spring. The material shall be certified that it meets the mechanical properties for a diameter of wire that has a diameter equivalent to the smallest cross-sectional dimension of the wire in the final shape.

(26) This material is permitted only when used for impulsively loaded vessels (see Article KG-6) operating above 32°F.

(25)

Table KM-400-1M
Carbon and Low Alloy Steels (Metric)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, mm	P-No.	Group No.	Specified Min. Tensile, MPa	Specified Min. Yield, MPa	Notes	Max. Design Temp., °C
Carbon steel	Pipe	SA-106	A	K02501	...	...	1	1	330	205	...	371
Carbon steel	Plate	SA-516	60	K02100	...	...	1	1	415	220	...	371
Carbon steel	Pipe	SA-106	B	K03006	...	...	1	1	415	240	...	371
Carbon steel	Smls. pipe	SA-333	6	K03006	...	...	1	1	415	240	...	371
Carbon steel	Plate	SA-516	65	K02403	...	...	1	1	450	240	...	371
Carbon steel	Plate	SA/EN 10025-2	S355J2+N	...	...	$63 < t \leq 80$	...	...	470	325	(13)(24)	38
Carbon steel	Plate	SA/EN 10025-2	S355J2+N	...	...	$40 < t \leq 63$	...	...	470	335	(13)(24)	38
Carbon steel	Plate	SA/EN 10025-2	S355J2+N	...	...	$16 < t \leq 40$	...	...	470	345	(13)(24)	38
Carbon steel	Plate	SA/EN 10025-2	S355J2+N	...	...	$3 \leq t \leq 16$	...	...	470	355	(13)(24)	38
Carbon steel	Forgings	SA-350	LF2	K03011	...	...	1	2	485	250	...	371
Carbon steel	Forgings	SA-105	...	K03504	...	...	1	2	485	250	...	371
Carbon steel	Plate	SA-516	70	K02700	...	...	1	2	485	260	...	371
Carbon steel	Pipe	SA-106	C	K03501	...	...	1	2	485	275	...	371
Carbon steel	Forgings	SA-765	IV	K02009	...	...	1	3	550	345	...	316
Carbon steel	Plate	SA/EN 10025-2	S355J2+N	...	...	<3	...	...	510	355	(13)(24)	38
Carbon steel	Plate	SA-738	B	K12007	...	...	1	3	585	415	...	316
Carbon steel	Plate	SA-724	A	K11831	...	...	1	4	620	485	...	371
Carbon steel	Plate	SA-724	C	K12037	...	...	1	4	620	485	...	371
Carbon steel	Plate	SA-724	B	K12031	...	...	1	4	655	515	...	371
Carbon steel	Flat wire	SA-905	...	...	2	1.5	...	...	1 695	1 450	(1)(2)(16)	38
Carbon steel	Flat wire	SA-905	...	...	2	1.3	...	...	1 725	1 475	(1)(2)(16)	38
Carbon steel	Flat wire	SA-905	...	...	2	1.02	...	...	1 765	1 525	(1)(2)(16)	38
Carbon steel	Flat wire	SA-905	...	...	2	0.76	...	...	1 805	1 560	(1)(2)(16)	38
Carbon steel	Flat wire	SA-905	...	...	2	0.51	...	...	1 850	1 600	(1)(2)(16)	38
Carbon steel	Flat wire	SA-905	...	...	1	1.5	...	...	1 895	1 650	(1)(2)(16)	93
Carbon steel	Flat wire	SA-905	...	...	1	1.3	...	...	1 930	1 675	(1)(2)(16)	93
Carbon steel	Flat wire	SA-905	...	...	1	1.02	...	...	1 965	1 725	(1)(2)(16)	93
Carbon steel	Flat wire	SA-905	...	...	1	0.76	...	...	2 000	1 760	(1)(2)(16)	93
Carbon steel	Flat wire	SA-905	...	...	1	0.51	...	...	2 040	1 795	(1)(2)(16)	93
Carbon steel	Plate	SA-841	A	...	1	≤65	1	2	485	345	(23)	343

Table KM-400-1M
Carbon and Low Alloy Steels (Metric) (Cont'd)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, mm	P-No.	Group No.	Specified Min. Tensile, MPa	Specified Min. Yield, MPa	Notes	Max. Design Temp., °C
Carbon steel	Plate	SA-841	B	...	2	≤65	1	3	550	415	(23)	343
Carbon steel	Plate	SA-841	F	...	6	≤32	3	3	565	485	(23)	65
Carbon steel	Plate	SA-841	F	...	7	≤25	3	3	590	515	(23)	65
Carbon steel	Bolt	SA-354	BC	K04100	...	64 < t ≤ 100	...	...	795	685	...	343
Carbon steel	Bolt	SA-354	BC	K04100	...	6 < t ≤ 64	...	...	860	750	...	343
Carbon steel	Bolt	SA-354	BD	K04100	...	64 < t ≤ 100	...	...	965	795	...	343
Carbon steel	Bolt	SA-354	BD	K04100	...	6 < t ≤ 64	...	...	1 035	895	(16)	343
C–¼Mo	Bolt	SA-320	L7A	G40370	...	≤65	...	...	860	725	...	38
C–½Mo	Pipe	SA-335	P1	K11522	...	...	3	1	380	205	...	371
½Cr–⅕Mo–V	Plate	SA-517	B	K11630	...	≤32	11B	4	795	690	(3)	371
½Cr–¼Mo–Si	Plate	SA-517	A	K11856	...	≤32	11B	1	795	690	(3)	371
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	0.80	...	...	2 080	...	(13)(19)(20)(21)(22)(25)	38
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	0.90	...	...	2 070	...	(13)(19)(20)(21)(22)(25)	38
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	1.00	...	...	2 060	...	(13)(19)(20)(21)(22)(25)	38
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	1.10	...	...	2 040	...	(13)(19)(20)(21)(22)(25)	38
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	1.20	...	...	2 020	...	(13)(19)(20)(21)(22)(25)	38
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	1.40	...	...	2 000	...	(13)(19)(20)(21)(22)(25)	38
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	1.60	...	...	1 980	...	(13)(19)(20)(21)(22)(25)	38
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	1.80	...	...	1 960	...	(13)(19)(20)(21)(22)(25)	38
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	2.00	...	...	1 940	...	(13)(19)(20)(21)(22)(25)	38
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	2.20	...	...	1 920	...	(13)(19)(20)(21)(22)(25)	38
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	2.50	...	...	1 900	...	(13)(19)(20)(21)(22)(25)	38
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	2.80	...	...	1 880	...	(13)(19)(20)(21)(22)(25)	38

Table KM-400-1M
Carbon and Low Alloy Steels (Metric) (Cont'd)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, mm	P-No.	Group No.	Specified Min. Tensile, MPa	Specified Min. Yield, MPa	Notes	Max. Design Temp., °C
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	3.00	...	...	1 860	...	(13)(19)(20)(21)(22)(25)	38
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	3.50	...	...	1 840	...	(13)(19)(20)(21)(22)(25)	38
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	4.00	...	...	1 820	...	(13)(19)(20)(21)(22)(25)	38
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	4.50	...	...	1 800	...	(13)(19)(20)(21)(22)(25)	38
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	5.00	...	...	1 780	...	(13)(19)(20)(21)(22)(25)	38
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	5.50	...	...	1 760	...	(13)(19)(20)(21)(22)(25)	38
0.7Cr–1.5Si	Wire	SA-401	9254	G92540	...	6.00	...	...	1 740	...	(13)(19)(20)(21)(22)(25)	38
1Cr–1/5Mo	Bolt	SA-193	B7	G41400	...	100 < t ≤ 200	...	...	690	515	...	343
1Cr–1/5Mo	Bolt	SA-320	L7M	G41400	...	≤65	...	...	690	550	(4)	38
1Cr–1/5Mo	Bolt	SA-193	B7	G41400	...	64 < t ≤ 100	...	...	795	655	...	343
1Cr–1/5Mo	Forgings	SA-372	E	K13047	70	...	...	...	825	485	(5)(6)	371
1Cr–1/5Mo	Forgings	SA-372	F	G41350	70	...	...	...	825	485	(5)(6)(7)	371
1Cr–1/5Mo	Forgings	SA-372	J	K13548	70	...	...	...	825	485	(5)(6)(7)	343
1Cr–1/5Mo	Bolt	SA-193	B7	G41400	...	≤64	...	...	860	725	...	343
1Cr–1/5Mo	Bolt	SA-320	L7	G41400	...	≤65	...	...	860	725	(4)	343
1Cr–1/5Mo	Forgings	SA-372	J	G41370	110	...	...	...	930	760	(6)(7)(8)(16)	343
1Cr–1/5Mo	Bolt	SA-574	4137	G41370	...	≥16	...	...	1 170	930	(13)(16)	288
1Cr–1/5Mo	Bolt	SA-574	4137	G41370	...	≤13	...	...	1 240	965	(13)(16)	288
1Cr–1/4Si–V	Wire	SA-231	...	...	Oil	12.00	...	...	1 320	...	(16)(19)(20)(21)(22)	38
1Cr–1/4Si–V	Wire	SA-232	...	...	Oil	12.00	...	...	1 320	...	(16)(19)(20)(21)(22)	38
1Cr–1/4Si–V	Wire	SA-231	...	...	Oil	11.00	...	...	1 340	...	(16)(19)(20)(21)(22)	38
1Cr–1/4Si–V	Wire	SA-232	...	...	Oil	11.00	...	...	1 340	...	(16)(19)(20)(21)(22)	38
1Cr–1/4Si–V	Wire	SA-231	...	...	Oil	10.00	...	...	1 360	...	(16)(19)(20)(21)(22)	38
1Cr–1/4Si–V	Wire	SA-232	...	...	Oil	10.00	...	...	1 360	...	(16)(19)(20)(21)(22)	38
1Cr–1/4Si–V	Wire	SA-231	...	...	Oil	9.00	...	...	1 380	...	(16)(19)(20)(21)(22)	38
1Cr–1/4Si–V	Wire	SA-232	...	...	Oil	9.00	...	...	1 380	...	(16)(19)(20)(21)(22)	38

Table KM-400-1M
Carbon and Low Alloy Steels (Metric) (Cont'd)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, mm	P-No.	Group No.	Specified Min. Tensile, MPa	Specified Min. Yield, MPa	Notes	Max. Design Temp., °C
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	8.00	...	...	1 400	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	8.00	...	...	1 400	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	7.00	...	...	1 420	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	7.00	...	...	1 420	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	6.50	...	...	1 440	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	6.50	...	...	1 440	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	6.00	...	...	1 460	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	6.00	...	...	1 460	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	5.50	...	...	1 480	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	5.50	...	...	1 480	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	5.00	...	...	1 520	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	5.00	...	...	1 520	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	4.50	...	...	1 560	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	4.50	...	...	1 560	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	4.00	...	...	1 580	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	4.00	...	...	1 580	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	3.50	...	...	1 620	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	3.50	...	...	1 620	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	3.00	...	...	1 660	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	3.00	...	...	1 660	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	2.80	...	...	1 680	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	2.80	...	...	1 680	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	2.50	...	...	1 720	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	2.50	...	...	1 720	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	2.20	...	...	1 750	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	2.20	...	...	1 750	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	2.00	...	...	1 780	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	2.00	...	...	1 780	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	1.80	...	...	1 800	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	1.80	...	...	1 800	...	(16)(19)(20)(21)(22)	38

Table KM-400-1M
Carbon and Low Alloy Steels (Metric) (Cont'd)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, mm	P-No.	Group No.	Specified Min. Tensile, MPa	Specified Min. Yield, MPa	Notes	Max. Design Temp., °C
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	1.60	...	...	1 820	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	1.60	...	...	1 820	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	1.40	...	...	1 860	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	1.40	...	...	1 860	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	1.20	...	...	1 900	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	1.20	...	...	1 900	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	1.10	...	...	1 920	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	1.10	...	...	1 920	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	1.00	...	...	1 940	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	1.00	...	...	1 940	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	0.90	...	...	1 960	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	0.90	...	...	1 960	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	0.80	...	...	1 980	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	0.80	...	...	1 980	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	0.70	...	...	2 000	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	0.70	...	...	2 000	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	0.65	...	...	2 010	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	0.65	...	...	2 010	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	0.60	...	...	2 030	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	0.60	...	...	2 030	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	0.55	...	...	2 050	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	0.55	...	...	2 050	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-231	...	...	Oil	0.50	...	...	2 060	...	(16)(19)(20)(21)(22)	38
1Cr–¼Si–V	Wire	SA-232	...	...	Oil	0.50	...	...	2 060	...	(16)(19)(20)(21)(22)	38
1Cr–½Mo–V	Bolt	SA-193	B16	K14072	...	100 < t ≤ 180	...	...	690	585	...	371
1Cr–½Mo–V	Bolt	SA-193	B16	K14072	...	64 < t ≤ 100	...	...	760	655	...	371
1Cr–½Mo–V	Bolt	SA-193	B16	K14072	...	≤64	...	...	860	725	...	371
¼Cr–½Mo–Si	Pipe	SA-335	P11	K11597	...	...	4	1	415	205	...	371
1¾Cr–½Mo–Ti	Plate	SA-517	E	K21604	...	65 < t ≤ 150	11B	2	725	620	(9)	371
1¾Cr–½Mo–Ti	Plate	SA-517	E	K21604	...	≤65	11B	2	795	690	...	371

Table KM-400-1M
Carbon and Low Alloy Steels (Metric) (Cont'd)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, mm	P-No.	Group No.	Specified Min. Tensile, MPa	Specified Min. Yield, MPa	Notes	Max. Design Temp., °C
2¼Cr–1Mo	Pipe	SA-335	P22	K21590	...	...	5A	1	415	205	(15)	371
2¼Cr–1Mo	Forgings	SA-336	F22	K21590	3	...	5A	1	515	310	(15)	371
2¼Cr–1Mo	Plate	SA-387	22	K21590	2	...	5A	1	515	310	(15)	371
2¼Cr–1Mo	Forgings	SA-508	22	K21590	3	...	5C	1	585	380	(15)	371
2¼Cr–1Mo–V	Forgings	SA-336	F22V	K31835	...	...	5C	1	585	415	(15)	371
2¼Cr–1Mo–V	Forgings	SA-182	F22V	K31835	...	...	5C	1	585	415	(15)	371
2¼Cr–1Mo–V	Forgings	SA-541	22V	K31835	...	...	5C	1	585	415	(15)	371
2¼Cr–1Mo–V	Plate	SA-542	D	K31835	4a	...	5C	1	585	415	(15)	371
2¼Cr–1Mo–V	Plate	SA-832	22V	K31835	...	...	5C	1	585	415	(15)	371
3Cr–1Mo–¼V–Ti–B	Forgings	SA-336	F3V	K31830	...	...	5C	1	585	415	(15)	371
3Cr–1Mo–¼V–Ti–B	Plate	SA-832	21V	K31830	...	...	5C	1	585	415	(15)	371
Mn–½Mo–¼Ni	Plate	SA-533	D	K12529	3	...	11A	4	690	570	...	371
Mn–½Mo–½Ni	Plate	SA-533	B	K12539	3	...	11A	4	690	570	...	371
Mn–½Mo–¾Ni	Plate	SA-533	C	K21554	2	...	3	3	620	485	...	371
Mn–½Ni–V	Plate	SA-225	C	K12524	...	...	10A	1	725	485	(11)	371
¾Ni–½Cr–½Mo–V	Plate	SA-517	F	K11576	...	≤65	11B	3	795	690	(12)	371
¾Ni–½Mo–⅓Cr–V	Forgings	SA-508	2	K12766	1	...	3	3	550	345	...	371
¾Ni–½Mo–Cr–V	Forgings	SA-508	3	K12042	1	...	3	3	550	345	...	371
¾Ni–1Cu–¾Cr	Plate	SA-736	A	...	3	≤50	...	...	585	515	...	343
¾Ni–1Cu–¾Cr	Plate	SA-736	A	...	3	50 < t ≤ 100	...	...	515	450	...	343
1¼Ni–1Cr–½Mo	Plate	SA-517	P	K21650	...	65 < t ≤ 100	11B	8	725	620	(9)	371
1¼Ni–1Cr–½Mo	Plate	SA-517	P	K21650	...	≤65	11B	8	795	690	...	371
1¾Ni–¾Cr–¼Mo	Bolt	SA-320	L43	G43400	...	≤100	...	...	860	725	...	371
1¾Ni–¾Cr–¼Mo	Bolt	SA-574	4340	G43400	...	≥16	...	...	1 170	930	(13)(16)	288
1¾Ni–¾Cr–¼Mo	Bolt	SA-574	4340	G43400	...	≤13	...	...	1 240	965	(13)(16)	288
2Ni–¾Cr–¼Mo	Bolt	SA-540	B23	H43400	5	150 < t ≤ 240	...	...	795	690	...	371
2Ni–¾Cr–¼Mo	Bolt	SA-540	B23	H43400	5	≤150	...	...	825	725	...	371
2Ni–¾Cr–¼Mo	Bolt	SA-540	B23	H43400	4	≤240	...	...	930	825	(16)	371
2Ni–¾Cr–¼Mo	Bolt	SA-540	B23	H43400	3	≤240	...	...	1 000	895	(16)	371
2Ni–¾Cr–⅓Mo	Bolt	SA-540	B24	K24064	5	150 < t ≤ 240	...	...	795	690	...	371

Table KM-400-1M
Carbon and Low Alloy Steels (Metric) (Cont'd)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, mm	P-No.	Group No.	Specified Min. Tensile, MPa	Specified Min. Yield, MPa	Notes	Max. Design Temp., °C
2Ni–¾Cr–⅓Mo	Bolt	SA-540	B24	K24064	5	≤150	...	...	825	725	...	371
2Ni–¾Cr–⅓Mo	Bolt	SA-540	B24	K24064	4	≤240	...	...	930	825	(16)	371
2Ni–¾Cr–⅓Mo	Bolt	SA-540	B24	K24064	3	≤240	...	...	1 000	895	(16)	371
2Ni–1½Cr–¼Mo–V	Forgings	SA-723	1	K23550	1	...	...	...	795	690	(13)(14)(18)	427
2Ni–1½Cr–¼Mo–V	Forgings	SA-723	1	K23550	2	...	...	...	930	825	(13)(14)(16)(18)	427
2Ni–1½Cr–¼Mo–V	Forgings	SA-723	1	K23550	2a	...	...	...	1 000	895	(13)(14)(16)(18)	427
2Ni–1½Cr–¼Mo–V	Forgings	SA-723	1	K23550	3	...	...	...	1 070	965	(13)(14)(16)(17)(18)	427
2Ni–1½Cr–¼Mo–V	Forgings	SA-723	1	K23550	4	...	...	...	1 205	1 105	(10)(13)(16)	371
2Ni–1½Cr–¼Mo–V	Forgings	SA-723	1	K23550	5	...	...	...	1 310	1 240	(10)(13)(16)	371
2¾Ni–1½Cr–½Mo	Plate	SA-543	C	K42338	1	...	11A	5	725	585	...	343
2¾Ni–1½Cr–½Mo	Plate	SA-543	C	K42338	2	...	11B	10	795	690	...	343
2¾Ni–1½Cr–½Mo–V	Forgings	SA-723	2	K34035	1	...	...	...	795	690	(13)(14)(18)	427
2¾Ni–1½Cr–¼Mo–V	Forgings	SA-723	2	K34035	2	...	...	...	930	825	(13)(14)(16)(18)	427
2¾Ni–1½Cr–¼Mo–V	Forgings	SA-723	2	K34035	2a	...	...	...	1 000	895	(13)(14)(16)(18)	427
2¾Ni–1½Cr–¼Mo–V	Forgings	SA-723	2	K34035	3	...	...	...	1 070	965	(13)(14)(16)(17)(18)	427
2¾Ni–1½Cr–½Mo–V	Forgings	SA-723	2	K34035	4	...	...	...	1 205	1 105	(10)(13)(16)	371
2¾Ni–1½Cr–½Mo–V	Forgings	SA-723	2	K34035	5	...	...	...	1 310	1 240	(10)(13)(16)	371
3Ni–1¾Cr–½Mo	Plate	SA-543	B	K42339	1	...	11A	5	725	585	...	343
3Ni–1¾Cr–½Mo	Plate	SA-543	B	K42339	2	...	11B	10	795	690	...	343
3½Ni–1½Cr–½Mo–½Mn	Castings	SA-487	17	...	A	≤150	...	...	780	670	(13)(26)	38
3½Ni–1½Cr–½Mo–½Mn	Castings	SA-487	17	...	A	150 < t ≤ 200	...	...	760	650	(13)(26)	38
3½Ni–1½Cr–½Mo–½Mn	Castings	SA-487	17	...	A	200 < t ≤ 300	...	...	730	625	(13)(26)	38
3½Ni–1½Cr–½Mo–½Mn	Castings	SA-487	17	...	A	300 < t ≤ 360	...	...	705	605	(13)(26)	38
3½Ni–1¾Cr–½Mo	Forgings	SA-508	4N	K22375	3	...	3	3	620	485	...	371
3½Ni–1¾Cr–½Mo	Forgings	SA-508	4N	K22375	1	...	11A	5	725	585	...	371
3½Ni–1¾Cr–½Mo	Forgings	SA-508	4N	K22375	2	...	11B	10	795	690	...	343
3½Ni–1¾Cr–½Mo–V	Forgings	SA-541	4N	K42343	3	...	...	...	620	485	...	371
3½Ni–1¾Cr–½Mo–V	Forgings	SA-541	5	K42348	1	...	...	...	725	585	...	371
3½Ni–1¾Cr–½Mo–V	Forgings	SA-541	4N	K42343	2	...	...	...	795	690	...	371
3½Ni–1¾Cr–½Mo–V	Forgings	SA-541	5	K42348	2	...	...	...	795	690	...	371

Table KM-400-1M
Carbon and Low Alloy Steels (Metric) (Cont'd)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, mm	P-No.	Group No.	Specified Min. Tensile, MPa	Specified Min. Yield, MPa	Notes	Max. Design Temp., °C
4Ni–1½Cr–½Mo–V	Forgings	SA-723	3	K44045	1	...	...	...	795	690	(13)(14)(18)	427
4Ni–1½Cr–½Mo–V	Forgings	SA-723	3	K44045	2	...	...	...	930	825	(13)(14)(16)(18)	427
4Ni–1½Cr–½Mo–V	Forgings	SA-723	3	K44045	2a	...	...	...	1 000	895	(13)(14)(16)(18)	427
4Ni–1½Cr–¼Mo–V	Forgings	SA-723	3	K44045	3	...	...	...	1 070	965	(13)(14)(16)(17)(18)	427
4Ni–1½Cr–½Mo–V	Forgings	SA-723	3	K44045	4	...	...	...	1 205	1 105	(10)(13)(16)	371
4Ni–1½Cr–½Mo–V	Forgings	SA-723	3	K44045	5	...	...	...	1 310	1 240	(10)(13)(16)	371

GENERAL NOTES:

(a) The following abbreviation is used: Smls. = Seamless.

(b) The P-Numbers and Group Numbers listed for some of these materials are for information only. For welded construction in this Division, Section IX, Table QW/QB-422 shall be consulted for P-Numbers and Group Numbers. When there is a conflict in P-Number or Group Number, the numbers in Section IX govern.

NOTES:

(1) This material is permitted only in wire form when used for wire-wound vessels and wire-wound frames as described in Article KD-9.

(2) Strength values listed in Section II, Part D, Subpart 1, Table Y-1 for intermediate thickness may be interpolated.

(3) The maximum nominal plate thickness shall not exceed 32 mm.

(4) The minimum tempering temperature shall be 425°C.

(5) This material is permitted in the liquid quenched and tempered condition only.

(6) Section IX, QW-250 Welding Variables, QW-404.12, QW-406.3, QW-407.2, and QW-409.1 shall also apply to this material. These variables shall be applied in accordance with the rules for welding of Part KF.

(7) Welding is not permitted when carbon content exceeds 0.35% by ladle analysis except as permitted in Article KF-7.

(8) The nominal wall thickness of the cylindrical shell of vessels constructed of SA-372 Grade J, Class 110 material shall not exceed 50 mm.

(9) The maximum nominal plate thickness shall not exceed 150 mm for Grade E or 100 mm for Grade P.

(10) This material is permitted only when used as an inner layer in a vessel whose design meets the leak-before-burst criteria of KD-141.

(11) The maximum nominal plate thickness shall not exceed 15 mm.

(12) The maximum nominal plate thickness shall not exceed 64 mm.

(13) No welding is permitted on this material.

(14) Caution is advised when using this material above 375°C. After exposure to temperatures above 375°C, this material may exhibit temper embrittlement and stress relaxation effects. The designer shall consider these effects and their influence on the vessel.

(15) When this material is used in welded construction, the following additional requirements apply:

(a) In fulfilling the requirements of Articles KT-1 and KT-2, sufficient tensile tests shall be made to represent postweld heat treatment at both the minimum and maximum times at temperature, and impact tests shall be made to represent the minimum time at temperature. The results of the tensile tests shall meet the tensile requirements of the material specification. The number and orientation of the impact specimens, the testing temperature, and the acceptance criteria shall meet the impact test requirements of Part KM.

(b) Welding procedure qualification tensile tests shall meet both the minimum and maximum tensile strength requirements of the material specification.

(c) Each heat or lot of consumable welding electrodes and each heat or lot of filler wire and flux combination shall be tested to meet the requirements of (a) above.

(16) Caution is advised when using these materials as they are more susceptible than lower strength materials to environmental stress corrosion cracking and/or embrittlement due to hydrogen exposure. This susceptibility increases as material strength increases. The designer shall consider these effects and their influence on the vessel. See Section II, Part D, Nonmandatory Appendix A, A-701 and A-702.

Table KM-400-1M
Carbon and Low Alloy Steels (Metric) (Cont'd)

NOTES: (Cont'd)

(17) These materials shall not be used for applications when the material, when loaded, is in contact with water or an aqueous environment.

(a) This restriction does not apply to components that are in hydrostatic compression during all loading cycles. Hydrostatic compression is assumed to exist if the sum of the three principal stresses is negative (compressive) at all locations within the component.

(b) This restriction does not apply to inner layers in a vessel whose design meets the leak-before-burst criteria of KD-141.

(18) The actual measured yield strength for these materials shall not be greater than 172 MPa above the minimum specified value.

(19) These wire materials are suitable only for use in special closure parts designed in accordance with Article KD-6, for which it is impractical or impossible to obtain yield strength data. The materials shall not be used for fabrication of other pressure-retaining components, such as bolting, wire-wound vessels, or wire-wound frames.

(20) For these wire materials, the value shown in the "Thickness" column is the wire diameter. The wire may be reshaped for final use from a round to some other cross section, provided the processing does not adversely affect the tensile strength of the material.

(21) Tensile strength values for intermediate diameters shall be interpolated. The values at intermediate diameters shall be rounded to the same number of decimal places as the value at the lesser diameter between which values are being interpolated. The rounding rule is: when the next digit beyond the last place to be retained is less than 5, retain unchanged the digit in the last place retained; when the digit next beyond the last place to be retained is 5 or greater, increase by 1 the digit in the last place retained.

(22) These wire materials have maximum tensile strength requirements. See Section II, Part A, SA-231, SA-232, or SA-401, as applicable.

(23) Welding of this material by the electroslag or electrogas process is not permitted. Except for local heating such as cutting and welding, heating of this material above 650°C during fabrication is also not permitted.

(24) This material is permitted only when used in the fabrication of external yokes.

(25) The mechanical testing of the material shall be performed once it is in the final cross-sectional shape and heat treated in accordance with the specification prior to coiling into a helical spring. The material shall be certified that it meets the mechanical properties for a diameter of wire that has a diameter equivalent to the smallest cross-sectional dimension of the wire in the final shape.

(26) This material is permitted only when used for impulsively loaded vessels (see Article KG-6) operating above 0°C.

Table KM-400-2
High Alloy Steels

(25)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, in.	P-No.	Group No.	Specified Min. Tensile, ksi	Specified Min. Yield, ksi	Notes	Max. Design Temp., °F
12Cr–9Ni–2Cu-1Ti	Bar	SA-564	XM-16	S45500	H1000	...	...	...	205	185	(1) (8)	100
12Cr–9Ni–2Cu-1Ti	Forgings	SA-705	XM-16	S45500	H1000	≥½	...	...	205	185	(1) (8)	100
12Cr–9Ni–2Cu-1Ti	Bar	SA-564	XM-16	S45500	H950	...	...	...	220	205	(1) (8)	100
12Cr–9Ni–2Cu-1Ti	Forgings	SA-705	XM-16	S45500	H950	≥½	...	...	220	205	(1) (8)	100
12Cr–9Ni–2Cu-1Ti	Bar	SA-564	XM-16	S45500	H900	...	...	...	235	220	(1) (8)	100
12Cr–9Ni–2Cu-1Ti	Forgings	SA-705	XM-16	S45500	H900	≥½	...	...	235	220	(1) (8)	100
13Cr–8Ni–2Mo	Bar	SA-564	XM-13	S13800	H1150M	...	...	...	125	85	...	100
13Cr–8Ni–2Mo	Forgings	SA-705	XM-13	S13800	H1150M	...	...	...	125	85	...	100
13Cr–8Ni–2Mo	Bar	SA-564	XM-13	S13800	H1150	...	...	...	135	90	...	100
13Cr–8Ni–2Mo	Forgings	SA-705	XM-13	S13800	H1150	...	...	...	135	90	...	100
13Cr–8Ni–2Mo	Bar	SA-564	XM-13	S13800	H1100	...	...	...	150	135	(8)	100
13Cr–8Ni–2Mo	Forgings	SA-705	XM-13	S13800	H1100	...	...	...	150	135	(8)	100
13Cr–8Ni–2Mo	Bar	SA-564	XM-13	S13800	H1050	...	...	...	175	165	(1) (8)	100
13Cr–8Ni–2Mo	Forgings	SA-705	XM-13	S13800	H1050	...	...	...	175	165	(1) (8)	100
13Cr–8Ni–2Mo	Bar	SA-564	XM-13	S13800	H1025	...	...	...	185	175	(1) (8)	100
13Cr–8Ni–2Mo	Forgings	SA-705	XM-13	S13800	H1025	...	...	...	185	175	(1) (8)	100
13Cr–8Ni–2Mo	Bar	SA-564	XM-13	S13800	H1000	...	...	...	205	190	(1) (8)	100
13Cr–8Ni–2Mo	Forgings	SA-705	XM-13	S13800	H1000	...	...	...	205	190	(1) (8)	100
13Cr–8Ni–2Mo	Bar	SA-564	XM-13	S13800	H950	...	...	...	220	205	(1) (8)	100
13Cr–8Ni–2Mo	Forgings	SA-705	XM-13	S13800	H950	...	...	...	220	205	(1) (8)	100
15Cr–5Ni–3Cu	Bar	SA-564	XM-12	S15500	H1150M	...	...	...	115	75	...	550
15Cr–5Ni–3Cu	Forgings	SA-705	XM-12	S15500	H1150M	...	...	...	115	75	...	550
15Cr–5Ni–3Cu	Bar	SA-564	XM-12	S15500	H1150	...	...	...	135	105	...	550
15Cr–5Ni–3Cu	Forgings	SA-705	XM-12	S15500	H1150	...	...	...	135	105	...	550
15Cr–5Ni–3Cu	Bar	SA-564	XM-12	S15500	H1100	...	...	...	140	115	(6)	550
15Cr–5Ni–3Cu	Forgings	SA-705	XM-12	S15500	H1100	...	...	...	140	115	(6)	550
15Cr–5Ni–3Cu	Bar	SA-564	XM-12	S15500	H1075	...	...	...	145	125	(6) (8)	550
15Cr–5Ni–3Cu	Forgings	SA-705	XM-12	S15500	H1075	...	...	...	145	125	(6) (8)	550

Table KM-400-2
High Alloy Steels (Cont'd)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, in.	P-No.	Group No.	Specified Min. Tensile, ksi	Specified Min. Yield, ksi	Notes	Max. Design Temp., °F
15Cr–5Ni–3Cu	Bar	SA-564	XM-12	S15500	H1025	...	...	...	155	145	(6) (8) (9) (10)	550
15Cr–5Ni–3Cu	Forgings	SA-705	XM-12	S15500	H1025	...	...	...	155	145	(6) (8) (9) (10)	550
15Cr–5Ni–3Cu	Bar	SA-564	XM-12	S15500	H925	...	...	...	170	155	(1) (6) (8)	550
15Cr–5Ni–3Cu	Forgings	SA-705	XM-12	S15500	H925	...	...	...	170	155	(1) (6) (8)	550
15Cr–5Ni–3Cu	Bar	SA-564	XM-12	S15500	H900	...	...	...	190	170	(1) (6) (8)	550
15Cr–5Ni–3Cu	Forgings	SA-705	XM-12	S15500	H900	...	...	...	190	170	(1) (6) (8)	550
15Cr–6Ni–Cu–Mo	Bar	SA-564	XM-25	S45000	H1150	...	...	...	125	75	...	100
15Cr–6Ni–Cu–Mo	Forgings	SA-705	XM-25	S45000	H1150	≥½	...	...	125	75	...	100
15Cr–6Ni–Cu–Mo	Bar	SA-564	XM-25	S45000	H1100	...	...	...	130	105	...	100
15Cr–6Ni–Cu–Mo	Forgings	SA-705	XM-25	S45000	H1100	≥½	...	...	130	105	...	100
15Cr–6Ni–Cu–Mo	Bar	SA-564	XM-25	S45000	H1050	...	...	...	145	135	(8)	100
15Cr–6Ni–Cu–Mo	Forgings	SA-705	XM-25	S45000	H1050	≥½	...	...	145	135	(8)	100
15Cr–6Ni–Cu–Mo	Bar	SA-564	XM-25	S45000	H1025	...	...	...	150	140	(8) (9) (10)	100
15Cr–6Ni–Cu–Mo	Forgings	SA-705	XM-25	S45000	H1025	≥½	...	...	150	140	(8) (9) (10)	100
15Cr–6Ni–Cu–Mo	Bar	SA-564	XM-25	S45000	H1000	...	...	...	160	150	(1) (8)	100
15Cr–6Ni–Cu–Mo	Forgings	SA-705	XM-25	S45000	H1000	≥½	...	...	160	150	(1) (8)	100
15Cr–6Ni–Cu–Mo	Bar	SA-564	XM-25	S45000	H950	...	...	...	170	160	(1) (8)	100
15Cr–6Ni–Cu–Mo	Forgings	SA-705	XM-25	S45000	H950	≥½	...	...	170	160	(1) (8)	100
15Cr–6Ni–Cu–Mo	Bar	SA-564	XM-25	S45000	H900	...	...	...	180	170	(1) (8)	100
15Cr–6Ni–Cu–Mo	Forgings	SA-705	XM-25	S45000	H900	≥½	...	...	180	170	(1) (8)	100
17Cr–4Ni–4Cu	Bar	SA-564	630	S17400	H1150M	...	...	...	115	75	(6)	550
17Cr–4Ni–4Cu	Forgings	SA-705	630	S17400	H1150M	...	...	...	115	75	(6)	550
17Cr–4Ni–4Cu	Bar	SA-564	630	S17400	H1150	...	...	...	135	105	(6)	550
17Cr–4Ni–4Cu	Forgings	SA-705	630	S17400	H1150	...	...	...	135	105	(6)	550
17Cr–4Ni–4Cu	Bar	SA-564	630	S17400	H1100	...	...	...	140	115	(6)	550
17Cr–4Ni–4Cu	Forgings	SA-705	630	S17400	H1100	...	...	...	140	115	(6)	550
17Cr–4Ni–4Cu	Bar	SA-564	630	S17400	H1075	...	...	...	145	125	(6) (8)	550

Table KM-400-2
High Alloy Steels (Cont'd)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, in.	P-No.	Group No.	Specified Min. Tensile, ksi	Specified Min. Yield, ksi	Notes	Max. Design Temp., °F
17Cr–4Ni–4Cu	Forgings	SA-705	630	S17400	H1075	...	...	...	145	125	(6) (8)	550
17Cr–4Ni–4Cu	Bar	SA-564	630	S17400	H1025	...	...	...	155	145	(6) (8) (9) (10)	550
17Cr–4Ni–4Cu	Forgings	SA-705	630	S17400	H1025	...	...	...	155	145	(6) (8) (9) (10)	550
17Cr–4Ni–4Cu	Forgings	SA-705	630	S17400	H925	...	...	...	170	155	(1) (6) (8)	550
17Cr–4Ni–4Cu	Forgings	SA-705	630	S17400	H900	...	...	...	190	170	(1) (6) (8)	550
17Cr–7Ni–1Al	Forgings	SA-705	631	S17700	TH1050	...	...	...	170	140	(1) (8)	100
17Cr–7Ni–1Al	Forgings	SA-705	631	S17700	RH950	...	...	...	185	150	(1) (8)	100
25Ni–15Cr–2Ti	Bolt	SA-453	660	S66286	A	...	...	...	130	85	(2)	900
25Ni–15Cr–2Ti	Bolt	SA-453	660	S66286	B	...	...	...	130	85	(2)	900
25Ni–15Cr–2Ti	Forgings	SA-638	660	S66286	1	...	...	...	130	85	(2)	900
25Ni–15Cr–2Ti	Forgings	SA-638	660	S66286	2	...	...	...	130	85	(2)	900
16Cr–12Ni–2Mo	Forgings	SA-965	F316	S31600	...	...	8	1	70	30	(11)	800
16Cr–12Ni–2Mo	Forgings	SA-965	F316H	S31609	...	...	8	1	70	30	(11)	800
16Cr–12Ni–2Mo	Pipe	SA-312	TP316	S31600	Seamless	...	8	1	75	30	(7) (11)	800
16Cr–12Ni–2Mo	Pipe	SA-312	TP316H	S31609	Seamless	...	8	1	75	30	(7) (11)	800
16Cr–12Ni–2Mo	Bolt	SA-320	B8M	S31600	1	...	...	...	75	30	(11)	800
16Cr–12Ni–2Mo	Bolt	SA-320	B8MA	S31600	1A	...	...	...	75	30	(11)	800
16Cr–12Ni–2Mo	Bar	SA-479	316	S31600	Annealed	...	8	1	75	30	(3) (4) (11)	800
16Cr–12Ni–2Mo	Bar	SA-479	316H	S31609	Annealed	...	8	1	75	30	(3) (11)	800
16Cr–12Ni–2Mo	Bar	SA-276	316	S31600	S	$2\frac{1}{2} < t \le 3$	...	...	80	55	(2) (11)	600
16Cr–12Ni–2Mo	Bolt	SA-320	B8M	S31600	2	$1\frac{1}{4} < t \le 1\frac{1}{2}$	...	...	90	50	(5) (11)	100
16Cr–12Ni–2Mo	Bar	SA-276	316	S31600	S	$2 < t \le 2\frac{1}{2}$	...	...	90	65	(2) (11)	600
16Cr–12Ni–2Mo	Bar	SA-276	316	S31600	B	$1\frac{1}{2} < t \le 1\frac{3}{4}$	...	...	95	45	(2) (11)	600
16Cr–12Ni–2Mo	Bolt	SA-320	B8M	S31600	2	$1 < t \le 1\frac{1}{4}$	...	...	95	65	(5) (11)	100
16Cr–12Ni–2Mo	Bar	SA-276	316	S31600	S	≤2	...	...	95	75	(2) (11)	600
16Cr–12Ni–2Mo	Bar	SA-276	316	S31600	B	$1\frac{1}{4} < t \le 1\frac{1}{2}$	...	...	100	50	(2) (11)	600
16Cr–12Ni–2Mo	Bolt	SA-320	B8M	S31600	2	$\frac{3}{4} < t \le 1$	...	...	100	80	(5) (11)	100
16Cr–12Ni–2Mo	Bar	SA-276	316	S31600	B	$1 < t \le 1\frac{1}{4}$	...	...	105	65	(2) (11)	600

Table KM-400-2
High Alloy Steels (Cont'd)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, in.	P-No.	Group No.	Specified Min. Tensile, ksi	Specified Min. Yield, ksi	Notes	Max. Design Temp., °F
16Cr–12Ni–2Mo	Bolt	SA-320	B8M	S31600	2	$\leq 3/4$	...	...	110	95	(5) (11)	100
16Cr–12Ni–2Mo	Bar	SA-276	316	S31600	B	$3/4 < t \leq 1$	...	...	115	80	(2) (11)	600
16Cr–12Ni–2Mo	Bar	SA-276	316	S31600	B	$\leq 3/4$	...	...	125	100	(2) (11)	600
18Cr–8Ni	Forgings	SA-182	F304	S30400	...	$t > 5$	8	1	70	30	(11)	800
18Cr–8Ni	Forgings	SA-182	F304	S30400	...	$t \leq 5$	8	1	75	30	(11)	800
18Cr–8Ni	Plate	SA-240	304	S30400	...	...	8	1	75	30	(11)	800
18Cr–8Ni	Bolt	SA-320	B8	S30400	1	...	...	...	75	30	(11)	800
18Cr–8Ni	Bolt	SA-320	B8A	S30400	1A	...	...	...	75	30	(11)	800
18Cr–8Ni	Bolt	SA-320	B8	S30400	2	$1 1/4 < t \leq 1 1/2$	...	...	100	50	(5) (11)	100
18Cr–8Ni	Bolt	SA-320	B8	S30400	2	$1 < t \leq 1 1/4$	...	...	105	65	(5) (11)	100
18Cr–8Ni	Bolt	SA-320	B8	S30400	2	$3/4 < t \leq 1$	...	...	115	80	(5) (11)	100
18Cr–8Ni	Bolt	SA-320	B8	S30400	2	$\leq 3/4$	...	...	125	100	(5) (11)	100
18Cr–8Ni	Forgings	SA-182	F304L	S30403	...	$t > 5$	8	1	65	25	(11)	800
18Cr–8Ni	Forgings	SA-182	F304L	S30403	...	$t \leq 5$	8	1	70	25	(11)	800
18Cr–8Ni	Plate	SA-240	304L	S30403	...	...	8	1	70	25	(11)	800
18Cr–8Ni–S	Bolt	SA-320	B8F	S30300	1	...	...	...	75	30	(11) (12)	800
18Cr–8Ni–S	Bolt	SA-320	B8FA	S30300	1A	...	...	...	75	30	(11) (12)	800
18Cr–8Ni–Se	Bolt	SA-320	B8F	S30323	1	...	...	...	75	30	(11) (12)	800
18Cr–8Ni–Se	Bolt	SA-320	B8FA	S30323	1A	...	...	...	75	30	(11) (12)	800
18Cr–10Ni–Cb	Bolt	SA-320	B8C	S34700	1	...	...	...	75	30	(11)	800
18Cr–10Ni–Cb	Bolt	SA-320	B8CA	S34700	1A	...	...	...	75	30	(11)	800
18Cr–10Ni–Cb	Bolt	SA-320	B8C	S34700	2	$1 1/4 < t \leq 1 1/2$	...	...	100	50	(5) (11)	100
18Cr–10Ni–Cb	Bolt	SA-320	B8C	S34700	2	$1 < t \leq 1 1/4$	...	...	105	65	(5) (11)	100
18Cr–10Ni–Cb	Bolt	SA-320	B8C	S34700	2	$3/4 < t \leq 1$	...	...	115	80	(5) (11)	100
18Cr–10Ni–Cb	Bolt	SA-320	B8C	S34700	2	$\leq 3/4$	...	...	125	100	(5) (11)	100
18Cr–10Ni–Ti	Bolt	SA-320	B8T	S32100	1	...	...	...	75	30	(11)	800
18Cr–10Ni–Ti	Bolt	SA-320	B8TA	S32100	1A	...	...	...	75	30	(11)	800

Table KM-400-2
High Alloy Steels (Cont'd)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, in.	P-No.	Group No.	Specified Min. Tensile, ksi	Specified Min. Yield, ksi	Notes	Max. Design Temp., °F
18Cr–10Ni–Ti	Bolt	SA-320	B8T	S32100	2	$1\frac{1}{4} < t \le 1\frac{1}{2}$	...	...	100	50	(5) (11)	100
18Cr–10Ni–Ti	Bolt	SA-320	B8T	S32100	2	$1 < t \le 1\frac{1}{4}$	...	...	105	65	(5) (11)	100
18Cr–10Ni–Ti	Bolt	SA-320	B8T	S32100	2	$\frac{3}{4} < t \le 1$	...	...	115	80	(5) (11)	100
18Cr–10Ni–Ti	Bolt	SA-320	B8T	S32100	2	$\le\frac{3}{4}$	...	...	125	100	(5) (11)	100

GENERAL NOTE: The P-Numbers and Group Numbers listed for some of these materials are for information only. For welded construction in this Division, Section IX, Table QW/QB-422 shall be consulted for P-Numbers and Group Numbers. When there is a conflict in P-Number or Group Number, the numbers in Section IX govern.

NOTES:

(1) This material is permitted only when used as an inner layer in a vessel whose design meets the leak-before-burst criteria of KD-141.

(2) No welding is permitted on this material.

(3) A tensile strength of 70 ksi minimum is permitted for extruded shapes.

(4) Yield strength values listed in Section II, Part D, Subpart 1, Table Y-1 are for material in the annealed condition.

(5) For all design temperatures, the maximum hardness shall be Rockwell C35 immediately under thread roots. The hardness shall be taken on a flat area at least $\frac{1}{8}$ in. across, prepared by removing threads; no more material than necessary shall be removed to prepare the flat area. Hardness determinations shall be made at the same frequency as tensile tests.

(6) This material has reduced toughness at room temperature after exposure at high temperature. The degree of embrittlement depends on composition, heat treatment, time, and temperature. The lowest temperature of concern is about 550°F. See Section II, Part D, Nonmandatory Appendix A, A-207.

(7) This material shall only be used in the seamless condition.

(8) Caution is advised when using these materials as they are more susceptible than lower strength materials to environmental stress corrosion cracking and/or embrittlement due to hydrogen exposure. This susceptibility increases as yield strength increases. The designer shall consider these effects and their influence on the vessel. See Section II, Part D, Nonmandatory Appendix A, A-701 and A-702.

(9) These materials shall not be used for applications when the material, when loaded, is in contact with water or an aqueous environment.

(a) This restriction does not apply to components that are in hydrostatic compression during all loading cycles. Hydrostatic compression is assumed to exist if the sum of the three principal stresses is negative (compressive) at all locations within the component.

(b) This restriction does not apply to inner layers in a vessel whose design meets the leak-before-burst criteria of KD-141.

(10) The actual measured yield strength for these materials shall not be greater than 25 ksi above the minimum specified value.

(11) This material is susceptible to chloride stress corrosion cracking. See Section II, Part D, Nonmandatory Appendix A, A-701.

(12) This free-machining material has lower corrosion resistance compared with its non-free-machining equivalent.

Table KM-400-2M
High Alloy Steels (Metric)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, mm	P-No.	Group No.	Specified Min. Tensile, MPa	Specified Min. Yield, MPa	Notes	Max. Design Temp., °C
12Cr–9Ni–2Cu–1Ti	Bar	SA-564	XM-16	S45500	H1000	...	...	...	1 415	1 275	(1) (8)	38
12Cr–9Ni–2Cu–1Ti	Forgings	SA-705	XM-16	S45500	H1000	≥13	...	...	1 415	1 275	(1) (8)	38
12Cr–9Ni–2Cu–1Ti	Bar	SA-564	XM-16	S45500	H950	...	...	...	1 515	1 415	(1) (8)	38
12Cr–9Ni–2Cu–1Ti	Forgings	SA-705	XM-16	S45500	H950	≥13	...	...	1 515	1 415	(1) (8)	38
12Cr–9Ni–2Cu–1Ti	Bar	SA-564	XM-16	S45500	H900	...	...	...	1 620	1 515	(1) (8)	38
12Cr–9Ni–2Cu–1Ti	Forgings	SA-705	XM-16	S45500	H900	≥13	...	...	1 620	1 515	(1) (8)	38
13Cr–8Ni–2Mo	Bar	SA-564	XM-13	S13800	H1150M	...	...	...	860	585	...	38
13Cr–8Ni–2Mo	Forgings	SA-705	XM-13	S13800	H1150M	...	...	...	860	585	...	38
13Cr–8Ni–2Mo	Bar	SA-564	XM-13	S13800	H1150	...	...	...	930	620	...	38
13Cr–8Ni–2Mo	Forgings	SA-705	XM-13	S13800	H1150	...	...	...	930	620	...	38
13Cr–8Ni–2Mo	Bar	SA-564	XM-13	S13800	H1100	...	...	...	1 035	930	(8)	38
13Cr–8Ni–2Mo	Forgings	SA-705	XM-13	S13800	H1100	...	...	...	1 035	930	(8)	38
13Cr–8Ni–2Mo	Bar	SA-564	XM-13	S13800	H1050	...	...	...	1 205	1 140	(1) (8)	38
13Cr–8Ni–2Mo	Forgings	SA-705	XM-13	S13800	H1050	...	...	...	1 205	1 140	(1) (8)	38
13Cr–8Ni–2Mo	Bar	SA-564	XM-13	S13800	H1025	...	...	...	1 275	1 205	(1) (8)	38
13Cr–8Ni–2Mo	Forgings	SA-705	XM-13	S13800	H1025	...	...	...	1 275	1 205	(1) (8)	38
13Cr–8Ni–2Mo	Bar	SA-564	XM-13	S13800	H1000	...	...	...	1 415	1 310	(1) (8)	38
13Cr–8Ni–2Mo	Forgings	SA-705	XM-13	S13800	H1000	...	...	...	1 415	1 310	(1) (8)	38
13Cr–8Ni–2Mo	Bar	SA-564	XM-13	S13800	H950	...	...	...	1 515	1 415	(1) (8)	38
13Cr–8Ni–2Mo	Forgings	SA-705	XM-13	S13800	H950	...	...	...	1 515	1 415	(1) (8)	38
15Cr–5Ni–3Cu	Bar	SA-564	XM-12	S15500	H1150M	...	...	...	795	515	...	288
15Cr–5Ni–3Cu	Forgings	SA-705	XM-12	S15500	H1150M	...	...	...	795	515	...	288
15Cr–5Ni–3Cu	Bar	SA-564	XM-12	S15500	H1150	...	...	...	930	725	...	288
15Cr–5Ni–3Cu	Forgings	SA-705	XM-12	S15500	H1150	...	...	...	930	725	...	288
15Cr–5Ni–3Cu	Bar	SA-564	XM-12	S15500	H1100	...	...	...	965	795	(6)	288
15Cr–5Ni–3Cu	Forgings	SA-705	XM-12	S15500	H1100	...	...	...	965	795	(6)	288
15Cr–5Ni–3Cu	Bar	SA-564	XM-12	S15500	H1075	...	...	...	1 000	860	(6) (8)	288
15Cr–5Ni–3Cu	Forgings	SA-705	XM-12	S15500	H1075	...	...	...	1 000	860	(6) (8)	288

Table KM-400-2M
High Alloy Steels (Metric) (Cont'd)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, mm	P-No.	Group No.	Specified Min. Tensile, MPa	Specified Min. Yield, MPa	Notes	Max. Design Temp., °C
15Cr–5Ni–3Cu	Bar	SA-564	XM-12	S15500	H1025	...	...	...	1 070	1 000	(6) (8) (9) (10)	288
15Cr–5Ni–3Cu	Forgings	SA-705	XM-12	S15500	H1025	...	...	...	1 070	1 000	(6) (8) (9) (10)	288
15Cr–5Ni–3Cu	Bar	SA-564	XM-12	S15500	H925	...	...	...	1 170	1 070	(1) (6) (8)	288
15Cr–5Ni–3Cu	Forgings	SA-705	XM-12	S15500	H925	...	...	...	1 170	1 070	(1) (6) (8)	288
15Cr–5Ni–3Cu	Bar	SA-564	XM-12	S15500	H900	...	...	...	1 310	1 170	(1) (6) (8)	288
15Cr–5Ni–3Cu	Forgings	SA-705	XM-12	S15500	H900	...	...	...	1 310	1 170	(1) (6) (8)	288
15Cr–6Ni–Cu–Mo	Bar	SA-564	XM-25	S45000	H1150	...	...	...	860	515	...	38
15Cr–6Ni–Cu–Mo	Forgings	SA-705	XM-25	S45000	H1150	≥13	...	...	860	515	...	38
15Cr–6Ni–Cu–Mo	Bar	SA-564	XM-25	S45000	H1100	...	...	...	895	725	...	38
15Cr–6Ni–Cu–Mo	Forgings	SA-705	XM-25	S45000	H1100	≥13	...	...	895	725	...	38
15Cr–6Ni–Cu–Mo	Bar	SA-564	XM-25	S45000	H1050	...	...	...	1 000	930	(8)	38
15Cr–6Ni–Cu–Mo	Forgings	SA-705	XM-25	S45000	H1050	≥13	...	...	1 000	930	(8)	38
15Cr–6Ni–Cu–Mo	Bar	SA-564	XM-25	S45000	H1025	...	...	...	1 035	965	(8) (9) (10)	38
15Cr–6Ni–Cu–Mo	Forgings	SA-705	XM-25	S45000	H1025	≥13	...	...	1 035	965	(8) (9) (10)	38
15Cr–6Ni–Cu–Mo	Bar	SA-564	XM-25	S45000	H1000	...	...	...	1 105	1 035	(1) (8)	38
15Cr–6Ni–Cu–Mo	Forgings	SA-705	XM-25	S45000	H1000	≥13	...	...	1 105	1 035	(1) (8)	38
15Cr–6Ni–Cu–Mo	Bar	SA-564	XM-25	S45000	H950	...	...	...	1 170	1 105	(1) (8)	38
15Cr–6Ni–Cu–Mo	Forgings	SA-705	XM-25	S45000	H950	≥13	...	...	1 170	1 105	(1) (8)	38
15Cr–6Ni–Cu–Mo	Bar	SA-564	XM-25	S45000	H900	...	...	...	1 240	1 170	(1) (8)	38
15Cr–6Ni–Cu–Mo	Forgings	SA-705	XM-25	S45000	H900	≥13	...	...	1 240	1 170	(1) (8)	38
17Cr–4Ni–4Cu	Bar	SA-564	630	S17400	H1150M	...	...	...	795	515	(6)	288
17Cr–4Ni–4Cu	Forgings	SA-705	630	S17400	H1150M	...	...	...	795	515	(6)	288
17Cr–4Ni–4Cu	Bar	SA-564	630	S17400	H1150	...	...	...	930	725	(6)	288
17Cr–4Ni–4Cu	Forgings	SA-705	630	S17400	H1150	...	...	...	930	725	(6)	288
17Cr–4Ni–4Cu	Bar	SA-564	630	S17400	H1100	...	...	...	965	795	(6)	288
17Cr–4Ni–4Cu	Forgings	SA-705	630	S17400	H1100	...	...	...	965	795	(6)	288
17Cr–4Ni–4Cu	Bar	SA-564	630	S17400	H1075	...	...	...	1 000	860	(6) (8)	288

Table KM-400-2M
High Alloy Steels (Metric) (Cont'd)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, mm	P-No.	Group No.	Specified Min. Tensile, MPa	Specified Min. Yield, MPa	Notes	Max. Design Temp., °C
17Cr–4Ni–4Cu	Forgings	SA-705	630	S17400	H1075	...	...	...	1 000	860	(6) (8)	288
17Cr–4Ni–4Cu	Bar	SA-564	630	S17400	H1025	...	...	...	1 070	1 000	(6) (8) (9) (10)	288
17Cr–4Ni–4Cu	Forgings	SA-705	630	S17400	H1025	...	...	...	1 070	1 000	(6) (8) (9) (10)	288
17Cr–4Ni–4Cu	Forgings	SA-705	630	S17400	H925	...	...	...	1 170	1 070	(1) (6) (8)	288
17Cr–4Ni–4Cu	Forgings	SA-705	630	S17400	H900	...	...	...	1 310	1 170	(1) (6) (8)	288
17Cr–7Ni–1Al	Forgings	SA-705	631	S17700	TH1050	...	...	...	1 170	965	(1) (8)	38
17Cr–7Ni–1Al	Forgings	SA-705	631	S17700	RH950	...	...	...	1 275	1 035	(1) (8)	38
25Ni–15Cr–2Ti	Bolt	SA-453	660	S66286	A	...	...	...	895	585	(2)	482
25Ni–15Cr–2Ti	Bolt	SA-453	660	S66286	B	...	...	...	895	585	(2)	482
25Ni–15Cr–2Ti	Forgings	SA-638	660	S66286	1	...	...	...	895	585	(2)	482
25Ni–15Cr–2Ti	Forgings	SA-638	660	S66286	2	...	...	...	895	585	(2)	482
16Cr–12Ni–2Mo	Forgings	SA-965	F316	S31600	...	...	8	1	485	205	(11)	427
16Cr–12Ni–2Mo	Forgings	SA-965	F316H	S31609	...	...	8	1	485	205	(11)	427
16Cr–12Ni–2Mo	Pipe	SA-312	TP316	S31600	Seamless	...	8	1	515	205	(7) (11)	427
16Cr–12Ni–2Mo	Pipe	SA-312	TP316H	S31609	Seamless	...	8	1	515	205	(7) (11)	427
16Cr–12Ni–2Mo	Bolt	SA-320	B8M	S31600	1	...	...	...	515	205	(11)	427
16Cr–12Ni–2Mo	Bolt	SA-320	B8MA	S31600	1A	...	...	...	515	205	(11)	427
16Cr–12Ni–2Mo	Bar	SA-479	316	S31600	Annealed	...	8	1	515	205	(3) (4) (11)	427
16Cr–12Ni–2Mo	Bar	SA-479	316H	S31609	Annealed	...	8	1	515	205	(3) (11)	427
16Cr–12Ni–2Mo	Bar	SA-276	316	S31600	S	64 < t ≤ 75	...	...	550	380	(2) (11)	316
16Cr–12Ni–2Mo	Bolt	SA-320	B8M	S31600	2	32 < t ≤ 38	...	...	620	345	(5) (11)	38
16Cr–12Ni–2Mo	Bar	SA-276	316	S31600	S	50 < t ≤ 64	...	...	620	450	(2) (11)	316
16Cr–12Ni–2Mo	Bar	SA-276	316	S31600	B	38 < t ≤ 44	...	...	655	310	(2) (11)	316
16Cr–12Ni–2Mo	Bolt	SA-320	B8M	S31600	2	25 < t ≤ 32	...	...	655	450	(5) (11)	38
16Cr–12Ni–2Mo	Bar	SA-276	316	S31600	S	≤50	...	...	655	515	(2) (11)	316
16Cr–12Ni–2Mo	Bar	SA-276	316	S31600	B	32 < t ≤ 38	...	...	690	345	(2) (11)	316
16Cr–12Ni–2Mo	Bolt	SA-320	B8M	S31600	2	19 < t ≤ 25	...	...	690	550	(5) (11)	38
16Cr–12Ni–2Mo	Bar	SA-276	316	S31600	B	25 < t ≤ 32	...	...	725	450	(2) (11)	316

Table KM-400-2M
High Alloy Steels (Metric) (Cont'd)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, mm	P-No.	Group No.	Specified Min. Tensile, MPa	Specified Min. Yield, MPa	Notes	Max. Design Temp., °C
16Cr–12Ni–2Mo	Bolt	SA-320	B8M	S31600	2	≤19	...	...	760	655	(5) (11)	38
16Cr–12Ni–2Mo	Bar	SA-276	316	S31600	B	19 < t ≤ 25	...	...	795	550	(2) (11)	316
16Cr–12Ni–2Mo	Bar	SA-276	316	S31600	B	≤19	...	...	860	690	(2) (11)	316
18Cr–8Ni	Forgings	SA-182	F304	S30400	...	t > 125	8	1	485	205	(11)	427
18Cr–8Ni	Forgings	SA-182	F304	S30400	...	t ≤ 125	8	1	515	205	(11)	427
18Cr–8Ni	Plate	SA-240	304	S30400	...	...	8	1	515	205	(11)	427
18Cr–8Ni	Bolt	SA-320	B8	S30400	1	...	...	...	515	205	(11)	427
18Cr–8Ni	Bolt	SA-320	B8A	S30400	1A	...	...	...	515	205	(11)	427
18Cr–8Ni	Bolt	SA-320	B8	S30400	2	32 < t ≤ 38	...	...	690	345	(5) (11)	38
18Cr–8Ni	Bolt	SA-320	B8	S30400	2	25 < t ≤ 32	...	...	725	450	(5) (11)	38
18Cr–8Ni	Bolt	SA-320	B8	S30400	2	19 < t ≤ 25	...	...	795	550	(5) (11)	38
18Cr–8Ni	Bolt	SA-320	B8	S30400	2	≤19	...	...	860	690	(5) (11)	38
18Cr–8Ni	Forgings	SA-182	F304L	S30403	...	t > 125	8	1	450	170	(11)	427
18Cr–8Ni	Forgings	SA-182	F304L	S30403	...	t ≤ 125	8	1	485	170	(11)	427
18Cr–8Ni	Plate	SA-240	304L	S30403	...	...	8	1	485	170	(11)	427
18Cr–8Ni–S	Bolt	SA-320	B8F	S30300	1	...	...	...	515	205	(11) (12)	427
18Cr–8Ni–S	Bolt	SA-320	B8FA	S30300	1A	...	...	...	515	205	(11) (12)	427
18Cr–8Ni–Se	Bolt	SA-320	B8F	S30323	1	...	...	...	515	205	(11) (12)	427
18Cr–8Ni–Se	Bolt	SA-320	B8FA	S30323	1A	...	...	...	515	205	(11) (12)	427
18Cr–10Ni–Cb	Bolt	SA-320	B8C	S34700	1	...	...	...	515	205	(11)	427
18Cr–10Ni–Cb	Bolt	SA-320	B8CA	S34700	1A	...	...	...	515	205	(11)	427
18Cr–10Ni–Cb	Bolt	SA-320	B8C	S34700	2	32 < t ≤ 38	...	...	690	345	(5) (11)	38
18Cr–10Ni–Cb	Bolt	SA-320	B8C	S34700	2	25 < t ≤ 32	...	...	725	450	(5) (11)	38
18Cr–10Ni–Cb	Bolt	SA-320	B8C	S34700	2	19 < t ≤ 25	...	...	795	550	(5) (11)	38
18Cr–10Ni–Cb	Bolt	SA-320	B8C	S34700	2	≤19	...	...	860	690	(5) (11)	38
18Cr–10Ni–Ti	Bolt	SA-320	B8T	S32100	1	...	...	...	515	205	(11)	427
18Cr–10Ni–Ti	Bolt	SA-320	B8TA	S32100	1A	...	...	...	515	205	(11)	427

Table KM-400-2M
High Alloy Steels (Metric) (Cont'd)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, mm	P-No.	Group No.	Specified Min. Tensile, MPa	Specified Min. Yield, MPa	Notes	Max. Design Temp., °C
18Cr–10Ni–Ti	Bolt	SA-320	B8T	S32100	2	$32 < t \le 38$	...	...	690	345	(5) (11)	38
18Cr–10Ni–Ti	Bolt	SA-320	B8T	S32100	2	$25 < t \le 32$	...	...	725	450	(5) (11)	38
18Cr–10Ni–Ti	Bolt	SA-320	B8T	S32100	2	$19 < t \le 25$	...	...	795	550	(5) (11)	38
18Cr–10Ni–Ti	Bolt	SA-320	B8T	S32100	2	≤19	...	...	860	690	(5) (11)	38

GENERAL NOTE: The P-Numbers and Group Numbers listed for some of these materials are for information only. For welded construction in this Division, Section IX, Table QW/QB-422 shall be consulted for P-Numbers and Group Numbers. When there is a conflict in P-Number or Group Number, the numbers in Section IX govern.

NOTES:

(1) This material is permitted only when used as an inner layer in a vessel whose design meets the leak-before-burst criteria of KD-141.

(2) No welding is permitted on this material.

(3) A tensile strength of 485 MPa minimum is permitted for extruded shapes.

(4) Yield strength values listed in Section II, Part D, Subpart 1, Table Y-1 are for material in the annealed condition.

(5) For all design temperatures, the maximum hardness shall be Rockwell C35 immediately under thread roots. The hardness shall be taken on a flat area at least 3 mm across, prepared by removing threads; no more material than necessary shall be removed to prepare the flat area. Hardness determinations shall be made at the same frequency as tensile tests.

(6) This material has reduced toughness at room temperature after exposure at high temperature. The degree of embrittlement depends on composition, heat treatment, time, and temperature. The lowest temperature of concern is about 288°C. See Section II, Part D, Nonmandatory Appendix A, A-207.

(7) This material shall only be used in the seamless condition.

(8) Caution is advised when using these materials as they are more susceptible than lower strength materials to environmental stress corrosion cracking and/or embrittlement due to hydrogen exposure. This susceptibility increases as yield strength increases. The designer shall consider these effects and their influence on the vessel. See Section II, Part D, Nonmandatory Appendix A, A-701 and A-702.

(9) These materials shall not be used for applications when the material, when loaded, is in contact with water or an aqueous environment.

(a) This restriction does not apply to components that are in hydrostatic compression during all loading cycles. Hydrostatic compression is assumed to exist if the sum of the three principal stresses is negative (compressive) at all locations within the component.

(b) This restriction does not apply to inner layers in a vessel whose design meets the leak-before-burst criteria of KD-141.

(10) The actual measured yield strength for these materials shall not be greater than 172 MPa above the minimum specified value.

(11) This material is susceptible to chloride stress corrosion cracking. See Section II, Part D, Nonmandatory Appendix A, A-701.

(12) This free-machining material has lower corrosion resistance compared with its non-free-machining equivalent.

Table KM-400-3
Nickel and Nickel Alloys

(25)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, in.	P-No.	Group No.	Specified Min. Tensile, ksi	Specified Min. Yield, ksi	Notes	Max. Design Temp., °F
67Ni–30Cu	Bar	SB-164	...	N04400	Annealed	...	42	...	70	25	...	800
67Ni–30Cu	Pipe	SB-165	...	N04400	Annealed	>5 O.D.	42	...	70	25	...	800
67Ni–30Cu	Forgings	SB-564	...	N04400	Annealed	...	42	...	70	25	...	800
67Ni–30Cu	Pipe	SB-165	...	N04400	Annealed	≤5 O.D.	42	...	70	28	...	800
67Ni–30Cu	Rounds	SB-164	...	N04400	Hot worked	$12 < t \leq 14$	42	...	75	40	...	800
67Ni–30Cu	Rounds	SB-164	...	N04400	Hot worked	≤12	42	...	80	40	...	800
67Ni–30Cu	Rounds	SB-164	...	N04400	CW & SR	$<1/2$	42	...	84	50	...	800
67Ni–30Cu	Rounds	SB-164	...	N04400	CW & SR	$3 1/2 < t \leq 4$	42	...	84	55	...	800
67Ni–30Cu	Pipe	SB-165	...	N04400	Stress rel.	...	42	...	85	55	...	800
67Ni–30Cu	Rounds	SB-164	...	N04400	CW & SR	$1/2 \leq t \leq 3 1/2$	42	...	87	60	...	800
67Ni–30Cu	Rounds	SB-164	...	N04400	Cold worked	$<1/2$	42	...	110	85	...	800
72Ni–15Cr–8Fe	Pipe	SB-167	...	N06600	Annealed	>5 O.D.	43	...	80	30	...	800
72Ni–15Cr–8Fe	Bar	SB-166	...	N06600	Annealed	...	43	...	80	35	...	800
72Ni–15Cr–8Fe	Pipe	SB-167	...	N06600	Annealed	≤5 O.D.	43	...	80	35	...	800
72Ni–15Cr–8Fe	Forgings	SB-564	...	N06600	Annealed	...	43	...	80	35	...	800
72Ni–15Cr–8Fe	Rounds	SB-166	...	N06600	Hot worked	>3	43	...	85	35	...	800
72Ni–15Cr–8Fe	Rounds	SB-166	...	N06600	Hot worked	$1/2 < t \leq 3$	43	...	90	40	...	800
72Ni–15Cr–8Fe	Rounds	SB-166	...	N06600	Hot worked	$1/4 \leq t \leq 1/2$	43	...	95	45	...	800
60Ni–22Cr–9Mo–3.5Cb	Bar, rod	SB-446	1	N06625	Annealed	$4 < t \leq 10$	43	...	110	50	...	800
60Ni–22Cr–9Mo–3.5Cb	Forgings	SB-564	...	N06625	Annealed	$4 < t \leq 10$	43	...	110	50	...	800
60Ni–22Cr–9Mo–3.5Cb	Pipe	SB-444	1	N06625	Annealed	...	43	...	120	60	...	800
60Ni–22Cr–9Mo–3.5Cb	Bar, rod	SB-446	1	N06625	Annealed	≤4	43	...	120	60	...	800
60Ni–22Cr–9Mo–3.5Cb	Forgings	SB-564	...	N06625	Annealed	≤4	43	...	120	60	...	800
42Fe–33Ni–21Cr	Bar	SB-408	...	N08800	Annealed	...	45	...	75	30	...	800
42Fe–33Ni–21Cr	Plate	SB-409	...	N08800	Annealed	...	45	...	75	30	...	800
42Fe–33Ni–21Cr	Forgings	SB-564	...	N08800	Annealed	...	45	...	75	30	...	800
42Fe–33Ni–21Cr	Pipe	SB-407	...	N08800	CW/ann.	...	45	...	75	30	...	800
42Fe–33Ni–21Cr	Bar	SB-408	...	N08810	Annealed	...	45	...	65	25	...	800

Table KM-400-3
Nickel and Nickel Alloys (Cont'd)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, in.	P-No.	Group No.	Specified Min. Tensile, ksi	Specified Min. Yield, ksi	Notes	Max. Design Temp., °F
42Fe–33Ni–21Cr	Plate	SB-409	...	N08810	Annealed	...	45	...	65	25	...	800
42Fe–33Ni–21Cr	Forgings	SB-564	...	N08810	Annealed	...	45	...	65	25	...	800
54Ni–16Mo–15Cr	Bar	SB-574	...	N10276	Solution ann.	...	44	...	100	41	...	800

GENERAL NOTES:

(a) The following abbreviations are used:
ann. = annealed
CW = cold worked
O.D. = outside diameter
rel. = relieved
SR = stress relieved

(b) The P-Numbers and Group Numbers listed for some of these materials are for information only. For welded construction in this Division, Section IX, Table QW/QB-422 shall be consulted for P-Numbers and Group Numbers. When there is a conflict in P-Number or Group Number, the numbers in Section IX govern.

Table KM-400-3M
Nickel and Nickel Alloys (Metric)

(25)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, mm	P-No.	Group No.	Specified Min. Tensile, MPa	Specified Min. Yield, MPa	Notes	Max. Design Temp., °C
67Ni–30Cu	Bar	SB-164	...	N04400	Annealed	...	42	...	485	170	...	427
67Ni–30Cu	Pipe	SB-165	...	N04400	Annealed	>125 O.D.	42	...	485	170	...	427
67Ni–30Cu	Forgings	SB-564	...	N04400	Annealed	...	42	...	485	170	...	427
67Ni–30Cu	Pipe	SB-165	...	N04400	Annealed	≤125 O.D.	42	...	485	195	...	427
67Ni–30Cu	Rounds	SB-164	...	N04400	Hot worked	$300 < t \leq 350$	42	...	515	275	...	427
67Ni–30Cu	Rounds	SB-164	...	N04400	Hot worked	≤300	42	...	550	275	...	427
67Ni–30Cu	Rounds	SB-164	...	N04400	CW & SR	<13	42	...	580	345	...	427
67Ni–30Cu	Rounds	SB-164	...	N04400	CW & SR	$89 < t \leq 100$	42	...	580	380	...	427
67Ni–30Cu	Pipe	SB-165	...	N04400	Stress rel.	...	42	...	585	380	...	427
67Ni–30Cu	Rounds	SB-164	...	N04400	CW & SR	$13 < t \leq 89$	42	...	600	415	...	427
67Ni–30Cu	Rounds	SB-164	...	N04400	Cold worked	<13	42	...	760	585	...	427
72Ni–15Cr–8Fe	Pipe	SB-167	...	N06600	Annealed	>125 O.D.	43	...	550	205	...	427
72Ni–15Cr–8Fe	Bar	SB-166	...	N06600	Annealed	...	43	...	550	240	...	427
72Ni–15Cr–8Fe	Pipe	SB-167	...	N06600	Annealed	≤125 O.D.	43	...	550	240	...	427
72Ni–15Cr–8Fe	Forgings	SB-564	...	N06600	Annealed	...	43	...	550	240	...	427
72Ni–15Cr–8Fe	Rounds	SB-166	...	N06600	Hot worked	>75	43	...	585	240	...	427
72Ni–15Cr–8Fe	Rounds	SB-166	...	N06600	Hot worked	$13 < t \leq 75$	43	...	620	275	...	427
72Ni–15Cr–8Fe	Rounds	SB-166	...	N06600	Hot worked	$6 < t \leq 13$	43	...	655	310	...	427
60Ni–22Cr–9Mo–3.5Cb	Bar, rod	SB-446	1	N06625	Annealed	$100 < t \leq 250$	43	...	760	345	...	427
60Ni–22Cr–9Mo–3.5Cb	Forgings	SB-564	...	N06625	Annealed	$100 < t \leq 250$	43	...	760	345	...	427
60Ni–22Cr–9Mo–3.5Cb	Pipe	SB-444	1	N06625	Annealed	...	43	...	825	415	...	427
60Ni–22Cr–9Mo–3.5Cb	Bar, rod	SB-446	1	N06625	Annealed	≤100	43	...	825	415	...	427
60Ni–22Cr–9Mo–3.5Cb	Forgings	SB-564	...	N06625	Annealed	≤100	43	...	825	415	...	427
42Fe–33Ni–21Cr	Bar	SB-408	...	N08800	Annealed	...	45	...	515	205	...	427
42Fe–33Ni–21Cr	Plate	SB-409	...	N08800	Annealed	...	45	...	515	205	...	427
42Fe–33Ni–21Cr	Forgings	SB-564	...	N08800	Annealed	...	45	...	515	205	...	427
42Fe–33Ni–21Cr	Pipe	SB-407	...	N08800	CW/ann.	...	45	...	515	205	...	427
42Fe–33Ni–21Cr	Bar	SB-408	...	N08810	Annealed	...	45	...	450	170	...	427

Table KM-400-3M
Nickel and Nickel Alloys (Metric) (Cont'd)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, mm	P-No.	Group No.	Specified Min. Tensile, MPa	Specified Min. Yield, MPa	Notes	Max. Design Temp., °C
42Fe–33Ni–21Cr	Plate	SB-409	...	N08810	Annealed	...	45	...	450	170	...	427
42Fe–33Ni–21Cr	Forgings	SB-564	...	N08810	Annealed	...	45	...	450	170	...	427
54Ni-16Mo-15Cr	Bar	SB-574	...	N10276	Solution ann.	...	44	...	690	285	...	427

GENERAL NOTES:

(a) The following abbreviations are used:
ann. = annealed
CW = cold worked
O.D. = outside diameter
rel. = relieved
SR = stress relieved

(b) The P-Numbers and Group Numbers listed for some of these materials are for information only. For welded construction in this Division, Section IX, Table QW/QB-422 shall be consulted for P-Numbers and Group Numbers. When there is a conflict in P-Number or Group Number, the numbers in Section IX govern.

Table KM-400-4
Aluminum Alloys

(25)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, in.	Specified Min. Tensile, ksi	Specified Min. Yield, ksi	Notes	Max. Design Temp., °F
Al-Mg-Si-Cu	Plate, sheet	SB-209	...	A96061	T6	0.051–0.249	42	35	(1)(2)	225
Al-Mg-Si-Cu	Plate, sheet	SB-209	...	A96061	T651	0.250–3.000	42	35	(1)(2)	225
Al-Mg-Si-Cu	Drawn smls. Tube	SB-210	...	A96061	T6	0.025–0.500	42	35	(1)(2)	225
Al-Mg-Si-Cu	Bar, rod, shapes	SB-221	...	A96061	T6	...	38	35	(1)(2)	225
Al-Mg-Si-Cu	Smls. extr. Tube	SB-241	...	A96061	T6	...	38	35	(1)(2)	225
Al-Mg-Si-Cu	Shapes	SB-308	...	A96061	T6	...	38	35	(1)(2)	225

NOTES:
(1) Welding and thermal cutting are not permitted.
(2) The material thickness shall not exceed 3 in.

(25)

Table KM-400-4M
Aluminum Alloys (Metric)

Nominal Composition	Product Form	Spec. No.	Type/ Grade	UNS No.	Class/ Condition/ Temper	Thickness, mm	Specified Min. Tensile, MPa	Specified Min. Yield, MPa	Notes	Max. Design Temp., °C
Al-Mg-Si-Cu	Plate, sheet	SB-209	...	A96061	T6	1.30–6.32	290	240	(1)(2)	107
Al-Mg-Si-Cu	Plate, sheet	SB-209	...	A96061	T651	6.35–75.0	290	240	(1)(2)	107
Al-Mg-Si-Cu	Drawn smls. Tube	SB-210	...	A96061	T6	0.64–12.7	290	240	(1)(2)	107
Al-Mg-Si-Cu	Bar, rod, shapes	SB-221	...	A96061	T6	...	260	240	(1)(2)	107
Al-Mg-Si-Cu	Smls. extr. Tube	SB-241	...	A96061	T6	...	260	240	(1)(2)	107
Al-Mg-Si-Cu	Shapes	SB-308	...	A96061	T6	...	260	240	(1)(2)	107

NOTES:
(1) Welding and thermal cutting are not permitted.
(2) The material thickness shall not exceed 75 mm.

ARTICLE KM-5
REQUIREMENTS FOR LAMINATE MATERIALS

Material requirements for laminate materials are found in Section X, Mandatory Appendix 10, 10-300.

ARTICLE KM-6
ANALYTICAL MATERIAL MODELS

KM-600 SCOPE

This Article contains material models available for use in analytical methods throughout this Division.

(25) KM-610 IDEALLY ELASTIC–PLASTIC (NON-STRAIN HARDENING) MATERIAL MODEL

A small amount of strain hardening may be used if necessary to stabilize the solution in the finite element analysis model. A linear stress–strain relationship shall be used. The increase in strength shall not exceed 5% at a plastic strain of 20%.

KM-620 ELASTIC–PLASTIC STRESS–STRAIN CURVE MODEL

The following procedure may be used to determine the true stress–strain curve model for use in a nonlinear assessment when the strain hardening characteristics of the material are to be considered. The nomenclature used for this procedure is given in Mandatory Appendix 1.

$$\varepsilon_{ts} = \frac{\sigma_t}{E_y} + \gamma_1 + \gamma_2 \quad \text{(KM-620.1)}$$

When $\gamma_1 + \gamma_2 \le \varepsilon_p$, eq. (KM-620.1) shall be reduced to

$$\varepsilon_{ts} = \sigma_t / E_y \quad \text{(KM-620.2)}$$

where

$$\gamma_1 = \frac{\varepsilon_1}{2}[1.0 - \tanh(H)] \quad \text{(KM-620.3)}$$

$$\gamma_2 = \frac{\varepsilon_2}{2}[1.0 + \tanh(H)] \quad \text{(KM-620.4)}$$

$$\varepsilon_1 = \left(\frac{\sigma_t}{A_1}\right)^{\frac{1}{m_1}} \quad \text{(KM-620.5)}$$

$$A_1 = \frac{\sigma_{ys}\left(1 + \varepsilon_{ys}\right)}{\left[\ln\left(1 + \varepsilon_{ys}\right)\right]^{m_1}} \quad \text{(KM-620.6)}$$

$$m_1 = \frac{\ln(R) + (\varepsilon_p - \varepsilon_{ys})}{\ln\left[\frac{\ln\left(1 + \varepsilon_p\right)}{\ln\left(1 + \varepsilon_{ys}\right)}\right]} \quad \text{(KM-620.7)}$$

$$\varepsilon_2 = \left(\frac{\sigma_t}{A_2}\right)^{\frac{1}{m_2}} \quad \text{(KM-620.8)}$$

$$A_2 = \frac{\sigma_{uts}\exp\left(m_2\right)}{m_2^{m_2}} \quad \text{(KM-620.9)}$$

$$H = \frac{2\left(\sigma_t - \left[\sigma_{ys} + K(\sigma_{uts} - \sigma_{ys})\right]\right)}{K(\sigma_{uts} - \sigma_{ys})} \quad \text{(KM-620.10)}$$

$$R = \frac{\sigma_{ys}}{\sigma_{uts}} \quad \text{(KM-620.11)}$$

$$\varepsilon_{ys} = 0.002 \quad \text{(KM-620.12)}$$

$$K = 1.5R^{1.5} - 0.5R^{2.5} - R^{3.5} \quad \text{(KM-620.13)}$$

and parameters m_2 and ε_p are given in Table KM-620.

The development of the stress–strain curve should be limited to a value of true ultimate tensile stress at true ultimate tensile strain. The stress–strain curve beyond this point should be perfectly plastic. The value of true ultimate tensile stress at true ultimate tensile strain is calculated as follows:

$$\sigma_{uts,\,t} = \sigma_{uts}\exp\left[m_2\right] \quad \text{(KM-620.14)}$$

KM-630 CYCLIC STRESS–STRAIN CURVE

The cyclic stress–strain curve of a material (i.e., strain amplitude versus stress amplitude) may be represented by eq. (KM-630.1). The material constants for this model are provided in Table KM-630 (Table KM-630M).

$$\varepsilon_{ta} = \frac{\sigma_a}{E_y} + \left[\frac{\sigma_a}{K_{css}}\right]^{\frac{1}{n_{css}}} \quad \text{(KM-630.1)}$$

The hysteresis loop stress–strain curve of a material (i.e., strain range versus stress range) obtained by scaling the cyclic stress–strain curve by a factor of two is represented by eq. (KM-630.2). The material constants provided in Table KM-630 (Table KM-630M) are also used in this equation.

$$\varepsilon_{tr} = \frac{\sigma_r}{E_y} + 2\left[\frac{\sigma_r}{2K_{css}}\right]^{\frac{1}{n_{css}}} \quad \text{(KM-630.2)}$$

Table KM-620
Tabular Values for Coefficients

Material	Maximum Temperature	m_2	m_3	m_4	m_5	ϵ_p
Ferritic steel [Note (1)]	900°F (480°C)	0.60 (1.00 − R)	2 In [1 + (El/100)]	In [100/(100 − RA)]	2.2	2.0 E−5
Austenitic stainless steel and nickel-based alloys	900°F (480°C)	0.75 (1.00 − R)	3 In [1 + (El/100)]	In [100/(100 − RA)]	0.6	2.0 E−5
Duplex stainless steel	900°F (480°C)	0.70 (0.95 − R)	2 In [1 + (El/100)]	In [100/(100 − RA)]	2.2	2.0 E−5
Precipitation hardening, nickel based	1,000°F (540°C)	1.09 (0.93 − R)	In [1 + (El/100)]	In [100/(100 − RA)]	2.2	2.0 E−5
Aluminum	250°F (120°C)	0.52 (0.98 − R)	1.3 In [1 + (El/100)]	In [100/(100 − RA)]	2.2	5.0 E−6
Copper	150°F (65°C)	0.50 (1.00 − R)	2 In [1 + (El/100)]	In [100/(100 − RA)]	2.2	5.0 E−6
Titanium and zirconium	500°F (260°C)	0.50 (0.98 − R)	1.3 In [1 + (El/100)]	In [100/(100 − RA)]	2.2	2.0 E−5

NOTE: (1) Ferritic steel includes carbon, low alloy, and alloy steels, and ferritic, martensitic, and iron-based age-hardening stainless steels.

Table KM-630
Cyclic Stress–Strain Curve Data

Material Description	Temperature, °F	n_{css}	K_{css}, ksi
Carbon steel (0.75 in.–base metal)	70	0.128	109.8
	390	0.134	105.6
	570	0.093	107.5
	750	0.109	96.6
Carbon steel (0.75 in.–weld metal)	70	0.110	100.8
	390	0.118	99.6
	570	0.066	100.8
	750	0.067	79.6
Carbon steel (2 in.–base metal)	70	0.126	100.5
	390	0.113	92.2
	570	0.082	107.5
	750	0.101	93.3
Carbon steel (4 in.–base metal)	70	0.137	111.0
	390	0.156	115.7
	570	0.100	108.5
	750	0.112	96.9
1Cr–½Mo (0.75 in.–base metal)	70	0.116	95.7
	390	0.126	95.1
	570	0.094	90.4
	750	0.087	90.8
1Cr–½Mo (0.75 in.–weld metal)	70	0.088	96.9
	390	0.114	102.7
	570	0.085	99.1
	750	0.076	86.9
1Cr–½Mo (2 in.–base metal)	70	0.105	92.5
	390	0.133	99.2
	570	0.086	88.0
	750	0.079	83.7
1Cr–1Mo–¼V	70	0.128	156.9
	750	0.128	132.3
	930	0.143	118.2
	1,020	0.133	100.5
	1,110	0.153	80.6
2¼Cr–1Mo	70	0.100	115.5
	570	0.109	107.5
	750	0.096	105.9
	930	0.105	94.6
	1,110	0.082	62.1

Table KM-630
Cyclic Stress–Strain Curve Data (Cont'd)

Material Description	Temperature, °F	n_{css}	K_{css}, ksi
9Cr–1Mo	70	0.177	141.4
	930	0.132	100.5
	1,020	0.142	88.3
	1,110	0.121	64.3
	1,200	0.125	49.7
Type 304	70	0.171	178.0
	750	0.095	85.6
	930	0.085	79.8
	1,110	0.090	65.3
	1,290	0.094	44.4
Type 304 (Annealed)	70	0.334	330.0
800H	70	0.070	91.5
	930	0.085	110.5
	1,110	0.088	105.7
	1,290	0.092	80.2
	1,470	0.080	45.7
Aluminum (Al–4.5Zn–0.6Mn)	70	0.058	65.7
Aluminum (Al–4.5Zn–1.5Mg)	70	0.047	74.1
Aluminum (1100–T6)	70	0.144	22.3
Aluminum (2014–T6)	70	0.132	139.7
Aluminum (5086)	70	0.139	96.0
Aluminum (6009–T4)	70	0.124	83.7
Aluminum (6009–T6)	70	0.128	91.8
Copper	70	0.263	99.1

Table KM-630M
Cyclic Stress–Strain Curve Data

Material Description	Temperature, °C	n_{css}	K_{CSS}, MPa
Carbon steel (20 mm-base metal)	20	0.128	757
	200	0.134	728
	300	0.093	741
	400	0.109	666
Carbon steel (20 mm-weld metal)	20	0.110	695
	200	0.118	687
	300	0.066	695
	400	0.067	549
Carbon steel (50 mm-base metal)	20	0.126	693
	200	0.113	636
	300	0.082	741
	400	0.101	643
Carbon steel (100 mm-base metal)	20	0.137	765
	200	0.156	798
	300	0.100	748
	400	0.112	668
1Cr–½Mo (20 mm-base metal)	20	0.116	660
	200	0.126	656
	300	0.094	623
	400	0.087	626
1Cr–½Mo (20 mm-weld metal)	20	0.088	668
	200	0.114	708
	300	0.085	683
	400	0.076	599
1Cr–½Mo (50 mm-base metal)	20	0.105	638
	200	0.133	684
	300	0.086	607
	400	0.079	577
1Cr–1Mo–¼V	20	0.128	1 082
	400	0.128	912
	500	0.143	815
	550	0.133	693
	600	0.153	556
2-¼Cr–1Mo	20	0.100	796
	300	0.109	741
	400	0.096	730
	500	0.105	652
	600	0.082	428

Table KM-630M
Cyclic Stress–Strain Curve Data (Cont'd)

Material Description	Temperature, °C	n_{css}	K_{CSS}, MPa
9Cr–1Mo	20	0.117	975
	500	0.132	693
	550	0.142	609
	600	0.121	443
	650	0.125	343
Type 304	20	0.171	1 227
	400	0.095	590
	500	0.085	550
	600	0.090	450
	700	0.094	306
Type 304 (Annealed)	20	0.334	2 275
800H	20	0.070	631
	500	0.085	762
	600	0.088	729
	700	0.092	553
	800	0.080	315
Aluminum (Al–4.5Zn–0.6Mn)	20	0.058	453
Aluminum (Al–4.5Zn–1.5Mg)	20	0.047	511
Aluminum (1100-T6)	20	0.144	154
Aluminum (2014-T6)	20	0.132	963
Aluminum (5086)	20	0.139	662
Aluminum (6009-T4)	20	0.124	577
Aluminum (6009-T6)	20	0.128	633
Copper	20	0.263	683

Table KM-630.1
Coefficients for the Welded Joint Fatigue Curves

	All Alloys in KD-371 Except Aluminum		Aluminum Alloys	
Statistical Basis	**C**	**h**	**C**	**h**
Mean Curve	1,408.7	0.31950	247.04	0.27712
Upper 68% Prediction Interval (+1σ)	1,688.3	0.31950	303.45	0.27712
Lower 68% Prediction Interval (–1σ)	1,175.4	0.31950	201.12	0.27712
Upper 95% Prediction Interval (+2σ)	2,023.4	0.31950	372.73	0.27712
Lower 95% Prediction Interval (–2σ)	980.8	0.31950	163.73	0.27712
Upper 99% Prediction Interval (+3σ)	2,424.9	0.31950	457.84	0.27712
Lower 99% Prediction Interval (–3σ)	818.3	0.31950	133.29	0.27712

GENERAL NOTE: In U.S. Customary units, the equivalent structural stress range parameter, $\Delta S_{ess,k}$, in KD-372 and the structural stress effective thickness, t_{ess}, defined in KD-340 are in ksi/(inches)$^{(2-m_{ss})/2m_{ss}}$ and inches, respectively. The parameter m_{ss} is defined in KD-340.

Table KM-630.1M
Coefficients for the Welded Joint Fatigue Curves

	All Alloys in KD-371 Except Aluminum		Aluminum Alloys	
Statistical Basis	**C**	**h**	**C**	**h**
Mean Curve	19 930.2	0.31950	3 495.13	0.27712
Upper 68% Prediction Interval (+1σ)	23 885.8	0.31950	4 293.19	0.27712
Lower 68% Prediction Interval (-1σ)	16 629.7	0.31950	2 845.42	0.27712
Upper 95% Prediction Interval (+2σ)	28 626.5	0.31950	5 273.48	0.27712
Lower 95% Prediction Interval (-2σ)	13 875.7	0.31950	2 316.48	0.27712
Upper 99% Prediction Interval (+3σ)	34 308.1	0.31950	6 477.60	0.27712
Lower 99% Prediction Interval (-3σ)	11 577.9	0.31950	1 885.87	0.27712

GENERAL NOTE: In SI units, the equivalent structural stress range parameter, $\Delta S_{ess,k}$, in KD-372 and the structural stress effective thickness, t_{ess}, defined in KD-340 are in MPa/(mm)$^{(2-m_{ss})/2m_{ss}}$ and mm, respectively. The parameter m_{ss} is defined in KD-340.

ARTICLE KM-7
RULES FOR COVERS ON IMPULSIVELY LOADED VESSELS

KM-700 GENERAL

A cover, or inserts within it, used for imaging purposes on impulsively loaded vessels, may consist of two layers in series as follows:

– an inner impulse and debris ejection protection layer
– an outer structural (pressure retaining) layer.

The outer structural layer shall fully resist the QSP and the impulse and debris ejection loadings imparted both through the vessel structure and through the inner layer of the cover. It shall meet all the requirements of this Division, and be made of materials listed in Part KM or certified by the Manufacturer as permitted by KM-100(c)(2). Materials not listed in Part KM may be used for the inner layer provided

(a) its strength and impact properties have been verified independently of the material supplier to ASTM E8 and ASTM E23, respectively, and the finished product has been surface inspected to ASME Section V, Article 6 or Article 7 requirements and volumetrically inspected to ASME Section V, Article 5 requirements, or

(b) the component has been verified using the methods of Article KD-12 with an impulse of at least 1.732 times the design basis impulse, the impulse may be reduced to 125% of the design basis impulse when external secondary containment or a barrier for personnel protection is present, or

(c) it may be shown that the failure of the inner layer does not result in failure of the outer layer.

A single combined layer may be used if it meets all the requirements of this Division.

ARTICLE KM-8
(25) RULES FOR CASTINGS FOR IMPULSIVELY LOADED VESSELS

KM-800 GENERAL

High-strength low-alloy steel castings used in this Division for impulsively loaded vessels are listed in Table KM-400-1 (Table KM-400-1M) with the following additional requirements:

(a) The liquid steel shall be degassed to achieve a hydrogen content of less than 3 ppm.

(b) Castings shall be made from a single heat and shall not exceed a final mass of 44,000 lb (20 000 kg). The maximum final diameter shall be less than 8 ft (2.4 m).

(c) Casting design shall ensure directional solidification of all casting sections back to the feeder heads. Feeder head sizes shall be calculated to ensure complete feeding of the casting during solidification. Machining allowances shall not exceed 1 in. (25 mm) except where this conflicts with these casting design requirements.

(d) The ladle composition shall be confirmed before pouring and the values reported in the Manufacturer's Data Report.

(e) Castings shall be allowed to cool below the transformation range directly after pouring and solidification, before they are reheated for normalizing.

(f) After annealing and before other heat treatment, the casting may be hot isostatically pressed at 14.5 ksi ± 0.3 ksi (1 000 bar ± 20 bar) and 2,085°F ± 18°F (1 140°C ± 10°C).

(g) Furnace temperature for heat treating shall be controlled by pyrometers, and the recorded temperature during heat treatment shall be included in the Manufacturer's Data Report.

(h) Castings should be cast oversized and machined to final dimensions to remove surface imperfections. The maximum final wall thickness shall not exceed 14 in. (360 mm).

(i) Full-size Charpy V notch specimens may be taken in either the longitudinal or circumferential direction. The minimum required energy values are given in Table KM-800-1. See KM-260 for possible retests.

(j) K_{Jc} determined according to ASTM E1820 at $T/4$ (see KM-211.5) and at the minimum operating temperature shall exceed 137 ksi $in.^{1/2}$ (150 MPa $m^{1/2}$). The validity requirement on crack extension (see ASTM E1820, para. 9.1.5.1) may be waived.

Table KM-800-1
Minimum Required Charpy V-Notch Impact Values

Number of Specimens	Energy, ft-lbf (J)
Average for 3	48 (65)
Minimum for 1	44 (60)

PART KD
DESIGN REQUIREMENTS

ARTICLE KD-1
GENERAL

KD-100 SCOPE

(a) The requirements of this Part KD provide specific design criteria for some commonly used pressure vessel shapes under pressure loadings and, within specified limits, criteria or guidance for treatment of other loadings. This Part does not contain rules to cover all details of design.

(b) A complete analysis, including a fatigue or fracture mechanics analysis, of all structural parts of the vessel shall be performed in accordance with applicable Articles of this Part. All of the loadings specified in the User's Design Specification (see KG-311) and all stresses introduced by the fabrication processing, autofrettage, temperature gradients, etc., shall be considered. This analysis shall be documented in the Manufacturer's Design Report. See KG-323.

KD-101 MATERIALS AND COMBINATIONS OF MATERIALS

A vessel shall be designed for and constructed of materials permitted in Part KM. Any combination of those materials in Part KM may be used, provided the applicable rules are followed and the requirements of Section IX for welding dissimilar metals are met, when welding is involved.

Material design values such as moduli of elasticity, coefficients of thermal expansion, yield and tensile strength values, and other material properties are given in Section II, Part D. With the publication of the 2004 Edition, Section II Part D is published as two separate publications. One publication contains values only in U.S. Customary units and the other contains values only in SI units. The selection of the version to use is dependent on the set of units selected for construction.

KD-102 TYPES OF CONSTRUCTION

Article KD-2 contains rules for the basic design of all pressure vessels within the scope of this Division. Article KD-2 also provides rules for designing nonwelded vessels that are constructed of forged or otherwise wrought material machined to its final configuration.

For openings, closures, and other types of construction, such as multiple-wall and layered, wire-wound, or welded, these rules shall be supplemented by those given in the appropriate Articles, i.e., Articles KD-6, KD-8, KD-9, and KD-11.

KD-103 PROTECTIVE LINERS

A protective liner is the innermost layer of a pressure vessel, whose function is to protect the surface of load-carrying members against chemical and mechanical damage. It can be of any suitable material, and this material need not be listed in Part KM. Credit shall not be given for the thickness of a protective liner in the static strength and primary stress calculations, but the effects of a liner shall be considered in the secondary stress and number of design cyclic loading calculations. The designer shall consider the consequences of the liner failure in order to preserve the integrity of the pressure boundary.

KD-104 CORROSION ALLOWANCE IN DESIGN FORMULAS

All dimensions used in equations, text, tables, and figures throughout this Division shall be in the corroded condition, with the exception of the calculations in Article KD-5.

KD-110 LOADINGS

Some of the loadings which shall be considered are as follows (see KG-311.8):

(a) internal and external pressure, at coincident temperature

(b) service temperature conditions that produce thermal stresses, such as those due to thermal gradients or differential thermal expansion

(c) weight of vessel and normal contents under operating or test conditions

(d) superimposed loads caused by other vessels, piping, or operating equipment

(e) wind loads and earthquake loads

(f) reactions of supporting lugs, rings, saddles, or other types of vessel supports

(g) impact loads, including rapidly fluctuating pressures and reaction forces from relief devices

(h) loadings resulting from expansion or contraction of attached piping or other parts

(i) residual stresses, introduced at fabrication, e.g., by autofrettage, hydrostatic test, shrink fit, prestressed wire winding, rolling, forming, welding, thermal treatments, and surface treatment such as shot peening

(j) the effect of fluid flow rates, density, jet impingement streams, inlet and outlet temperatures, on loadings

(k) acceleration loads on the vessel or its contents due to motion of the structure to which the vessel is fastened

KD-111 LIMITS OF TEST PRESSURE

The lower and upper limits on test pressure are specified in Article KT-3.

KD-112 BASIS FOR DESIGN TEMPERATURE

(a) When the occurrence of different material temperatures during operation can be definitely predicted for different axial zones of the vessel, the design of the different zones may be based on their predicted temperatures.

When the vessel is expected to operate at more than one temperature and under different pressure conditions, all significant sets of temperature and coincident pressure shall be considered.

The material temperature under steady operating conditions may vary significantly through the thickness. The temperature used in the design shall be not less than the mean temperature through the thickness of the part being examined under the set of conditions considered. If necessary, the material temperature shall be determined by computations or by measurements from equipment in service under equivalent operating conditions. However, in no case shall the temperature at any point in the material or the design temperature exceed the maximum temperature in Tables KM-400-1 through KM-400-3 (Tables KM-400-1M through KM-400-3M) for the material in question or exceed the temperature limitations specified elsewhere in this Division, except as provided in KD-113.

In vessels exposed to repeated fluctuations of temperature in normal operation, the design shall be based on the highest fluid temperature, unless the designer can demonstrate by calculation or experiment that a lower temperature can be justified.

For determination of the fracture toughness to be used in the fracture mechanics evaluation, the minimum design metal temperature (MDMT) at the point of interest shall be used. See KG-311.4(d) for a definition of MDMT and for service restriction when the vessel temperature is below MDMT.

The lower limit of the material temperature during the hydrostatic test is given in KT-320.

(b) It is the responsibility of the designer to specify the anticipated temperature of the overpressure relief device.

KD-113 UPSET CONDITIONS

Sudden process upsets, which occur infrequently, can cause local increases or decreases in material surface temperature. For the purpose of the static pressure design requirements, no credit shall be taken for that portion of the wall thickness which is predicted to exceed the maximum temperature permitted in the material's yield strength table. The minimum metal surface temperature that occurs during sudden cooling shall be considered in the fracture toughness evaluations.

A complete stress and fracture mechanics analysis is required for any credible upset condition.

KD-114 ENVIRONMENTAL EFFECTS

The designer shall consider environmental effects, such as corrosion, erosion, and stress corrosion cracking, and their influence on the material thickness, fatigue, and fracture behavior.

KD-120 DESIGN BASIS (25)

The design of the vessel is based on the requirement of having an adequate design margin against relevant failure modes under the stated conditions. The fulfillment of this requirement shall be demonstrated by calculations based on the following:

(a) tensile strength, S_u (see Part KM and Section II, Part D)

(b) yield strength S_y (see Part KM and Section II, Part D)

(c) fracture toughness K_{Ic} (see Article KD-4)

(d) fatigue crack growth constants C and m (see Article KD-4)

(e) fatigue strength S_a (see Article KD-3)

(f) mill undertolerance on material thickness

(g) corrosion/erosion allowances [see KG-311.7(b)]

KD-121 RELEVANT FAILURE MODES

Some of the relevant failure modes are the following:

(a) plastic collapse

(b) through the thickness yielding

(c) local yielding of a magnitude which could produce excessive distortion and unacceptable transfer of load to other portions of the structure, or leakage

(d) leak caused by stable fatigue crack propagation through the wall (leak-before-burst)

(e) unstable crack growth, i.e., fast fracture

(f) buckling (see KD-233)

KD-130 DESIGN CRITERIA

KD-131 YIELD STRESS THEORIES

The ductile yielding theories used in this Division are the following:

(a) Maximum Shear Stress Theory. In accordance with this theory, yielding at any point occurs when the difference between the algebraically largest and the algebraically smallest principal stress reaches the yield strength of the material.

(b) Distortion Energy Yield Stress Theory. In accordance with this theory, yielding at any point occurs when the equivalent stress reaches the yield strength of the material. The equivalent stress is the von Mises stress calculated from the three principal stresses at that point using the following equation:

$$\sigma_e = \frac{1}{\sqrt{2}}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]^{0.5} \quad \text{(KD-131.1)}$$

KD-132 RESIDUAL STRESS

(a) Residual stresses are not considered in the static analysis, except:

(1) as provided in KD-9;

(2) when so specified as assembly loads, W_A. In this case, residual stresses shall be included in the load cases of Table KD-230.1.

(b) Residual stresses shall be considered in the calculated number of design cycles in accordance with Article KD-3 or KD-4.

(c) The vessel may contain residual stresses of predetermined magnitudes and distributions. These residual stresses may be produced by assembling concentric cylinders with an interference in the dimensions of the mating surfaces (shrink fitting). Such vessels shall meet the requirements of Articles KD-8 and KF-8.

(d) Residual stresses also may be produced by autofrettage and wire winding, in which case the component shall meet the requirements of Article KD-5, KD-9, KF-5, or KF-9, as appropriate.

(e) Residual stresses from fabrication operations such as welding and thermal heat treatments may also be present. See KD-110(i).

KD-133 OPENINGS AND CLOSURES

Article KD-6 provides rules for the design of openings through vessel walls, connections made to these openings, and end closures and their attachment to cylindrical vessels. Additional guidance is provided in Nonmandatory Appendix H.

KD-140 FATIGUE EVALUATION

If it can be shown that the vessel will have a leak-before-burst mode of failure (see KD-141), the calculated number of design cycles may be determined using the rules of either Article KD-3, Article KD-4, or KD-1260. However, if the leak-before-burst mode of failure cannot be shown, then the Article KD-4 procedure shall be used. When performing analysis using methods of Article KD-3 on vessels where leak-before-burst has been established (see KD-141), welded vessel construction details shall be analyzed using the Structural Stress method (see KD-340). The Structural Stress method shall only be used for welded details.

KD-141 LEAK-BEFORE-BURST MODE OF FAILURE

(a) For the purpose of this Code, it may be assumed that a leak-before-burst failure mode will occur in a single-wall component or a concentrically wrapped welded layered vessel if the critical crack depth in the appropriate plane is greater than the wall thickness at the location considered. Since many of the available methods for calculating stress intensity factors are not accurate for very deep cracks, it may not be possible to determine critical crack depths that are greater than 0.8 times the wall thickness. In such cases, leak-before-burst mode of failure may be assumed if both of the following conditions are met:

(1) the crack, at a depth equal to 0.8 times the wall thickness, is shown to be below the critical flaw size when evaluated using the failure assessment diagram from API 579-1/ASME FFS-1 [see KD-401(c)]

(2) the remaining ligament (distance from the crack tip to the free surface that the crack is approaching) is less than the quantity $(K_{Ic}/S_y)^2$

(b) For the case of failure due to a crack in the tangential-radial plane, such as a crack growing radially from an end closure thread or a blind end, it may not be possible to ensure a leak-before-burst mode of failure. In such cases the number of design cycles shall be calculated using Article KD-4.

(c) For leak-before-burst criteria for shrink-fit layered vessels, see KD-810(f). For wire-wound vessels, see KD-931.

(d) Alternately, leak-before-burst mode of failure can be established by the User based on documented experience within the industry with vessels of similar design, size, material properties, and operating conditions (see KG-311.10).

ARTICLE KD-2
BASIC DESIGN REQUIREMENTS

KD-200 SCOPE

This Article provides basic design rules and definitions for vessels constructed in accordance with this Division. Additional rules for fatigue life and special construction techniques are given in later Articles of this Part.

(a) All vessels shall meet the requirements of KD-220 through KD-222 as applicable except as provided in KD-230.

(b) The Designer may use the elastic–plastic analysis method (see KD-230) for vessels with cylindrical and spherical shells of all diameter ratios (see KD-221). If the Designer uses KD-230 through KD-236, Mandatory Appendix 9 need not be satisfied.

(c) The Designer shall use the elastic–plastic analysis method (see KD-230) for vessels with cylindrical and spherical shells that have diameter ratios equal to or greater than 1.25 (see KD-221).

(d) The Designer may use Mandatory Appendix 9 for the linear elastic analysis of vessels with cylindrical or spherical shells with wall ratios less than 1.25 [see (c)]. If the Designer chooses to use Mandatory Appendix 9, KD-230 through KD-232 and KD-234 through KD-236 need not be satisfied.

(e) If construction details do not satisfy the various configurations contained herein, or if no applicable equations are presented, a detailed stress analysis shall be made to show conformance with this Part. Vessel details that conform to the design requirements of Nonmandatory Appendix E, E-100 through E-120, or Nonmandatory Appendix G, are not required to be evaluated using the elastic–plastic analysis methods of KD-230 through KD-236 or the linear elastic analysis of Mandatory Appendix 9.

(f) Use of the design equations in KD-221 or elastic–plastic analysis in KD-230 may result in dimensional changes due to permanent strain during hydrostatic test or autofrettage. The designer shall consider the effect of these dimensional changes for applications where slight amounts of distortion can cause leakage or malfunction (also see KD-661).

KD-210 TERMS RELATING TO STRESS ANALYSIS

(a) Autofrettage. Autofrettage is a process for introducing favorable residual stresses into a vessel by straining the vessel interior to cause plastic deformation through part or all of the wall thickness.

(b) Deformation. Deformation of a component part is alteration of its shape or size due to stress or temperature changes.

(c) Equivalent Stress. The equivalent stress is defined in 9-200 based on the maximum distortion energy (von Mises theory).

(d) Fatigue Strength Reduction Factor. This is a stress intensification factor which accounts for the effect of a local structural discontinuity (stress concentration) on the fatigue strength. Values for some specific cases, based on experiment, are given elsewhere in this Division. In the absence of experimental data, the theoretical stress concentration factor may be used.

(e) Gross Structural Discontinuity. A gross structural discontinuity is a source of stress or strain intensification which affects a relatively large portion of a structure and has a significant effect on the overall stress or strain pattern or on the structure as a whole. Examples of gross structural discontinuities are head-to-shell and flange-to-shell junctions, nozzles, and junctions between shells of different diameters or thicknesses.

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

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

(2) Plastic Analysis. Plastic analysis is that method which computes the structural behavior under given loads considering the plasticity characteristics of the materials including strain hardening and the stress redistribution occurring in the structure. (Strain rate effects may also be significant where impact or other dynamic loads are involved.)

(3) Plastic Instability Load. The plastic instability load for members under predominantly tensile or compressive loading is defined as that load at which

unbounded plastic deformation can occur without an increase in load. At the plastic tensile instability load, the true stress in the material increases faster than strain hardening can accommodate.

(4) Strain Limiting Load. When a limit is placed upon a strain, the load associated with the strain limit is called the strain limiting load.

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

(6) Collapse Load — Limit Analysis. The methods of limit analysis are used to compute the maximum load a structure made of ideally plastic material can carry. The deformations of an ideally plastic structure increase without bound at this load, which is termed collapse load.

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

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

(9) Ratcheting. Ratcheting is a progressive incremental inelastic deformation or strain which can occur in a component that is subjected to variations of mechanical stress, thermal stress, or both (thermal stress ratcheting is partly or wholly caused by thermal stress).

(10) 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.

(11) Free End Displacement. Free end displacement consists of the relative motions that would occur between an attachment and connected structure or equipment if the two members were separated. Examples of such motions are those that would occur because of relative thermal expansion of piping, equipment, and equipment supports, or because of rotations imposed upon the equipment by sources other than the piping.

(12) Expansion Stresses. Expansion stresses are those stresses resulting from restraint of free end displacement.

(g) Load Stress. The stress resulting from the application of a load, such as internal pressure or the effects of gravity, as distinguished from thermal stress.

(h) Local Primary Membrane Stress, P_L. Cases arise in which a membrane stress produced by pressure or other mechanical loading and associated with a primary loading, discontinuity, or both effects would, if not limited, produce excessive distortion in the transfer of load to other portions of the structure. Conservatism requires that such a stress be classified as a local primary membrane stress even though it has some characteristics of a secondary stress. An example of a local primary membrane stress is the membrane stress in a shell produced by external load and moment at a permanent support or at a nozzle connection.

(i) Local Structural Discontinuity. A local structural discontinuity is a source of stress or strain intensification that affects a relatively small volume of material and does not have a significant effect on the overall stress or strain pattern or on the structure as a whole. Examples are small fillet radii and small attachments.

(j) Membrane Stress. Membrane stress is the component of normal stress that is uniformly distributed and equal to the average value of stress across the thickness of the section under consideration.

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

(l) Operational Cycle. An 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. Three types of operational cycles are considered:

(1) start-up/shutdown cycle, defined as any cycle that has atmospheric temperature, pressure, or both as its extremes and normal operation conditions as its other extreme

(2) the initiation of and recovery from any emergency or upset condition that shall be considered in the design

(3) normal operating cycle, defined as any cycle between start-up and shutdown which is required for the vessel to perform its intended purpose

(m) Peak Stress, F. The basic characteristic of a peak stress is that it does not cause any noticeable distortion and is objectionable only as a possible source of a fatigue crack or a brittle fracture. A stress that is not highly localized falls into this category if it is of a type which cannot cause progressive deformation (ratcheting). Examples of peak stress are:

(1) the thermal stress which occurs when a relatively thin inner shell material is dissimilar from a relatively thick outer shell material

(2) the thermal stress in the wall of a vessel or pipe caused by a rapid change in temperature of the contained fluid

(3) the stress at a local structural discontinuity

(n) Primary Stress. A normal stress or a shear stress developed by the imposed loading which is necessary to satisfy the simple laws of equilibrium of external and internal forces and moments. The basic characteristic of a primary stress is that it is not self-limiting. Primary stresses that considerably exceed the yield strength will result in failure or at least in gross distortion. A thermal stress is not classified as a primary stress. Primary membrane stress is divided into general and local categories. A general primary membrane stress is one which is so distributed in the structure that no redistribution of load occurs as a result of yielding. Examples of primary stress are:

(1) average through-wall longitudinal stress and the average through-wall circumferential stress in a closed cylinder under internal pressure, remote from discontinuities

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

(o) Secondary Stress. A secondary stress is a normal stress or a shear stress developed by the constraint of adjacent parts or by self-constraint of a structure. The basic characteristic of a secondary stress is that it is self-limiting. Local yielding and minor distortions can satisfy the conditions that cause the stress to occur and failure from one application of the stress is not to be expected. Examples of secondary stress are:

(1) general thermal stress [see (m)(1)]

(2) bending stress at a gross structural discontinuity

(p) Shear Stress, τ. The shear stress is the component of stress tangent to the plane of reference.

(q) Stress Intensity, S. The stress intensity is defined as twice the maximum shear stress. In other words, the stress intensity is the difference between the algebraically largest principal stress and the algebraically smallest principal stress at a given point. Tension stresses are considered positive and compression stresses are considered negative.

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

(1) general thermal stress, which is associated with distortion of the structure in which it occurs. If a stress of this type, neglecting local stress concentrations, exceeds twice the yield strength of the material, the elastic analysis may be invalid and successive thermal cycles may produce incremental distortion. Therefore, this type is classified as secondary stress in Figure 9-200.1. Examples of general thermal stress are:

(-a) stress produced by an axial temperature gradient in a cylindrical shell.

(-b) stress produced by temperature differences between a nozzle and the shell to which it is attached.

(-c) the equivalent linear stress produced by the radial temperature gradient in a cylindrical shell. Equivalent linear stress is defined as the linear stress distribution which has the same net bending moment as the actual stress distribution.

(2) local thermal stress, which is associated with almost complete suppression of the differential expansion and thus produces no significant distortion. Such stresses shall be considered only from the fatigue standpoint and are therefore classified as peak stresses in Figure 9-200.1. Examples of local thermal stress are:

(-a) the stress in a small hot spot in a vessel wall

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

(-c) the thermal stress in a liner material that has a coefficient of expansion different from that of the base metal

(s) Stress Cycle. A stress cycle is a condition in which the alternating stress difference (see Article KD-3) goes from an initial value through an algebraic maximum value and an algebraic minimum value, and then returns to the initial value. A single operational cycle may result in one or more stress cycles.

(t) Impulsive Loading. Impulsive loading is a loading whose duration is a fraction of the periods of the significant dynamic response modes of the vessel components. For a vessel, this fraction is limited to less than 35% of the fundamental, membrane-stress dominated (breathing) mode.

(u) Quasi-static Pressure (QSP). Quasi-static pressure is the maximum pressure in the vessel which is not the direct result of impulsive loading, such as a residual after pressure from the maximum design explosive detonation. The stress at any point resulting from the QSP may be determined by averaging the stress response over at least 10 times the fundamental structural period.

KD-220 EQUATIONS FOR CYLINDRICAL AND SPHERICAL SHELLS

Below are equations for the limits of the design pressure. The purpose of these requirements is to ensure adequate safety against collapse. These equations are

only appropriate for spherical and cylindrical shells remote from discontinuities.

KD-221 SHELLS UNDER INTERNAL PRESSURE

The shell shall have a diameter ratio Y (see 9-300) which meets the requirements of KD-221.1, KD-221.2, KD-221.3, or KD-221.4, as applicable. The hydrostatic test pressure used during manufacture shall be considered in the design (see KT-312).

The designer is cautioned that hydrostatic test pressure corresponding to design pressure calculated using eqs. (KD-221.1) through (KD-221.6), as applicable, may result in through-thickness yielding and excessive component distortion when the ratio of hydrostatic test pressure to design pressure is greater than 1.25.

(25) **KD-221.1 Cylindrical Monobloc Shells.** The design pressure P_D shall not exceed the limit set by the equation:

Open-end cylindrical shell for $Y \le 2.85$:

$$P_D = \min\left(\left[2.986K_{ut}\left(S_y\right)\left(Y^{0.268}-1\right)\right], \left[1.0773\left(S_y+S_u\right)\left(Y^{0.268}-1\right)\right]\right) \quad \text{(KD-221.1)}$$

Open-end cylindrical shell for $Y > 2.85$ and closed-end cylindrical shell for all Y values:

$$P_D = \min\left(\left[0.924K_{ut}\left(S_y\right)\ln(Y)\right], \left[\frac{1}{3}\left(S_y+S_u\right)\ln(Y)\right]\right) \quad \text{(KD-221.2)}$$

where

K_{ut} = hydrostatic test pressure upper limit factor (see KT-312)

S_u = tensile strength at design temperature from Section II, Part D, Subpart 1, Table U. If the tensile strength is not listed in Section II, Part D, Subpart 1, Table U, yield strength instead of tensile strength may be used.

S_y = yield strength at design temperature from Section II, Part D, Subpart 1, Table Y-1

open-end cylindrical shell: a cylindrical shell in which the force due to pressure acting on the closures at the ends of the cylinder is transmitted to an external yoke or other structure, such that the cylindrical shell does not carry the pressure end load.

closed-end cylindrical shell: a cylindrical shell in which the force due to pressure acting on the closures at the ends of the cylinder is transmitted through the cylindrical wall, creating an axial stress in the cylindrical shell that carries the pressure end load.

(25) **KD-221.2 Cylindrical Layered Shells.** For shells consisting of n layers with different yield strengths, the equation in KD-221.1 is replaced by:

Open-end cylindrical shell for $Y \le 2.85$:

$$P_D = \min\left(\left[\sum_{j=1}^{n} 2.986K_{utj}\left(S_{yj}\right)\left(Y_j^{0.268}-1\right)\right], \left[\sum_{j=1}^{n} 1.0773\left(S_{yj}+S_{uj}\right)\left(Y_j^{0.268}-1\right)\right]\right) \quad \text{(KD-221.3)}$$

Open-end cylindrical shell for $Y > 2.85$ and closed-end cylindrical shell for all Y values:

$$P_D = \min\left(\left[\sum_{j=1}^{n} 0.924K_{utj}\left(S_{yj}\right)\ln\left(Y_j\right)\right], \left[\sum_{j=1}^{n} \frac{1}{3}\left(S_{yj}+S_{uj}\right)\ln\left(Y_j\right)\right]\right) \quad \text{(KD-221.4)}$$

where

K_{utj} = hydrostatic test pressure upper limit factor for each individual layer (see KT-312)

S_{uj} = tensile strength at design temperature for each layer from Section II, Part D, Subpart 1, Table U. If the tensile strength is not listed in Section II, Part D, Subpart 1, Table U, yield strength instead of tensile strength may be used.

S_{yj} = yield strength at design temperature for each layer from Section II, Part D, Subpart 1, Table Y-1

Y_j = diameter ratio for each layer

KD-221.3 Spherical Monobloc Shells. The design pressure P_D shall not exceed the limit set by the equation:

$$P_D = \min\left(\left[1.6K_{ut}\left(S_y\right)\ln(Y)\right], \left[\frac{1}{\sqrt{3}}\left(S_y+S_u\right)\ln\left(Y\right)\right]\right) \quad \text{(KD-221.5)}$$

KD-221.4 Spherical Layered Shells. For shells consisting of n layers with different yield strengths, the equation in KD-221.3 is replaced by:

$$P_D = \min\left(\left[\sum_{j=1}^{n} 1.6K_{utj}\left(S_{yj}\right)\ln\left(Y_j\right)\right], \left[\sum_{j=1}^{n} \frac{1}{\sqrt{3}}\left(S_{yj}+S_{uj}\right)\ln\left(Y_j\right)\right]\right) \quad \text{(KD-221.6)}$$

KD-221.5 Additional Loads. If the shell is subject to loading in addition to the internal pressure, the design shall be modified as necessary so that the collapse pressure in the presence of the additional load is greater than or equal to 1.732 times the design pressure.

KD-222 SHELLS UNDER EXTERNAL PRESSURE

The shells shall have a diameter ratio that shall ensure the same safety against collapse as in KD-221. This means that the same equations are applicable for controlling the diameter ratios for shells under external pressure as those given in KD-221 for shells under internal pressure, provided that all loadings are considered and the longitudinal stress remains the intermediate principal stress (i.e., closed-end case). Shells under external pressure shall also be checked for safety against buckling. For the special case of cylindrical monobloc shells, the following equation shall be used:

$$P_D = \frac{E(Y-1)^3}{40\left(1-\nu^2\right)Y^3} \qquad \text{(KD-222.1)}$$

but in no case shall exceed the value of P_D given by the equation in KD-221.1.

KD-230 ELASTIC–PLASTIC ANALYSIS

The equations for cylindrical and spherical shells in KD-220 need not be used if a nonlinear elastic–plastic analysis (see KD-231) is conducted using numerical methods such as elastic–plastic finite element or finite difference analysis for the loadings described in Table KD-230.1 and Table KD-230.2. When elastic–plastic analysis is used, the Designer shall also comply with KD-232 through KD-236.

KD-231 ELASTIC–PLASTIC ANALYSIS METHOD

Protection against plastic collapse is evaluated by determining the plastic collapse load of the component using an elastic–plastic stress analysis. The allowable load on the component is established by applying a load factor to the calculated plastic collapse load. Elastic–plastic stress analysis closely approximates the actual structural behavior by considering the redistribution of stress that occurs as a result of inelastic deformation (plasticity) and deformation characteristics of the component.

KD-231.1 Elastic–Plastic Numerical Analysis. The plastic collapse load can be obtained using a numerical analysis technique (e.g., finite element method) by incorporating an elastic–plastic material model (see KM-620 or KM-630, as appropriate) to obtain a solution. The effects of nonlinear geometry shall be considered in this analysis. The plastic collapse load is the load that causes overall structural instability. This point is indicated by the inability to achieve an equilibrium solution for a small increase in load (i.e., the solution will not converge).

KD-231.2 Elastic–Plastic Acceptance Criteria. The acceptability of the component using elastic–plastic analysis shall be demonstrated by evaluation of the plastic collapse load. The plastic collapse load is taken as the load that causes structural instability. This shall be demonstrated by satisfying the following criteria:

(a) Global Criteria. A global plastic collapse load is established by performing an elastic–plastic analysis of the component subject to the specified loading conditions. The concept of Load and Resistance Factor Design (LRFD) is used as an alternative to the rigorous computation of a plastic collapse load to design a component. In this procedure, factored loads that include a load factor to account for uncertainty and the resistance of the component to these factored loads are analyzed using elastic–plastic analysis (see Table KD-230.4).

(b) Service Criteria. Service criteria that limit the potential for unsatisfactory performance shall be analyzed at every location in the component when subject to the service loads (see Table KD-230.4). Examples of service criteria are limits on the rotation of a mating flange pair to avoid possible flange leakage concerns, and limits on tower deflection that may cause operational concerns. In addition, the effect of deformation of the component on service performance shall be evaluated at the service load combinations. This is especially important for components that experience an increase in resistance (geometrically stiffen) with deformation under applied loads such as elliptical or torispherical heads subject to internal pressure loading. The plastic collapse criteria may be satisfied but the component may have excessive deformation at the service conditions. In this case, the design and service loads have to be reduced based on a deformation criterion. Examples of some of the considerations in this evaluation are the effect of deformation on

(1) piping connections

(2) misalignment of trays, platforms, and other internal or external appurtenances

(3) interference with adjacent structures and equipment

(4) load-bearing interfaces

If applicable, the service criteria shall be specified in the User's Design Specification (see KG-311).

(c) Local Criteria. A component shall satisfy the local criteria requirements given in KD-232.

(d) Hydrostatic Test Criteria. A component shall satisfy the criteria for hydrostatic test from Table KD-230.4 using the methodology of KD-236. The suitability and integrity of the vessel shall be evaluated by the designer and the results of this evaluation shall be included in the Manufacturer's Design Report. However, the hydrostatic test criteria of Table KD-230.4 are not mandatory for analysis provided that the ratio of yield to tensile strength at design

Table KD-230.1
Loads and Load Cases to Be Considered in Design

Loading Condition	Design Loads
Pressure Testing	Assembly loads
	Dead load of component plus insulation, fireproofing, installed internals, platforms, and other equipment supported from the component in the installed position
	Piping loads including pressure thrust
	Applicable live loads excluding vibration and maintenance live loads
	Pressure and fluid loads (water) for testing and flushing equipment and piping unless a pneumatic test is specified
	Wind loads
Normal Operation	Assembly loads
	Dead load of component plus insulation, refractory, fireproofing, installed internals, catalyst, packing, platforms, and other equipment supported from the component in the installed position
	Piping loads including pressure thrust
	Applicable live loads
	Pressure and fluid loading during normal operation
	Thermal loads
	Loads imposed by the motion of the structure to which the vessel is fastened
Normal Operation Plus Occasional [Note (1)]	Assembly loads
	Dead load of component plus insulation, refractory, fireproofing, installed internals, catalyst, packing, platforms, and other equipment supported from the component in the installed position
	Piping loads including pressure thrust
	Applicable live loads
	Pressure and fluid loading during normal operation
	Thermal loads
	Wind, earthquake, or other occasional loads, whichever is greater
	Loads due to wave action
	Loads imposed by the motion of the structure to which the vessel is fastened
Abnormal or Start-up Operation Plus Occasional [Note (1)]	Assembly loads
	Dead load of component plus insulation, refractory, fireproofing, installed internals, catalyst, packing, platforms, and other equipment supported from the component in the installed position
	Piping loads including pressure thrust
	Applicable live loads
	Pressure and fluid loading associated with the abnormal or start-up conditions
	Thermal loads
	Wind loads

NOTE: (1) Occasional loads are usually governed by wind and earthquake; however, other load types such as snow and ice loads may govern (see ASCE/SEI 7).

Table KD-230.2
Load Descriptions

Design Load Parameter	Description
P_D	Internal and external design pressure
P_o	Internal and external operating pressure
P_S	Static head from liquid or bulk materials (e.g., catalyst)
P_t	Hydrostatic test pressure determined in Article KT-3
D	Dead weight of the vessel, contents, and appurtenances at the location of interest, including the following:
	Weight of vessel including internals, supports (e.g., skirts, lugs, saddles, and legs), and appurtenances (e.g., platforms, ladders, etc.)
	Weight of vessel contents under operating and test conditions
	Refractory linings, insulation
	Static reactions from the weight of attached equipment, such as motors, machinery, other vessels, and piping
L	Appurtenance live loading
	Effects of fluid momentum, steady state and transient
L_A	Floating transporter acceleration loads due to spectral motion response determined in KD-237
E	Earthquake loads (see ASCE/SEI 7 for the specific definition of the earthquake load, as applicable)
W [Note (1)]	Wind loads
W_A	Assembly loads (e.g., shrink fit, wire winding, sealing preload)
W_{pt} [Note (1)]	Pressure test wind load case. The design wind speed for this case shall be specified by the Owner-User.
S_S	Snow loads
T	Self-restraining load case (i.e., thermal loads, applied displacements). This load case does not typically affect the collapse load, but should be considered in cases where elastic follow-up causes stresses that do not relax sufficiently to redistribute the load without excessive deformation.

NOTE: (1) The wind loads, W and W_{pt}, are based on ASCE/SEI 7 wind maps and probability of occurrence. If a different recognized standard for wind loading is used, the User's Design Specification shall cite the standard to be applied and provide suitable load factors if different from ASCE/SEI 7.

temperature for all components is greater than that shown in Table KD-230.3 based on the actual hydrostatic test pressure that will be used for testing the component. Interpolation between the values of test pressure is permissible in Table KD-230.3.

KD-231.3 Elastic–Plastic Assessment Procedure. The following assessment procedure is used to determine the acceptability of a component or an assembly of components using elastic–plastic stress analysis.

Table KD-230.3
Combination for Analysis Exemption of Hydrostatic Test Criterion

Ratio of Hydrostatic Test Pressure to Design Pressure	Ratio of Yield Strength to Tensile Strength
1.25	≥0.612
1.30	≥0.653
1.35	≥0.694
1.40	≥0.799
1.43	≥0.910

Step 1. Develop a numerical model of the component including all relevant geometry characteristics. The model used for the analysis shall be selected to accurately represent the component geometry, boundary conditions, and applied loads. In addition, refinement of the model around areas of stress and strain concentrations shall be provided. The analysis of one or more numerical models may be required to ensure that an accurate description of the stresses and strains in the component is achieved.

Step 2. Define all relevant loads and applicable load cases. The loads to be considered in the design shall include, but not be limited to, those given in Table KD-230.1.

Step 3. An elastic–plastic material model that includes hardening or softening, or an elastic–perfectly plastic model (see Article KM-6) shall be utilized. A true stress–strain curve model that includes temperature dependent hardening behavior is provided in KM-620. When an assembly comprised of multiple components is analyzed, all components shall use a consistent elastic–plastic material model. The effects of nonlinear geometry shall be considered in the analysis.

Step 4. Determine the load combinations to be used in the analysis using the information from Step 2 in conjunction with Table KD-230.4. Each of the indicated load cases

Table KD-230.4
Load Combinations and Load Factors for an Elastic–Plastic Analysis (25)

Criteria	Load Combinations
Design Conditions	
Global criteria	(1) 1.80 ($P_D + P_S + D$)
	(2) 1.58 ($P_D + P_S + D + T$) + 2.03L + 2.03L_A + 0.65S_S
	(3) 1.58 ($P_D + P_S + D$) + 2.03S_S + max. [1.28L + 1.28L_A, 0.65W]
	(4) 1.58 ($P_D + P_S + D$) + 1.28W + 1.28L + 1.28L_A + 0.65S_S
	(5) 1.58 ($P_D + P_S + D$) + 1.28E + 1.28L + 1.28L_A + 0.65S_S
Local criteria	1.28($P_D + P_S + D$) + 1.00W_A
Service criteria	According to User's Design Specification, if applicable. See KD-231.2(b).
Hydrostatic Test Conditions	
Global criteria	$(1/K_{ut})P_t + P_s + D + 0.6W_{pt}$ (see KD-236)
Service criteria	According to User's Design Specification, if applicable. See KD-231.2(b).

GENERAL NOTES:
(a) The parameters used in the Load Combinations column are defined in Table KD-230.2.
(b) See KD-231.2 for descriptions of global and serviceability criteria.
(c) If the vessel is made of layered construction, the following equation shall be used for K_{ut}.

$$K_{ut} = \left(\sum_{j=1}^{n} \left(K_{utj} t_j \right) / \sum_{j=1}^{n} t_j \right)$$

where
K_{ut} = hydrostatic test pressure upper limit factor (see KT-312)
K_{utj} = hydrostatic test pressure upper limit factor for each layer
t_j = thickness of each layer

shall be evaluated. The effects of one or more loads not acting shall be investigated. Additional load cases for special conditions not included in Table KD-230.4 shall be considered, as applicable.

Step 5. Perform an elastic–plastic analysis for each of the load cases defined in Step 4. If convergence is achieved, the component is stable under the applied loads for this load case. Otherwise, the component configuration (i.e., thickness) shall be modified or applied loads reduced and the analysis repeated.

KD-232 PROTECTION AGAINST LOCAL FAILURE

In addition to demonstrating protection against plastic collapse as defined in KD-231, the local failure criteria below shall be satisfied.

KD-232.1 Elastic–Plastic Analysis Procedure. The following procedure shall be used to evaluate protection against local failure.

(a) Each analysis used with respect to KD-232.1 shall use an elastic–plastic stress–strain model in KM-620. Nonlinear geometry shall be used in the analysis.

(b) The following evaluation shall be performed using two independent elastic–plastic analyses for the following loading conditions:

(1) all loads listed as local criteria in Table KD-230.4.

(2) a series of applied loads as described in KD-234. The same loading histogram needed to demonstrate compliance with KD-234 shall be used in this analysis. KD-350 contains guidance in development of that loading histogram.

(c) Loads from fabrication operations such as pressure testing, autofrettage, shrink fitting, and wire winding shall be included if they produce plastic deformation. These loads shall not be included in the evaluation of cold-forming damage, $D\varepsilon_{\text{form}}$.

(d) For a location in the component subject to evaluation, determine the principal stresses, σ_1, σ_2, σ_3, the equivalent stress, σ_e, using eq. (KD-232.1) below, and the total equivalent plastic strain, ϵ_{peq}.

$$\sigma_e = \frac{1}{\sqrt{2}} \left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]^{0.5} \quad \text{(KD-232.1)}$$

(e) Determine the limiting triaxial strain $\epsilon_{L,k}$, for the kth load step increment using the equation below, where ϵ_{Lu}, m_2, and m_5 are determined from the coefficients given in Table KM-620.

$$\epsilon_{L,k} = \epsilon_{Lu}\left[e^{\frac{-m_5}{1+m_2}\left(\frac{\sigma_{1,k}+\sigma_{2,k}+\sigma_{3,k}}{3\sigma_{e,k}} - \frac{1}{3}\right)}\right] \quad \text{(KD-232.2)}$$

where

ϵ_{peq} = total equivalent plastic strain
e = 2.7183, approximate value of the base of the natural logarithm
El = minimum specified elongation, %
$\epsilon_{L,k}$ = maximum permitted local total equivalent plastic strain at any point at the kth load increment
ϵ_{Lu} = maximum of m_2, m_3, and m_4
ln = natural logarithm
m_2 = value calculated from Table KM-620
m_3 = value calculated from Table KM-620
m_4 = value calculated from Table KM-620
m_5 = value listed in Table KM-620
R = S_y/S_u
RA = minimum specified reduction of area, %
$\sigma_{1,k}$ = principal stress in the "1" direction at the point of interest for the kth load increment
$\sigma_{2,k}$ = principal stress in the "2" direction at the point of interest for the kth load increment
$\sigma_{3,k}$ = principal stress in the "3" direction at the point of interest for the kth load increment
$\sigma_{e,k}$ = equivalent stress at the point of interest
S_y = yield strength at the analysis temperature (see Section II, Part D, Subpart 1, Table Y-1)
S_u = tensile strength at the analysis temperature (see Section II, Part D, Subpart 1, Table U)

(f) Determine the strain limit damage for the kth load step increment using the following equations:

$$\begin{aligned}\Delta\epsilon_{peq,k} = \frac{\sqrt{2}}{3}\Big[&\left(\Delta\epsilon_{p,11,k} - \Delta\epsilon_{p,22,k}\right)^2 \\ &+ \left(\Delta\epsilon_{p,22,k} - \Delta\epsilon_{p,33,k}\right)^2 \\ &+ \left(\Delta\epsilon_{p,33,k} - \Delta\epsilon_{p,11,k}\right)^2 \\ &+ 1.5\left(\Delta\epsilon_{p,12,k}^2 + \Delta\epsilon_{p,23,k}^2 + \Delta\epsilon_{p,31,k}^2\right)\Big]^{0.5}\end{aligned} \quad \text{(KD-232.3)}$$

$$D_{\epsilon,k} = \Delta\epsilon_{peq,k}/\epsilon_{L,k} \quad \text{(KD-232.4)}$$

where

$D_{\epsilon,k}$ = strain limit damage for the kth loading condition
$\Delta\epsilon_{peq,k}$ = equivalent plastic strain range for the kth loading condition or cycle
$\Delta\varepsilon_{p,11,k}$ = plastic strain range in the "11" direction for the kth loading condition or cycle
$\Delta\varepsilon_{p,22,k}$ = plastic strain range in the "22" direction for the kth loading condition or cycle
$\Delta\varepsilon_{p,33,k}$ = plastic strain range in the "33" direction for the kth loading condition or cycle
$\Delta\varepsilon_{p,12,k}$ = plastic strain range in the "12" direction for the kth loading condition or cycle
$\Delta\varepsilon_{p,23,k}$ = plastic strain range in the "23" direction for the kth loading condition or cycle
$\Delta\varepsilon_{p,31,k}$ = plastic strain range in the "31" direction for the kth loading condition or cycle

(g) Add the damage occurring during the kth load step increment, $D_{\epsilon,k}$, to the sum of the incremental damage occurring at each previous increment to obtain the accumulated damage, D_ϵ.

(h) Repeat the process in (d) through (g) for all load step increments in the analysis.

(i) If the component has been cold-formed without subsequent heat treatment, calculate the damage from forming, $D_{\epsilon\text{form}}$, using the equation below. If the component has not been cold formed, or if heat treatment has been performed after forming, the damage from forming, $D_{\epsilon\text{form}}$, may be assumed to be zero.

$$D_{\epsilon\text{form}} = \epsilon_{cf}/\left(\epsilon_{Lu}e^{\left[-\frac{1}{3}(m_5/(1+m_2))\right]}\right) \quad \text{(KD-232.5)}$$

where

$D_{\epsilon\text{form}}$ = damage occurring during forming at the location in the component under consideration
ϵ_{cf} = forming strain at the location in the component under consideration

(j) Add the damage from forming to the accumulated damage during loading to obtain the total accumulated damage, $D_{\epsilon t}$:

$$D_{\epsilon t} = D_{\epsilon\text{form}} + D_\epsilon \quad \text{(KD-232.6)}$$

(k) The total accumulated damage, $D_{\epsilon t}$, shall be separately calculated for the two load cases of (b). These separately calculated $D_{\varepsilon t}$ values shall be no greater than 1.0, indicating the local failure criteria to be specified (see KD-232).

The designer is cautioned that excessive distortion in the structure of the vessel may lead to failure of the pressure boundary. This could be in the form of buckling or bellmouthing (see KD-631.5).

KD-233 PROTECTION AGAINST BUCKLING COLLAPSE

In addition to evaluating protection against plastic collapse as defined in KD-231, a load factor for protection against collapse from buckling shall be satisfied to avoid buckling of components with a compressive stress field under applied design loads.

KD-233.1 Buckling Load Factors. The load factor to be used in structural stability assessment is based on the type of buckling analysis performed. If a collapse analysis is performed in accordance with KD-231, and imperfections are explicitly considered in the analysis model geometry, the load factor is accounted for in the factored load combinations in Table KD-230.4.

KD-233.2 Buckling Numerical Analysis. When a numerical analysis is performed to determine the buckling load for a component, all possible buckling mode shapes shall be considered in determining the minimum buckling load for the component. Care should be taken to ensure that simplification of the model does not result in exclusion of a critical buckling mode shape. For example, when determining the minimum buckling load for a ring-stiffened cylindrical shell, both axisymmetric and nonaxisymmetric buckling modes shall be considered in determination of the minimum buckling load.

KD-234 RATCHETING ASSESSMENT ELASTIC–PLASTIC STRESS ANALYSIS

Vessel components connected by nonintegral mechanical means may be subject to failure by progressive deformation. If any combination of loads produces yielding, such connections may be subject to ratcheting behavior. Stresses that produce slippage between such parts in which disengagement could occur as a result of progressive distortion shall be limited to the yield strength at design temperature from Section II, Part D, Subpart 1, Table Y-1, S_y, or evaluated using the procedure in KD-234.1.

To evaluate protection against ratcheting using elastic–plastic analysis, an assessment is performed by application, removal, and reapplication of the applied loadings. If protection against ratcheting is satisfied, it may be assumed that progression of the stress–strain hysteresis loop along the strain axis cannot be sustained with cycles and that the hysteresis loop will stabilize. A separate check for plastic shakedown to alternating plasticity is not required. The following assessment procedure can be used to evaluate protection against ratcheting using elastic–plastic analysis.

KD-234.1 Assessment Procedure.

Step 1. Develop a numerical model of the component including all relevant geometry characteristics. The model used for analysis shall be selected to accurately represent the component geometry, boundary conditions, and applied loads.

Step 2. Define all relevant loads and applicable load cases (see Table KD-230.1).

Step 3. An ideally elastic–plastic (non-strain hardening) material model (see KM-610) shall be used in the analysis. The distortion energy yield function and associated flow rule should be utilized. The yield strength defining the plastic limit shall be the minimum specified yield strength at design temperature from Section II, Part D, Subpart 1, Table Y-1. The effects of nonlinear geometry shall be considered in the analysis.

Step 4. Perform an elastic–plastic analysis for the applicable loading from Step 2 for a number of repetitions of a loading event, or, if more than one event is applied, of two events that are selected so as to produce the highest likelihood of ratcheting.

Step 5. The ratcheting criteria below shall be evaluated after application of a minimum of three complete repetitions of the loading cycle following the hydrotest. Additional cycles may need to be applied to demonstrate convergence. If any one of the following conditions is met, the ratcheting criteria are satisfied. If the criteria shown below are not satisfied, the component configuration (i.e., thickness) shall be modified or applied loads reduced and the analysis repeated.

(a) There is no plastic action (i.e., zero plastic strains incurred) in the component.

(b) There is an elastic core in the primary-load-bearing boundary of the component.

(c) There is not a permanent change in the overall dimensions of the component. This can be demonstrated by developing a plot of relevant component dimensions versus time between the last and the next to the last cycles.

KD-235 ADDITIONAL REQUIREMENTS FOR ELASTIC–PLASTIC ANALYSIS

(a) A fatigue analysis shall be conducted in accordance with Article KD-3, or a fracture mechanics evaluation in accordance with Article KD-4, whichever is applicable. The stress and strain values used in these fatigue analyses shall be obtained from the numerical analysis.

(b) The designer shall consider the effect of component displacements on the performance of vessel components and sealing elements, under design, hydrotest, and autofrettage loads as appropriate.

KD-236 HYDROSTATIC TEST CRITERIA (25)

KD-236.1 Analysis Using Ideally Elastic–Plastic (Non-Strain Hardening) Material (See KM-610).

(a) This analysis shall be performed on the vessel for load combinations of hydrostatic test conditions given in Table KD-230.4 using the yield strength at test temperature from Section II, Part D, Subpart 1, Table Y-1.

(b) The collapse loads shall be not less than load factors given in Table KD-230.4.

KD-236.2 Analysis Using Elastic–Plastic (True Stress–Strain) Material (See KM-620).

(a) This analysis may be used for evaluation of the hydrostatic criteria, in lieu of the elastic perfectly plastic model described in KD-236.1.

(b) The load combination to be used with the model in KM-620 shall be in accordance with eq. (KD-236.1) in lieu of that given in Table KD-230.4.

$$1.25\left(P_t + P_s + D + 0.6W_{pt}\right) \quad \text{(KD-236.1)}$$

KD-237 FLOATING TRANSPORTER (SHIP) LOADS

This paragraph describes the procedure that shall be used to define the loads on the pressure vessel while under operation due to the motion of a floating mobile transporter.

(a) Acceleration loads due to a spectral motion response, L_A, shall be determined by the vessel's (or ship's) Response Amplitude Operator (RAO). The RAO describes the motion response of the vessel as a function of wave frequency. The wave spectrum, $S_{\omega\omega}$, is the distribution of wave energy as a function of frequency. The motion spectrum of the vessel, S_{xx}, is the combination of the RAO and wave spectrum. Equations (KD-237.1) through (KD-237.3) below shall be used to determine the accelerations for a given sea state (based on a wave spectrum) and direction (based on an RAO).

$$S_{\chi\chi} = S_{\omega\omega}\,(\text{RAO})^2 \quad \text{(KD-237.1)}$$

$$\sigma^2{}_{\text{x}} = \int S_{\chi\chi} d_\omega \quad \text{(KD-237.2)}$$

$$\sigma^2{}_{\ddot{x}} = \int \omega^4 S_{\chi\chi} d_\omega \quad \text{(KD-237.3)}$$

where

RAO = Response Amplitude Operator
$S_{\omega\omega}$ = wave spectrum
S_{xx} = motion spectrum
σ_x = standard deviation of motion response
$\sigma_{\ddot{x}}$ = standard deviation of acceleration
ω = frequency

The same equations shall be used for both strength and fatigue assessments. The strength assessment shall use accelerations for a maximum sea state event (a 100-yr hurricane for example). The fatigue assessment shall use accelerations for a multitude of sea states to determine an acceleration spectrum.

(b) The acceleration loads, L_A, found from (a) shall be applied in Tables KD-230.1 and KD-230.2.

(c) Alternative methods of determining acceleration loads are permitted provided the calculation results are as conservative as those provided by these rules.

(25) ## KD-240 ADDITIONAL REQUIREMENTS FOR IMPULSIVELY LOADED VESSELS

The limits of KD-230 shall be met with the following additional requirements:

(a) All elastic–plastic analyses under KD-230 shall be conducted using vessel material mechanical properties evaluated at metal temperature just prior to impulsive event.

(b) Strain-rate material dependent stress–strain curve data shall be used where available and as justified by the designer. Otherwise, static stress–strain curve data shall be used for all analyses.

(c) The design margin against a plastic instability state for the specified impulsive load shall be 1.732. For example, this margin may be demonstrated by an elastic–plastic dynamic analysis, with an impulse equal to 175% of the design-basis impulse, which does not result in the formation of a plastic instability state (e.g., the formation of a complete plastic hinge around an opening or closure).

(d) For vessels subjected to either single or multiple impulsive loading events, the principal elastic–plastic strain components ($\varepsilon_1, \varepsilon_2, \varepsilon_3$) through the entire wall thickness shall be examined over strain cycles within a single-loading event, or strain cycles within successive loading events, respectively. The principal elastic–plastic strain components are used in determining the average through-thickness membrane strains. The maximum principal elastic–plastic membrane strain shall not exceed $m_2/8$, where m_2 is given in Table KM-620. In addition, local failure damage shall be evaluated (see KD-232).

The Designer shall consider the need to reduce these strain limits for areas of high biaxial or triaxial tension.

(e) Any bolts shall be in accordance with KD-620. The equivalent stress due to quasi-static pressure (QSP) shall be treated as primary. The equivalent stress associated with the impulse event shall be treated as secondary. Where bolted joints that form part of the pressure boundary are sealed with face seals or gaskets, the design analysis shall demonstrate there is no separation of the joint faces during the transient. Where bolted components are sealed with piston seals, the relative motion shall be considered by the designer.

(f) Thermal-induced skin stresses on the inner surface of the vessel resulting from the design basis impulse detonation event need not be limited, as these are predominantly under compression during the transient.

(g) A fracture mechanics fatigue evaluation shall be conducted in accordance with Article KD-4. One method of performing this is given in Nonmandatory Appendix K.

(h) Residual stresses shall be taken into account. Weld residual stresses shall be analyzed in accordance with guidance provided in Annex E of API 579-1/ASME FFS-1.

(i) An elastic–plastic analysis shall be conducted using the hydrostatic test pressure determined in KT-351. Plastic strain accumulation limits of (d) are applicable.

(j) An elastic–plastic analysis of the dynamic test (see KT-352) shall be conducted using 125% of the design basis impulse loading for the worst case operational load

combination resulting at the limiting section of the vessel. Plastic strain accumulation limits of (d) are applicable.

(k) An elastic–plastic ratcheting analysis shall be conducted using the 100% design basis impulse. The ratcheting assessment shall include evaluation of the hydrostatic test, dynamic proof test and a minimum of at least three complete repetitions of the loading cycle. Additional cycles may need to be applied to demonstrate convergence. Material properties as defined in (a) and (b) may be used that includes strain-hardening behavior.

(l) It shall be verified that fragment-induced damage to the inner surface of vessels subjected to multiple impulsive loading events is not more severe than the flaws assumed in the fatigue evaluation. If this verification cannot be established, internal protective lining is required.

ARTICLE KD-3
FATIGUE EVALUATION

KD-300 SCOPE

This Article presents a traditional fatigue analysis design approach. In accordance with KD-140, if it can be shown that the vessel will fail in a leak-before-burst mode, then the number of design cycles shall be calculated in accordance with either Article KD-3 or Article KD-4. When using methods of this Article on vessels where leak-before-burst has been established (see KD-141), welded vessel construction details shall be analyzed using the Structural Stress method (see KD-340). The Structural Stress method shall only be used for welded details. If a leak-before-burst mode of failure cannot be shown, then the number of design cycles shall be calculated in accordance with Article KD-4.

KD-301 GENERAL

Cyclic operation may cause fatigue failure of pressure vessels and components. While cracks often initiate at the bore, cracks may initiate at outside surfaces or at layer interfaces for autofrettaged and layered vessels. In all cases, areas of stress concentrations are a particular concern. Fatigue-sensitive points shall be identified and a fatigue analysis made for each point. The result of the fatigue analysis will be a calculated number of design cycles N_f for each type of operating cycle, and a calculated cumulative effect number of design cycles when more than one type of operating cycle exists.

The resistance to fatigue of a nonwelded component shall be based on the design fatigue curves for the materials used. Fatigue resistance of weld details shall be determined using the Structural Stress method (see KD-340), which is based on fatigue data of actual welds.

In some cases it may be convenient or necessary to obtain experimental fatigue data for a nonwelded component itself rather than for small specimens of the material (see KD-1260). If there are two or more types of stress cycles which produce significant stresses, their cumulative effect shall be evaluated by calculating for each type of stress cycle the usage factors U_1, U_2, U_3, etc., and the cumulative usage factor U in accordance with KD-330. The cumulative usage factor U shall not exceed 1.0.

KD-302 THEORY

The theory used in this Article postulates that fatigue at any point is controlled by the alternating stress intensity S_{alt} and the associated mean stress σ_{nm} normal to the plane of S_{alt}. They are combined to define the equivalent alternating stress intensity S_{eq}, which is used with the design fatigue curves to establish the number of design cycles N_f.

KD-302.1 Alternating Stress Intensity. The alternating stress intensity S_{alt} represents the maximum range of shear stress.

KD-302.2 Associated Mean Stress. The associated mean stress σ_{nm} is the mean value of stress normal to the plane subjected to the maximum alternating stress intensity.

When using the design fatigue curves of Figure KD-320.2, Figure KD-320.3, Figure KD-320.5, or Figure KD-320.7 (Figure KD-320.2M, Figure KD-320.3M, Figure KD-320.5M, or Figure KD-320.7M), the associated mean stress shall not be combined with the alternating stress intensity [see KD-312.4(a)].

KD-310 STRESS ANALYSIS FOR FATIGUE EVALUATION

The calculation of the number of design cycles shall be based on a stress analysis of all fatigue-sensitive points.

KD-311 LOADING CONDITIONS AND RESIDUAL STRESSES

In this analysis, consideration shall be taken of the following loadings and stresses.

KD-311.1 Residual Stresses Due to Manufacturing.

(a) Some manufacturing processes such as forming, etc., introduce residual tensile stresses of unknown magnitude. Unless these stresses are controlled by some method, such as postfabrication heat treatment or mechanical overstrain processes like autofrettage, these initial residual stresses shall be assumed to have a peak magnitude corresponding to the yield strength of the material.

(b) Manufacturing processes such as welding, heat treatment, forming, autofrettage, shrink fitting, and wire wrapping introduce residual stresses. Tensile residual stresses shall be included in the calculation of associated mean stresses. Compressive residual stresses may also be included. When calculating the residual stresses introduced by autofrettage, due account shall be taken of the influence of the Bauschinger effect (see Article KD-5). If any combination of operational or hydrotest loadings will produce yielding at any point, any resulting change in the residual stress values shall be taken into account.

(c) In welded construction, no credit shall be taken for beneficial residual stresses within the weld metal or the heat-affected zone.

(d) In austenitic stainless steel construction, no credit shall be taken for beneficial residual stresses.

KD-311.2 Operating Stresses. Mean and alternating stresses shall be calculated for all loading conditions specified in the User's Design Specification. Stress concentration factors shall be determined by analytical or experimental techniques.

Ranges of stress intensities due to cyclic loadings and associated mean stresses (residual plus operational) shall be calculated on the assumption of elastic behavior. If these calculations show that yielding occurs, a correction shall be made. See KD-312.3.

KD-312 CALCULATION OF FATIGUE STRESSES WHEN PRINCIPAL STRESS DIRECTIONS DO NOT CHANGE

For any case in which the directions of the principal stresses at the point being considered do not change during the operating cycle, the methods stated in KD-312.1 through KD-312.4 shall be used to determine the fatigue controlling stress components.

KD-312.1 Principal Stresses. Determine the values of the three principal stresses at the point being investigated for the complete operating cycle assuming the loading and conditions described in KD-311. These stresses are designated σ_1, σ_2, and σ_3.

KD-312.2 Alternating Stress Intensities. Determine the stress differences (maintain the proper algebraic sign for the complete operating cycle):

$$S_{12} = \sigma_1 - \sigma_2 \tag{KD-312.1}$$

$$S_{23} = \sigma_2 - \sigma_3 \tag{KD-312.2}$$

$$S_{31} = \sigma_3 - \sigma_1 \tag{KD-312.3}$$

In the following, the symbol S_{ij} is used to represent any one of these three differences.

Identify the algebraic largest stress difference $S_{ij,\max}$ and the algebraic smallest difference $S_{ij,\min}$ of each S_{ij} during the complete operating cycle. Then the alternating stress intensity $S_{\text{alt},ij}$ is determined by:

$$S_{\text{alt},ij} = 0.5\left(S_{ij,\max} - S_{ij,\min}\right) \tag{KD-312.4}$$

The absolute magnitude of these three alternating stress intensities ($S_{\text{alt},12}$, $S_{\text{alt},23}$, and $S_{\text{alt},31}$) are the three ranges of shear stress that shall be considered in a fatigue analysis. Each will have an associated mean stress (determined below), which also influences the fatigue behavior.

KD-312.3 Associated Mean Stress.

(a) When using the design fatigue curves of Figure KD-320.2, Figure KD-320.3, Figure KD-320.5, or Figure KD-320.7 (Figure KD-320.2M, Figure KD-320.3M, Figure KD-320.5M, or Figure KD-320.7M), the mean stress shall not be combined with the alternating stress intensity [see KD-312.4(a)].

(b) When using the design fatigue curves of Figure KD-320.1 or Figure KD-320.4 (Figure KD-320.1M or Figure KD-320.4M), the associated mean stresses $\sigma_{nm,ij}$ shall be calculated in accordance with the following method.

The stresses σ_n normal to the plane of the maximum shear stress, associated with the three $S_{\text{alt},ij}$, are given by:

$$\sigma_{n,12} = 0.5(\sigma_1 + \sigma_2) \quad \text{(KD-312.5)}$$

$$\sigma_{n,23} = 0.5(\sigma_2 + \sigma_3) \quad \text{(KD-312.6)}$$

$$\sigma_{n,31} = 0.5(\sigma_3 + \sigma_1) \quad \text{(KD-312.7)}$$

In the following, the symbol $\sigma_{n,ij}$ is used to represent any one of these normal stresses.

Identify the maximum $\sigma_{n,ij,\max}$ and the minimum $\sigma_{n,ij,\min}$ value of each $\sigma_{n,ij}$ during the complete operating cycle. Then the mean normal stresses $\sigma_{nm,ij}$ shall be calculated by:

For autofrettaged vessels or nonautofrettaged vessel with compressive mean stress

(1) when $S_{ij,\max} < S_y$ and $S_{ij,\min} > -S_y$, then

$$\sigma_{nm,ij} = 0.5\left(\sigma_{ni,j,\max} + \sigma_{ni,j,\min}\right) \quad \text{(KD-312.8)}$$

(2) when $S_{\text{alt},ij} \geq S_y$, then

$$\sigma_{nm,ij} = 0 \quad \text{(KD-312.9)}$$

If neither (1) nor (2) applies, then the stress values used in this analysis shall be determined from an elastic–plastic analysis with ideally elastic–plastic (non-strain hardening) material using S_y. S_y is yield strength at operating temperature from Section II, Part D, Subpart 1, Table Y-1. Alternatively, $\sigma_{nm,ij}$ may be calculated as equal to $0.5(\sigma_{n,ij,\max} + \sigma_{n,ij,\min})$ but not less than zero.

For nonautofrettaged vessels with tensile mean stress

(3) when $S_{ij,\max} < S_y/2$ and $S_{ij,\min} > -S_y/2$, then

$$\sigma_{nm,ij} = 0.5\left(\sigma_{ni,j,\max} + \sigma_{ni,j,\min}\right) \quad \text{(KD-312.10)}$$

(4) when $S_{\text{alt},ij} \geq S_y/2$, then

$$\sigma_{nm,ij} = 0 \quad \text{(KD-312.11)}$$

If neither (3) nor (4) applies, then the stress values used in this analysis shall be determined from an elastic–plastic analysis with ideally elastic–plastic (non-strain hardening) material using $S_y/2$. Alternatively, $\sigma_{nm,ij}$ may be calculated as equal to 0.5 $(\sigma_{n,ij,\max} + \sigma_{n,ij,\min})$ but not less than 0.

KD-312.4 Equivalent Alternating Stress Intensity.

(a) For nonwelded construction made of carbon or low alloy steels when using the design fatigue curves of Figure KD-320.2 (Figure KD-320.2M), austenitic stainless steels [see Figure KD-320.3 (Figure KD-320.3M)], high-strength low alloy steel bolting [see Figure KD-320.5 (Figure KD-320.5M)], or aluminum alloys [see Figure KD-320.7 (Figure KD-320.7M)], effects of mean stress are incorporated in the design fatigue curves. Therefore:

$$S_{\text{eq},ij} = S_{\text{alt},ij} \quad \text{(KD-312.12)}$$

(b) For nonwelded construction made of carbon or low alloy steels when using the design fatigue curves of Figure KD-320.1 (Figure KD-320.1M) or 15-5PH/17-4PH stainless steels [see Figure KD-320.4 (Figure KD-320.4M)], the equivalent alternating stress intensity S_{eq}, which is assumed to have the same effect on fatigue as the combination of the alternating stress intensity S_{alt} and its associated mean stress σ_{nm}, shall be calculated in accordance with the equation:

$$S_{\text{eq},ij} = S_{\text{alt},ij}\,\frac{1}{1 - \beta\sigma_{nm,ij} / S'_a} \quad \text{(KD-312.13)}$$

where S'_a is the allowable amplitude of the alternating stress component when $\sigma_{nm} = 0$ and $N = 10^6$ cycles (see KD-321). The value of β shall be 0.2 for carbon or low alloy steel forged nonwelded construction [see Figure KD-320.1 (Figure KD-320.1M)]. The value of β shall be 0.2 for $\sigma_{nm,ij} \leq 0$ and 0.5 for $\sigma_{nm,ij} > 0$ for 17-4PH or 15-5PH stainless steel nonwelded construction using forgings or bar [see Figure KD-320.4 (Figure KD-320.4M)]. Other values of β may be used if justified by experimental evidence. If the values of $\beta\sigma_{nm,ij}/S'_a$ exceeds 0.9, limit its value to 0.9.

Using this equation, three values of $S_{\text{eq},ij}$ are obtained. The largest of these three shall be used in combination with the design fatigue curve to establish the number of design cycles in accordance with KD-322(a) or KD-322(f).

KD-313 CALCULATION OF FATIGUE STRESSES WHEN PRINCIPAL STRESS AXES CHANGE

When the directions of the principal stresses change during the loading cycle, the plane carrying the maximum range of shear stress may not be easily identified using equations based on principal stresses. If the maximum shear stress plane cannot be easily identified, the orientation of each plane at the point of interest can be defined by two angles and a convenient set of Cartesian axes. By varying this combination of angles in increments, it is possible to determine the range of shear stress on each plane. The largest of these shear stress ranges shall be considered to be the alternating stress intensity, S_{alt}, used in the calculation of design cycles. This procedure for determining the orientation of the plane is commonly known as the "Critical Plane Approach".

KD-320 CALCULATED NUMBER OF DESIGN CYCLES

The calculation of the number of design cycles N_f shall be based either on design fatigue curves described in KD-321 or on results of experimental fatigue tests on components as stated in KD-1260.

KD-321 BASIS FOR DESIGN FATIGUE CURVES

(a) The conditions and procedures of this paragraph are based on a comparison between the calculated equivalent alternating stress intensity S_{eq} and strain cycling fatigue data. The strain cycling fatigue data have been used to derive design fatigue curves. These curves show the allowable amplitude S_a of the alternating stress component (one-half of the alternating stress range) plotted against the number of design cycles N_f, which the component is assumed to safely endure without failure.

(b) The design fatigue curves have been derived from strain-controlled push–pull tests with zero mean stress (i.e., $\sigma_{nm} = 0$) on polished unnotched specimens in dry air. The imposed strains have been multiplied by the elastic modulus and a design margin has been provided so as to make the calculated equivalent stress intensity amplitude and the allowable stress amplitude directly comparable. S_{eq} and S_a have the dimensions of stress, but they do not represent a real stress when the elastic range is exceeded.

(c) The design fatigue curves for forged nonwelded construction presented in Figure KD-320.1 (Figure KD-320.1M) have been developed from fatigue tests in dry air with polished specimens of steels having an ultimate tensile strength in the range of 90 ksi to 180 ksi (620 MPa to 1 200 MPa). Fatigue tests with small cylinders pressurized from the inside by oil and made of low alloy steels having an ultimate tensile strength in the range of 130 ksi to 180 ksi (900 MPa to 1 200 MPa) have been used to confirm the validity of these curves for carbon or low alloy forgings with machined surfaces. For design fatigue curves, see Figure KD-320.1 and Table KD-320.1 (Figure KD-320.1M and Table KD-320.1M) for forged carbon or low alloy steel construction, Figure KD-320.2 (Figure KD-320.2M) for nonforged nonwelded carbon or low alloy steels having an ultimate tensile strength less than or equal to 130 ksi (896 MPa) and for forged nonwelded carbon or low alloy steels having an ultimate tensile strength less than 90 ksi (620 MPa), Figure KD-320.3 (Figure KD-320.3M) for austenitic stainless steel construction, Figure KD-320.4 (Figure KD-320.4M) for 17-4PH or 15-5PH stainless steel construction, Figure KD-320.5 (Figure KD-320.5M) for high-strength low alloy steel bolting, and Figure KD-320.7 (Figure KD-320.7M) for aluminum alloy construction.

(d) The design fatigue curves are not applicable in the presence of aggressive environments. For conditions not covered by these design fatigue curves, the Manufacturer shall provide supplementary fatigue data.

KD-322 USE OF DESIGN FATIGUE CURVE

The fatigue strength reduction factor, K_f, which accounts for the effect of a local structural discontinuity, shall be included in a fatigue analysis if the local effect is not accounted for in the numerical model. Recommended values of K_f for threaded connections are provided in (f). If the local effect is accounted for in the numerical model, then $K_f = 1.0$.

Interpolation between tabular values for individual design fatigue curves in Table KD-320.1 (Table KD-320.1M) is permissible based upon data representation by straight lines on a log–log plot. The design fatigue curve values for Figures KD-320.1 and KD-320.2 (Figures KD-320.1M and KD-320.2M) may be linearly interpolated for intermediate values of the ultimate tensile strength.

(a) Figure KD-320.1 (Figure KD-320.1M) shall be used for forged nonwelded parts with machined surfaces made of carbon or low alloy steels having a specified minimum value of the ultimate tensile strength S_u greater than 90 ksi (620 MPa). The curves are applicable for an average surface roughness of $19R_a$ μin. ($0.5R_a$ μm) or a maximum surface roughness of 59 μin. (1.5 μm) R_{max} (peak-to-valley height) in fatigue-sensitive areas. Lower quality surface finish will influence fatigue. This influence is considered by a factor K_r {see Figure KD-320.6(a) or Figure KD-320.6(b) [Figure KD-320.6M(a)

or Figure KD-320.6M(b)]}, which shall be combined with S_{eq} as specified in (g) when determining the calculated number of design cycles N_f.

(b) Figure KD-320.2 (Figure KD-320.2M) shall be used for nonforged nonwelded parts with machined surfaces made of carbon or low alloy steels having an ultimate tensile strength less than or equal to 130 ksi (896 MPa), and for forged nonwelded parts with machined surfaces made of carbon or low alloy steels having an ultimate tensile strength less than 90 ksi (620 MPa). The influence of the surface roughness is included in the curve, i.e., K_r = 1.0; therefore, a surface roughness factor need not be applied.

(c) Figure KD-320.3 (Figure KD-320.3M) shall be used for forged nonwelded parts with machined surfaces made of austenitic stainless steels. The influence of the surface roughness is included in the curve, i.e., K_r = 1.0; therefore, a surface roughness factor need not be applied.

(d) Figure KD-320.4 (Figure KD-320.4M)shall be used for nonwelded parts with machined surfaces made of 17-4PH/15-5PH stainless steel having ultimate tensile strength S_u of 115 ksi (793 MPa) or greater. The curve is applicable for an average surface roughness of 19 R_a μin. (0.5 μm) or a maximum surface roughness of 59 μin. (1.5 μm) R_{max} in fatigue-sensitive areas. Lower quality surface finish will influence fatigue. This influence is considered by a factor K_r {see Figure KD-320.6(a) or Figure KD-320.6(b) [Figure KD-320.6M(a) or Figure KD-320.6M(b)]}, which shall be combined with S_{eq} as specified in (f) when determining the calculated number of design cycles N_f.

(e) Figure KD-320.7 (Figure KD-320.7M) shall be used for nonwelded 6061-T6 and 6061-T651 aluminum alloys.

(f) High-strength alloy steel bolts and studs may be evaluated for cyclic operation by the methods of Article KD-3 using the design fatigue curve of Figure KD-320.5 (Figure KD-320.5M), provided

(1) the material is one of the following:

(-a) SA-193, Grade B7; SA-193, B16; SA-320, L7

(-b) SA-320, L7M and SA-320, L43

(2) V-type threads shall have a minimum thread root radius no smaller than 0.032 times the pitch, and in no case smaller than 0.004 in. (0.102 mm).

(3) fillet radii at the end of the shank shall be such that the ratio of the fillet radius to shank diameter is not less than 0.060.

The bolt stress shall be determined using the root area. Unless it can be shown by analysis or test that a lower value is appropriate, the fatigue strength reduction factor for V-type threads, K_f, shall be not less than 4.0 for cut thread and 3.0 for rolled threads. K_r may be assumed to be 1.0 when Figure KD-320.5 (Figure KD-320.5M) is used. The designer should use caution in calculating bolt load from applied torque. The designer shall consider that corrosion effects on a bolted connection can reduce bolt fatigue life.

(g) When the operational cycle being considered is the only one that produces significant fluctuating stresses, the calculated number of design cycles N_f is determined as follows.

(1) Evaluate the fatigue penalty factor, K_e, using ΔS_n and the following equations where parameters m and n are determined from Table KD-322.1:

$$K_e = 1.0 \text{ for } \Delta S_n \le 2S_y \tag{KD-322.1}$$

$$K_e = 1.0 + \frac{(1-n)}{n(m-1)}\left(\frac{\Delta S_n}{2S_y} - 1\right) \text{ for } 2S_y < \Delta S_n < 2mS_y \tag{KD-322.2}$$

$$K_e = \frac{1}{n} \text{ for } \Delta S_n \ge 2mS_y \tag{KD-322.3}$$

where ΔS_n is the primary-plus-secondary ($P_L + P_b + Q$) stress intensity range.

Otherwise, the alternate method given in KD-323 may be used to calculate K_e.

(2) Identify the applicable fatigue curve for the material as explained in (a).

(3) Enter the curve from the ordinate axis at the value:

$$S_a = K_f K_r K_e S_{eq} \frac{E(\text{curve})}{E(\text{analysis})} \tag{KD-322.4}$$

where

E(curve) = Modulus of Elasticity given on the Design Fatigue Curve
E(analysis) = Modulus of Elasticity used in the analysis

(4) Read the corresponding number of cycles on the abscissa. This is the calculated number of design cycles N_f.

KD-323 ALTERNATIVE METHOD FOR EVALUATING THE FATIGUE PENALTY FACTOR, K_E

The fatigue penalty factor, K_e, may be calculated using the following operations:

$$K_e = \frac{(\Delta\varepsilon_p)_{ep} + (\Delta\varepsilon_t)_e}{(\Delta\varepsilon_t)_e} \tag{KD-323.1}$$

where

$$(\Delta\varepsilon_p)_{ep} = \frac{\sqrt{2}}{3}\Big[(\Delta\varepsilon_{p,11} - \Delta\varepsilon_{p,22})^2 + (\Delta\varepsilon_{p,22} - \Delta\varepsilon_{p,33})^2 + (\Delta\varepsilon_{p,33} - \Delta\varepsilon_{p,11})^2 + 1.5(\Delta\varepsilon_{p,12}^2 + \Delta\varepsilon_{p,23}^2 + \Delta\varepsilon_{p,31}^2)\Big]^{0.5} \tag{KD-323.2}$$

$$(\Delta\varepsilon_t)_e = \frac{\Delta\sigma_e}{E_{ya}} \tag{KD-323.3}$$

$$\Delta\sigma_e = \frac{1}{\sqrt{2}}[(\Delta\sigma_1 - \Delta\sigma_2)^2 + (\Delta\sigma_2 - \Delta\sigma_3)^2 + (\Delta\sigma_3 - \Delta\sigma_1)^2]^{0.5} \tag{KD-323.4}$$

and where

E_{ya} = the modulus of elasticity at the point under consideration, evaluated at the mean temperature of the cycle
$(\Delta\varepsilon_p)_{ep}$ = the equivalent plastic strain range from the elastic–plastic analysis for the points of interest
$(\Delta\varepsilon_t)_e$ = the equivalent total strain range from the elastic analysis for the points of interest
$\Delta\sigma_e$ = the range of primary-plus-secondary-plus-peak equivalent stress

However, if using this alternative method, K_e = 1.0 if shakedown is shown in accordance with KD-234.

KD-330 CALCULATED CUMULATIVE EFFECT NUMBER OF DESIGN CYCLES

If there are two or more types of stress cycles which produce significant stresses, the alternating stress intensity and the associated mean stress shall be calculated for each type of stress cycle. The cumulative effect of all of the stress cycles shall be evaluated using a linear damage relationship as specified in (a) through (e).

(a) Determine the number of times each type of stress cycle of type 1, 2, 3, etc., will be repeated during a specific design service life period based on the expected useful operating life specified in the User's Design Specification; designate these numbers n_1, n_2, n_3, etc., or generally n_i.

(b) For each type of stress cycle, determine S_a by the procedures given in KD-312.4. Designate these quantities $S_{a,1}$, $S_{a,2}$, $S_{a,3}$, etc., or generally $S_{a,i}$.

(c) For each value $S_{a,i}$, use the applicable design fatigue curve to determine the maximum number of design repetitions N_i if this type of cycle were the only one acting. Designate these as N_1, N_2, N_3, etc., or generally N_i.

(d) For each type of stress cycle, calculate the usage factor $U_i = n_i/N_i$.

(e) Calculate the cumulative usage factor from:

$$U = \sum_{i=1}^{i} \frac{n_i}{N_i}, \text{ or } = U_1 + U_2 \ldots \tag{KD-330.1}$$

The cumulative usage factor U shall not exceed 1.0.

KD-340 FATIGUE ASSESSMENT OF WELDS — ELASTIC ANALYSIS AND STRUCTURAL STRESS

(a) An equivalent structural stress range parameter is used to evaluate the fatigue damage for results obtained from a linear elastic stress analysis. The controlling stress for the fatigue evaluation is the structural stress that is a function of the membrane and bending stresses normal to the hypothetical crack plane.

(b) Fatigue cracks at pressure vessel welds are typically located at the toe of a weld. For as-welded and weld joints subject to post weld heat treatment, the expected orientation of a fatigue crack is along the weld toe in the through-thickness direction, and the structural stress normal to the expected crack is the stress measure used to correlate fatigue life data. For fillet welded components, fatigue cracking may occur at the toe of the fillet weld or the weld throat, and both locations shall be considered in the assessment. It is difficult to accurately predict fatigue life at the weld throat due to variability in throat dimension, which is a function of the depth of the weld penetration. It is recommended to perform sensitivity analysis where the weld throat dimension is varied.

KD-341 ASSESSMENT PROCEDURE

The following procedure can be used to evaluate protection against failure due to cyclic loading using the equivalent structural stress range.

Step 1. Determine a load history based on the information in the User's Design Specification and the histogram development methods in KD-350. The load history should include all significant operating loads and events that are applied to the component.

Step 2. For a location at a weld joint subject to a fatigue evaluation, determine the individual stress–strain cycles using the cycle counting methods in KD-350. Define the total number of cyclic stress ranges in the histogram as M.

Step 3. Determine the elastically calculated membrane and bending stress normal to the assumed hypothetical crack plane at the start and end points (time points ${}^{m}t$ and ${}^{n}t$, respectively) for the kth cycle counted in Step 2. See Section VIII, Division 2, Annex 5-A for guidance on linearization of stress results to obtain membrane and bending stresses. Using this data, calculate the membrane and bending stress ranges between time points ${}^{m}t$ and ${}^{n}t$, and the maximum, minimum, and mean stress.

$$\Delta\sigma^{e}_{m,k} = \left({}^{m}\sigma^{e}_{m,k} + {}^{m}P_k\right) - \left({}^{n}\sigma^{e}_{m,k} + {}^{n}P_k\right) \tag{KD-341.1}$$

$$\Delta\sigma^{e}_{b,k} = {}^{m}\sigma^{e}_{b,k} - {}^{n}\sigma^{e}_{b,k} \tag{KD-341.2}$$

$$\sigma_{\max,k} = \max\left[\left({}^{m}\sigma^{e}_{m,k} + {}^{m}P_k + {}^{m}\sigma^{e}_{b,k}\right),\ \left({}^{n}\sigma^{e}_{m,k} + {}^{n}P_k + {}^{n}\sigma^{e}_{b,k}\right)\right] \tag{KD-341.3}$$

$$\sigma_{\min,k} = \min\left[\left({}^{m}\sigma^{e}_{m,k} + {}^{m}P_k + {}^{m}\sigma^{e}_{b,k}\right),\ \left({}^{n}\sigma^{e}_{m,k} + {}^{n}P_k + {}^{n}\sigma^{e}_{b,k}\right)\right] \tag{KD-341.4}$$

$$\sigma_{\text{mean},k} = \frac{\sigma_{\max,k} + \sigma_{\min,k}}{2} \tag{KD-341.5}$$

Step 4. Determine the elastically calculated structural stress range for the kth cycle, $\Delta\sigma^{e}_{k}$, using eq. (KD-341.6).

$$\Delta\sigma^{e}_{k} = \Delta\sigma^{e}_{m,k} + \Delta\sigma^{e}_{b,k} \tag{KD-341.6}$$

Step 5. Determine the elastically calculated structural strain, $\Delta\varepsilon^{e}_{k}$, from the elastically calculated structural stress, $\Delta\sigma^{e}_{k}$, using eq. (KD-341.7).

$$\Delta\varepsilon^{e}_{k} = \frac{\Delta\sigma^{e}_{k}}{E_{ya,k}} \tag{KD-341.7}$$

The corresponding local nonlinear structural stress and strain ranges, $\Delta\sigma_k$ and $\Delta\varepsilon_k$, respectively, are determined by simultaneously solving Neuber's Rule, eq. (KD-341.8), and a model for the material hysteresis loop stress–strain curve given by eq. (KD-341.9); see KM-630.

$$\Delta\sigma_k \bullet \Delta\varepsilon_k = \Delta\sigma^{e}_{k} \bullet \Delta\varepsilon^{e}_{k} \tag{KD-341.8}$$

$$\Delta\varepsilon_k = \frac{\Delta\sigma_k}{E_{ya,k}} + 2\left(\frac{\Delta\sigma_k}{2K_{css}}\right)^{\frac{1}{n_{css}}} \tag{KD-341.9}$$

The structural stress range computed solving eqs. (KD-341.8) and (KD-341.9) is subsequently modified for low-cycle fatigue using eq. (KD-341.10).

$$\Delta\sigma_k = \left(\frac{E_{ya,k}}{1-\nu^2}\right)\Delta\varepsilon_k \tag{KD-341.10}$$

NOTE: The modification for low-cycle fatigue should always be performed because the exact distinction between high-cycle fatigue and low-cycle fatigue cannot be determined without evaluating the effects of plasticity which is a function of the applied stress range and cyclic stress–strain curve. For high-cycle fatigue applications, this procedure will provide correct results, i.e., the elastically calculated structural stress will not be modified.

Step 6. Compute the equivalent structural stress range parameter for the kth cycle using the following equations. In eq. (KD-341.11), for SI units, the thickness, t, stress range, $\Delta\sigma_k$, and the equivalent structural stress range parameter, $\Delta S_{ess,k}$, are in mm, MPa, and MPa/(mm)$^{(2-m_n)/2m_n}$, respectively, and for U.S. Customary units, the thickness, t, stress range, $\Delta\sigma_k$, and the equivalent structural stress range parameter, $\Delta S_{ess,k}$, are in in., ksi, and ksi/(in.)$^{(2-m_n)/2m_n}$, respectively.

$$\Delta S_{ess,k} = \frac{\Delta\sigma_k}{t_{ess}^{\left(\frac{2-m_{ss}}{2m_{ss}}\right)} \bullet I^{\frac{1}{m_{ss}}} \bullet f_{M,k}} \tag{KD-341.11}$$

where

$$m_{ss} = 3.6 \tag{KD-341.12}$$

$$t_{ess} = 16\text{ mm (0.625 in.)} \text{ for } t \le 16\text{ mm (0.625 in.)} \tag{KD-341.13}$$

$$t_{ess} = t \text{ for } 16\text{ mm (0.625 in.)} < t < 150\text{ mm (6 in.)} \tag{KD-341.14}$$

$$t_{ess} = 150\text{ mm (6 in.)} \text{ for } t \ge 150\text{ mm (6 in.)} \tag{KD-341.15}$$

$$I^{\frac{1}{m_{ss}}} = \frac{1.23 - 0.364R_{b,k} - 0.17R_{b,k}^2}{1.007 - 0.306R_{b,k} - 0.178R_{b,k}^2} \tag{KD-341.16}$$

$$R_{b,k} = \frac{\left|\Delta\sigma_{b,k}^e\right|}{\left|\Delta\sigma_{m,k}^e\right| + \left|\Delta\sigma_{b,k}^e\right|} \tag{KD-341.17}$$

$$f_{M,k} = (1 - R_k)^{\frac{1}{m_{ss}}} \text{ for } \begin{vmatrix} \sigma_{\text{mean},k} \ge 0.5S_{y,k}, \text{ and} \\ R_k > 0, \text{ and} \\ \left|\Delta\sigma_{m,k}^e + \Delta\sigma_{b,k}^e\right| \le 2S_{y,k} \end{vmatrix} \tag{KD-341.18}$$

$$f_{M,k} = 1.0 \text{ for } \begin{vmatrix} \sigma_{\text{mean},k} < 0.5S_{y,k}, \text{ or} \\ R_k \le 0, \text{ or} \\ \left|\Delta\sigma_{m,k}^e + \Delta\sigma_{b,k}^e\right| > 2S_{y,k} \end{vmatrix} \tag{KD-341.19}$$

$$R_k = \frac{\sigma_{\min.k}}{\sigma_{\max,k}} \tag{KD-341.20}$$

Step 7. Determine the permissible number of cycles, N_k, based on the equivalent structural stress range parameter for the kth cycle computed in Step 6. Fatigue curves for welded joints are provided in KD-370.

Step 8. Determine the fatigue damage for the kth cycle, where the actual number of repetitions of the kth cycle is n_k.

$$D_{f,k} = \frac{n_k}{N_k} \tag{KD-341.21}$$

Step 9. Repeat Steps 6 through 8 for all stress ranges, M, identified in the cycle counting process in Step 3.

Step 10. Compute the accumulated fatigue damage using the following equation. The location along the weld joint is suitable for continued operation if this equation is satisfied.

$$D_f = \sum_{i=1}^{M} D_{f,k} \leq 1.0 \tag{KD-341.22}$$

Step 11. Repeat Steps 5 through 10 for each point along the weld joint that is subject to a fatigue evaluation.

KD-342 ASSESSMENT PROCEDURE MODIFICATIONS

The assessment procedure in KD-341 may be modified as shown below.

(a) Multiaxial Fatigue. If the structural shear stress range is not negligible, i.e., $\Delta\tau_k > \Delta\sigma_k/3$, a modification should be made when computing the equivalent structural stress range. Two conditions need to be considered:

(1) If $\Delta\sigma_k$ and $\Delta\tau_k$ are out of phase, the equivalent structural stress range, $\Delta S_{ess,k}$, in Step 6, eq. (KD-341.11) should be replaced by

$$\Delta S_{ess,k} = \frac{1}{F(\delta)}\left[\left(\frac{\Delta\sigma_k}{t_{ess}^{\left(\frac{2-m_{ss}}{2m_{ss}}\right)} \bullet I_{\tau}^{\frac{1}{m_{ss}}} \bullet f_{M,k}}\right)^2 + 3\left(\frac{\Delta\tau_k}{t_{ess}^{\left(\frac{2-m_{ss}}{2m_{ss}}\right)} \bullet I_{\tau}^{\frac{1}{m_{ss}}}}\right)^2\right]^{0.5} \tag{KD-342.1}$$

where

$$I_{\tau}^{\frac{1}{m_{ss}}} = \frac{1.23 - 0.364R_{b\tau,k} - 0.17R_{b\tau,k}^2}{1.007 - 0.306R_{b,\tau,k} - 0.178R_{b\tau,k}^2} \tag{KD-342.2}$$

$$R_{b\tau,k} = \frac{\left|\Delta\tau_{b,k}^e\right|}{\left|\Delta\tau_{m,k}^e\right| + \left|\Delta\tau_{b,k}^e\right|} \tag{KD-342.3}$$

$$\Delta\tau_k = \Delta\tau_{m,k}^e + \Delta\tau_{b,k}^e \tag{KD-342.4}$$

$$\Delta\tau_{m,k}^e = {}^m\tau_{m,k}^e - {}^n\tau_{m,k}^e \tag{KD-342.5}$$

$$\Delta\tau_{b,k}^e = {}^m\tau_{b,k}^e - {}^n\tau_{b,k}^e \tag{KD-342.6}$$

In eq. (KD-342.1), $F(\delta)$ is a function of the out-of-phase angle between $\Delta\sigma_k$ and $\Delta\tau_k$ if both loading modes can be described by sinusoidal functions, or:

$$F(\delta) = \frac{1}{\sqrt{2}}\left(1 + \left[1 - \frac{12 \bullet \Delta\sigma_k^2 \bullet \Delta\tau_k^2 \bullet \sin^2(\delta)}{\left(\Delta\sigma_k^2 + 3\Delta\tau_k^2\right)^2}\right]^{0.5}\right)^{0.5} \tag{KD-342.7}$$

A conservative approach is to ignore the out-of-phase angle and recognize the existence of a minimum possible value for $F(\delta)$ in eq. (KD-342.7) given by:

$$F(\delta) = \frac{1}{\sqrt{2}} \tag{KD-342.8}$$

(2) If $\Delta\sigma_k$ and $\Delta\tau_k$ are in-phase, the equivalent structural stress range, $\Delta S_{ess,k}$, is given by eq. (KD-342.1) with $F(\delta)$ = 1.0.

(b) Weld Quality. If a defect exists at the toe of a weld that can be characterized as a crack-like flaw, i.e., undercut, and this defect exceeds the value permitted by ASME Section VIII, Division 2, Part 7, then a reduction in fatigue life shall be calculated by substituting the value of I^{1/m_n} in eqs. (KD-341.16) and (a)(1)(KD-342.2) with the value given by eq. (KD-342.9). In this equation, a is the depth of the crack-like flaw at the weld toe. Equation (KD-342.9) is valid only when $a/t \le 0.1$.

$$\frac{1}{I^{m_{ss}}} = \frac{1.229 - 0.365R_{b,k} + 0.789\left(\frac{a}{t}\right) - 0.17R_{b,k}^2 + 13.771\left(\frac{a}{t}\right)^2 + 1.243R_{b,k}\left(\frac{a}{t}\right)}{1 - 0.302R_{b,k} + 7.115\left(\frac{a}{t}\right) - 0.178R_{b,k}^2 + 12.903\left(\frac{a}{t}\right)^2 - 4.091R_{b,k}\left(\frac{a}{t}\right)} \quad \text{(KD-342.9)}$$

KD-350 HISTOGRAM DEVELOPMENT AND CYCLE COUNTING FOR FATIGUE ANALYSIS

This paragraph contains cycle counting procedures required to perform a fatigue assessment for irregular stress or strain versus time histories. These procedures are used to break the loading history down into individual cycles that can be evaluated using the fatigue assessment rules of KD-340. Two cycle counting methods are presented in this paragraph. An alternative cycle counting method may be used if agreed to by the Owner-User.

KD-351 DEFINITIONS

The definitions used in this section are shown below.

cycle: a relationship between stress and strain that is established by the specified loading at a location in a vessel or component. More than one stress–strain cycle may be produced at a location, either within an event or in transition between two events, and the accumulated fatigue damage of the stress–strain cycles determines the adequacy for the specified operation at that location. This determination shall be made with respect to the stabilized stress–strain cycle.

event: the User's Design Specification may include one or more events that produce fatigue damage. Each event consists of loading components specified at a number of time points over a time period and is repeated a specified number of times. For example, an event may be the startup, shutdown, upset condition, or any other cyclic action. The sequence of multiple events may be specified or random.

nonproportional loading: if the orientation of the principal axes are not fixed, but changes orientation during cyclic loading, the loading is called nonproportional. An example of nonproportional loading is a shaft subjected to out-of-phase torsion and bending, where the ratio of axial and torsional stress varies continuously during cycling.

peak: the point at which the first derivative of the loading or stress histogram changes from positive to negative.

proportional loading: during constant amplitude loading, as the magnitudes of the applied stresses vary with time, the size of Mohr's circle of stress also varies with time. In some cases, even though the size of Mohr's circle varies during cyclic loading, if the orientation of the principal axes remains fixed, the loading is called proportional. An example of proportional loading is a shaft subjected to in-phase torsion and bending, where the ratio of axial and torsional stress remains constant during cycling.

valley: the point at which the first derivative of the loading or stress histogram changes from negative to positive.

KD-352 HISTOGRAM DEVELOPMENT

The loading histogram should be determined based on the specified loadings provided in the User's Design Specification. The loading histogram should include all significant operating loads and events that are applied to the component. The following should be considered in developing the loading histogram:

(a) The number of repetitions of each event during the operation life.

(b) The sequence of events during the operation life, if applicable.

(c) Applicable loadings such as pressure, temperature, supplemental loads such as weight, support displacements, and nozzle reaction loadings.

(d) The relationship between the applied loadings during the time history.

KD-353 CYCLE COUNTING USING THE RAINFLOW METHOD

The Rainflow Cycle Counting Method ASTM E1049 is recommended to determine the time points representing individual cycles for the case of situations where the variation in time of loading, stress, or strain can be represented by a single parameter. This cycle counting method is not applicable for nonproportional loading. Cycles counted with the Rainflow Method correspond to closed stress–strain hysteresis loops, with each loop representing a cycle.

KD-353.1 Recommended Procedure.

Step 1. Determine the sequence of peaks and valleys in the loading histogram. If multiple loadings are applied, it may be necessary to determine the sequence of peaks and valleys using a stress histogram. If the sequence of events is unknown, the worst case sequence should be chosen.

Step 2. Reorder the loading histogram to start and end at either the highest peak or lowest valley, so that only full cycles are counted. Determine the sequence of peaks and valleys in the loading history. Let X denote the range under consideration, and let Y denote the previous range adjacent to X.

Step 3. Read the next peak or valley. If out of data, go to Step 8.

Step 4. If there are less than three points, go to Step 3; if not, form ranges X and Y using the three most recent peaks and valleys that have not been discarded.

Step 5. Compare the absolute values of ranges X and Y.

(a) If $X < Y$, go to Step 3

(b) If $X \geq Y$, go to Step 6

Step 6. Count range Y as one cycle; discard the peak and valley of Y. Record the time points and loadings or component stresses, as applicable, at the starting and ending time points of the cycle.

Step 7. Return to Step 4 and repeat Steps 4 through 6 until no more time points with stress reversals remain.

Step 8. Using the data recorded for the counted cycles, perform fatigue assessment in accordance with this Article.

KD-354 CYCLE COUNTING USING MAX-MIN CYCLE COUNTING METHOD

The Max-Min Cycle Counting Method is recommended to determine the time points representing individual cycles for the case of nonproportional loading. The cycle counting is performed by first constructing the largest possible cycle, using the highest peak and lowest valley, followed by the second largest cycle, etc., until all peak counts are used.

KD-354.1 Recommended Procedure.

Step 1. Determine the sequence of peaks and valleys in the loading history. If some events are known to follow each other, group them together, but otherwise arrange the random events in any order.

Step 2. Calculate the elastic stress components, σ_{ij}, produced by the applied loading at every point in time during each event at a selected location of a vessel. All stress components must be referred to the same global coordinate system. The stress analysis must include peak stresses at local discontinuities.

Step 3. Scan the interior points of each event and delete the time points at which none of the stress components indicate reversals (peaks or valleys).

Step 4. Using the stress histogram from Step 2, determine the time point with the highest peak or lowest valley. Designate the time point as ${}^{m}t$, and the stress components as ${}^{m}\sigma_{ij}$.

Step 5. If time point ${}^{m}t$ is a peak in the stress histogram, determine the component stress range between time point ${}^{m}t$ and the next valley in the stress histogram. If time point ${}^{m}t$ is a valley, determine the component stress range between time point ${}^{m}t$ and the next peak. Designate the next time point as ${}^{n}t$, and the stress components as ${}^{n}\sigma_{ij}$. Calculate the stress component ranges and the equivalent stress range between time points ${}^{m}t$ and ${}^{n}t$.

$$ {}^{mn}\Delta\sigma_{ij} = {}^{m}\sigma_{ij} - {}^{n}\sigma_{ij} \tag{KD-354.1} $$

$$ {}^{mn}\Delta S_{\text{range}} = \frac{1}{\sqrt{2}}\left[\left({}^{mn}\Delta\sigma_{11} - {}^{mn}\Delta\sigma_{22}\right)^2 + \left({}^{mn}\Delta\sigma_{22} - {}^{mn}\Delta\sigma_{33}\right)^2 + \left({}^{mn}\Delta\sigma_{33} - {}^{mn}\Delta\sigma_{11}\right)^2 + 6\left({}^{mn}\Delta\sigma_{12}^2 + {}^{mn}\Delta\sigma_{23}^2 + {}^{mn}\Delta\sigma_{31}^2\right)\right]^{0.5} \tag{KD-354.2} $$

Step 6. Repeat Step 5 for the current point, ${}^{m}t$, and the time point of the next peak or valley in the sequence of the stress histogram. Repeat this process for every remaining time point in the stress histogram.

Step 7. Determine the maximum equivalent stress range obtained in Step 5 and record the time points ${}^{m}t$ and ${}^{n}t$ that define the start and end points of the kth cycle.

Step 8. Determine the event or events to which the time points ${}^{m}t$ and ${}^{n}t$ belong and record their specified number of repetitions as ${}^{m}N$ and ${}^{n}N$, respectively.

Step 9. Determine the number of repetitions of the kth cycle.

(a) If ${}^{m}N < {}^{n}N$, delete the time point ${}^{m}t$ from those considered in Step 4 and reduce the number of repetitions at time point ${}^{n}t$ from ${}^{n}N$ to $({}^{n}N - {}^{m}N)$.

(b) If ${}^{m}N > {}^{n}N$, delete the time point ${}^{n}t$ from those considered in Step 4 and reduce the number of repetitions at time point ${}^{m}t$ from ${}^{m}N$ to $({}^{m}N - {}^{n}N)$.

(c) If ${}^{m}N = {}^{n}N$, delete both time points ${}^{m}t$ and ${}^{n}t$ from those considered in Step 4.

Step 10. Return to Step 4 and repeat Steps 4 through 10 until no more time points with stress reversals remain.

Step 11. Using the data recorded for the counted cycles, perform fatigue assessment in accordance with this Article.

KD-370 WELDED JOINT DESIGN FATIGUE CURVES

KD-371 FATIGUE CURVE MATERIALS

Subject to the limitations of KD-340, eq. (KD-372.1) in KD-372(a) can be used to evaluate design fatigue life of welded joints for the following materials and associated temperature limits:

(a) Carbon, Low Alloy, Series 4xx, and High Tensile Strength Steels for temperatures not exceeding 700°F (371°C)

(b) Series 3xx High Alloy Steels, Nickel-Chromium-Iron Alloy, Nickel-Iron-Chromium Alloy, and Nickel-Copper Alloy for temperatures not exceeding 800°F (427°C)

(c) Wrought 70 Copper-Nickel for temperatures not exceeding 450°F (232°C)

(d) Nickel-Chromium-Molybdenum-Iron, Alloys X, G, C-4, and C-276 for temperatures not exceeding 800°F (427°C)

(e) Aluminum Alloys for temperatures not exceeding 225°F (107°C)

KD-372 DESIGN CYCLE COMPUTATION

The number of allowable design cycles for the welded joint fatigue curve shall be computed as follows:

(a) The design number of allowable design cycles, N, can be computed from eq. (KD-372.1) based on the equivalent structural stress range parameter, $\Delta S_{ess,k}$, determined in accordance with KD-340 of this Division. The constants C and h for use in eq. (KD-372.1) are provided in Table KM-630.1 (Table KM-630.1M). The lower 99% Prediction Interval (-3σ) shall be used for design unless otherwise agreed to by the Owner-User and the Manufacturer.

$$N = \frac{f_I}{f_E}\left(\frac{f_{MT} \bullet C}{\Delta S_{ess,k}}\right)^{\frac{1}{h}} \tag{KD-372.1}$$

(b) If a fatigue improvement method is performed that exceeds the fabrication requirements of this Division, then a fatigue improvement factor, f_I, may be applied. The fatigue improvement factors shown below may be used. An alternative factor determined may also be used if agreed to by the User or User's designated agent and the Manufacturer.

(1) For burr grinding in accordance with Figure KD-372.1

$$f_I = 1.0 + 2.5 \bullet (10)^q \tag{KD-372.2}$$

(2) For TIG dressing

$$f_I = 1.0 + 2.5 \bullet (10)^q \tag{KD-372.3}$$

(3) For hammer peening

$$f_I = 1.0 + 4.0 \bullet (10)^q \tag{KD-372.4}$$

In the above equations, the parameter q is given by the following equation:

$$q = -0.0016 \bullet \left(\frac{\Delta S_{ess,k}}{C_{us}}\right)^{1.6} \tag{KD-372.5}$$

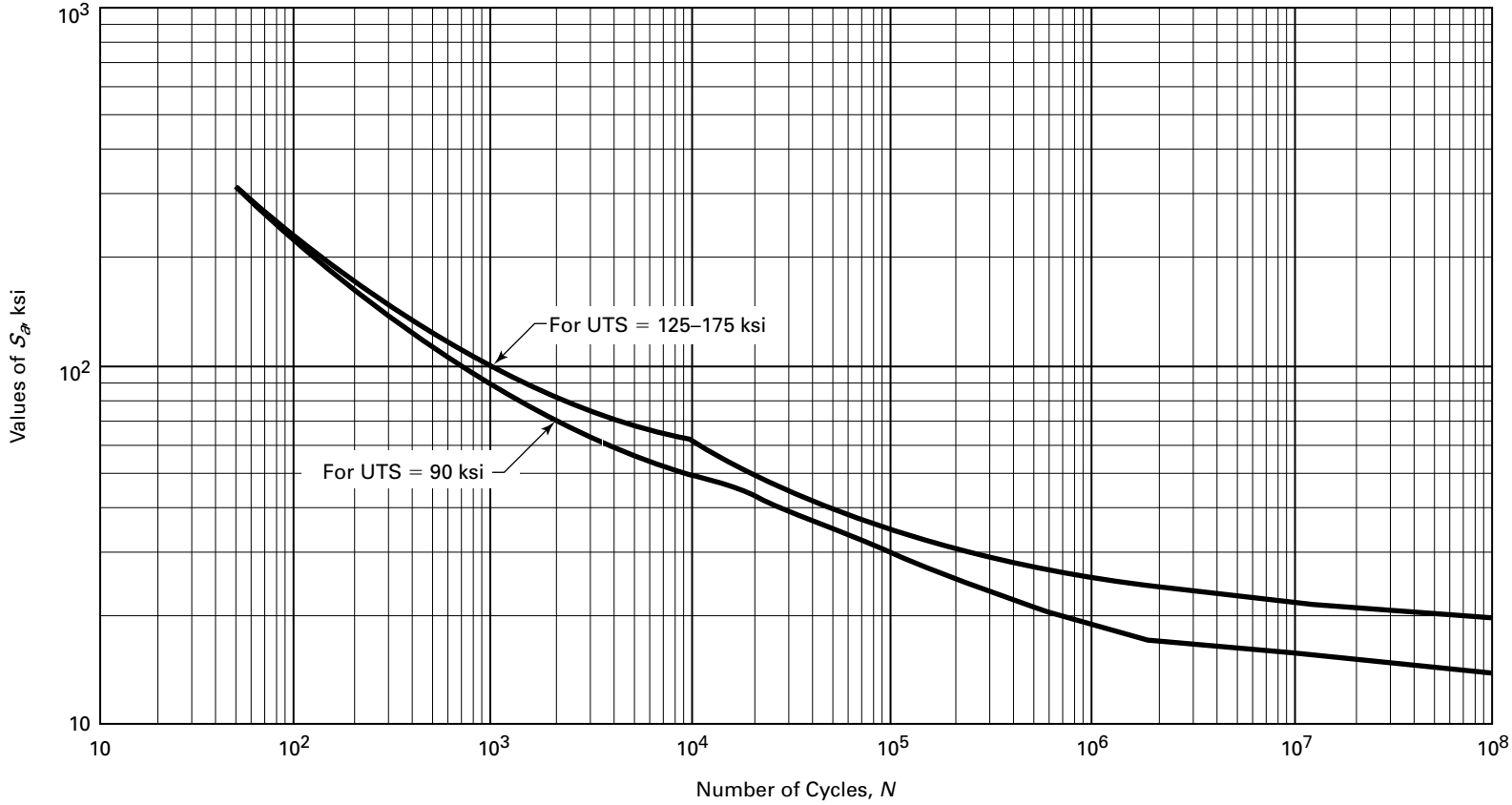
(c) The design fatigue cycles given by eq. (KD-372.1) may be modified to account for the effects of environment other than dry ambient air that may cause corrosion or subcritical crack propogation. The environmental modification factor, f_E, is typically a function of the fluid environment, loading frequency, temperature, and material variables such as grain size

and chemical composition. A value of f_E = 4.0 shall be used unless there is specific information to justify an alternate value based on the severity of the material/environmental interaction. A value of f_E = 1.0 may be used for dry ambient air. The environmental modification factor, f_E, shall be specified in the User's Design Specification.

(d) A temperature adjustment is required to the fatigue curve for materials other than carbon steel and/or for temperatures above 21°C (70°F). The temperature adjustment factor is given by eq. (KD-372.6).

$$f_{MT} = \frac{E_T}{E_{ACS}} \tag{KD-372.6}$$

Figure KD-320.1
Design Fatigue Curves $S_a = f(N_f)$ for Nonwelded Machined Parts Made of Forged Carbon or Low Alloy Steels for Temperatures Not Exceeding 700°F



GENERAL NOTES:
(a) $E = 28.3 \times 10^6$ psi
(b) Interpolate for UTS = 90 ksi to 125 ksi.
(c) Table KD-320.1 contains tabulated values and equations for these curves, and an equation for an accurate interpolation of these curves.

(25)

Table KD-320.1
Tabulated Values of S_a, ksi, From Figures Indicated

		Number of Design Operating Cycles, N_f																		
Figure	**Curve**	**5E1**	**1E2**	**2E2**	**5E2**	**1E3**	**2E3**	**5E3**	**1E4**	**2E4**	**5E4**	**1E5**	**2E5**	**5E5**	**1E6**	**2E6**	**5E6**	**1E7**	**2E7**	**5E7**	**1E8**
320.1	UTS 90 ksi	311	226	164	113	89	72	57	49	43	34	29	25	21	19	17	16.2	15.7	15.2	14.5	14
320.1	UTS 125 ksi	317	233	171	121	98	82	68	61	49	39	34	31	28	26	24	22.9	22.1	21.4	20.4	19.7
320.2	UTS ≤ 80 ksi	275	205	155	105	83	64	48	38	31	23	20	16.5	13.5	12.5	12.1	11.5	11.1	10.8	10.3	9.9
320.2	UTS 115–130 ksi	230	175	135	100	78	62	49	44	36	29	26	24	22	20	19.3	18.5	17.8	17.2	16.4	15.9
320.3	[Note (1)]	378	275	204	142	110	87	65	52	43	34	28.9	24.6	20.4	18.0	16.2	14.89	14.39	14.3	14.18	14.10
320.4	17-4PH/15-5PH stainless steel	205	171	149	129	103	86.1	72.0	65.1	60.0	54.8	51.6	48.7	45.2	42.8	40.6	37.8	35.9	...	...	...
320.5	HSLA steel bolting	450	300	205	122	81	55	33	22.5	15	10.5	8.4	7.1	6.0	5.3	...	...	...	...	...	...

GENERAL NOTES:

(a) All notes on the referenced figures apply to these data.

(b) Number of design cycles indicated shall be read as follows: 1EJ = 1 × 10^J, e.g., 5E2 = 5 × 10^2 or 500 cycles.

(c) Logarithmic interpolation between tabular values is permissible for individual fatigue curves based upon data representation by straight lines on a log–log plot. Accordingly, for $S_i > S > S_j$,

$$\frac{N}{N_i} = \left(\frac{N_j}{N_i}\right)^{\left[\log(S_i/S)/\log\left(S_i/S_j\right)\right]}$$

where

S, S_i, S_j = values of S_a

N, N_i, N_j = corresponding calculated number of design cycles from design fatigue data

For example, from the data above, use the interpolation equation above to find the calculated number of design cycles N for S_a = 50.0 ksi when UTS ≥ 125 ksi on Figure KD-320.1:

$$\frac{N}{10{,}000} = \left(\frac{20{,}000}{10{,}000}\right)^{[\log(61/50)/\log(61/49)]}$$

$$N = 18{,}800 \text{ cycles}$$

(d) The fatigue curve values in Figures KD-320.1 and KD-320.2 may be linearly interpolated for intermediate values of the ultimate tensile strength.

(e) Equations for number of design operating cycles:

(1) Figure KD-320.1, UTS = 90 ksi

$311 \text{ ksi} \geq S_a \geq 42.6 \text{ ksi}$ $\quad N = \text{EXP}\left[15.433 - 2.0301 \ln(S_a) + 1036.035 \ln(S_a)/S_a^2\right]$

$17 \text{ ksi} < S_a < 42.6 \text{ ksi}$ $\quad N = \left[(2.127\text{ E}{-}05) + (7.529\text{ E}{-}10)S_a^3 - (8.636\text{ E}{-}06)\ln(S_a)\right]^{-1}$

$17 \text{ ksi} \geq S_a \geq 14 \text{ ksi}$ $\quad N = \text{EXP}\left[-20.0 \ln(S_a/35.12)\right]$

Table KD-320.1
Tabulated Values of S_a, ksi, From Figures Indicated (Cont'd)

GENERAL NOTES: (Cont'd)

(2) Figure KD-320.1, UTS = 125–175 ksi

$317\ \text{ksi} \geq S_a \geq 60.6\ \text{ksi}$ $\quad N = \left[0.00122 - (7.852\,\text{E}{-05})S_a + (7.703\,\text{E}{-06})S_a^{1.5}\right]^{-1}$

$24\ \text{ksi} < S_a < 60.6\ \text{ksi}$ $\quad N = \left[\left((7.8628\,\text{E}{-05}) + (3.212\,\text{E}{-03})S_a + (9.36\,\text{E}{-02})S_a^2\right)/\left(1 - (8.599\,\text{E}{-02})S_a + (1.816\,\text{E}{-03})S_a^2 + (4.05774\,\text{E}{-06})S_a^3\right)\right]^2$

$24\ \text{ksi} \geq S_a \geq 19.7\ \text{ksi}$ $\quad N = \text{EXP}\left[-20.0\ln(S_a/49.58)\right]$

(3) Figure KD-320.2, UTS ≤ 80 ksi

$S_a \geq 38\ \text{ksi}$ $\quad N = \left[-(7.125\,\text{E}{-04}) + (4.4692\,\text{E}{-08})(S_a^2)\ln(S_a) + (3.561\,\text{E}{-03})/S_a^{0.5}\right]^{-1}$

$12.5\ \text{ksi} < S_a < 38\ \text{ksi}$ $\quad N = \text{EXP}\left[\left(18.0353 - 1.3526S_a - (1.549\,\text{E}{-02})S_a^2\right)/\left(1 - (4.031\,\text{E}{-02})S_a - (3.854\,\text{E}{-03})S_a^2\right)\right]$

$S_a \leq 12.5\ \text{ksi}$ $\quad N = \text{EXP}[-20.0\ln(S_a/24.94)]$

(4) Figure KD-320.2, UTS = 115–130 ksi

$S_a \geq 43\ \text{ksi}$ $\quad N = \text{EXP}\left[\left(9.363 - 3.004\,\text{E}{-01}(S_a) + 1.488\,\text{E}{-04}(S_a^{\,2})\right)/\left(1 - 2.4133\,\text{E}{-02}(S_a) - 1.6829\,\text{E}{-04}(S_a^{\,2})\right)\right]$

$20\ \text{ksi} < S_a < 43\ \text{ksi}$ $\quad N = \left[-1974.51 + 1063.7(S_a^{\,0.5}) - 146.64(S_a)\right]/\left[1 - 6.73933\,\text{E}{-01}(S_a^{\,0.5}) + 1.51483\,\text{E}{-01}(S_a) - 1.1358\,\text{E}{-02}(S_a^{\,1.5})\right]$

$S_a \leq 20\ \text{ksi}$ $\quad N = \text{EXP}\,[-20.0\ln(S_a/39.91)]$

Table KD-320.1
Tabulated Values of S_a, ksi, From Figures Indicated (Cont'd)

GENERAL NOTES: (Cont'd)

(5) Figure KD-320.4, 17-4PH/15-5PH stainless steel

$129\text{ ksi} \le S_a < 207\text{ ksi}$	$N = 10^{(-10.600[\log(S_a)]^3 + 80.024[\log(S_a)]^2 - 203.37[\log(S_a)] + 175.13)}$
$103\text{ ksi} \le S_a < 129\text{ ksi}$	$N = 10^{(56.735[\log(S_a)]^3 - 347.76[\log(S_a)]^2 + 707.66[\log(S_a)] - 475.12)}$
$71\text{ ksi} \le S_a < 103\text{ ksi}$	$N = 10^{(-29.577[\log(S_a)]^3 + 180.59[\log(S_a)]^2 - 370.92[\log(S_a)] + 259.15)}$
$71\text{ ksi} > S_a \ge 35.7\text{ ksi}$	$N = 10^{(41.740[\log(S_a)]^3 - 201.51[\log(S_a)]^2 + 311.25[\log(S_a)] - 146.68)}$

(6) Figure KD-320.5, HSLA steel bolting

$81\text{ ksi} < S_a \le 450\text{ ksi}$	$N = -73.187 + \frac{10{,}789.34}{\sqrt{(S_a)}} - \frac{95{,}157.4[\ln(S_a)]}{(S_a)} + \frac{407{,}873.1}{(S_a)}$
$22.5\text{ ksi} < S_a \le 81\text{ ksi}$	$N = 19.878 + \frac{1{,}711.095}{(S_a)} + \frac{992{,}406[\ln(S_a)]}{[(S_a)^2]} + \frac{1{,}916{,}134}{[(S_a)^2]}$
$8.4\text{ ksi} < S_a \le 22.5\text{ ksi}$	$N = \text{EXP}\left(23.9644 + 1.1258[\ln(S_a)]^2 - 8.2446[\ln(S_a)]\right)$
$5.3\text{ ksi} \le S_a \le 8.4\text{ ksi}$	$N = \left[\left(7.6208\text{ E}{-06}\right) - (3.9025\text{ E}{-06})\left(S_a\right) + \left(4.97327\text{ E}{-07}\right)(S_a)^2\right]^{-1}$

(7) Figure KD-320.7, nonwelded 6061-T6 and 6061-T651 aluminum

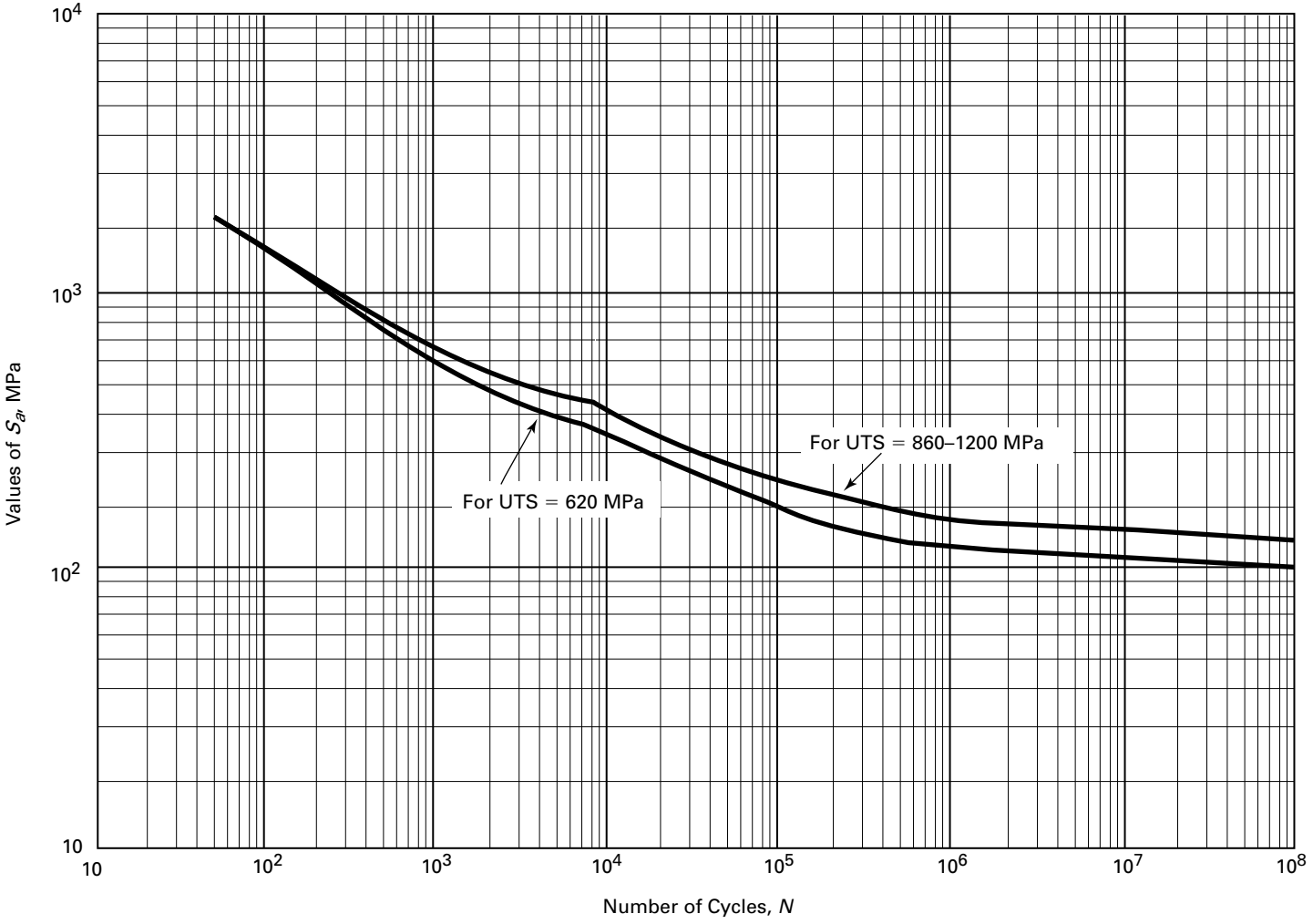
$70\text{ ksi} \ge S_a > 7.18\text{ ksi}$	$N = \text{EXP}\left[\left(7.2617 - 2.1069S_a + 6.7452\text{ E}{-03}S_a{}^2\right)/\left(1 - 0.2140S_a - 2.3734\text{ E}{-03}S_a{}^2\right)\right]$
$7.18\text{ ksi} \ge S_a > 2.87\text{ ksi}$	$N = \left[\left(2.9649\text{E}2\right)/\left(\sqrt{S_a} - 1.6837\right)\right]^2$

(f) Equations shall not be used outside of the cycle range given in the Table.

NOTE: (1) Figure KD-320.3, nonwelded Series 3XX high alloy steel, nickel–chromium–iron alloy, nickel–iron–chromium alloy, and nickel–copper alloy

$S_a \ge 14.4\text{ ksi}$	$N = 10^{(17.0181 - 19.8713\log(S_a) + 4.21366[\log(S_a)]^2)/(1 - 0.1720606\log(S_a) - 0.633592[\log(S_a)]^2)}$
$S_a < 14.4\text{ ksi}$	$N = 10^{1/(-0.331096 + 4.3261\ln[\log(S_a)]/[\log(S_a)]^2)}$

Figure KD-320.1M
Design Fatigue Curves $S_a = f(N_f)$ for Nonwelded Machined Parts Made of Forged Carbon or Low Alloy Steels for Temperatures Not Exceeding 371°C



GENERAL NOTES:
(a) $E = 195 \times 10^3$ MPa
(b) Interpolate for UTS = 620 MPa to 860 MPa.
(c) Table KD-320.1M contains tabulated values and equations for these curves, and an equation for an accurate interpolation of these curves.

(25)

Table KD-320.1M
Tabulated Values of S_a, MPa, From Figures Indicated

		Number of Design Operating Cycles, N_f																			
Figure	**Curve**	**5E1**	**1E2**	**2E2**	**5E2**	**1E3**	**2E3**	**5E3**	**1E4**	**2E4**	**5E4**	**1E5**	**2E5**	**5E5**	**1E6**	**2E6**	**5E6**	**1E7**	**2E7**	**5E7**	**1E8**
320.1M	UTS 620 MPa	2 140	1 560	1 130	779	614	496	393	338	297	234	200	172	145	131	117.2	111.8	108.2	104.8	100	96.5
320.1M	UTS 860 MPa	2 190	1 610	1 200	834	675	565	469	421	338	269	234	214	193	179	165	157.9	152.4	147.6	140.7	135.8
320.2M	UTS ≤ 552 MPa	1 900	1 410	1 070	724	572	441	331	262	214	159	138	114	93	86	83	79	77	74	71	68
320.2M	UTS 793 – 896 MPa	1 586	1 207	931	690	538	427	338	303	248	200	179	165	152	138	133	127	123	119	113	110
320.3M	[Note (1)]	2 605	1 896	1 410	981	761	600	447	364	299	235	199	170	140	124	112	102.6	99.2	98.54	97.74	97.21
320.4M	17-4PH/15-5PH stainless steel	1 410	1 180	1 030	889	710	594	496	449	414	378	356	336	312	295	280	261	248	...	...	...
320.5M	HSLA steel bolting	3 100	2 070	1 410	841	558	379	228	155	103	72	58	49	41	37	...	...	...	...	...	...

GENERAL NOTES:

(a) All notes on the referenced figures apply to these data.

(b) Number of design cycles indicated shall be read as follows: 1EJ = 1 × 10^J, e.g., 5E2 = 5 × 10^2 or 500 cycles.

(c) Logarithmic interpolation between tabular values is permissible for individual fatigue curves based upon data representation by straight lines on a log–log plot. Accordingly, for $S_i > S > S_j$,

$$\frac{N}{N_i} = \left(\frac{N_j}{N_i}\right)^{\left[\log(S_i/S)/\log\left(S_i/S_j\right)\right]}$$

where

S, S_i, S_j = values of S_a

N, N_i, N_j = corresponding calculated number of design cycles from design fatigue data

For example, from the data above, use the interpolation equation above to find the calculated number of design cycles N for S_a = 345 MPa when UTS ≥ 860 MPa on Figure KD-320.1M:

$$\frac{N}{10{,}000} = \left(\frac{20{,}000}{10{,}000}\right)^{[\log(421/345)/\log(421/338)]}$$

$$N = 18{,}800 \text{ cycles}$$

(d) The fatigue curve values in Figures KD-320.1M and KD-320.2M may be linearly interpolated for intermediate values of the ultimate tensile strength.

(e) Equations for number of design operating cycles:

(1) Figure KD-320.1M, UTS = 620 MPa

$2140 \text{ MPa} \geq S_a \geq 294 \text{ MPa}$ $\quad N = \text{EXP}\left[19.353 - 2.0301\ln(S_a) + (49254.16\ln(S_a) - 95099.7)/S_a^2\right]$

$117 \text{ MPa} < S_a < 294 \text{ MPa}$ $\quad N = \left[(3.794\text{E}{-}05) + (2.297\text{E}{-}12)S_a^3 - (8.636\text{E}{-}06)\ln(S_a)\right]^{-1}$

$117 \text{ MPa} \geq S_a \geq 96.5 \text{ MPa}$ $\quad N = \text{EXP}\left[-20.0\ln(S_a/242.11)\right]$

Table KD-320.1M
Tabulated Values of S_a, MPa, From Figures Indicated (Cont'd)

GENERAL NOTES: (Cont'd)

(2) Figure KD-320.1M, UTS = 860–1 210 MPa

2190 MPa $\geq S_a \geq$ 418 MPa	$N = \left[0.00122 - (1.139\,\text{E}{-05})S_a + (4.255\,\text{E}{-07})S_a^{1.5}\right]^{-1}$
166 MPa $< S_a <$ 418 MPa	$N = \left[\left((7.8628\,\text{E}{-05}) + (4.659\,\text{E}{-04})S_a + (1.97\,\text{E}{-03})S_a^2\right)/\left(1 - (1.247\,\text{E}{-02})S_a + (3.820\,\text{E}{-05})S_a^2 + (1.238\,\text{E}{-08})S_a^3\right)\right]^2$
166 MPa $\geq S_a \geq$ 135.8 MPa	$N = \text{EXP}\left[-20.0\ln(S_a/341.81)\right]$

(3) Figure KD-320.2M, UTS ≤ 552 MPa

$S_a \geq$ 262 MPa	$N = \left[-\left(7.125\,\text{E}{-04}\right) + (9.401\,\text{E}{-10})(S_a^2)\ln(S_a) - \left(1.8512\,\text{E}{-09}\right)S_a^2 + (9.35\,\text{E}{-03})/S_a^{0.5}\right]^{-1}$
86 MPa $< S_a <$ 262 MPa	$N = \text{EXP}\left[(18.0353 - 0.19617S_a - (3.258\,\text{E}{-04})S_a^2)/(1 - (5.846\,\text{E}{-03})S_a - (8.107\,\text{E}{-05})S_a^2)\right]$
$S_a \leq$ 86 MPa	$N = \text{EXP}\left[-20.0\ln(S_a/171.96)\right]$

(4) Figure KD-320.2M, UTS = 793–896 MPa

$S_a \geq$ 296 MPa	$N = \text{EXP}\left[\left(9.2095 - 4.3897\,\text{E}{-02}(S_a) + 3.3186\,\text{E}{-06}(S_a{}^2)\right)/\left(1 - 3.60\,\text{E}{-03}(S_a) - 3.4936\,\text{E}{-06}(S_a{}^2)\right)\right]$
138 MPa $< S_a <$ 296 MPa	$N = \left[-1974.51 + 405.043(S_a{}^{0.5}) - 21.2626(S_a)\right]/\left[1.0 - 0.256625(S_a{}^{0.5}) + 2.19648\,\text{E}{-02}(S_a) - 6.27115\text{E}{-04}(S_a{}^{1.5})\right]$
$S_a \leq$ 138 MPa	$N = \text{EXP}\left[-20.0\ln\left(S_a/275.35\right)\right]$

Table KD-320.1M
Tabulated Values of S_a, MPa, From Figures Indicated (Cont'd)

GENERAL NOTES: (Cont'd)

(5) Figure KD-320.4M, 17-4PH/15-5PH stainless steel

889 MPa $\leq S_a <$ 1 410 MPa	$N = 10^{(-10.600\,[\log(S_a)]^3 + 106.689\,[\log(S_a)]^2 - 359.932\,[\log(S_a)] + 408.175)}$
710 MPa $\leq S_a <$ 889 MPa	$N = 10^{(56.735\,[\log(S_a)]^3 - 490.48\,[\log(S_a)]^2 + 1410.54\,[\log(S_a)] - 1346.471)}$
490 MPa $\leq S_a <$ 710 MPa	$N = 10^{(-29.577\,[\log(S_a)]^3 + 254.993\,[\log(S_a)]^2 - 736.164\,[\log(S_a)] + 714.587)}$
490 MPa $> S_a \geq$ 248 MPa	$N = 10^{(41.740\,[\log(S_a)]^3 - 306.509\,[\log(S_a)]^2 + 737.234\,[\log(S_a)] - 573.962)}$

(6) Figure KD-320.5M, HSLA steel bolting

3 100 MPa $\geq S_a >$ 558 MPa	$N = -7.3187\,\text{E01} + (2.8331\,\text{E04})/S_a^{0.5} - (6.5611\,\text{E05})\ln(S_a)/S_a + (4.0791\,\text{E06})/S_a$
558 MPa $\geq S_a >$ 155 MPa	$N = 1.9878\,\text{E01} + (1.1798\,\text{E04})/S_a + (4.7180\,\text{E07})\ln(S_a)/S_a^2$
155 MPa $\geq S_a >$ 58 MPa	$N = \text{EXP}\left[4.4080\,\text{E01} + (1.1258)\ln(S_a)^2 - (1.2592\,\text{E01})\ln(S_a)\right]$
58 MPa $\geq S_a \geq$ 37 MPa	$N = \left[7.6208\,\text{E}{-06} - (5.6599\text{E}{-07})S_a + (1.0461\,\text{E}{-08})S_a{}^2\right]^{-1}$

(7) Figure KD-320.7M, nonwelded 6061-T6 and 6061-T651 aluminum

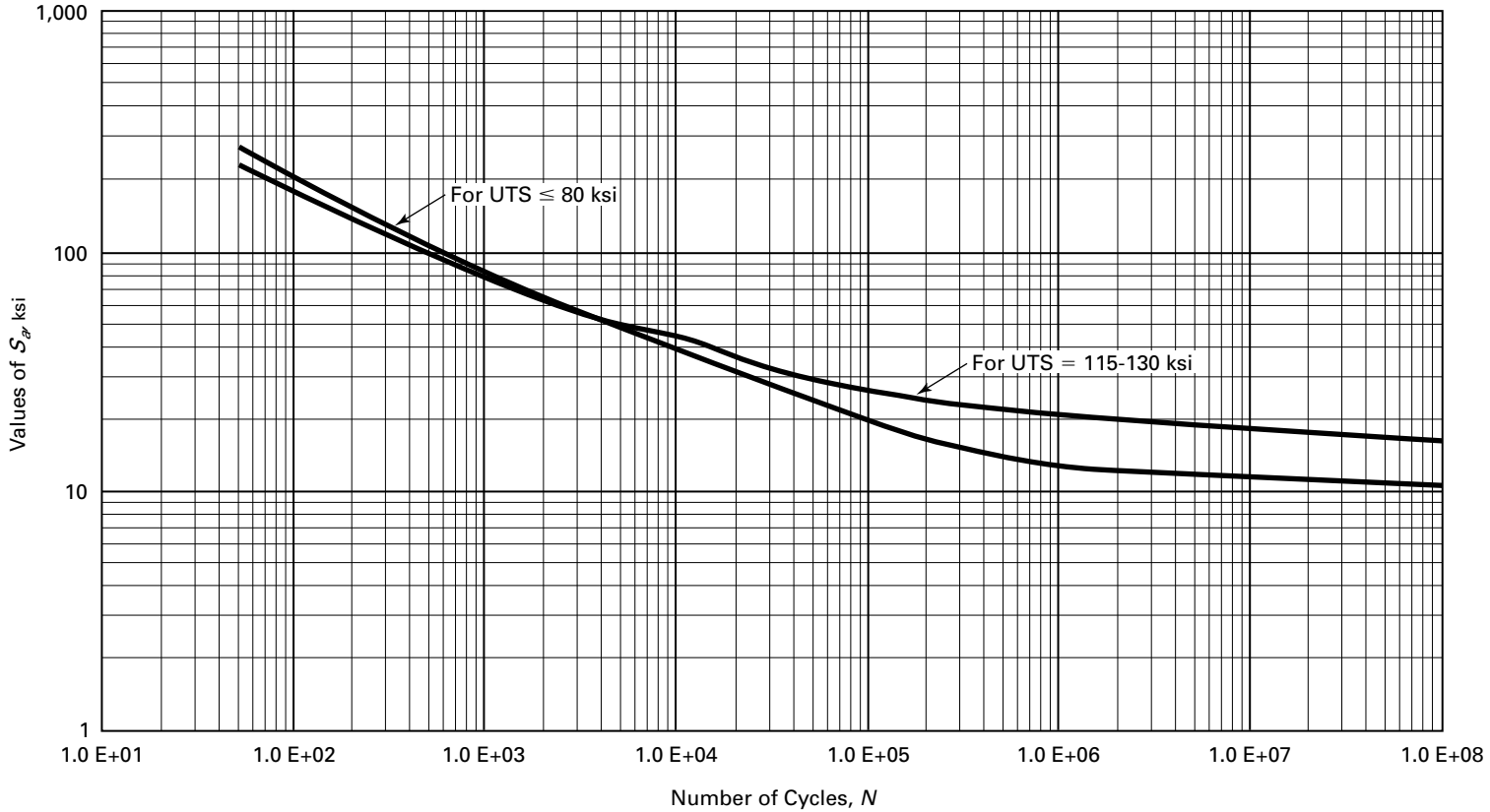
483 MPa $\geq S_a >$ 49.5 MPa	$N = \text{EXP}\left[\left(7.2617 - 3.0551\,\text{E}{-01}S_a + 1.4182\,\text{E}{-04}S_a{}^2\right)/\left(1 - 3.1034\,\text{E}{-02}S_a - 4.9901\,\text{E}{-05}S_a{}^2\right)\right]$
49.5 MPa $\geq S_a >$ 20.0 MPa	$N = \left[\left(2.9649\,\text{E2}\right)/\left(0.3808\sqrt{S_a} - 1.6837\right)\right]^2$

(f) Equations shall not be used outside of the cycle range given in the Table.

NOTE: (1) Figure KD-320.3M, Nonwelded Series 3XX high alloy steel, nickel–chromium–iron alloy, nickel–iron–chromium alloy, and nickel–copper alloy

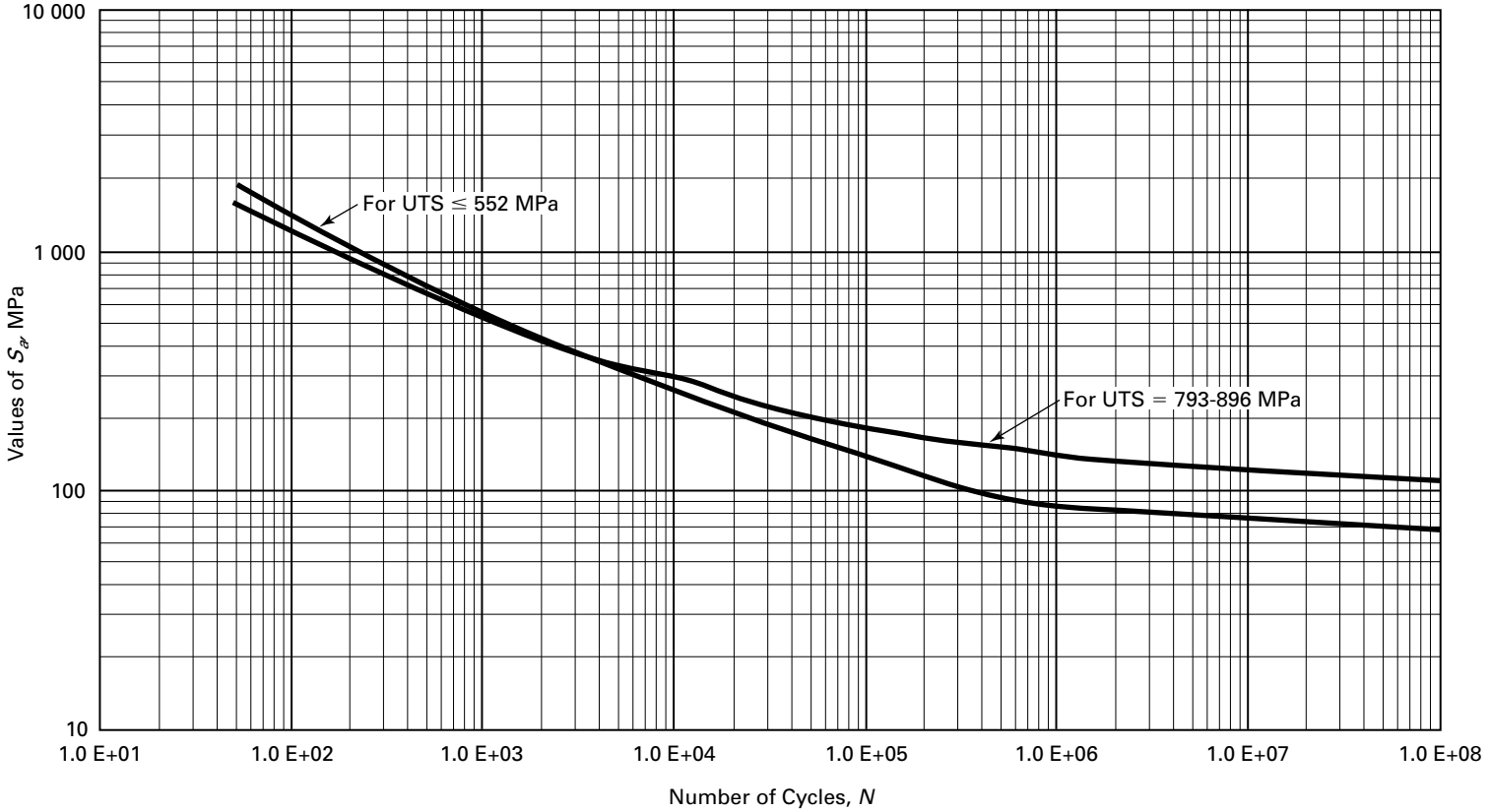
$S_a \geq$ 99.2 MPa	$N = 10^{(17.0181 - 19.8713\log[(28.3/195)S_a] + 4.21366(\log[(28.3/195)S_a])^2]/(1 - 0.1720606\log[(28.3/195)S_a] - 0.633592(\log[(28.3/195)S_a])^2)}$
$S_a <$ 99.2 MPa	$N = 10^{1/(-0.331096 + 4.3261\ln(\log[28.3/195)S_a])/(\log[(28.3/195)S_a])^2)}$

Figure KD-320.2
Design Fatigue Curve $S_a = f(N_f)$ for Nonwelded Parts Made of Carbon or Low Alloy Steels for Temperatures Not Exceeding 700°F



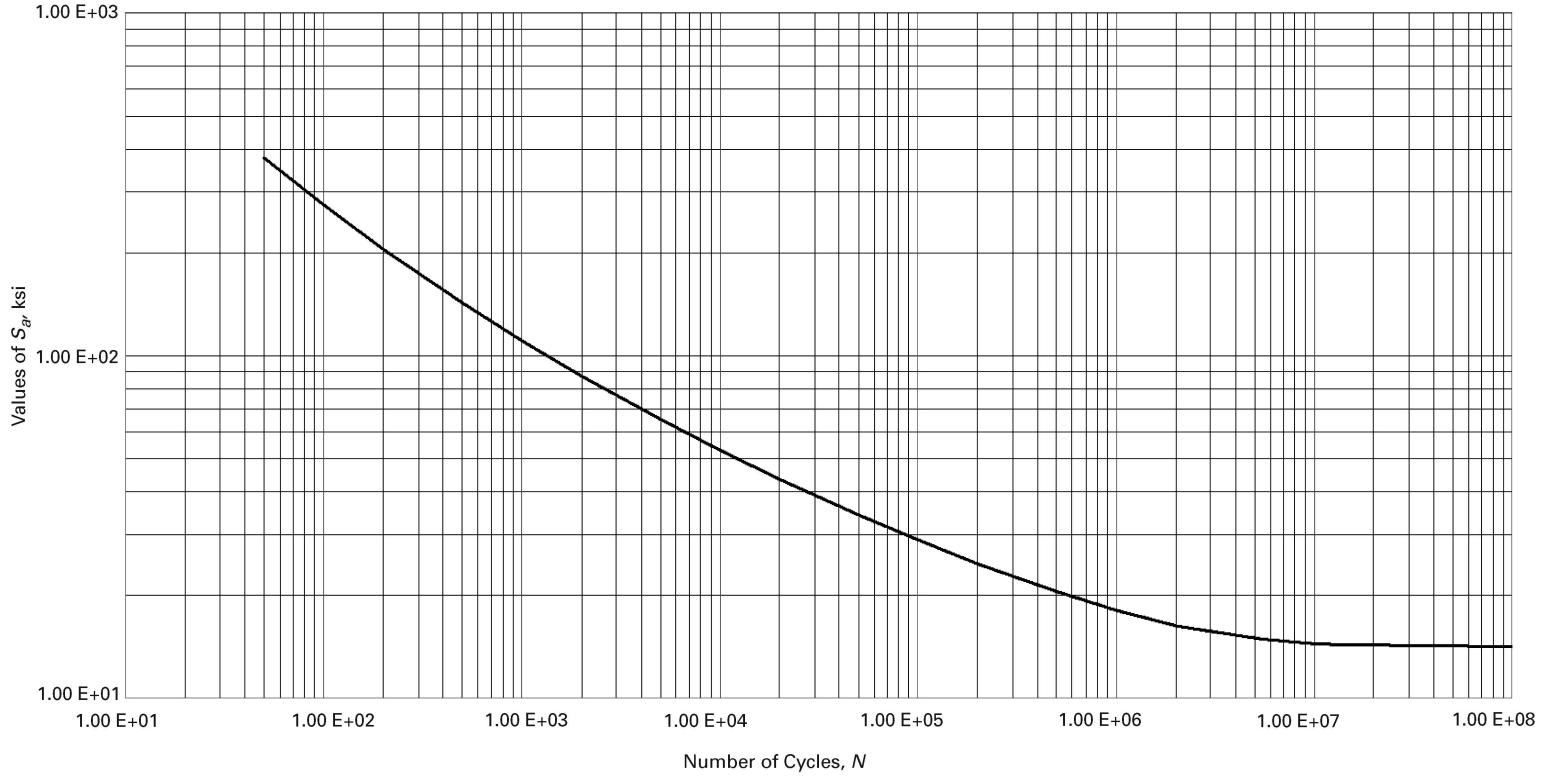
GENERAL NOTES:
(a) $E = 30 \times 10^6$ psi.
(b) For forgings, this figure shall only be used for UTS less than 90 ksi.
(c) Interpolate for UTS = 80 ksi to 115 ksi.
(d) Table KD-320.1 contains tabulated values and equations for these curves, and a formula for an accurate interpolation of these curves.

Figure KD-320.2M
Design Fatigue Curve $S_a = f(N_f)$ for Nonwelded Parts Made of Carbon or Low Alloy Steels for Temperatures Not Exceeding 371°C



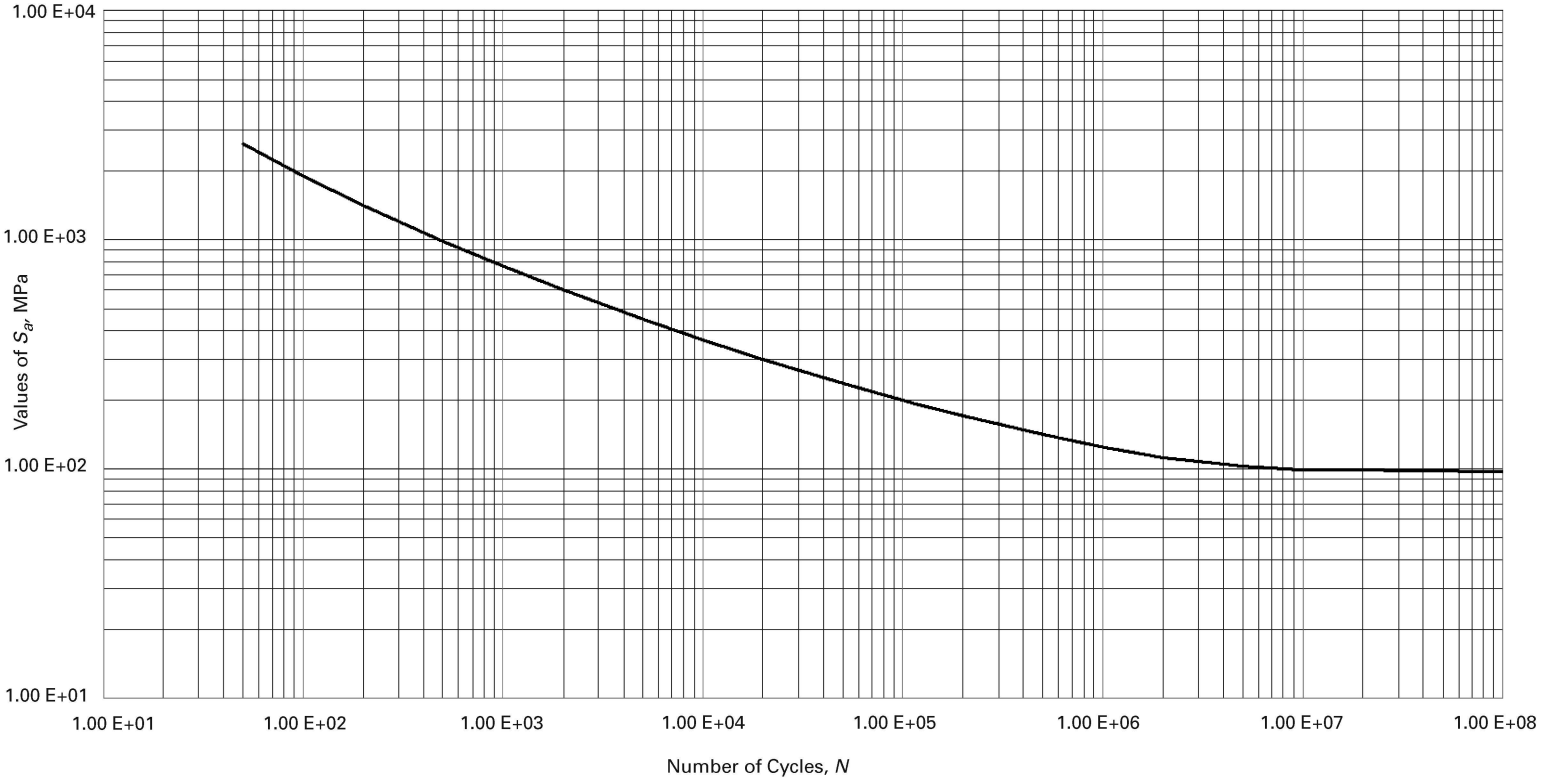
GENERAL NOTES:
(a) $E = 207 \times 10^3$ MPa.
(b) For forgings, this figure shall only be used for UTS less than 620 MPa.
(c) Interpolate for UTS = 552 MPa to 793 MPa.
(d) Table KD-320.1M contains tabulated values and equations for these curves, and a formula for an accurate interpolation of these curves.

Figure KD-320.3
Fatigue Curve for Nonwelded Series 3XX High Alloy Steel, Nickel–Chromium–Iron Alloy, Nickel–Iron–Chromium Alloy, and Nickel–Copper Alloy for Temperatures Not Exceeding 800°F



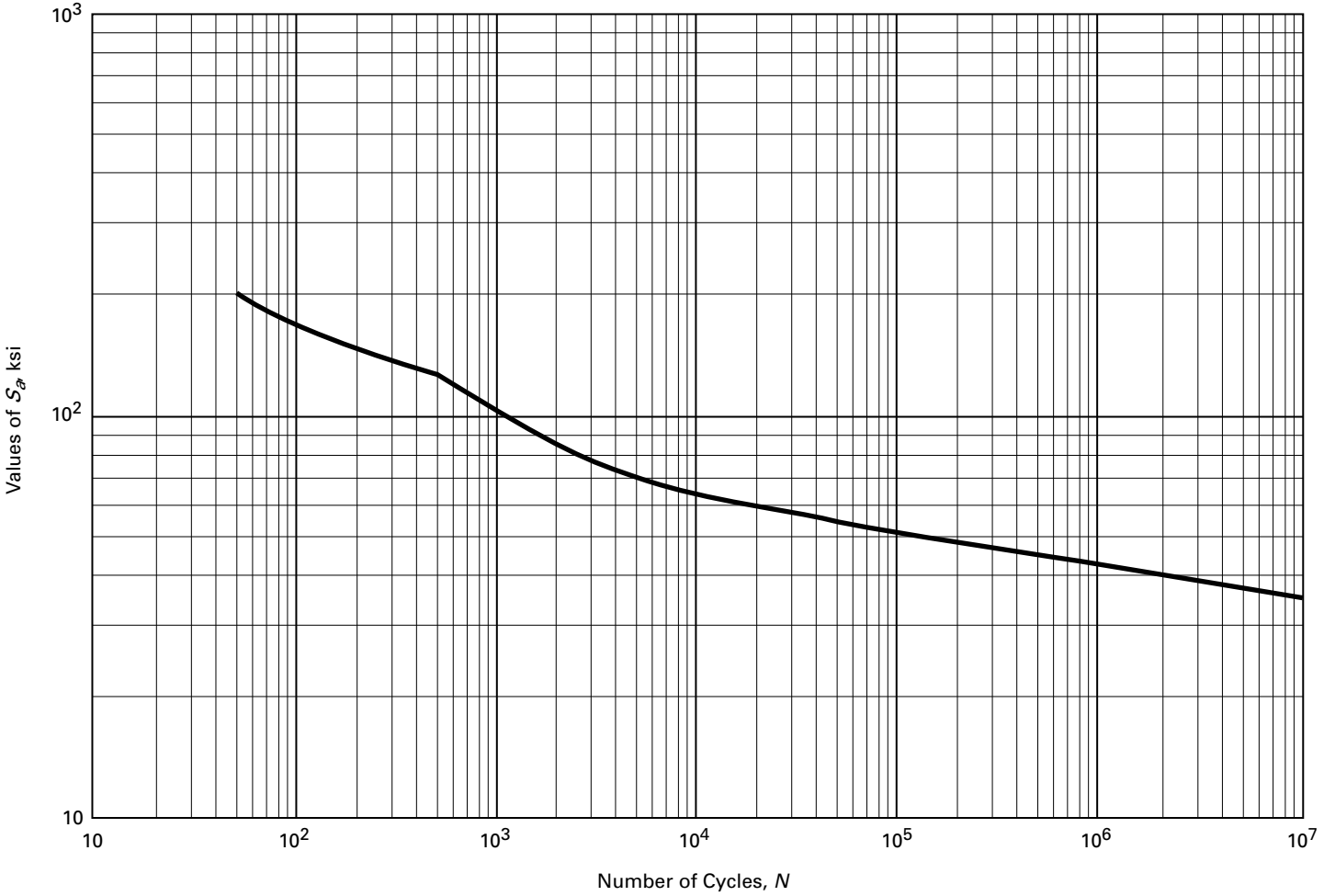
GENERAL NOTES:
(a) $E = 28.3 \times 10^6$ psi
(b) Table KD-320.1 contains tabulated values and an equation for this curve, and an equation for an accurate interpolation of this curve.

Figure KD-320.3M
Fatigue Curve for Nonwelded Series 3XX High Alloy Steel, Nickel–Chromium–Iron Alloy, Nickel–Iron–Chromium Alloy, and Nickel–Copper Alloy for Temperatures Not Exceeding 427°C



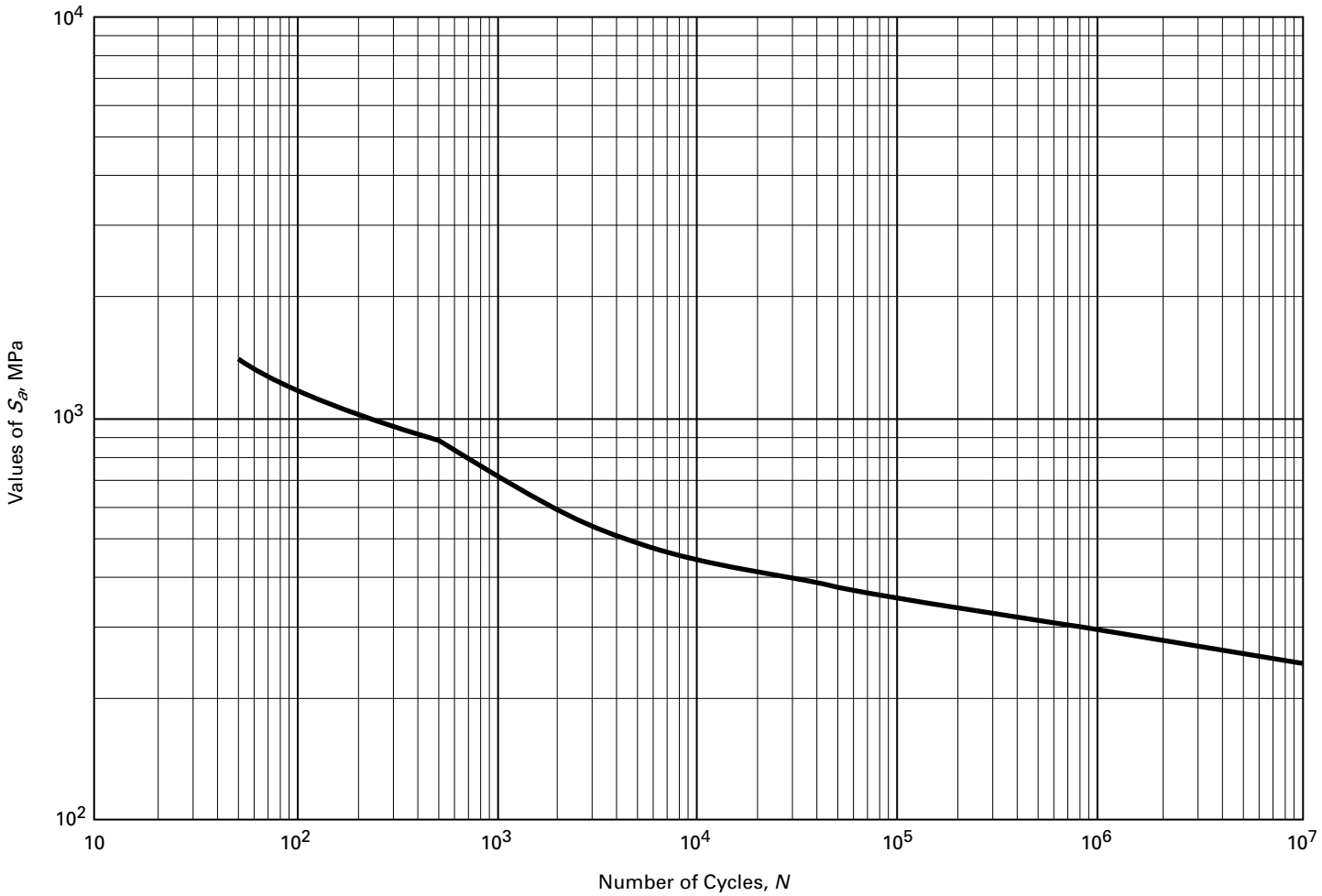
GENERAL NOTES:
(a) $E = 195 \times 10^3$ MPa
(b) Table KD-320.1M contains tabulated values and an equation for this curve, and an equation for an accurate interpolation of this curve.

Figure KD-320.4
Design Fatigue Curve $S_a = f(N_f)$ for Nonwelded Machined Parts Made of 17-4PH/15-5PH Stainless Steel Bar or Forgings, for Temperatures Not Exceeding 550°F



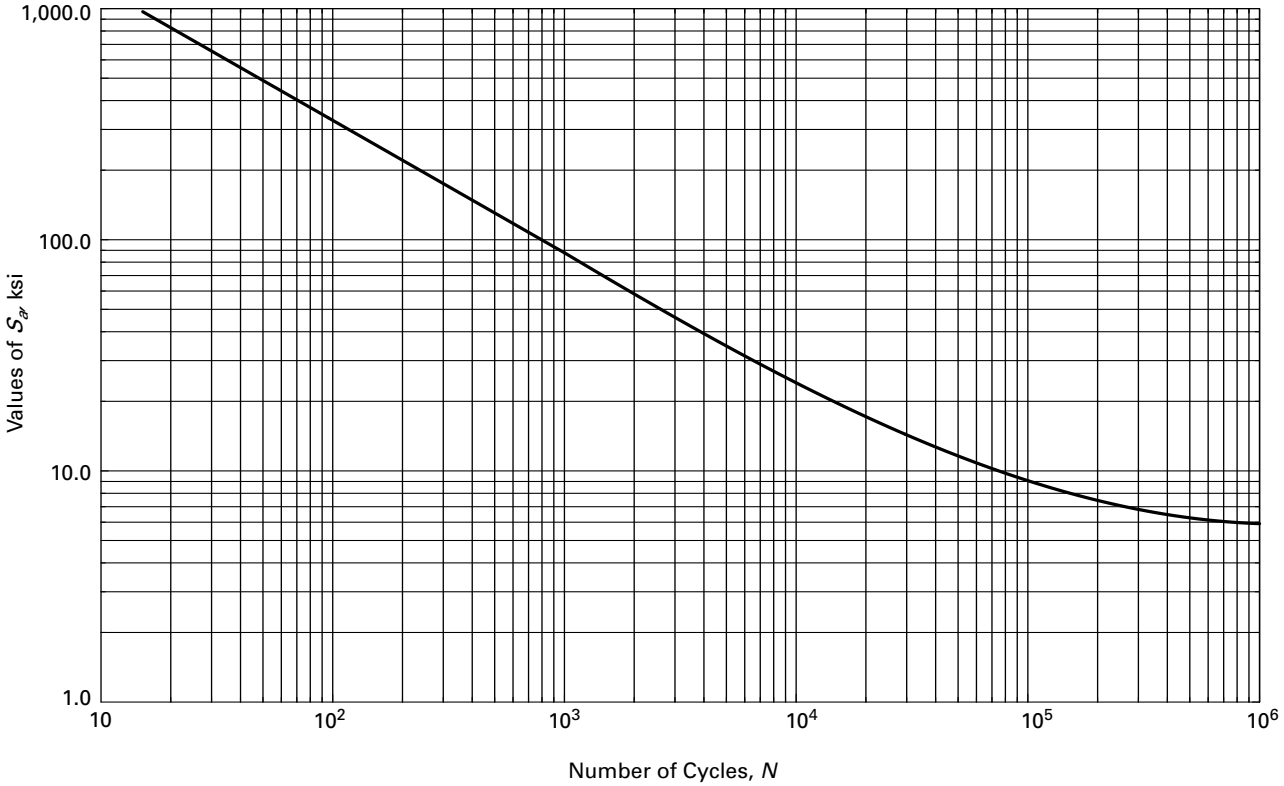
GENERAL NOTES:
(a) E = 29.0 × 10^6 psi
(b) Table KD-320.1 contains tabulated values and an equation for this curve, and an equation for the accurate interpolation of this curve.
(c) When the 17-4PH/15-5PH heat treat condition is H1025 or stronger, this curve may be used only for analysis of either protective liners or inner layers in vessels demonstrated to be leak-before-burst (see KD-103 and KD-141).
(d) Use of this curve is limited to cases where the peak Tresca strain range from mechanical loading is less than 1%.

Figure KD-320.4M
Design Fatigue Curve $S_a = f(N_f)$ for Nonwelded Machined Parts Made of 17-4PH/15-5PH Stainless Steel Bar or Forgings, for Temperatures Not Exceeding 290°C



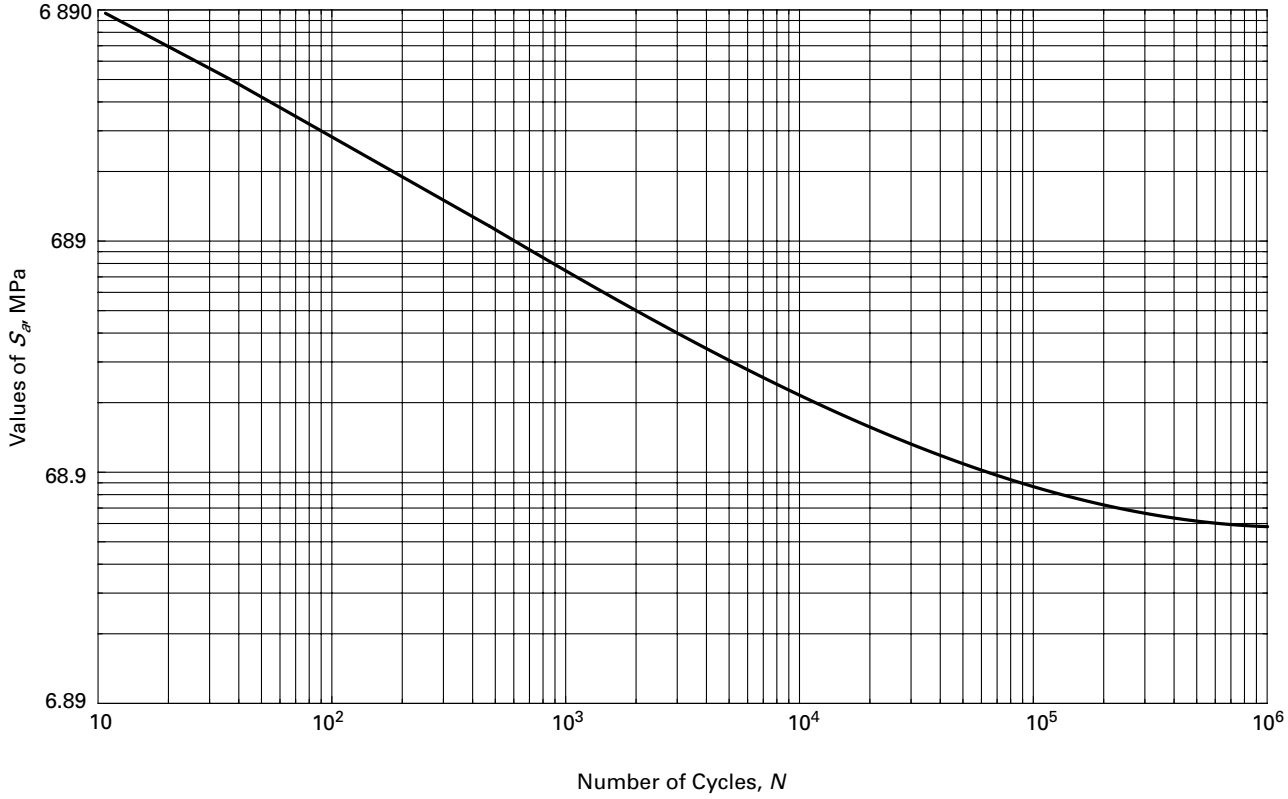
GENERAL NOTES:
(a) $E = 200 \times 10^3$ MPa
(b) Table KD-320.1M contains tabulated values and an equation for this curve, and an equation for the accurate interpolation of this curve.
(c) When the 17-4PH/15-5PH heat treat condition is H1025 or stronger, this curve may be used only for analysis of either protective liners or inner layers in vessels demonstrated to be leak-before-burst (see KD-103 and KD-141).
(d) Use of this curve is limited to cases where the peak Tresca strain range from mechanical loading is less than 1%.

Figure KD-320.5
Design Fatigue Curve for High-Strength Steel Bolting for Temperatures Not Exceeding 700°F



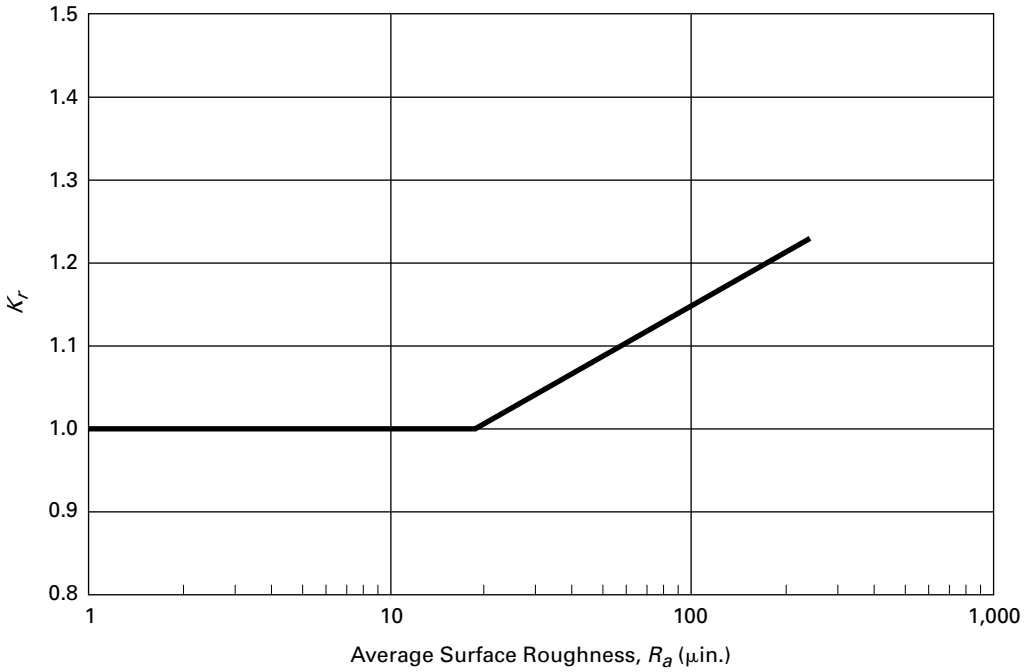
GENERAL NOTES:
(a) $E = 30 \times 10^6$ psi
(b) Table KD-320.1 contains tabulated values and equations for this curve and equations for accurate interpolation of this curve.

Figure KD-320.5M
Design Fatigue Curve for High-Strength Steel Bolting for Temperatures Not Exceeding 371°C



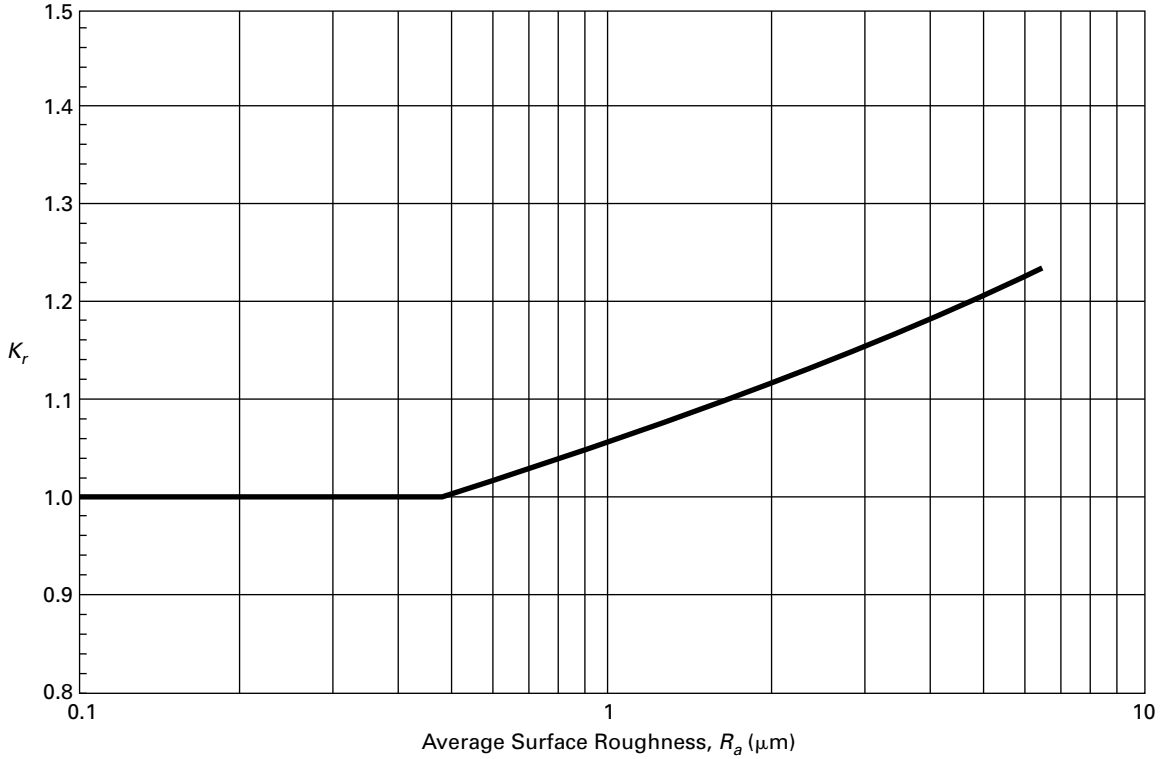
GENERAL NOTES:
(a) E = 206 MPa.
(b) Table KD-320.1M contains tabulated values and equations for this curve and equations for accurate interpolation of this curve.

Figure KD-320.6(a)
Roughness Factor K_r Versus Average Surface Roughness R_a (μin.) AA



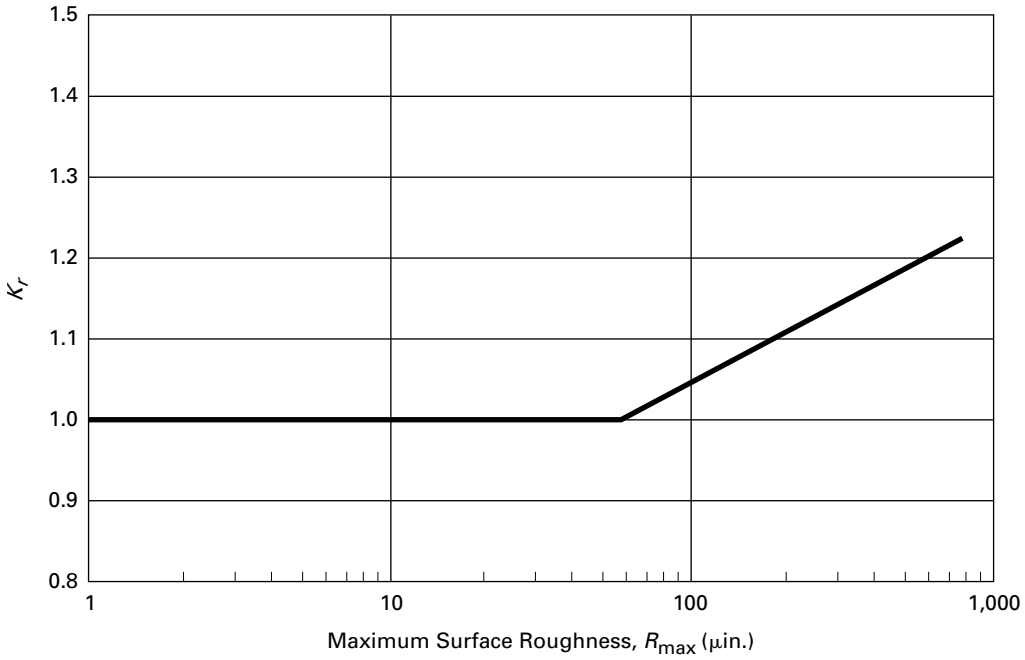
GENERAL NOTES:
(a) See ASME B46.1 for definition of arithmatic average surface roughness, R_a.
(b) Curve equations:
$R_a \le 19$ μin.
$K_r = 1.0$
$19 < R_a \le 250$ μin.
$K_r = 1/\{ - 0.16998 \log [R_a \text{ (μin.)}] + 1.2166\}$

Figure KD-320.6M(a)
Roughness Factor K_r Versus Average Surface Roughness R_a (μm) AA



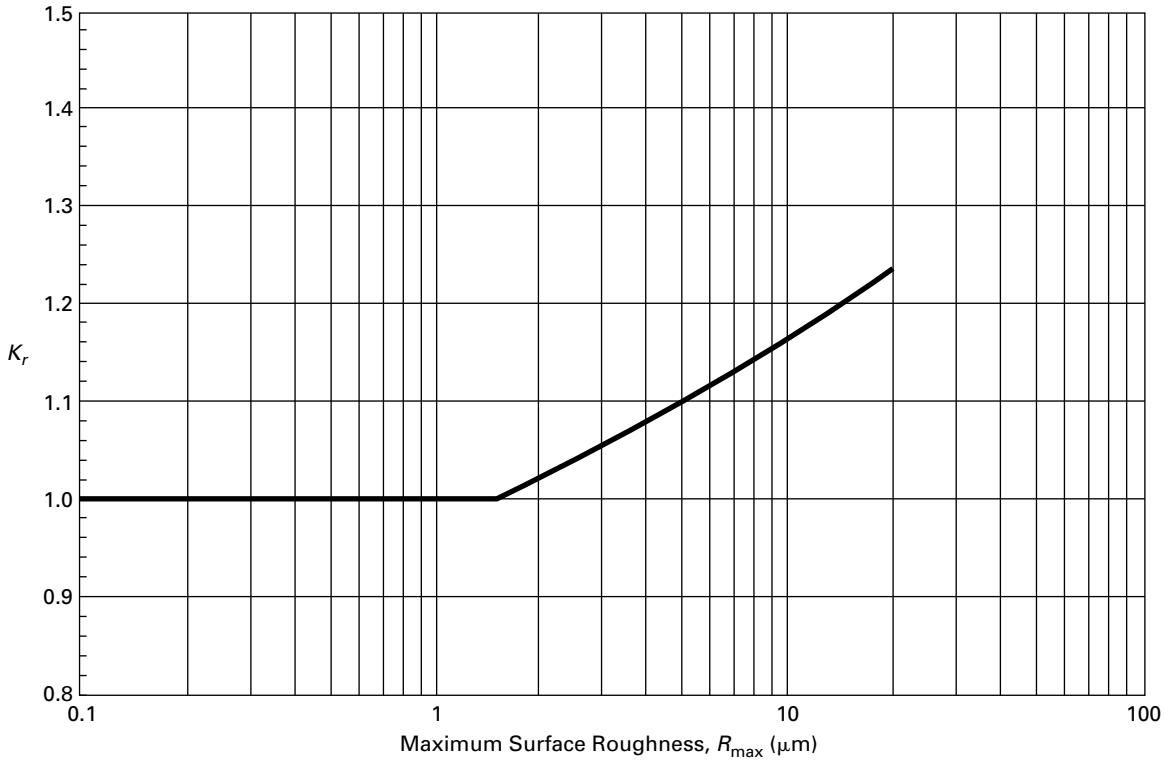
GENERAL NOTES:
(a) See ASME B46.1 for definition of arithmatic average surface roughness, R_a.
(b) Curve equations:
$R_a \le 0.48$ μm
$K_r = 1.0$
$0.5 < R_a \le 6.4$ μm
$K_r = 1/\{ - 0.16998 \log [R_a \text{ (μm)}] + 0.94545\}$

Figure KD-320.6(b)
Roughness Factor K_r Versus Maximum Surface Roughness R_{max} (μin.)



GENERAL NOTES:
(a) See ASME B46.1 for definition of arithmatic average surface roughness, R_a.
(b) Curve equations:
$R_{max} \le 59$ μin.
$K_r = 1.0$
$59 < R_{max} \le 785$ μin.
$K_r = 1/\{ - 0.16998 \log [R_{max} (\mu in.)] + 1.3011\}$

Figure KD-320.6M(b)
Roughness Factor K_r Versus Maximum Surface Roughness R_{max} (μm)



GENERAL NOTES:
(a) See ASME B46.1 for definition of arithmatic average surface roughness, R_a.
(b) Curve equations:
$R_{max} \le 1.50$ μm
$K_r = 1.0$
$1.50 < R_{max} \le 20$ μm
$K_r = 1/\{ - 0.16998 \log [R_{max} (\mu m)] + 1.02995\}$

Table KD-320.7
Tabulated Values of S_a Alternating Stress Intensity From Figures KD-320.7 and KD-320.7M

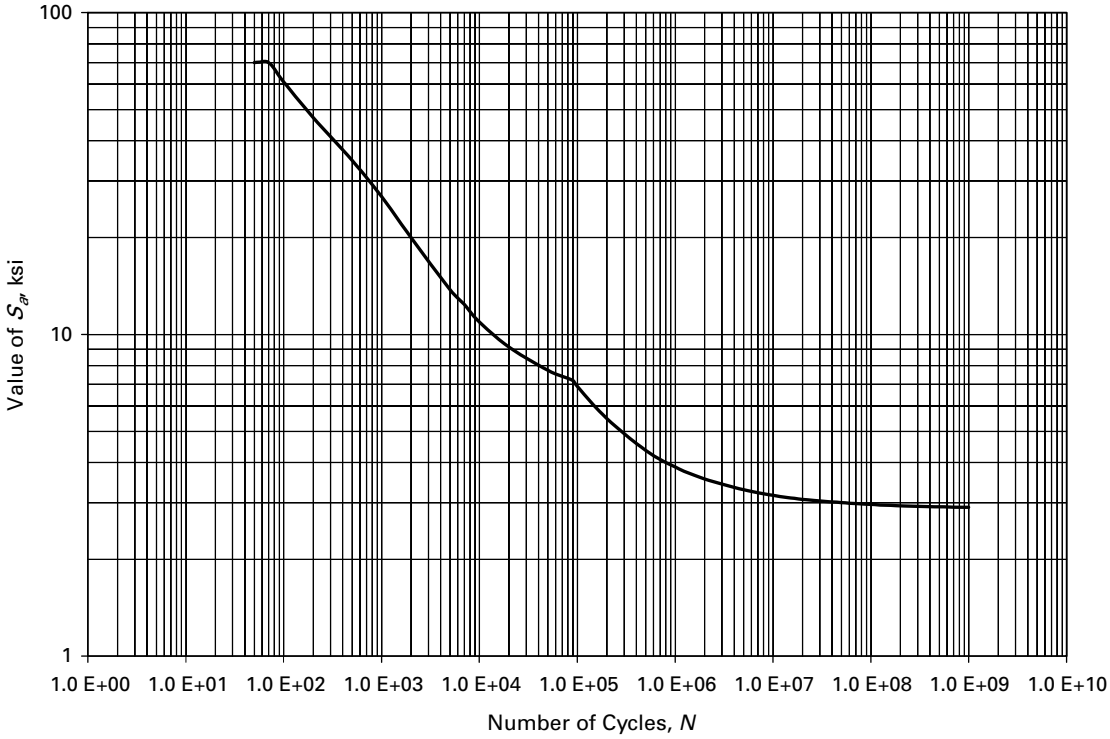
N, Number of Cycles	S_a With Maximum Mean Stress, ksi	S_a With Maximum Mean Stress, MPa
7.0 E+01	70.00	483
1.0 E+02	60.96	420
2.0 E+02	47.20	325
5.0 E+02	34.80	240
1.0 E+03	26.79	185
2.0 E+03	20.00	138
5.0 E+03	13.78	95
7.0 E+03	12.40	85
1.0 E+04	10.93	75
2.0 E+04	9.14	63
5.0 E+04	7.74	53
9.0 E+04	7.18	50
1.0 E+05	6.89	48
2.0 E+05	5.47	38
5.0 E+05	4.36	30
1.0 E+06	3.87	27
2.0 E+06	3.55	24
5.0 E+06	3.29	23
1.0 E+07	3.16	22
2.0 E+07	3.07	21
5.0 E+07	3.00	21
1.0 E+08	2.96	20
2.0 E+08	2.93	20
5.0 E+08	2.91	20
1.0 E+09	2.90	20

GENERAL NOTES:

(a) Number of design cycles indicated shall be as follows: 1.0 E+J = 1×10^{J}, e.g., 5.0 E+2 = 5×10^{2}.

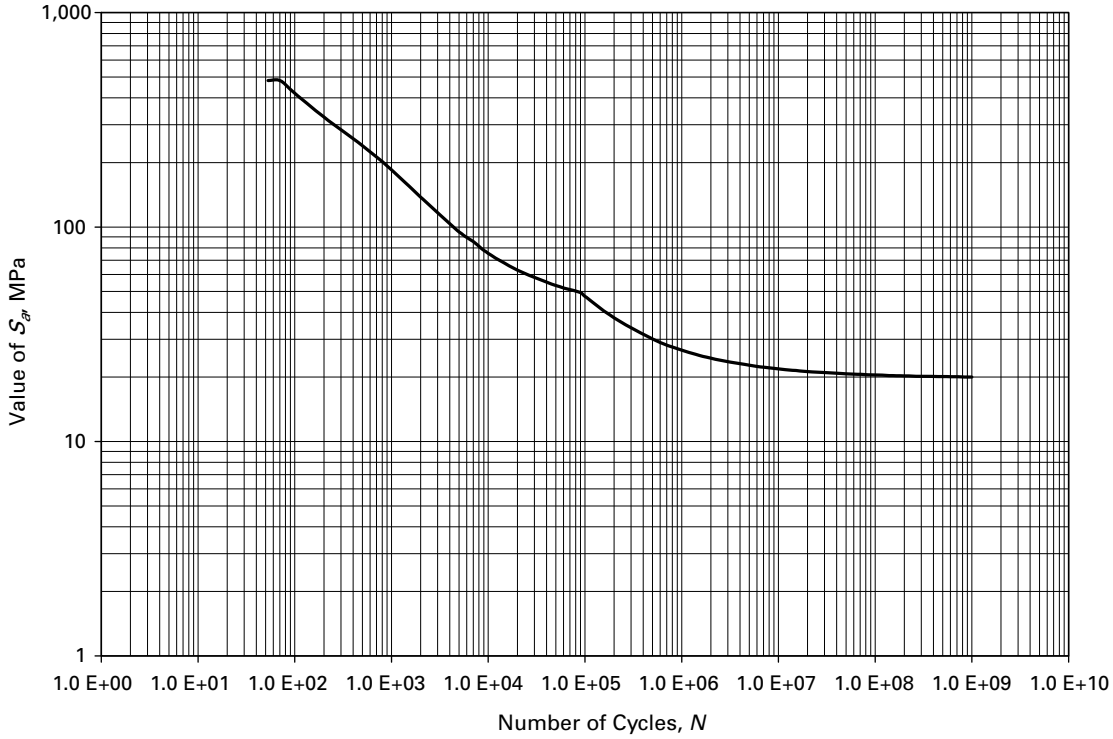
(b) Interpolation between tabular values is permissible based upon data representation by straight lines on a log-log plot. Accordingly, for Si > S > Sj, $(N/Ni) = (Nj/Ni)^{[\log (Si/S)/\log (Si/Sj)]}$.

Figure KD-320.7
Design Fatigue Curve for Nonwelded 6061-T6 and 6061-T651 Aluminum for Temperatures Not Exceeding 225°F



GENERAL NOTES:
(a) $E = 10 \times 10^6$ psi.
(b) Table KD-320.7 contains tabulated values.

Figure KD-320.7M
Design Fatigue Curve for Nonwelded 6061-T6 and 6061-T651 Aluminum for Temperatures Not Exceeding 107°C



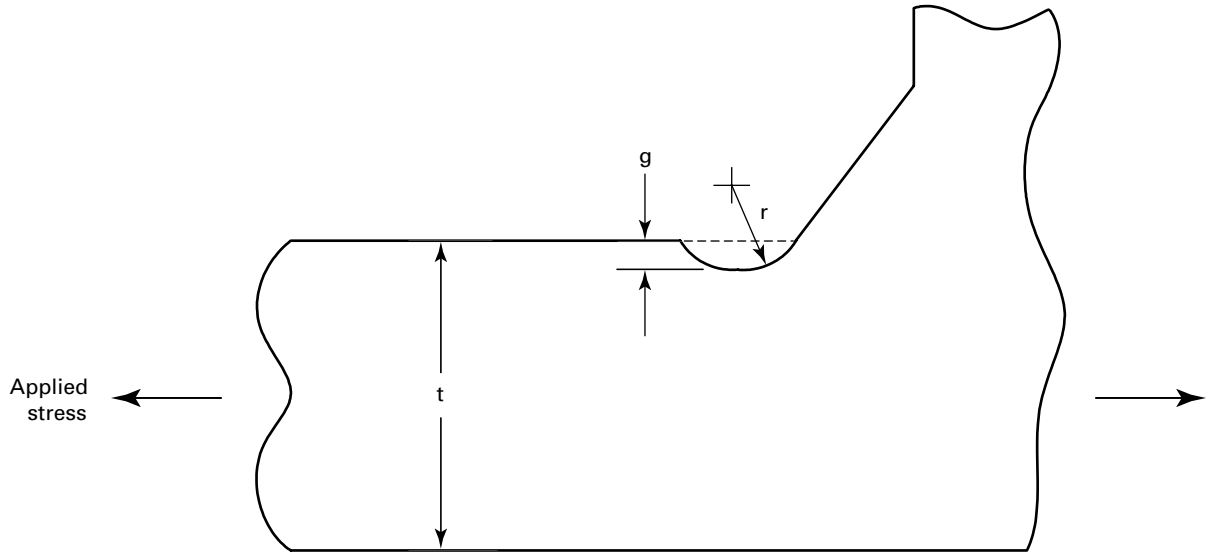
GENERAL NOTES:
(a) $E = 69 \times 10^3$ MPa.
(b) Table KD-320.7 contains tabulated values.

Table KD-322.1
Fatigue Penalty Parameters

Material	*m*	*n*
Low alloy steel	2.0	0.2
Martensitic stainless steel	2.0	0.2
Carbon steel	3.0	0.2
Austenitic stainless steel	1.7	0.3
Nickel-chromium-iron	1.7	0.3
Nickel-copper	1.7	0.3

GENERAL NOTE: The fatigue penalty factor shall only be used if the component is not subjected to thermal ratcheting.

Figure KD-372.1
Burr Grinding of Weld Toe



GENERAL NOTE: g = 0.5 mm (0.02 in.) below undercut; $r \geq 0.25t \geq 4g$.

ARTICLE KD-4
FRACTURE MECHANICS EVALUATION

KD-400 SCOPE

This Article presents a fracture mechanics design approach. In accordance with KD-140, if it can be shown that the vessel will fail in a leak-before-burst mode, then the number of design cycles shall be calculated in accordance with either Article KD-3 or Article KD-4. If a leak-before-burst mode of failure cannot be shown, then the number of design cycles shall be calculated in accordance with this Article.

KD-401 GENERAL (25)

(a) This Article is based on the assumption that the crack initiation stage is complete and that cracks exist at highly stressed points in the pressure vessel. Cracks are defined in this Division as flaws that are predominantly characterized by length and depth, with a sharp root radius. The principles of linear elastic fracture mechanics were used to develop the criteria in this Article for calculating the number of design cycles to propagate these cracks to the allowable final crack size in KD-412.

(b) Manufacturing processes such as welding, heat treatment, forming, autofrettage, shrink fitting, and wire wrapping introduce residual stresses. Some cracks may propagate through the resulting residual stress field due to cyclic loading. A method for accounting for these residual stresses is given in KD-420.

(c) The critical crack size for a given loading condition is defined as the crack size that is calculated using the failure assessment diagram from API 579-1/ASME FFS-1. Variation of fracture toughness through the thickness of a component shall be considered to ensure the toughness used in this Article is representative of the material at the location being considered. The critical crack size shall be calculated for the most severe combination of loading conditions. If the critical crack depth is less than the wall thickness, it may not be possible to assume a leak-before-burst mode of failure. However, see KD-141.

KD-410 CRACK SIZE CRITERIA

KD-411 ASSUMED INITIAL CRACK SIZE (25)

The initial crack size to be used for the calculation of the crack propagation design cycles shall be based on the nondestructive examination method to be used. Unless the nondestructive examination method used can establish both length and depth of the indication, initial semielliptical cracks are assumed to have an aspect ratio a/ℓ of $^1/_3$.

(a) A surface crack not associated with a stress concentration shall be assumed to be semielliptical. The assumed flaw size shall not be less than the maximum acceptable nondestructive examination indication as given in Part KE unless a smaller flaw size is specified in the User's Design Specification [see KG-311.12(a)]. If a smaller initial flaw size is specified, it shall be clearly demonstrated that the nondestructive examination method used will reliably detect indications of that size or smaller. The acceptance criteria for the nondestructive examination method used shall be equal to or less than the specified initial flaw size.

(b) For a thread root or circumferential groove, the crack shall be assumed to be annular or semielliptical.

KD-412 ALLOWABLE FINAL CRACK SIZE

To calculate the number of design cycles N_p based on crack propagation, it is necessary to determine an allowable final crack size. The allowable final crack size shall be calculated using the failure assessment diagram (FAD) in API 579-1/ASME FFS-1. The calculated number of design cycles is the number of cycles required to propagate a crack of the assumed initial crack size to that allowable final crack size. The calculated number of design cycles is defined as the lesser of

(a) the number of cycles corresponding to one-half of the number of cycles required to propagate a crack from the initial assumed crack size to the critical crack size [see KD-401(c)]

(b) the number of cycles required to propagate a crack from the initial assumed crack size to the depth as defined in KD-412.1 and KD-412.2

KD-412.1 Monobloc Vessels. For monobloc vessels, the allowable final crack depth shall be the lesser of

(a) 25% of the section thickness being considered

(b) the assumed initial crack depth defined in KD-411 plus 25% of the dimensional difference between the theoretical critical crack depth and that of the assumed initial crack

KD-412.2 Vessels With Two or More Layers.

(a) For vessels with two or more layers, the final crack depth in the inner layer may be equal to the layer thickness, provided the theoretical collapse pressure (1.732 times the value calculated in KD-221.2) of the combined remaining layers is at least 20% higher than the design pressure of the unflawed vessel.

Otherwise, the allowable final crack depth shall not exceed 25% of the inner layer thickness.

The theoretical collapse pressure of the combined remaining layers shall be calculated using the inside diameter of the innermost of the remaining layers as the pressure loading diameter.

(b) For all other layers, the allowable final crack depth shall not exceed 25% of the layer thickness except as in (c).

(c) The allowable final crack depth of the outermost layer also shall not exceed the dimension equal to the assumed initial crack depth defined in KD-411 plus 25% of the dimensional difference between the theoretical critical crack depth and that of the assumed initial crack.

(25) KD-420 STRESS INTENSITY FACTOR K_I CALCULATION

(a) For finite length cracks, crack growth along the surface and in the through-thickness directions shall be considered. Crack growth shall be calculated using eqs. KD-430(a)(1) and KD-430(a)(2). The aspect ratio shall be updated as the crack size increases. Methods in API 579-1/ASME FFS-1 for the calculation of stress intensity factors and reference stresses shall be used where applicable.

(b) All forms of loading shall be considered, including pressure, thermal, discontinuity, and residual stresses. Weld residual stresses may be estimated using API 579-1/ASME FFS-1, BS 7910, finite element, or other analytical methods. In some cases, the stresses produced by the action of the fluid pressure in the crack shall be considered.

(c) The K_I values for all loadings except residual stresses shall be assessed by considering their minimum and maximum values and their chronological relationship. The combined effects of these loadings shall be reported as minimum $K^*_{I,\min}$ and maximum $K^*_{I,\max}$ stress intensity factors. The effects of residual stresses, such as those due to autofrettage, shrink fitting, welding, or wire winding, shall be assessed by calculating an equivalent positive or negative stress intensity factor due to these residual stresses $K_{I,\text{res}}$. KD-430 specifies how $K_{I,\text{res}}$, $K^*_{I,\min}$ and $K^*_{I,\max}$ are combined to calculate a crack growth rate which shall be integrated to solve for a calculated number of design cycles N_p based on crack propagation.

KD-430 CALCULATION OF CRACK GROWTH RATES (25)

(a) The crack growth rate at the deepest point on the crack periphery da/dN, in./cycle (mm/cycle), is assumed to be a function of the range of stress intensity factor ΔK, ksi-in.$^{1/2}$ (MPa-m$^{1/2}$), and the stress intensity factor ratio R_K where

$$\frac{da}{dN} = C[f(R_K)](\Delta K)^m$$

$$\Delta K = K^*_{I,\max} - K^*_{I,\min} \quad (1)$$

and

$$R_K = \frac{K^*_{I,\min} + K_{I,\text{res}}}{K^*_{I,\max} + K_{I,\text{res}}}$$

and near the surface from

$$dl/dN = 2C[f(R_K)](\Delta K)^m \quad (2)$$

where ΔK is calculated as described above using the methods in KD-420(a). Equation (2) is only required for calculation of elliptical crack growth.

When calculating crack growth rates, the plastic zone correction to the stress intensity factor may be neglected. If $(K^*_{I,\max} + K_{I,\text{res}}) \le 0$, da/dN may be assumed to be equal to zero. The values of C and m to be used for some materials are given in Table KD-430 (Table KD-430M) for the case of $f(R_K) = 1$. If $R_K = 0$, then $f(R_K) = 1$. The relationship $f(R_K)$, which may be used for some materials, is given in Table KD-431.

For materials that are not listed in Table KD-430, fatigue crack growth-rate testing shall be conducted in accordance with ASTM E647.

(1) The testing shall be performed for each of three heats of the material per heat treat condition.

(2) The test specimens shall be in the final heat-treated condition (if applicable) to be used in the vessel construction.

(3) Specimen orientation shall be in the TL direction, as shown in ASTM E399. In the weld metal tests, the notch shall be machined in the center of the width of the weld and shall be normal to the surface of the material. In the heat-affected zone tests, the notch shall be machined approximately normal to the surface of the material and in such a manner that the precrack shall include as much heat-affected zone material as possible in the resulting fracture.

(4) Three da/dN versus ΔK datasets shall be generated per heat of material.

(5) The upper-bound data shall be used in the fracture mechanics analysis.

(6) The data in the form of $da/dN = c(\Delta K)^m$ shall be obtained for the full range of ΔK of interest used in the fracture mechanics analysis.

(7) The R-ratio defined as $K_{\text{min.}}/K_{\text{max.}}$ shall be not less than that used in the vessel design.

(8) The data obtained may be used for other vessels manufactured from the same material specification or grade or from a similar specification or grade having the same nominal chemical composition and heat treatment condition, provided the tensile and yield strengths on the material test report do not exceed by more than 5% the average values for the material used in the qualification tests.

(b) If the value of ΔK is less than the value of the threshold ΔK (ΔK_{th}) as given by the following equation, the value of da/dN may be assumed to be zero.

(1) If $(K^*_{I,\max} + K_{I,\text{res}}) \le 0$, ΔK may be assumed to be equal to zero.

(2) If $R_k < 0$, i.e., $(K^*_{I,\min} + K_{I,\text{res}}) < 0$, ΔK compared with ΔK_{th} shall be $\Delta K = (K^*_{I,\max} + K_{I,\text{res}})$ instead of eq. (1)

For carbon and low alloy steels [$S_y \le 90$ ksi (620 MPa)]

ΔK_{th} = the lesser of $G(1 - HR_K)$ or I, but not less than 1.8 ksi-in.$^{1/2}$ (2.0 MPa-m$^{1/2}$)

For high-strength low alloy steels and martensitic precipitation-hardened steels [$S_y > 90$ ksi (620 MPa)]

ΔK_{th} = the lesser of G (1–HR_K) or I, but not less than 2 ksi-in.$^{1/2}$ (2.2 MPa-m$^{1/2}$)

For aluminum alloys

ΔK_{th} = the lesser of G (1–HR_K) or I, but not less than 0.64 ksi-in.$^{1/2}$ (0.7 MPa-m$^{1/2}$)

Values of G, H, and I for some common pressure vessel materials are given in Table KD-430 (Table KD-430M).

(c) If corrosion fatigue is involved, crack growth rates can increase significantly. Environmental effects in conjunction with loading frequency shall be considered when calculating crack growth rates.

(d) When the operating temperature is higher than room temperature, C in eq. (1) and eq. (2) shall be adjusted using eq. (3), as follows:

$$C = C_o\left(\frac{E_o}{E}\right)^m \tag{3}$$

where

C_o = room-temperature crack growth rate factor given in Table KD-430 (Table KD-430M)

E = elastic modulus at operating temperature

E_o = elastic modulus at room temperature

m = crack growth rate exponent given in Table KD-430 (Table KD-430M)

KD-440 CALCULATED NUMBER OF DESIGN CYCLES

Crack growth is dependent on both cyclic stress and the crack size when the cycle occurs. Thus, the calculated number of design cycles N_p is highly dependent on the sequence of loadings. The designer shall provide a summary of the sequence and magnitude of all loadings and a projection of the calculated crack growth associated with each point in the loading sequence. This summary shall be documented in the Manufacturer's Design Report.

The number of design cycles may be calculated by numerical integration of the crack growth rate [see eq. KD-430(a)(1)]. It shall be assumed that K_I values are constant over an interval of crack growth Δa and Δl that is small relative to the crack size. To ensure that the interval of crack depth is sufficiently small, the calculation shall be repeated using intervals of decreasing size until no significant change in the calculated number of design cycles N_p is obtained.

KD-450 ALTERNATIVE METHODS FOR GENERATION OF WELD FLAW SIZE ACCEPTANCE CRITERIA (25)

The Manufacturer shall develop a table of flaw size acceptance criteria for every weld that is to use alternative criteria from the requirements of KE-301(i)(3)(-d).

(a) The flaw acceptance criteria shall be developed based on the initial flaw sizes used in the fracture mechanics life assessment in Article KD-4.

(b) The acceptance criteria shall be equal to or less than the initial flaw size used in each flaw evaluation in Article KD-4.

KD-451 ACCEPTANCE CRITERIA TABLE (25)

A table of acceptance criteria shall be developed for each weld.

(a) The table shall include

(1) a surface-connected flaw that is parallel to the weld axis

(2) a surface-connected flaw that is perpendicular to the weld axis

(3) a subsurface flaw that is parallel to the weld axis

(4) a subsurface flaw that is perpendicular to the weld axis

The definition of a surface-connected flaw from Figure KE-301-1 shall be used.

(b) The table shall include the following aspect ratios as a minimum:

(1) 2 units long to 1 unit deep.

(2) 3 units long to 1 unit deep.

(3) 6 units long to 1 unit deep.

(c) The specific geometry of each weld shall be used in the fracture mechanics evaluations.

(d) All loading conditions, including any residual stresses considering the amount of PWHT used, shall be considered for each weld.

(25)

Table KD-430
Room-Temperature Crack Growth Rate Factors (U.S. Customary Units)

Material	C_o, in./cycle (ksi-in.$^{1/2}$)$^{-m}$	m	G, ksi-in.$^{1/2}$	H	I, ksi-in.$^{1/2}$
Carbon and low alloy steels ($S_y \le 90$ ksi)	2.00 E–10	3.07	5.0	0.8	5.0
High strength low alloy steels, $S_y > 90$ ksi	1.95 E–10	3.26	6.4	0.85	5.5
Cast high strength alloy steels ($S_y > 90$ ksi)	2.47 E–9	2.40	NA [Note (1)]	NA [Note (1)]	NA [Note (1)]
Martensitic precipitation-hardened steels	2.38 E–10	3.15	6.4	0.85	5.5
Austenitic stainless steels	1.1 E–10	3.30	NA [Note (1)]	NA [Note (1)]	NA [Note (1)]
Aluminum alloys	7.01 E–9	3.26	1.64	1.22	1.64

GENERAL NOTE: The effect of the specific corrosive environment and load condition on fatigue crack growth rate factors shall be considered. The actual growth rates used in the design shall be by agreement between the User and Manufacturer.

NOTE: (1) Threshold values for cast steels and austenitic stainless steels have not yet been established.

(25)

Table KD-430M
Room-Temperature Crack Growth Rate Factors (SI Units)

Material	C_o, mm/cycle (MPa-m$^{1/2}$)$^{-m}$	m	G, MPa-m$^{1/2}$	H	I, MPa-m$^{1/2}$
Carbon and low alloy steels ($S_y \le 620$ MPa)	3.80 E–9	3.07	5.5	0.8	5.5
High strength low alloy steels, $S_y > 620$ MPa	3.64 E–9	3.26	7.0	0.85	6.0
Cast high strength alloy steels ($S_y > 90$ ksi)	5.0 E–8	2.40	NA [Note (1)]	NA [Note (1)]	NA [Note (1)]
Martensitic precipitation-hardened steels	4.49 E–9	3.15	7.0	0.85	6.0
Austenitic stainless steels	2.05 E–9	3.30	NA [Note (1)]	NA [Note (1)]	NA [Note (1)]
Aluminum alloys	1.31 E–7	3.26	1.8	1.22	1.8

GENERAL NOTE: The effect of the specific corrosive environment and load condition on fatigue crack growth rate factors shall be considered. The actual growth rates used in the design shall be by agreement between the User and Manufacturer.

NOTE: (1) Threshold values for cast steels and austenitic stainless steels have not yet been established.

(25)

Table KD-431
Crack Growth Rate Factors

Carbon and low alloy steels, $S_y \le 90$ ksi (620 MPa)	
$0 \le R_K < 1$	$f(R_K) = [2.88/(2.88 - R_K)]^m$
$R_K < 0$	$f(R_K) = [1/(1 - R_K)]^m$
High strength low alloy steels, $S_y > 90$ ksi (620 MPa)	$C_2 = 1.5$ $C_3 = 3.53$
$R_K \ge 0$	$f(R_K) = 1.0 + C_3 R_k$
$R_K < 0$	$f(R_K) = [C_2/(C_2 - R_k)]^m$
Martensitic precipitation-hardened steels	$C_2 = 1.5$ $C_3 = 3.48$
$R_k \ge 0.67$	$f(R_K) = 30.53R_K - 17.0$
$0 \le R_K < 0.67$	$f(R_K) = 1.0 + C_3 R_k$
$R_K < 0$	$f(R_K) = [C_2/(C_2 - R_k)]^m$
Austenitic stainless steels	
$0.79 < R_k < 1.0$	$f(R_K) = -43.35 + 57.97R_K$
$0 < R_K \le 0.79$	$f(R_K) = 1.0 + 1.8R_K$
$R_K \le 0$	$f(R_K) = 1.0$

ARTICLE KD-5
DESIGN USING AUTOFRETTAGE

KD-500 SCOPE

This Article provides means to calculate residual stress distribution after autofrettage has been performed, in straight single-wall cylinders with no crossholes or discontinuities. Numerical elastic–plastic analyses or experimental techniques may be used for more complex geometries. Other approaches may be used if they can be shown to be conservative.

Autofrettage is one of several processes that can be used to produce favorable residual stresses in thick-walled pressure vessels. Autofrettage may be used alone or combined with other processes such as shrink fitting or wrapping to produce a more favorable residual stress distribution than can be conveniently produced by autofrettage alone. See Article KD-8 for rules on combining these residual stresses.

The method for vessel fatigue design accounting for the residual stresses produced by autofrettage is given in Articles KD-3 and KD-4. The guidelines for accomplishing the autofrettage operation are given in Article KF-5.

Calculations in the Article shall use the dimensions in the new, uncorroded condition (see KD-104).

KD-501 THEORY

(a) The theory of autofrettage is based on the fact that the stress in a thick-walled cylindrical vessel is higher at the bore than at the outside surface for a given internal pressure. If such a vessel is subjected to a continuously increasing pressure, the entire vessel will deform elastically until some pressure is reached at which the material at the bore begins to plastically deform. As the pressure continues to increase, the boundary at which material begins to yield moves from the bore through the vessel wall until it reaches the outer wall, causing plastic collapse [see KD-210(f)(6)]. In the process of autofrettage, the pressure is increased from the point of first yielding at the bore to a pressure that will place the elastic–plastic interface at the desired radius. The removal of this pressure then produces compressive residual tangential stress at the bore and tensile residual tangential stress at the outer wall.

(b) The effects of these residual compressive tangential stresses are to

(1) increase the value of any subsequent application of internal pressure which will cause the onset of additional permanent deformation of the cylinder

(2) reduce the effective mean stress value of the cyclic bore stresses and thus increase the fatigue life

(3) reduce the effective fracture mechanics stress intensity factor at the tip of a crack or cracklike flaw near the bore due to internal pressure. This will retard the growth of fatigue or stress corrosion cracks near the bore surface.

KD-502 NOMENCLATURE

A_{cs} = cross-sectional area normal to the longitudinal axis, in.^{2} (mm^2)
D = diameter of the cylindrical vessel at any point in the wall, in. (mm)
D_I = inside diameter, in. (mm)
D_O = outside diameter, in. (mm)
D_P = diameter of the plastic–elastic interface before unloading the autofrettage pressure, in. (mm)
D_Z = diameter where $\sigma_{tRA} = \sigma_{rRA}$, in. (mm)
E = elastic modulus, ksi (MPa)
F_b = correction factor for the Bauschinger effect for $D_Z \le D \le D_P$
F_1 = total longitudinal force on the cylinder at the maximum autofrettage pressure. If all of the force on the end closures is supported by an external device such as a frame, $F_1 =$ 0 kips *(N)*
M = wall overstrain ratio, $(D_P - D_I)/(D_O - D_I)$
P_A = maximum pressure applied during the autofrettage operation, ksi (MPa)
S_y = actual measured yield strength of the material being autofrettaged at the temperature at which the autofrettage is performed, ksi (MPa)
Y = ratio of D_O/D_I

ε_m = average value of the maximum tangential strain on the outside surface of the vessel, taken at a minimum of three axial locations and measured at the maximum pressure used for the autofrettage operation P_A
ε_p = average value of the permanent tangential strain on the inside surface of the vessel, taken at a minimum of three axial locations and measured after the release of the autofrettage pressure
σ_{AD} = value of σ_{tRA} at $D = D_I$, ksi (MPa)
σ_{CD} = value of the residual tangential stress at $D = D_I$ corrected for the Bauschinger effect, ksi (MPa)
σ_{rR} = residual radial stress corrected for the Bauschinger effect, ksi (MPa)
σ_{rRA} = first approximation of the residual radial stress after autofrettage for $D_I \le D \le D_P$, ksi (MPa)
σ_{tR} = residual tangential stress corrected for the Bauschinger effect, ksi (MPa)
σ_{tRA} = first approximation of the residual tangential stress after autofrettage for $D_I \le D \le D_P$, ksi (MPa)
ν = Poisson's ratio

KD-510 LIMITS ON AUTOFRETTAGE PRESSURE

There is no specified upper limit on autofrettage pressure. However, the permanent tangential strain at the bore surface resulting from the autofrettage operation shall not exceed 2%.

KD-520 CALCULATION OF RESIDUAL STRESSES

(a) In order to evaluate the design of a vessel utilizing autofrettage, a calculation of the residual stress distribution produced by autofrettage shall first be performed. This calculation requires knowledge of the actual extent of autofrettage obtained during the process. This is defined by the diameter of the elastic–plastic interface D_P or by the overstrain ratio $(D_P - D_I)/(D_O - D_I)$. Possible methods for determining D_P are given below. Other methods may be used if they can be shown to be more accurate or conservative.

(b) Machining after autofrettage is permitted. The resulting extent of autofrettage (overstrain ratio) for this condition is calculated using the final dimensions of the vessel and the assumption that D_P remains as determined above. However, any residual tensile stresses introduced by the machining shall be considered.

(c) Calculations in this Article shall use the dimensions in the new, uncorroded condition (see KD-104).

KD-521 CALCULATION OF THE ELASTIC–PLASTIC INTERFACE DIAMETER

The diameter of the elastic–plastic interface D_P may be determined from one or more of the following measurements:

(a) ε_m.

(b) ε_p.

(c) P_A. This shall only be used to determine D_P if the value of the resulting overstrain ratio so determined is less than 0.4.

KD-521.1 When Outside Strain Is Known. If ε_m is measured, calculate D_P/D_O as follows.

(a) For vessels supporting end load during autofrettage,

$$(D_P/D_O)^2 = \left[E\varepsilon_m + \nu\left(\frac{P_A D_I^2}{D_O^2 - D_I^2}\right)\right]/1.15S_y$$

(b) For all other cases,

$$(D_P/D_O)^2 = [E\varepsilon_m + \nu\,(F_1/A_{cs})]/1.15S_y$$

KD-521.2 When Residual Inside Strain Is Known. If ε_p is measured, calculate D_P from the following equation using an iterative procedure:

$$2E\varepsilon_p/1.15S_y = (1 - 2\nu)\left[\ln\left(D_I^2/D_P^2\right) - 1\right] + (2 - \nu)(D_P/D_I)^2 + (1 - \nu)(D_P/D_O)^2 - \frac{\left[\ln\left(D_P^2/D_I^2\right) + \left(D_O^2 - D_P^2\right)/D_0^2\right]\left[1 - \nu + (1 + \nu)Y^2\right]}{Y^2 - 1}$$

KD-521.3 When Autofrettage Pressure Is Known. If P_A is measured and the requirements of KD-521(c) are met, then D_P can be determined from the following equation using an iterative procedure:

$$P_A = 1.15S_y\left[\ln\left(D_P/D_I\right) + \left(D_O^2 - D_P^2\right)/2D_O^2\right]$$

KD-522 RESIDUAL STRESSES BETWEEN BORE AND ELASTIC–PLASTIC INTERFACE

The general method for calculating the autofrettage residual stresses is given below for a monobloc cylinder.

KD-522.1 When No Reverse Yielding Occurs. Calculate the first approximation of the tangential and radial residual stress distributions (σ_{tRA} and σ_{rRA}) using eqs. (1) and (2) for $D_I < D < D_P$.

$$\frac{\sigma_{tRA}}{S_y} = \frac{D_P^2 + D_O^2}{2D_O^2} + \ln\left(\frac{D}{D_P}\right) - \left[\frac{D_I^2}{D_O^2 - D_I^2}\right]\left[\frac{D_O^2 - D_P^2}{2D_O^2} + \ln\left(\frac{D_P}{D_I}\right)\right]\left(1 + \frac{D_O^2}{D^2}\right) \quad (1)$$

$$\frac{\sigma_{rRA}}{S_y} = \frac{D_P^2 - D_O^2}{2D_O^2} + \ln\left(\frac{D}{D_P}\right) - \left[\frac{D_I^2}{D_O^2 - D_I^2}\right]\left[\frac{D_O^2 - D_P^2}{2D_O^2} + \ln\left(\frac{D_P}{D_I}\right)\right]\left(1 - \frac{D_O^2}{D^2}\right) \quad (2)$$

KD-522.2 Correction for Reverse Yielding (Bauschinger Effect). The residual stresses shall be corrected for the fact that reverse yielding may occur on unloading from the autofrettage pressure due to the reduction of the compressive yield strength of the material resulting from tensile plastic deformation. This is known as the *Bauschinger Effect*. This correction shall be accomplished as follows:

(a) Using eqs. KD-522.1(1) and KD-522.1(2), calculate the value of D at which $(\sigma_{tRA} - \sigma_{rRA}) = 0$ using an iterative procedure, and define this as D_Z.

(b) Calculate the value of σ_{tRA} at $D = D_I$ from eq. KD-522.1(1) and define this as σ_{AD}. Calculate the corrected value of the residual stress at $D = D_I$ (defined as σ_{CD}), from both eqs. (1) and (2) below.

$$\sigma_{CD}/\sigma_{AD} = 1.6695 - 0.1651Y - 1.8871M + 1.9837M^2 - 0.7296M^3 \quad (1)$$

If the end load on the closures is not supported by the cylinder wall during autofrettage (open end)

$$\sigma_{CD}/\sigma_{AD} = -0.5484 + 1.8141Y - 0.6502Y^2 + 0.0791Y^3 \quad (2)$$

If the end load on the closures is supported by the cylinder wall during autofrettage (closed end), replace eq. (2) with $\sigma_{CD}/\sigma_{AD} = 1.15$.

The value of σ_{CD} to be used is the least negative value of those determined from eq. (1) or (2) above.

(c) If $\sigma_{CD}/S_y < -0.7$, then let $\sigma_{CD}/S_y = -0.7$.

(d) For $D_I < D < D_Z$, calculate the residual stress distribution from eqs. (3) and (4):

$$\frac{\sigma tR}{\sigma_{CD}} = \frac{D_Z\,[\ln(D\,/\,D_I) + 1] + D_I - 2D}{D_Z - D_I} \quad (3)$$

$$\frac{\sigma rR}{\sigma_{CD}} = \frac{D_Z \ln(D\,/\,D_I) + D_I - D}{D_Z - D_I} \quad (4)$$

(e) For $D > D_Z$, the residual stresses shall be corrected to ensure that continuity and equilibrium conditions are met. This shall be accomplished by calculating a correction factor F_b as follows:

(1) Calculate σ_{rR} at $D = D_Z$ using eq. (d)(4) above.

(2) Calculate σ_{rRA} at $D = D_Z$ using eq. KD-522.1(2).

(3) Divide the results of subpara. (1) by the results of subparagraph (2) and this equals F_b.

(f) For $D_Z < D < D_P$, calculate the residual stresses using eqs. KD-522.1(1) and KD-522.1(2) and multiply the results at each value of D by F_b.

KD-523 RESIDUAL STRESSES BETWEEN ELASTIC–PLASTIC INTERFACE AND OUTSIDE DIAMETER

For $D_P < D < D_O$, calculate the residual stresses using eqs. (1) and (2):

$$\frac{\sigma_{tR}}{S_y} = F_b\left(1 + \frac{D_O^2}{D^2}\right)\left\{\frac{D_P^2}{2D_O^2} + \frac{D_I^2}{D_O^2 - D_I^2} \times \left[\frac{D_P^2 - D_O^2}{2D_O^2} - \ln\left(\frac{D_P}{D_I}\right)\right]\right\} \quad (1)$$

$$\frac{\sigma_{rR}}{S_y} = F_b\left(1 - \frac{D_O^2}{D^2}\right)\left\{\frac{D_P^2}{2D_O^2} + \frac{D_I^2}{D_O^2 - D_I^2} \times \left[\frac{D_P^2 - D_O^2}{2D_O^2} - \ln\left(\frac{D_P}{D_I}\right)\right]\right\} \quad (2)$$

KD-530 DESIGN CALCULATIONS

These residual stress values are used in the fatigue analysis as described in Article KD-3 and in the fracture mechanics analysis as described in Article KD-4.

ARTICLE KD-6
DESIGN REQUIREMENTS FOR CLOSURES, INTEGRAL HEADS, THREADED FASTENERS, AND SEALS

KD-600 SCOPE

The requirements in this Article apply to integral heads, closures, threaded fasteners, and seals. These requirements are additional to the general requirements given in Articles KD-1 and KD-2.

KD-601 GENERAL

(a) Closures, integral heads, threaded fasteners, and seals shall have the capability to contain pressure with the same assurance against failure as the vessel for which it will be used.

(b) The Designer shall consider the influence of cross bores and other openings on the static strength integrity of the vessel.

(c) A complete stress analysis shall be made of all components that contribute to the strength and sealing capability of the closure.

(d) For applications involving cyclic loads, the requirements of Article KD-3, Article KD-4, Article KD-10, or Article KD-12, as applicable, shall be met for all parts except the sealing element.

(e) Provisions shall be made to prevent separation of joints under all service loadings.

(f) The effects of the total load to be resisted, the number of threads, the number of threaded fasteners, the thread form, the relative stiffness of mating parts, and friction shall be considered in both the static and fatigue analyses.

(g) Vent passages shall be provided to prevent pressure buildup caused by accidental or incidental development of any secondary sealing areas exterior to the designated sealing surface (e.g., threads).

(h) Flared, flareless, and compression-type joints for tubing are not permitted. Proprietary fittings are addressed in KD-625.

(25) KD-620 THREADED FASTENERS AND COMPONENTS

(a) Threaded fasteners are frequently described as bolts, studs, and tie rods.

(b) Straight threads and taper pipe threads shall conform to the following rules:

(1) Straight threaded connections are permitted as provided for in this Article.[2]

(2) Taper pipe threads are permitted provided the following rules are met:

(-a) Taper threads shall be used in nozzle necks on the inside surface only.

(-b) Thread types shall be National Gas Taper (NGT) in accordance with CGA V-1 or in accordance with ISO 11363-1.

(-c) Nominal thread size shall not exceed 1.0 in. NGT in accordance with CGA V-1 or 25E in accordance with ISO 11363-1.

(-d) Design pressure shall not exceed 6,000 psi (41 MPa). Maximum design temperature shall not exceed 200°F (93°C).

(-e) An elastic–plastic finite element analysis of the connection shall be performed in accordance with KD-230 through KD-236 considering the loads due to the specified assembly torque and all other load cases in Table KD-230.1.

(-f) Seal welding of the threads is not permitted.

(c) Where tapped holes are provided in pressure boundaries, the effect of such holes (e.g., stress riser, material loss) shall be considered in the vessel design.

(d) Thread load distribution shall be considered in design cyclic analysis in accordance with KD-622.

(e) The length of engagement used in design shall be the minimum that can occur within the drawing tolerances with no credit for partial threads.

KD-621 ELASTIC–PLASTIC BASIS

The Designer may use the elastic–plastic method and meet the applicable requirements of KD-230 for all threaded joints or fasteners of any thread form.

(a) The elastic–plastic rules of KD-231 are applied for all the loads and load cases to be considered as listed in Table KD-230.1 and defined in KD-231.2.

(b) The load combinations and load factors as listed in Table KD-230.4 are applied and the components are stable under the applied loads.

KD-622 FATIGUE AND FRACTURE MECHANICS ANALYSIS

(a) A fatigue analysis in accordance with Article KD-3 or a fracture mechanics analysis in accordance with Article KD-4 is required for all threaded connections.

(b) The fatigue evaluation of a threaded joint is made by the same methods as are applied to any other structure that is subjected to cyclic loading.

(c) ASME B18.2.2 Standard nuts of materials permitted by this Division do not require fatigue analysis. Internal threads mating with a stud or bolt do not require fatigue analysis for bolting loads. However, the effects of the internally threaded penetration on the nominal primary-plus-secondary stresses in the internally threaded member shall be considered.

KD-623 LINEAR ELASTIC BASIS

Linear elastic analysis of threaded fasteners and components may be used in lieu of elastic–plastic methods of KD-621 for vessels that are permitted by the rules of KD-200 to use the linear elastic methods of Mandatory Appendix 9.

KD-624 THREADING AND MACHINING OF STUDS

Studs shall be threaded full length, or shall be machined down to the root diameter of the thread in the unthreaded portion. The threaded portions shall have a length of at least $1^{1}/_{2}$ times the nominal diameter, unless analysis (see KD-621) using the most unfavorable combination of tolerances at assembly demonstrates adequate thread engagement is achieved with a shorter thread length.

Studs greater than eight times the nominal diameter in length may have an unthreaded portion which has the nominal diameter of the stud, provided the following requirements are met.

(a) The stud shall be machined down to the root diameter of the thread for a minimum distance of 0.5 diameters adjacent to the threaded portion.

(b) A suitable transition shall be provided between the root diameter portion and the full diameter portion.

(c) Threads shall be of a "V" type, having a minimum thread root radius no smaller than 0.08 times the pitch.

(d) Fillet radii at the end of the shank shall be such that the ratio of fillet radius to shank diameter is not less than 0.06.

KD-625 SPECIAL THREADS AND PROPRIETARY JOINTS

Mechanical joints for which no standards exist and other proprietary joints may be used. A prototype of such a proprietary joint shall be subjected to performance tests to determine the safety of the joint under simulated service loadings in accordance with Article KD-12. When vibration, fatigue, cyclic conditions, low temperature, thermal expansion, or hydraulic shock is anticipated, the applicable loads shall be incorporated in the tests.

KD-630 LOAD-CARRYING SHELL WITH SINGLE THREADED END CLOSURES

Because of the many variables involved, and in order not to restrict innovative designs, detailed rules are kept to a minimum. The effects of the total load to be resisted, the number of threads, the thread form, the relative stiffness of mating parts, and friction shall be considered in both the static and fatigue analyses of the closure. Stresses can be minimized by providing generous undercuts ahead of the first threads and providing flexibility in mating parts to promote equalization of the thread loads.

KD-631 STRESSES IN VESSEL AT THREADS

The Designer shall identify the area of the threaded closure where the maximum equivalent stress occurs. This is generally the area at the root of the most highly loaded thread, which is usually the first or second thread. Calculation of this equivalent stress requires consideration of the actual thread load, stress concentration factor due to thread form (in particular, the thread root radius), thread bending stress, and the membrane and bending stresses in the vessel at the thread.

KD-631.1 Longitudinal Bending Stresses. Unless it can be shown by analysis or test that a lower value is appropriate, the primary longitudinal bending stress in the vessel at the first thread shall be considered to be 3.0 times the primary longitudinal membrane stress.

KD-631.2 Circumferential Stresses. The circumferential stresses are significantly affected by the distance to the pressure seal. Unless shown by analysis or test that a lower value is appropriate, the circumferential stresses in the vessel at the first thread shall be considered to be those in the cylinder derived with the equations in 9-200. In addition, circumferential stresses due to resultant radial loading of the threads shall be included.

KD-631.3 Thread Load Distribution. In general, the threads do not carry the end load uniformly. The Designer shall determine thread load distribution. See E-200.

KD-631.4 Fracture Mechanics Analysis. Fracture mechanics analysis shall be made in accordance with Article KD-4. This analysis shall include as a minimum the combined effects of bending of the thread, and the shell membrane and bending stresses.

KD-631.5 Progressive Distortion. Screwed-on caps and screwed-in plugs are examples of nonintegral connections which are subject to failure by bellmouthing or other types of progressive deformation. Such joints may be

subject to ratcheting, causing the mating members to progressively disengage. See KD-210(f)(9).

KD-631.6 Interrupted Threads. Closures utilizing interrupted threads may be analyzed as closures with continuous threads provided that a multiplier is applied to the resultant stresses. The multiplier is the ratio of the continuous thread circumferential length to that of the interrupted thread. The contact length used when calculating the stress distribution for an interrupted thread may be less than the thread length because of the profiling of the thread ends.

KD-634 SPECIAL CLOSURES AND MATERIALS

(a) Threaded closures for which no standards exist may be used, provided the closure is analyzed in accordance with the rules of Articles KD-2, KD-3, and KD-4, or a prototype has been evaluated in accordance with the rules of Article KD-12.

(b) For parts for which it is impossible or impractical to measure the yield strength after final processing, the maximum allowable tensile stress at design pressure shall be one-third the ultimate strength at design temperature, so long as the final processing does not adversely affect the ultimate strength.

(c) The loads used in the design of a clamped connection shall be no less than that determined by Nonmandatory Appendix G, G-400(b).

KD-640 INTEGRAL HEADS

Integral heads shall be designed in accordance with KD-230 or Mandatory Appendix 9. The designer may use Nonmandatory Appendix E instead of KD-230 or Mandatory Appendix 9 if the conditions in Nonmandatory Appendix E are satisfied.

KD-650 QUICK-ACTUATING CLOSURES

KD-651 GENERAL DESIGN REQUIREMENTS

Quick-actuating closures shall be so designed and installed that it can be determined by visual external observation that the holding elements are in good condition and that their locking elements, when the closure is in the closed position, are in full engagement. Alternatively, other means may be provided to ensure full engagement.

KD-652 SPECIFIC DESIGN REQUIREMENTS

Quick-actuating closures that are held in position by positive locking devices and that are fully released by partial rotation or limited movement of the closure itself or the locking mechanism, and any automated closure, shall be designed to meet the following conditions:

(a) The closure and its holding elements are fully engaged in their intended operating position before the vessel can be pressurized.

(b) Pressure tending to open the closure shall be released before the locking mechanism is disengaged.

(c) A coefficient of friction less than or equal to 0.02 shall be used in the design analysis.

KD-652.1 Permissible Design Deviations for Manually Operated Closures Quick-actuating closures that are held in position by a locking device or mechanism that requires manual operation and are so designed that there shall be leakage of the contents of the vessel prior to disengagement of the locking elements and release of closure need not satisfy KD-652(a), KD-652(b), and KD-652(c). However, such closures shall be equipped with an audible or visible warning device that shall serve to warn the operator if pressure is applied to the vessel before the closure and its holding elements are fully engaged in their intended position and, further, will serve to warn the operator if an attempt is made to operate the locking mechanism or device before the pressure within the vessel is released.

KD-652.2 Yokes. Yokes or frames are quick-actuating closures that shall comply with all the requirements of this Division.

KD-653 REQUIRED PRESSURE-INDICATING DEVICES

All vessels having quick-actuating closures shall be provided with a pressure-indicating device visible from the operating station.

KD-660 REQUIREMENTS FOR CLOSURES AND SEALS

The requirement of a leak-tight seal is of primary importance in closures for high pressure vessels. This is because even small leaks produce a damaging (cutting) effect through the sealing surfaces, which may progress rapidly to increasingly hazardous conditions.

KD-661 REQUIREMENTS FOR CLOSURES

(a) Adequate venting shall be provided in the closure design in the event of seal failure.

(b) The effects of dilation, distortion, or both on the closure components under all expected conditions of pressure and temperature shall not result in an increase in the seal clearances greater than the values required to retain the sealing element.

KD-662 REQUIREMENTS FOR SEALING ELEMENTS

The material selected shall be compatible with all normally expected process and environmental conditions, such as pressure, temperature, corrosion, solubility,

chemical reaction, etc., as specified in the User's Design Specification.

KD-662.1 Contained Sealing Elements. The materials of construction for sealing elements are generally not covered in Part KM. The User's Design Specification shall either specify the required material or furnish enough information to enable the Designer to make an appropriate selection.

KD-662.2 Unsupported Metallic Sealing Elements. Sealing elements which themselves provide the strength required to contain the pressure (i.e., cone joint, lapped joint, etc.) shall satisfy the requirements of this Division.

ARTICLE KD-7
DESIGN REQUIREMENTS FOR ATTACHMENTS, SUPPORTS, AND EXTERNAL HEATING AND COOLING JACKETS

KD-700 GENERAL REQUIREMENTS

The requirements of this Article are in addition to the requirements given in Articles KD-2, KD-3, and KD-4.

(a) Supports, lugs, brackets, stiffeners, and other attachments may be welded or bolted to the vessel wall. A detailed fatigue and fracture mechanics analysis in accordance with the requirements of Article KD-3 or KD-4, as applicable, of the effect of all attachments on the pressure boundary is required.

(b) Attachments shall approximately conform to the curvature of the shell to which they are to be attached.

(c) Attachments may be welded to a pressure vessel only as permitted by the rules of this Division.

(1) Resistance welded studs, clips, etc., shall not be used.

(2) Some acceptable types of welds are shown in Figure KD-700.

(3) All welds joining nonpressure parts to pressure parts shall be continuous full-penetration welds; see KF-220(c).

(d) Attachments may be welded directly to weld deposit cladding, in which case the following requirements shall apply.

(1) For clad construction, attachments may be made directly to the cladding only if loadings producing primary stresses in the attachment weld do not exceed 10% of the design equivalent stress value of the attachment or the cladding material, whichever is less. For higher loadings, there shall be sufficient attachment welding either directly to the base metal or to weld overlay cladding to develop the strength for the primary stress loadings (portions of weld not required for strength, e.g., for weld continuity or sealing, may be welded directly to the cladding).

(2) For linings, attachments should be made directly to the base metal or to weld overlay cladding. Analysis and tests shall be made to establish the adequacy and reliability of attachment before making any attachments directly to the lining (successful experience with similar linings in comparable service may provide a basis for judgment).

KD-710 MATERIALS FOR ATTACHMENTS

KD-711 ATTACHMENTS TO PRESSURE PARTS

Those attachments welded directly to pressure parts shall be of a material listed in Part KM. The material and the weld metal shall be compatible with that of the pressure part. The designer is cautioned to consider the effects of differences in coefficients of expansion modulus of elasticity and yield strength between materials at the design temperature.

KD-712 MINOR ATTACHMENTS

Minor attachments are defined as parts of small size [not over $\frac{3}{8}$ in. (10 mm) thick or 5 in.^{3} (80 000 mm^3) volume] carrying no load or insignificant load requiring no load calculation in the Designer's judgment, such as nameplates, insulation supports, and locating lugs.

Except as limited by Part KF or Part KM, where no welding is permitted, minor attachments may be of material not listed in Section II, Part D and may be welded directly to the pressure part, provided

(a) the material is identified as complying with an ASTM specification and is suitable for welding

(b) the material of the attachment and the pressure part are compatible insofar as welding is concerned

(c) the welds are postweld heat treated when required in Part KF

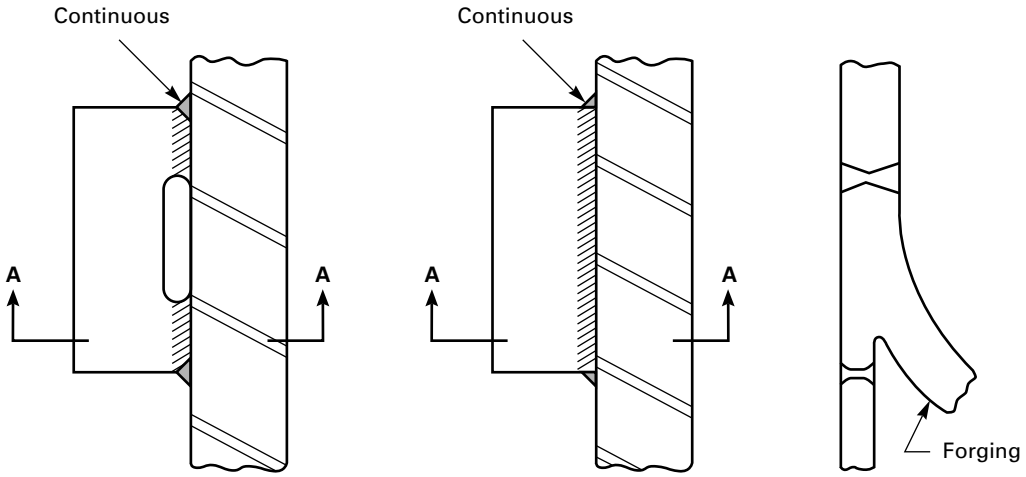
KD-720 WELDS ATTACHING NONPRESSURE PARTS TO PRESSURE PARTS

KD-721 LOCATION RESTRICTIONS

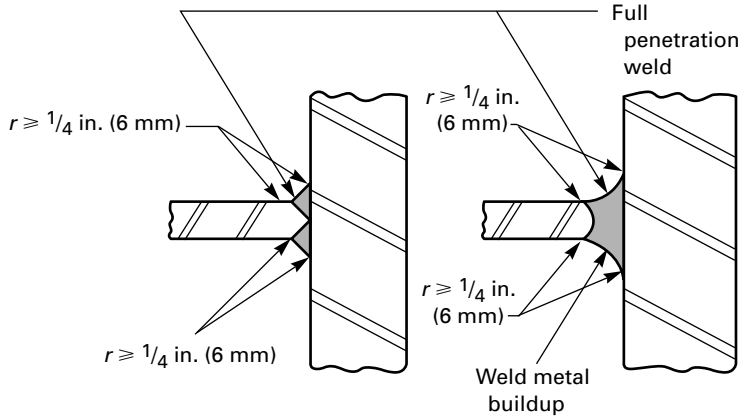
Welds attaching nonpressure parts to pressure parts shall be no closer than $(R_m t_s)^{0.5}$ to a gross structural discontinuity, where

R_m = mean radius of curvature of shell at the discontinuity
t_s = shell thickness

Figure KD-700
Some Illustrative Weld Attachment Details



(a) Bracket and Lug Attachments **(b) Bracket and Lug Attachments** **(c) Support Skirts**



(d) Section A–A

KD-722 TYPES OF ATTACHMENT WELDS

Attachment of nonpressure parts to pressure parts shall be one of the following types:

(a) full-penetration weld[3] [see Figure KD-700, illustration (c)]

(b) full-penetration weld plus fillet weld on one or both sides, in accordance with Figure KD-700, illustrations (a) and (b)

KD-723 STRESS VALUES FOR WELD MATERIALS

Attachment weld strength shall be based on the minimum weld area and the design equivalent stress value in Section II, Part D and stress criteria in Mandatory Appendix 9 for the weaker of the two materials joined.

KD-724 ATTACHMENT WELDS — FATIGUE ANALYSIS

The fatigue analysis evaluations of Article KD-3 or KD-4, as applicable, shall apply.

KD-730 DESIGN OF ATTACHMENTS

The effects of attachments, including external and internal piping connections, shall be taken into account in checking for compliance with the other requirements of this Division.

KD-740 DESIGN OF SUPPORTS

(a) Vessel supports shall accommodate the maximum imposed loadings. The imposed loadings include those due to pressure, weight of the vessel and its contents, machinery and piping loads, wind, earthquake, etc. (see Article KD-1). Wind and earthquake loads need not be assumed to occur simultaneously.

(b) Supports within the jurisdiction of this Division shall meet the requirements of Article KD-2.

(c) Supports of vertical vessels provided with removable bottom closures shall be designed so as to allow the bottom closure to be periodically removed for service and inspection.

(d) Loads imposed on the pressure-retaining components from the supports shall be considered in the design (see KD-110).

When the support method is unknown at the time of manufacture, the Manufacturer shall document in the Manufacturer's Design Report all parameters used in the design of the pressure vessel that are required for the User to complete the design of the support.

KD-750 JACKETED VESSELS

When a vessel constructed to this Division is to be fitted with a jacket for heating or cooling purposes, the jacket shall meet the following rules:

(a) The portion of a jacket welded directly to a Division 3 vessel shall meet the rules of Division 3 for the direct attachment weldment (actual attachment weld and attachment material) as covered by Parts KF and KM. The remainder of the jacket shall meet the design rules of this Division, Division 2, or Division 1, in accordance with the User's Design Specification.

(b) A jacket attached by means other than direct welding to the vessel shall meet the design rules of this Division, Division 2, or Division 1. Spacer bars and jacket closures shall meet the materials and fabrication requirements of the same Division.

ARTICLE KD-8
SPECIAL DESIGN REQUIREMENTS FOR LAYERED VESSELS

KD-800 GENERAL

(a) For the purposes of this Division, a *layered vessel* is defined as any cylindrical or spherical vessel that is constructed of two or more concentric, hollow cylinders or spheres assembled in such a way that the outer surface of each cylinder or sphere is in contact with the inner surface of the next larger cylinder or sphere. Each individual cylinder or sphere is referred to as a *layer*.

(b) There are three types of layered vessel constructions considered in this Article:

(1) vessels made of forged, machined layers that are shrink-fitted together

(2) vessels made of rolled, welded, and machined layers that are shrink-fitted together

(3) vessels made of concentrically wrapped and welded layers

(c) This Article addresses layers and inner shells (see KD-104) that are considered in the static strength of the vessels. Liners are not considered in the static strength of vessels and shall meet the requirements of KD-103.

KD-801 DESIGN CRITERIA

(a) The static strength of layered vessels with no significant gaps between the layers, those that meet the requirements of KD-810, or those for which $Q_c = 1$ (see KD-822 and KD-824) shall be determined in accordance with Article KD-1 and either Article KD-2 or Mandatory Appendix 9.

(b) The equations given in this Article are based on elastic analysis. However, in the case of shrunk fit vessels, if additional prestressing is obtained from autofrettage, the residual stress distribution from the local plastic deformation shall be calculated in accordance with the rules of Article KD-5. In determining the final residual stress distribution using an autofrettaged liner, the nonlinear effects of the Bauschinger effect shall be considered.

(c) The beneficial residual stress distribution in vessels assembled by shrink fitting shall be calculated according to the rules given in KD-810. For welded layer shrink-fit vessel construction, the beneficial effects from the residual stress shall only be considered in the Article KD-3 and Article KD-4 analysis in areas of the vessel not located in a weld or a heat-affected zone of a weld.

(d) Concentrically wrapped, welded, layered vessels shall be treated as monobloc vessels except that the radial and circumferential stresses shall be calculated with corrections for the effects of the gaps between the layers. Rules for calculating these stresses are given in KD-820. No beneficial effects from compressive residual stresses shall be considered in the fatigue analysis of these types of vessels.

KD-802 NOMENCLATURE

D = diameter at any point in the wall, in. (mm)
D_I = diameter of inside surface of innermost layer, in. (mm)
D_{if} = diameter of the interface between layers, in. (mm)
D_n = diameter of outside surface of layer n, in. (mm)
D_O = diameter of outside surface of outermost layer, in. (mm)
E = elastic modulus, ksi (MPa)
E_I = elastic modulus of inner layer, ksi (MPa)
E_n = elastic modulus of the nth layer, ksi (MPa)
E_O = elastic modulus of outer layer, ksi (MPa)
F_c = calculated factor for circumferential expansion of permissible layer gaps
K = layer number that diameter D is within
N = total number of layers
P = pressure, ksi (MPa)
P_{if} = interface pressure between shrunk fit layers, ksi (MPa)
P_n = pressure between layers n and $n + 1$, caused by layer interference, ksi (MPa)
P_t = internal test pressure, ksi (MPa)
Q_c = ratio of the measured circumferential displacement at hydrotest to the calculated value of a vessel with zero gaps
Y = D_O/D_I
Y_i = ratio of outside diameter to inside diameter of inner layer
Y_o = ratio of outside diameter to inside diameter of outer layer
e_m = actual circumferential growth, in. (mm), to be measured at the hydrotest pressure as specified in KD-822 and KD-824
e_{th} = theoretical circumferential growth, in. (mm)
n = layer number in which stresses are to be calculated
t = total thickness, in. (mm)

t_n = thickness of layer n, in. (mm)
δ = diametrical interference between inner and outer layers, for two-piece shrink-fit vessels only, in. (mm)
δ_n = diametrical interference between layers n and $n + 1$, in. (mm)
ν = Poisson's ratio
ν_i = Poisson's ratio for inner layer
ν_o = Poisson's ratio for outer layer
σ_r = radial stress component at radius r, ksi (MPa)
σ_{rr} = radial residual stresses, ksi (MPa)
σ_t = tangential stress component at radius r, ksi (MPa)
σ_{tr} = tangential residual stresses, ksi (MPa)

KD-810 RULES FOR SHRINK-FIT LAYERED VESSELS

(a) This type of construction differs from concentrically wrapped and welded layers in that each layer is fabricated individually and machined to cause an interference pressure to exist in the assembled layered vessel. The manufacture and assembly of the cylindrical layers shall be accomplished so that the interference stress distribution in all layers can be determined within ±10%. Documentation of the manufacturing and assembly process shall be reviewed by the Professional Engineer who signs the Manufacturer's Design Report so that the actual stress distribution in the completed vessel can be verified.

(b) The final residual stress shall be calculated and shall not exceed the yield strength in any layer at any diameter for the interference fit condition except in the case of autofrettaged liners [see (c)].

(c) Residual stresses from the interference fitting operation shall be combined with other residual stresses from other manufacturing or assembly operations in the layers or completed vessel. See KD-801(a) and KD-801(b). Plastic analysis in accordance with KD-230 may also be used.

(d) Any reduction in yield strength or relaxation in the residual stress distribution due to elevated temperatures during the shrink-fitting operation or as a result of welding shall be considered.

(e) Rules for vessels constructed from two layers are given in KD-811 and rules for vessels constructed of more than two layers are given in KD-812.

(f) For shrink-fit vessels of two or more layers, the Designer may assume a leak-before-burst failure mode for the vessel if all the following conditions are met:

(1) A fast fracture failure of one or more inner layers causes no parts or fragments to be ejected, and one or more outer layers remain intact.

(2) The end closures remain intact and in place.

(3) The calculated collapse pressure of the remaining intact vessel's pressure boundary shall be greater than 120% of the design pressure of the entire vessel.

The materials used in the construction of the inner layers that are assumed to fail in a fast fracture mode must meet the Charpy V-notch impact energy requirements stated in their applicable material specification in Section II, but do not have to meet the additional Charpy V-notch impact energy requirements given in Table KM-234.2(a). All of the pressure boundary components that are assumed to remain intact shall meet the requirements given in Table KM-234.2(a).

Some plastic deformation is permitted in this type of failure. It is also recognized that some leakage from the vessel may occur and the Designer is cautioned that this type of analysis may not be appropriate if the vessel contains harmful or lethal substances.

KD-811 CONSTRUCTION WITH ONLY TWO LAYERS

KD-811.1 Interference Pressure. The interference pressure between the inner and outer layers is calculated as follows:

$$P_{if} = \frac{\delta}{D_{if} A}$$

where

$$A = \frac{1}{E_I}\left(\frac{D_I^2 + D_{if}^2}{D_{if}^2 - D_I^2} - \nu_i\right) + \frac{1}{E_O}\left(\frac{D_{if}^2 + D_O^2}{D_O^2 - D_{if}^2} + \nu_O\right)$$

This analysis assumes that there is no longitudinal force transmitted between the inner and outer cylinder due to friction at the interface. In some cases of shrink fit, longitudinal stresses can be developed which will affect the interface pressure obtained due to the Poisson effect. For such cases, a more detailed analysis is required to determine the residual stresses.

KD-811.2 Residual Shrink-Fit Stresses. The residual stresses at any point removed from discontinuities in the inner layer, $D_I \le D \le D_{if}$, are then calculated from eqs. (1) and (2):

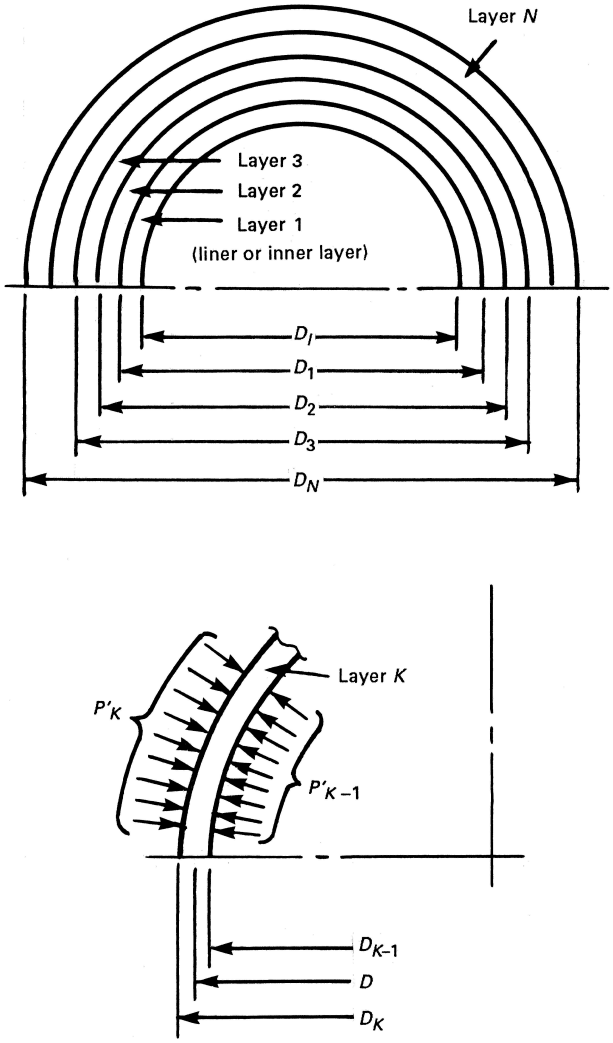
$$\sigma_{tr} = -\frac{P_{if} Y_i^2}{Y_i^2 - 1}\left(1 + \frac{D_I^2}{D^2}\right) \quad (1)$$

$$\sigma_{rr} = -\frac{P_{if} Y_i^2}{Y_i^2 - 1}\left(1 - \frac{D_I^2}{D^2}\right) \quad (2)$$

and in the outer layer, $D_{if} \le D \le D_O$, from eqs. (3) and (4):

$$\sigma_{tr} = \frac{P_{if}}{Y_o^2 - 1}\left(1 + \frac{D_O^2}{D^2}\right) \quad (3)$$

Figure KD-812
Diameters and Layer Numbers for Concentric Shrink-Fit Layered Cylinder



$$\sigma_{rr} = \frac{P_{if}}{Y_o^2 - 1}\left(1 - \frac{D_O^2}{D^2}\right) \tag{4}$$

where

$$Y_i = D_{if}/D_I$$

$$Y_o = D_O/D_{if}$$

KD-811.3 Final Distribution of Residual Stresses. If the vessel components contain known residual stresses produced by autofrettage prior to assembly, these residual stresses shall be combined with the stresses determined from eqs. KD-811.2(1) through KD-811.2(4) above to determine the final distribution of residual stresses after assembly; see KD-801(a) and KD-801(b).

KD-812 CONSTRUCTION WITH MORE THAN TWO LAYERS

For the case of vessels composed of more than two layers assembled with interference, the following procedure shall be used.

(a) Assemble the first two layers and calculate the residual stresses as in KD-811.

(b) Determine the interference between this assembly and the next layer and calculate the resulting residual stresses as if the first two layers were a single layer. If the first two layers do not have the same elastic modulus, then an appropriate composite value shall be used.

(c) Add the stresses calculated in (b) to those calculated in (a) and determine the total residual stress distribution in the resulting assembly. This procedure may be repeated for any number of successive layers.

(d) Equations for calculating the linear elastic stress distribution in a layered cylindrical vessel are given below (see Figure KD-812).

(1) Layer interference pressure:

$$P_n = \frac{\delta_n E}{2D_n^3}\frac{\left(D_n^2 - D_I^2\right)\left(D_{n+1}^2 - D_n^2\right)}{D_{n+1}^2 - D_I^2}$$

(2) Tangential layer stress component due to prestress:

(-a) for $D > D_I$, $K > 1$,

$$\sigma_{tr} = \frac{P_{K-1}D_{K-1}^2}{D_K^2 - D_{K-1}^2}\left(\frac{D_K^2}{D^2} + 1\right) - \left(1 + \frac{D_I^2}{D^2}\right)\sum_{n=K}^{N}\frac{P_n D_n^2}{D_n^2 - D_I^2}$$

(-b) for $K = 1$, $D > D_I$, $P_{K-1} = P_I = 0$,

$$\sigma_{tr} = -\left(1 + \frac{D_I^2}{D^2}\right)\sum_{n=1}^{N}\frac{P_n D_n^2}{D_n^2 - D_I^2}$$

(3) Radial layer stress component due to prestress:

(-a) for $D > D_I$, $K > 1$,

$$\sigma_{rr} = -\frac{P_{K-1}D_{K-1}^2}{D_K^2 - D_{K-1}^2}\left(\frac{D_K^2}{D^2} - 1\right) - \left(1 - \frac{D_I^2}{D^2}\right) \sum_{n=K}^{N} \frac{P_n D_n^2}{D_n^2 - D_I^2}$$

(-b) for $K = 1$, $D > D_I$, $P_{K-1} = P_I = 0$,

$$\sigma_{rr} = -\left(1 - \frac{D_I^2}{D^2}\right) \sum_{n=1}^{N} \frac{P_n D_n^2}{D_n^2 - D_I^2}$$

KD-820 RULES FOR CONCENTRICALLY WRAPPED AND WELDED LAYERED VESSELS

KD-821 WELDED LAYERS

The rules given in KD-820 are valid only if (a) through (d) are met.

(a) Each layer shall have an outer diameter to inner diameter ratio no greater than 1.10 and a minimum layer thickness of ¼ in. (6 mm).

(b) All layers in a vessel shall have the same modulus of elasticity and Poisson's ratio over the design temperature range.

(c) No beneficial effects from prestress can be taken into account in the fatigue analysis of the vessel.

(d) The effects of gaps between layers on the stress developed in the layers shall be considered in the stress analysis of the vessel; see KD-822 through KD-825.

KD-822 CIRCUMFERENTIAL EXPANSION OF CYLINDRICAL LAYERS

When a layered cylindrical shell is pressurized, the outside circumference will not expand as much as a monobloc vessel of the same dimensions unless all layers are in intimate contact with each other. A measure of the extent of the gaps between layers is to calculate the circumferential expansion e_{th} [see eq. (1)] of a monobloc cylindrical shell of the same dimensions and compare that to the actual measured circumferential expansion e_m of the layered vessel. This is done at the hydrotest pressure. The ratio of the actual expansion during hydrotest, divided by the theoretical elastic expansion during hydrotest is denoted as Q_c [see eq. (2)].

$$e_{th} = \frac{P_t(2-\nu)\pi D_O}{E(Y^2 - 1)} \tag{1}$$

The designer may perform a more rigorous analysis to calculate e_{th}, considering end effects and constraint.

$$Q_c = \frac{e_m}{e_{th}} \tag{2}$$

Q_c shall be between 0.5 and 1.0; see KF-827.

KD-823 CALCULATION OF STRESSES IN CYLINDRICAL SHELLS

The designer shall assume a value of Q_c between 0.5 and 1.0 to determine the stress distribution in the vessel. The actual value of Q_c measured at hydrotest shall be reported to the designer to verify that the vessel meets the rules of this Division. Assuming a value of Q_c, or using the measured value of Q_c, the value of F_c, the gap correction factor, is calculated using eq. (1):

$$F_c = \frac{2PD_I^2(1.0 - Q_c)}{D_O^2 - D_I^2} \tag{1}$$

Once the value of F_c is known for a particular vessel, the three principal stresses due to internal pressure are calculated according to eqs. (2), (3), and (4). These calculated stresses are primary membrane stresses used in 9-200, and in place of those calculated in 9-300 for a monobloc vessel, and must meet the requirements of 9-210.

$$\sigma_t = \frac{PD_I^2\left(D_O^2 + D^2\right)}{D^2\left(D_O^2 - D_I^2\right)} + F_c\frac{D_O + D_I - 2D}{D_O - D_I} \tag{2}$$

$$\sigma_r = \frac{1}{D}\left\{-PD_I + \frac{PD_I^2}{D_O^2 - D_I^2}\left[D - D_I - D_O^2\left(\frac{I}{D} - \frac{1}{D_I}\right)\right] + \frac{F_c}{D_O - D_I}\left[D(D_I + D_O) - D^2 - D_O D_I\right]\right\} \tag{3}$$

$$\sigma_L = \frac{PD_I^2}{D_O^2 - D_I^2} \tag{4}$$

KD-824 CIRCUMFERENTIAL EXPANSION OF WELDED LAYERED SPHERICAL SHELLS AND HEMISPHERICAL HEADS

The theoretical circumferential expansion of a spherical shell at a given pressure e_{th} is given by eq. (1). The ratio of the actual circumferential expansion in a layered spherical vessel measured at the hydrotest pressure e_m to the theoretical expansion at the same pressure Q_c is given by eq. (2):

$$e_{th} = \frac{3P_t(1-\nu)\pi D_O}{2E(Y^3 - 1)} \tag{1}$$

$$Q_c = \frac{e_m}{e_{th}} \tag{2}$$

Q_c shall be between 0.5 and 1.0; see KF-827.

KD-825 CALCULATED LAYER STRESS IN SPHERICAL SHELLS AND HEMISPHERICAL HEADS DUE TO INTERNAL PRESSURE

(a) Tangential layer stress component due to internal pressure

$$\sigma_t = \frac{PD_I^3\left(D_O^3 + 2D^3\right)}{2D^3\left(D_O^3 - D_I^3\right)} + F_c\frac{D_I + D_O - 2D}{D_O - D_I}$$

where

$$F_c = \frac{1.5D_I^3P(1.0 - Q_c)}{D_O^3 - D_I^3}$$

(b) Radial layer stress component due to internal pressure

$$\sigma_r = \frac{1}{D^2}\left\{-PD_I^2 + \frac{PD_I^3}{D_O^3 - D_I^3}\left[D^2 - D_I^2 - D_O^3\left(\frac{1}{D} - \frac{1}{D_I}\right)\right] + \frac{F_c}{D_O - D_I}\left[D^2(D_I + D_O) - \frac{4D^3 - D_I^3}{3} - D_OD_I^2\right]\right\}$$

KD-830 DESIGN OF WELDED JOINTS

(a) For vessels assembled by shrink fitting cylindrical shells, all welds in the individual layers shall be Type No. 1 butt welds in accordance with the requirements of Article KD-11, Article KF-2, and Article KF-4. These welds shall be ground flush to provide smooth continuous surfaces at all layer interfaces so that the requirements of KD-810(a) are met.

(b) For vessels assembled by the concentrically wrapped, welded layer technique, the weld in the innermost layer shall be a Type No. 1 butt weld, and the welds in all other layers shall be Type No. 2 butt welds. Additional welding requirements to those in (a) are given in Article KF-8.

(c) Some acceptable examples of welded construction are shown in Figures KD-830.1 through KD-830.6.

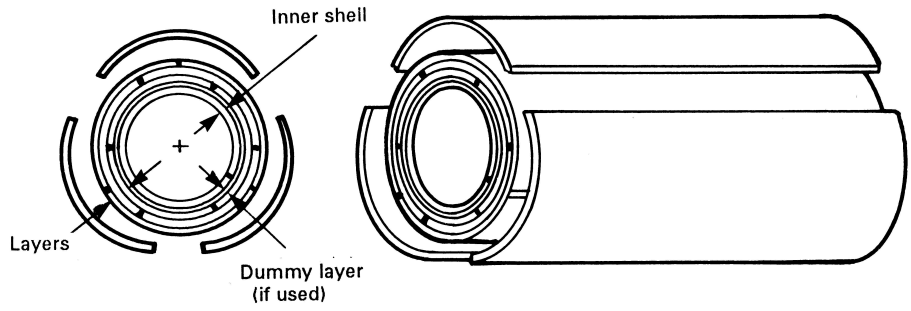
KD-840 OPENINGS AND THEIR REINFORCEMENT

All reinforcements required for openings shall be integral with the nozzles or provided in the layered section or both. Additional complete full circumferential layers may be included for required reinforcement. Pad type reinforcements are not permitted. See Nonmandatory Appendix H.

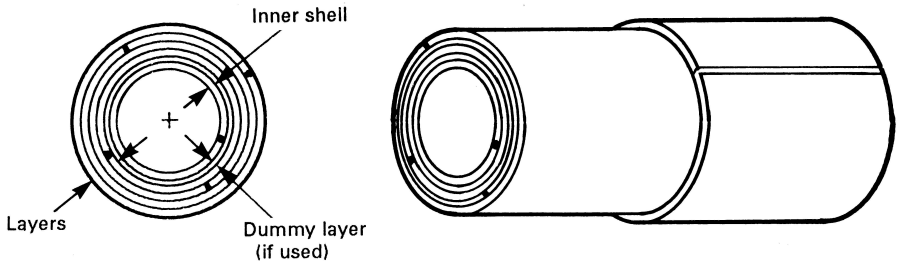
KD-850 SUPPORTS

Some acceptable support details are shown in Figure KD-850. The design and attachment details shall be in accordance with Article KD-7. Local loadings imposed on the outer wraps by the supports shall be considered.

Figure KD-830.1
Acceptable Layered Shell Types

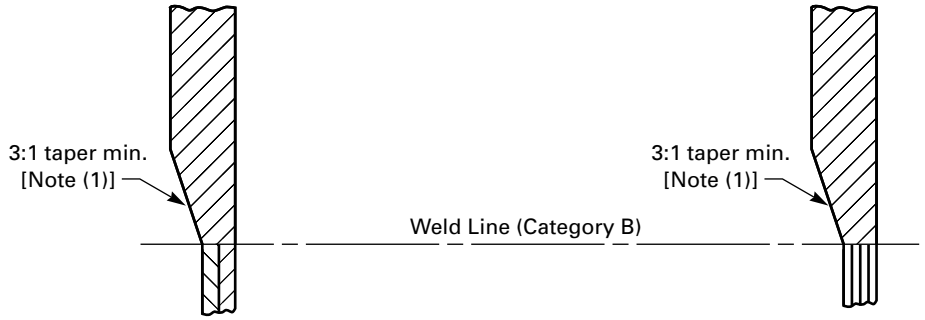


(a) Concentric Wrapped



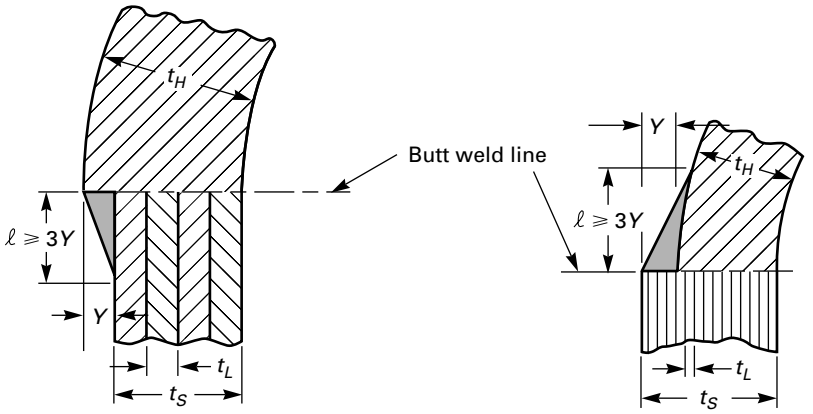
(b) Shrink Fit

Figure KD-830.2
Some Acceptable Solid-to-Layered Attachments



(a) For Layers Over $^5/_8$ in. (16 mm) Thickness

(b) For Layers $^5/_8$ in. (16 mm) or Less in Thickness



(c) For Layers $^5/_8$ in. (16 mm) or Less in Thickness

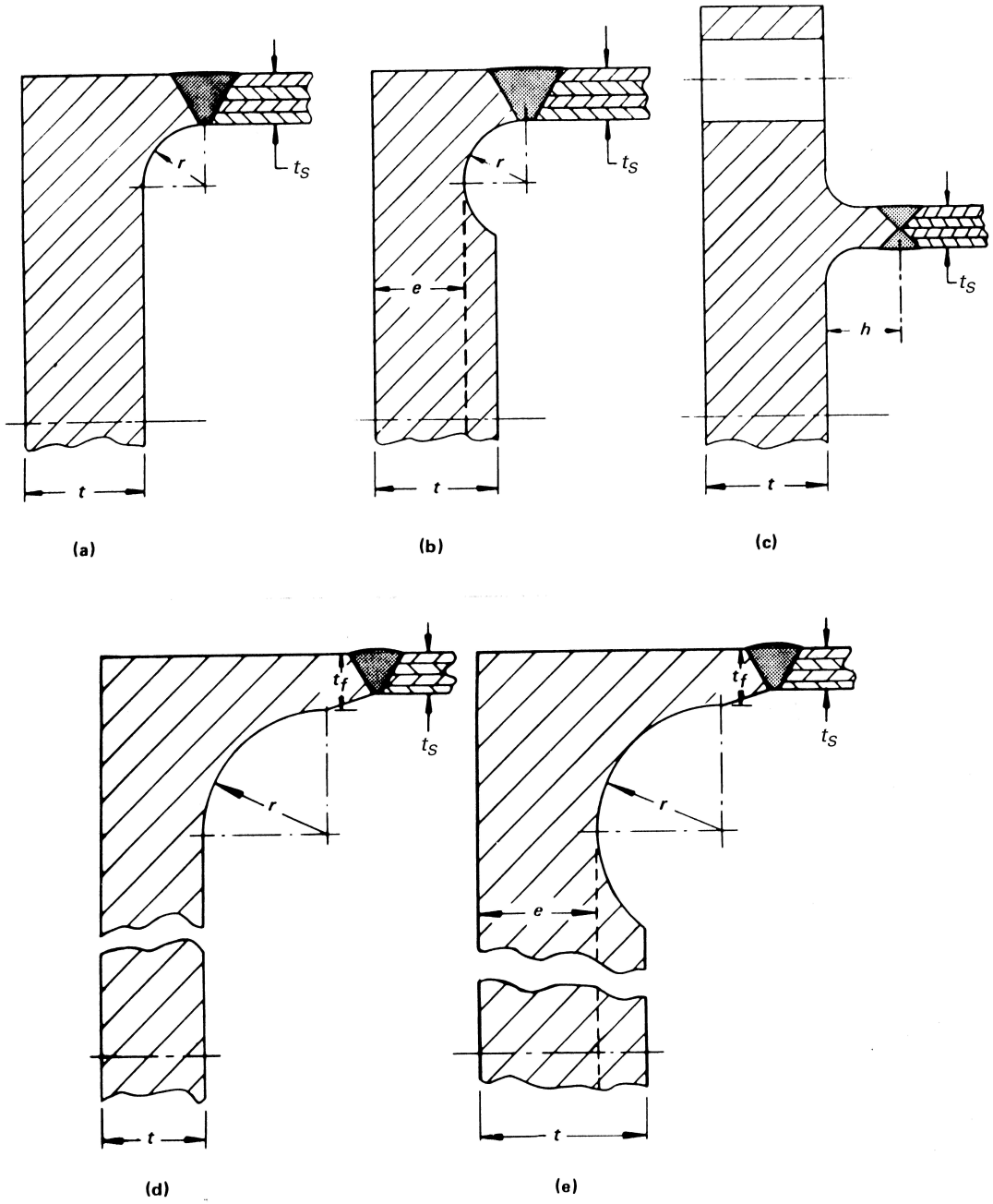
(d) For Layers of Any Thickness

Legend:
t_H = thickness of head at joint
t_L = thickness of one layer
t_S = thickness of layered shell
Y = offset

GENERAL NOTES:
(a) Actual thickness shall be not less than theoretical head thickness.
(b) In illustration (c), Y shall be not larger than t_L. In illustration (d), Y shall be not larger than $^1/_2 t_S$. In all cases ℓ shall be not less than 3 times Y. The shell centerline may be on both sides of the head centerline by a maximum of $^1/_2(t_S - t_H)$. The length of required taper may include the width of the weld.

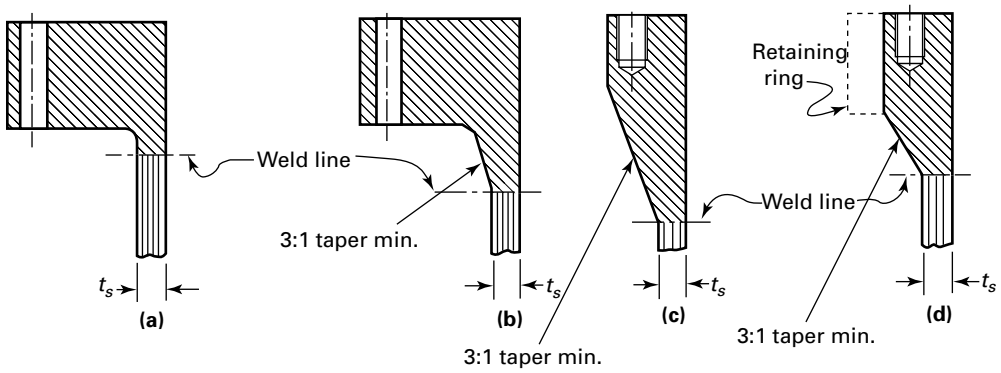
NOTE: (1) Taper may be inside, outside, or both.

Figure KD-830.3
Some Acceptable Flat Heads With Hubs Joining Layered Shell Sections



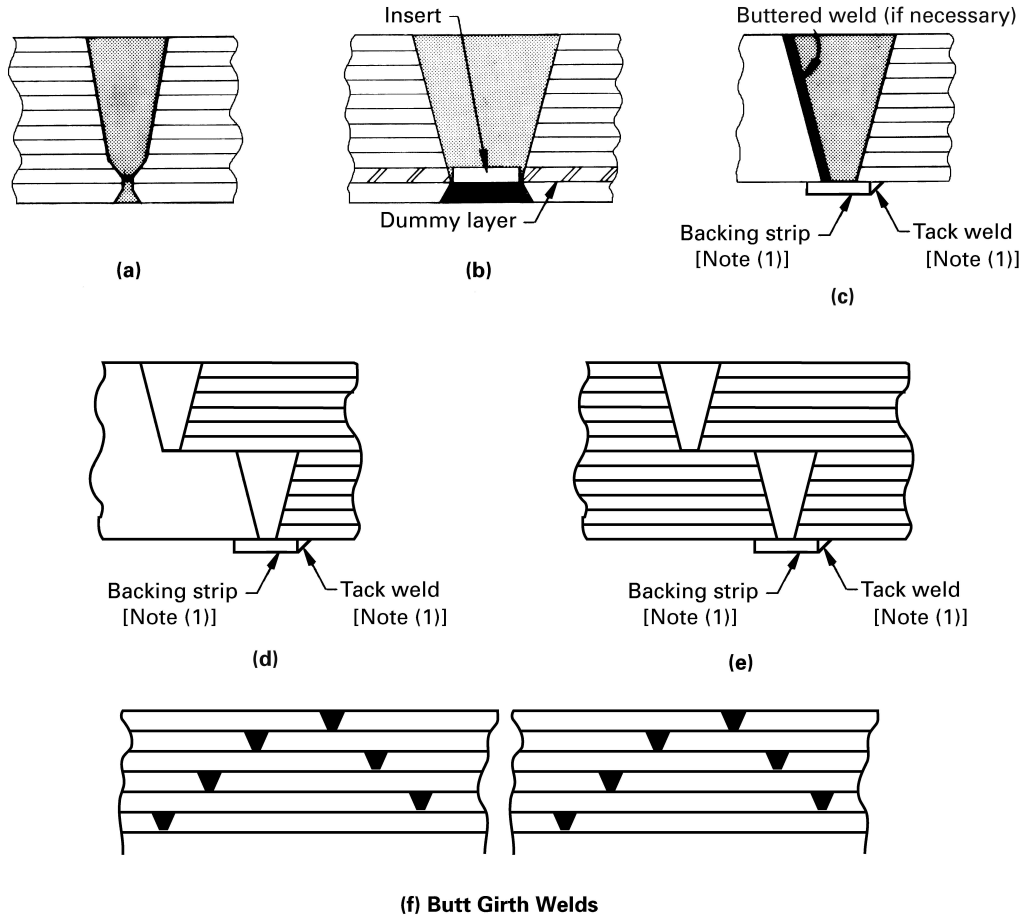
GENERAL NOTES:
(a) t_S = thickness of layered shell
(b) t = thickness of flat head
(c) For all other dimensions, see Figure KD-1112.

Figure KD-830.4
Some Acceptable Flanges for Layered Shells



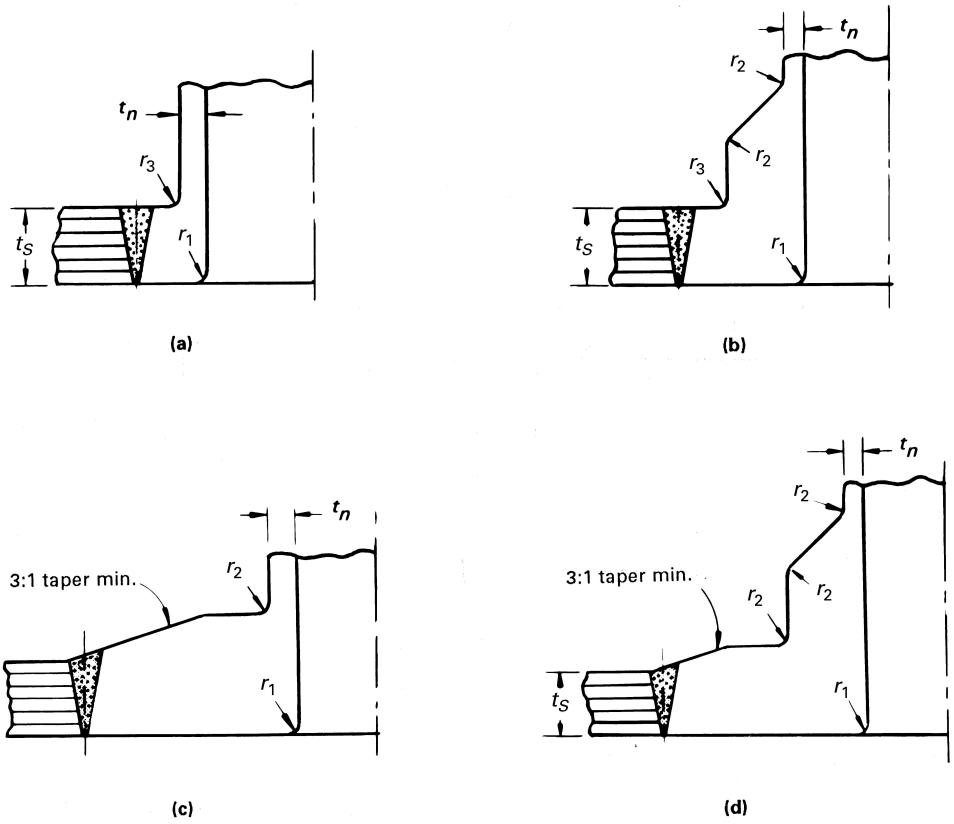
Legend:
t_S = thickness of layered shell

Figure KD-830.5
Some Acceptable Welded Joints of Layered-to-Layered and Layered-to-Solid Sections



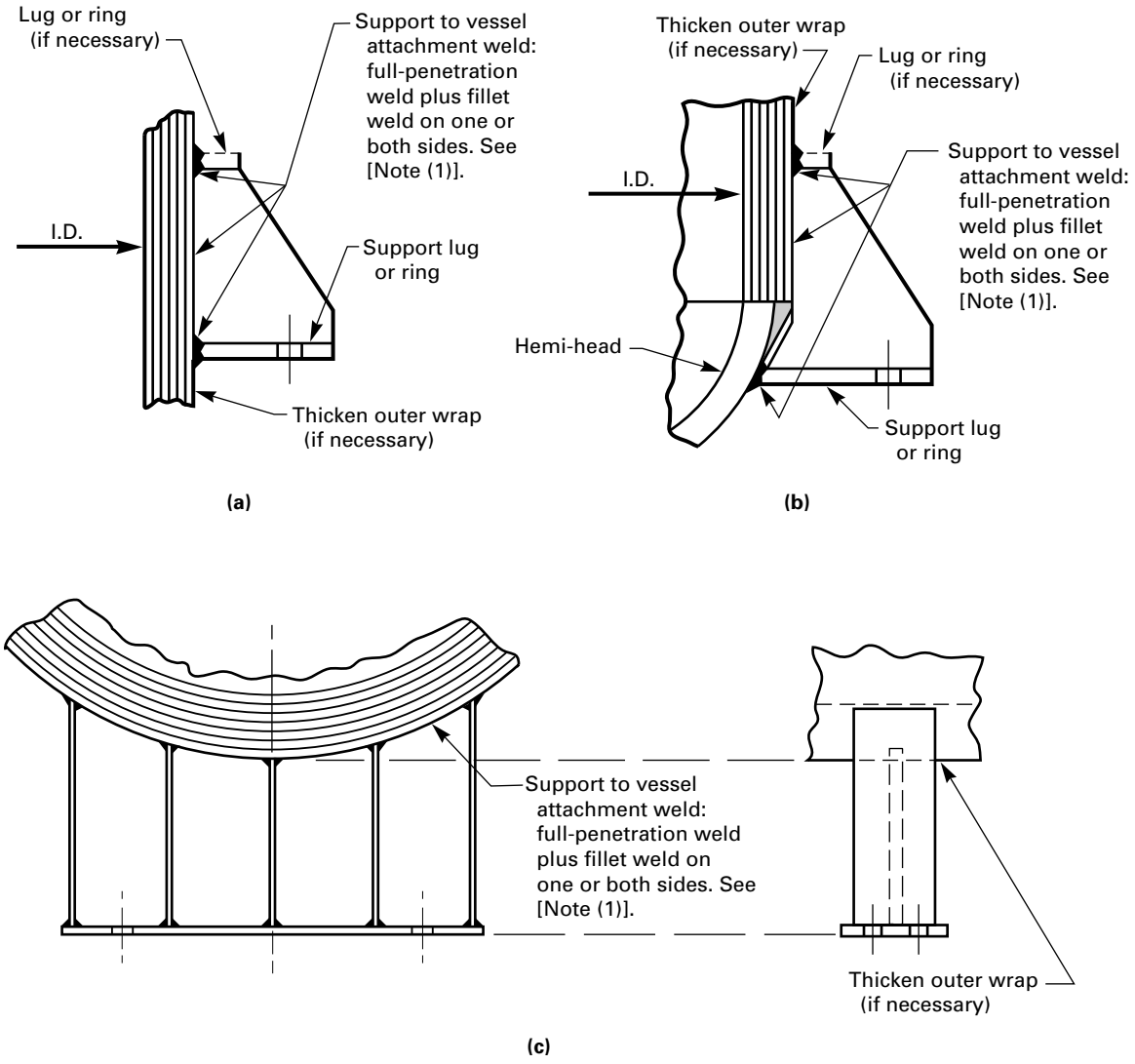
NOTE: (1) Shall be removed after welding.

Figure KD-830.6
Some Acceptable Nozzle Attachments in Layered Shell Sections



Legend:
r_1 min. = $\frac{1}{4}t_n$ or $\frac{3}{4}$ in. (19 mm), whichever is less
r_2 = $\frac{1}{4}$ in. (6 mm) minimum
r_3 min. = r_1 minimum
t_n = nominal thickness of nozzle wall less corrosion allowance
t_S = thickness of layered shell, in.

Figure KD-850
Some Acceptable Supports for Layered Vessels



NOTE: (1) See Figure KD-700, illustrations (a) and (b).

ARTICLE KD-9
SPECIAL DESIGN REQUIREMENTS FOR WIRE-WOUND VESSELS AND WIRE-WOUND FRAMES

KD-900 SCOPE

The requirements of this Article apply specifically to pressure vessels consisting of an inner cylinder (or a number of concentric cylinders) prestressed by a surrounding winding consisting of at least ten layers. The end load is not carried by the cylinder(s) or the winding. The winding consists of a wire helically wound edge-to-edge in pretension in a number of turns and layers around the outside of the cylinder. These requirements also apply to wire-wound frames used to carry the load from the closures. See Figure KD-900.

The special requirements are in addition to the general requirements given in Articles KD-2, KD-3, KD-4, and Mandatory Appendix 9.

KD-910 STRESS ANALYSIS

The stresses in the vessel due to the internal pressure shall be calculated in accordance with Articles KD-1, KD-2, and Mandatory Appendix 9.

The calculation of the prestressing of the cylinder shall be based on a winding procedure that specifies the wire force that has to be used for each winding layer at the application (see KF-913). The calculation shall give the decrease of the inner diameter of the cylinder and the residual stresses at all points of the vessel wall induced by the winding operation. Equations for this calculation are given in KD-911.

A corresponding winding procedure and stress calculation for the wire-wound frame shall give the decrease of a reference length of the frame and residual principal stresses in the frame and at the different layers of the winding.

The calculated decrease of the inner diameter and the reference length of the frame shall be determined in intervals and shall be used for comparison with the results from corresponding measurements made during the winding operation.

KD-911 RESIDUAL STRESSES AND DEFLECTIONS IN CYLINDERS DUE TO FLAT WIRE WINDING

The equations in this paragraph are valid for flat wire with rectangular cross section wound edge-to-edge. For other wire shapes, appropriate corrections shall be made. It is assumed that the winding operation is performed with the stress $S_w(x)$ in the wire and that this stress is a function of the diameter coordinate x (see Figure KD-911). When the winding layers are applied between $x = D_{if}$ and $x = D_w$, then the following tangential stresses $\sigma_t(x_1)$, radial stresses $\sigma_r(x_1)$, and diametral deformation δ are introduced at the diameter x_1 of the inner cylinders:

$$\sigma_t(x_1) = -\left[1 + \left(\frac{D_I}{x_1}\right)^2\right] \int_{D_{if}}^{D_w} \left(\frac{x}{x^2 - D_I^2} S_w(x)\right) dx$$

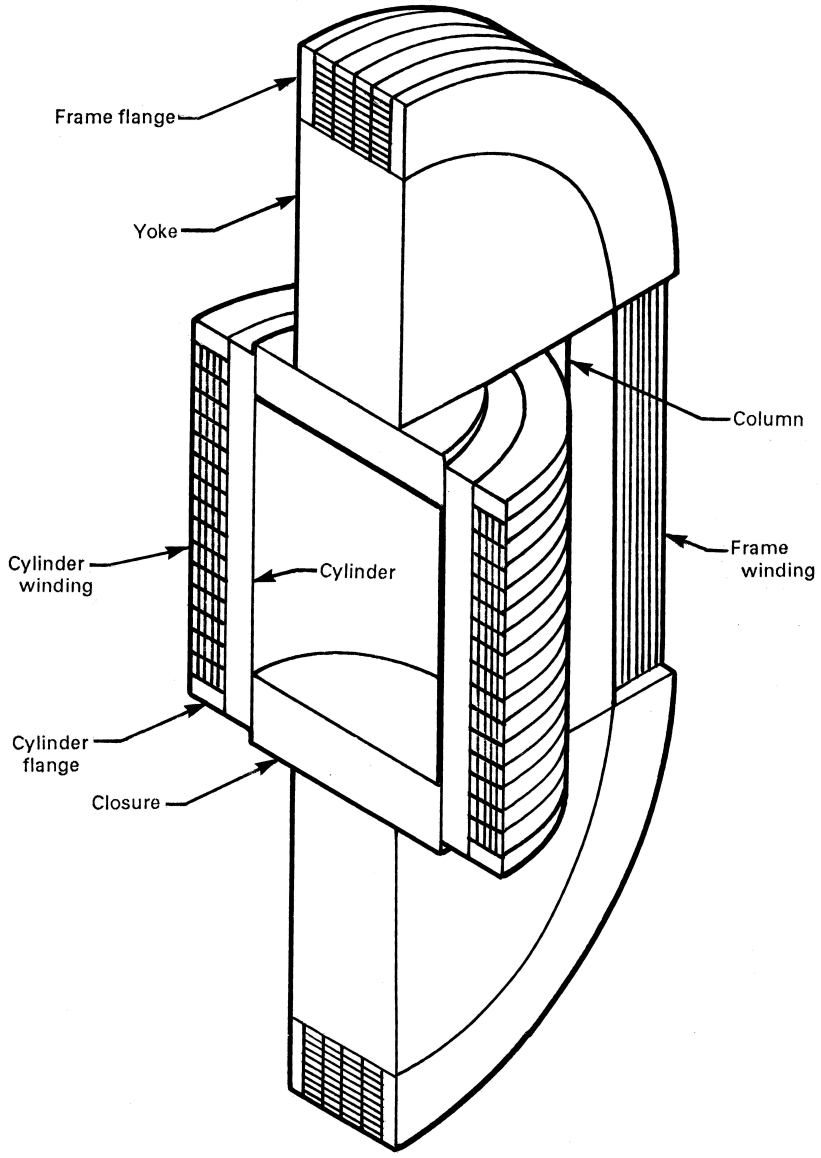
$$\sigma_r(x_1) = -\left[1 - \left(\frac{D_I}{x_1}\right)^2\right] \int_{D_{if}}^{D_w} \left(\frac{x}{x^2 - D_I^2} S_w(x)\right) dx$$

$$\delta = -\frac{2D_I}{E} \int_{D_{if}}^{D_w} \left(\frac{x}{x^2 - D_I^2} S_w(x)\right) dx$$

where

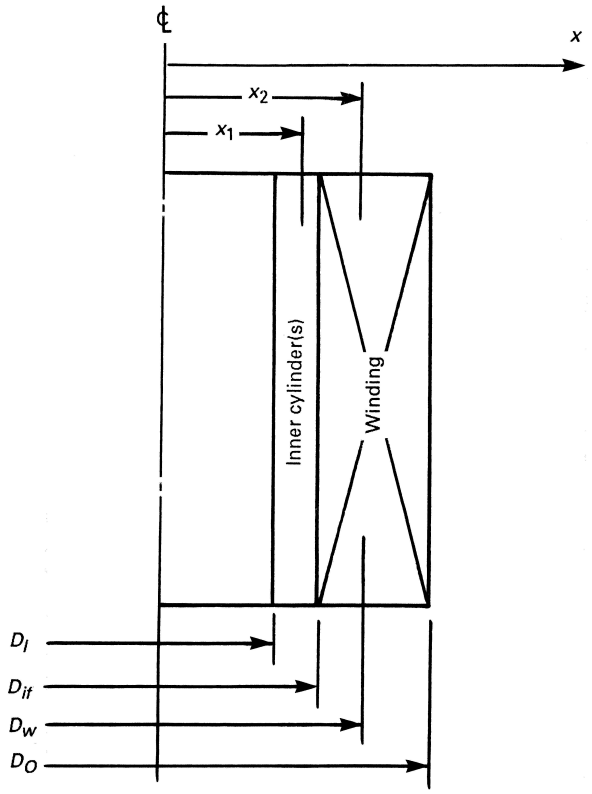
D_I = inside diameter, in. (mm)
D_{if} = diameter of the interface between cylinder and winding, in. (mm)
D_O = outside diameter after finished winding operation, in. (mm)
D_w = instantaneous applied outside diameter of winding, in. (mm)
E = modulus of elasticity, ksi (MPa)
x_1 = any diameter of the cylinder, in. (mm)
x_2 = any diameter of the winding, in. (mm)

Figure KD-900
Wire-Wound Vessel and Frame Construction



GENERAL NOTE: Not to scale.

Figure KD-911
Nomenclature for Wire-Wound Cylinders



The corresponding stresses introduced in the winding area at the diameter $x_2(<D_w)$ of the winding are:

$$\sigma_t(x_2) = S_w(x_2) - \left[1 + \left(\frac{D_I}{x_2}\right)^2\right] \int_{x_2}^{D_w} \left(\frac{x}{x^2 - D_I^2} S_w(x)\right) dx$$

$$\sigma_r(x_2) = - \left[1 - \left(\frac{D_I}{x_2}\right)^2\right] \int_{x_2}^{D_w} \left(\frac{x}{x^2 - D_I^2} S_w(x)\right) dx$$

The equations given above are valid as long as

(a) the helix angle of the winding is less than 1.0 deg

(b) the maximum gap between the wires in the longitudinal direction of the vessel is less than 5% of the wire width, or 0.010 in. (0.25 mm), whichever is less

(c) neither the inner cylinder(s) [liner(s)] nor the wire yields (see KD-920), except that yielding of inner cylinder(s) [liner(s)] is permitted, provided the additional requirements below are met.

(1) Yielding is permitted only in compression during the wire-winding process.

(2) Yielding is not permitted at any value of operating pressure from atmospheric to design pressure at any specified coincident temperature, or at any value of operating pressure from atmospheric to test pressure at the test temperature.

(3) The inner cylinder(s) [liner(s)] shall meet the requirements of KD-230 for elastic–plastic analysis, including the requirements of KD-232 for protection against local failure.

(4) Stresses in the wire may be calculated using the requirements in KD-230 or using the equations in KD-911.

(5) Deformation of the inner cylinder(s) [liner(s)] shall be calculated using the requirements in KD-230.

KD-912 STRESS IN WIRE-WOUND FRAMES

Because of the many possible geometric forms of frames, specific equations are not given here. Such frames shall satisfy the requirements of Articles KD-2, KD-3, KD-4, and Mandatory Appendix 9.

KD-920 STRESS LIMITS

KD-921 DIAMETER RATIO OF VESSEL WALL

When flat wire with rectangular cross section is used, the overall diameter ratio shall not be lower than the limit given by the equation in KD-221.2. For other wire shapes, corrections shall be made.

KD-922 EQUIVALENT STRESS LIMITS FOR INNER CYLINDER(S) AND WIRE

(a) Under design conditions and hydrostatic test conditions, the average equivalent stress over the cross section of each individual wire at any point in the winding shall not exceed S_y.

(b) For welded wire joints (see KF-912), the corresponding average equivalent stress shall not exceed two-thirds of S_y, where S_y is the yield strength of the unwelded wire material.

(c) The calculated primary-plus-secondary equivalent stress for the inner cylinder(s) shall not exceed S_y at any value of pressure from atmospheric to design pressure at any specified coincident temperature, or at any value of pressure from atmospheric to test pressure at the test temperature.

KD-923 MINIMUM LEVEL OF PRESTRESSING OF FRAMES MADE FROM COLUMNS AND YOKES

In the case when the frame is made up of nonintegral columns and yokes, the prestressing of the frame by the winding shall be high enough to ensure that the yokes and columns are in mechanical contact even at a load corresponding to 105% of the pressure to be applied at the hydrostatic test (see Article KT-3). This requirement

shall be checked by calculation and documented in the Manufacturer's Data Report.

KD-930 FATIGUE EVALUATION

KD-931 GENERAL

(a) A calculation to determine the number of design cycles shall be performed for all components of wire-wound vessels and frames in accordance with the methods stated in KD-140, except for the wire-wound layers. The fatigue life of the wire-wound layers shall be calculated in accordance with the rules stated in KD-933. The wire fatigue curves shall be derived in accordance with KD-932.

For environmental conditions not covered by the derived design fatigue curve, the Manufacturer shall obtain supplementary fatigue test data.

(b) For wire-wound vessels, the Designer may assume a leak-before-burst failure mode for the vessel if all the following conditions are met in case of a fast fracture failure of one or more inner layers:

(1) No parts or fragments are ejected, and one or more outer layers remain intact. For this purpose, the entire cross section of the wire winding is considered to be a layer.

(2) The end closures remain intact and in place.

(3) The calculated collapse pressure of the remaining intact vessel's pressure boundary shall be greater than 120% of the design pressure of the entire vessel.

The materials used in the construction of the inner layer that are assumed to fail in a fast fracture mode must meet the Charpy V-notch impact energy requirements stated in their applicable material specification in Section II, but do not have to meet the additional Charpy V-notch impact energy requirements given in Table KM-234.2(a). All of the pressure boundary components that are assumed to remain intact shall meet the requirements given in Table KM-234.2(a).

Some plastic deformation is permitted in this type of failure. It is also recognized that some leakage from the vessel may occur and the Designer is cautioned that this type of analysis may not be appropriate if the vessel contains harmful or lethal substances.

KD-932 DERIVATION OF A DESIGN FATIGUE CURVE FOR WIRE

The design fatigue life N_D of the winding is defined as the number of operating cycles when the probability is 10% that the calculated average distance between fatigue cracks in the wire is 6,500 ft (2 000 m). The design fatigue curve for wire shall be derived in the way stated in KD-932.1 through KD-932.3 (see Figure KD-932).

KD-932.1 Wire Fatigue Curve. The calculation of the design fatigue life of the winding shall be based on a wire fatigue curve derived as follows:

(a) Make fatigue tests with wire pieces with a length of at least 30 times the maximum cross sectional dimension, taken from wire coils delivered from the same manufacturer and produced from the same material quality and by the same manufacturing method as the wire to be used in the vessel or frame.

(b) Select a mean stress which will avoid buckling the test specimen. Make all tests at this mean stress for all stress amplitudes used.

(c) Make the tests at no less than four levels of stress amplitude S with at least six wire pieces at each stress level. The cyclic rate of the test shall be such that appreciable heating of the wire does not occur. Note the number of cycles to complete fatigue rupture N_f.

(d) Plot the points of corresponding S and N_f on a semilog graph and draw a best-fit curve $S_f = f(\log N_f)$ based on these points.

(e) Transform this curve to a wire fatigue curve $S'_f = f\left(\log N_f\right)$ valid at mean stress = 0 using the equation

$$S'_f = S_f + K_s \beta \sigma_{nm}$$

where σ_{nm} is the associated mean stress used in the test (see KD-312.3). The value of β shall be 0.2 unless experimental evidence justifies another value. K_s is calculated according to eq. KD-932.3(1).

KD-932.2 Design Fatigue Curve. The design fatigue curve $S_a = f(\log N_D)$ shall be derived from the wire fatigue curve as stated in (a) through (c).

(a) Divide the S'_f values of the wire fatigue curve by a factor K_S, the value of which shall be determined as stated in eq. KD-932.3(1), and plot the curve:

$$S'_a = S'_f / K_S = f_2\ (\log N_D)$$

(b) Divide the N_f values of the wire fatigue curve by a factor K_N, the value of which shall be determined as stated in eq. KD-932.3(2), and plot the curve:

$$S''_a = f_3 \left[\log\left(N_f / K_N\right)\right] = f_3\ (\log N_D)$$

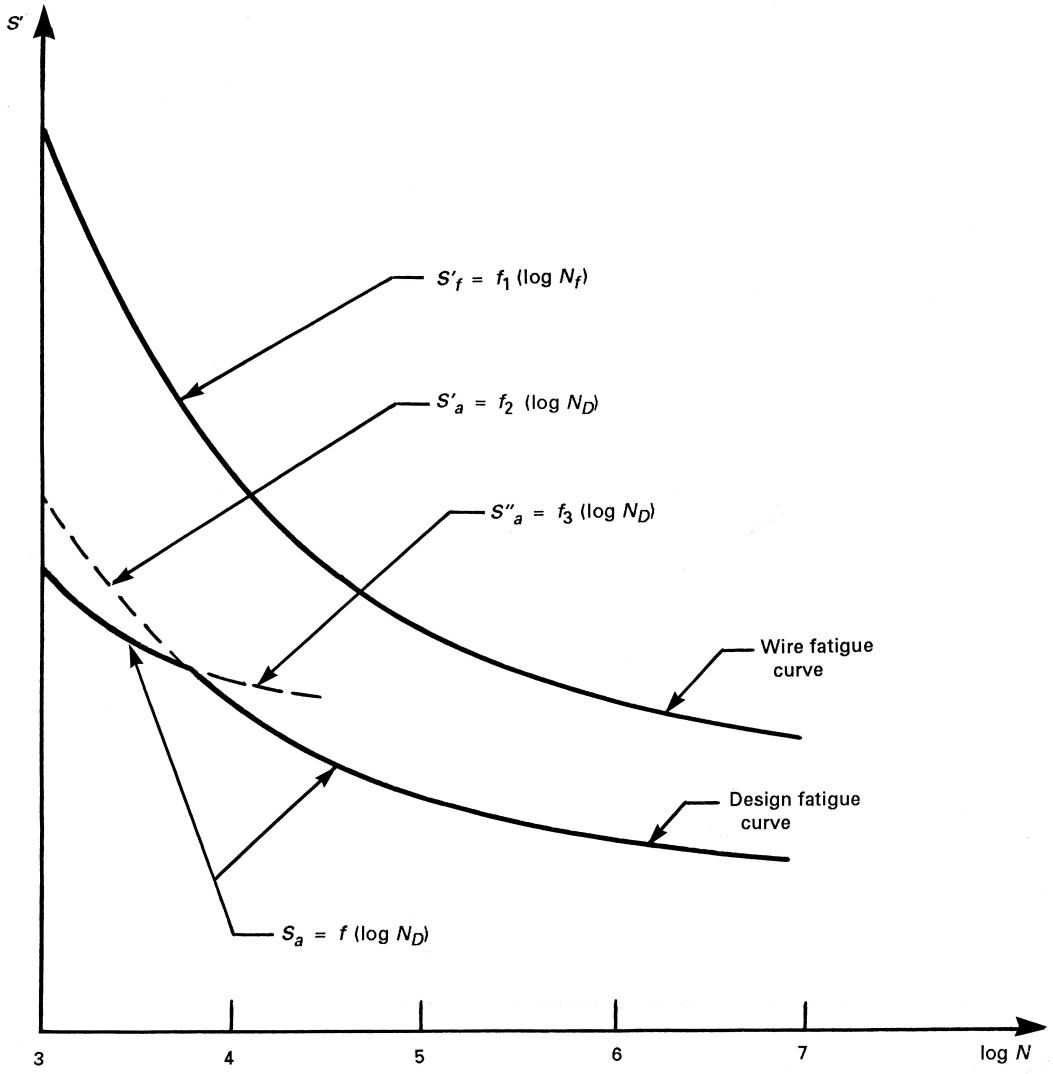
(c) The design fatigue curve, $S_a = f(\log N_D)$, is the lower of the two values S'_a or S''_a for all values of N_D in (a) and (b).

KD-932.3 Factors K_S and K_N. The values of the factors K_S and K_N are multiples of factors which account for the effects of stressed length and of scatter in fatigue strength of the wire. They shall be determined as stated below:

$$K_S = K_{SL} K_{SS} \quad (1)$$

where K_{SL} is the factor for the effect of stressed length and K_{SS} is the factor for the effect of statistical variation (scatter) in fatigue strength:

Figure KD-932
Derivation of Design Fatigue Curve From Wire Fatigue Curve



$$K_{SL} = (L_W/L_T)^{1/30} \quad (2)$$

where L_W is the accepted average distance between wire cracks at $N = N_D$ and a crack probability of 10% (see KD-932) and L_T is the length of the wire pieces at the fatigue tests (see KD-932.1). Assuming a case where L_W equals 6,500 ft (2 000 m) and L_T equals 8 in. (200 mm), the equation gives K_{SL} = 1.35.

$$K_{SS} = 1/(1 - 1.30\bar{\Delta}s) \quad (3)$$

where $\bar{\Delta}s$ is the average value of the relative standard deviation of the fatigue strength from each stress amplitude level, expressed as a decimal and derived from the wire fatigue test data.

In the calculation of K_{SS}, the scatter in fatigue strength is assumed to have a standard Gaussian distribution.

The value of 1.30 in the equation corresponds to a probability of 10% for a fatigue crack to occur (see KD-932).

$$K_N = (K_S)^{4.3} \quad (4)$$

KD-933 CALCULATION OF DESIGN FATIGUE LIFE OF WINDING

The design fatigue curve derived in KD-932 is used to calculate the design fatigue life of the winding as described in Article KD-3.

ARTICLE KD-10
SPECIAL REQUIREMENTS FOR VESSELS IN HYDROGEN SERVICE

KD-1000 SCOPE

(a) The requirements of this Article shall be met for all vessels in hydrogen service, as defined by (b) below. Each pressure component shall be evaluated for the specified fatigue cycles and shall meet the fracture toughness requirements in this Article.

The requirements in this Article are in addition to the other requirements of this Division.

(b) The requirements of this Article are mandatory for the following vessels in hydrogen service.

(1) Nonwelded vessels operating at temperatures less than 200°F (95°C).

(-a) Nonwelded vessels with hydrogen partial pressure exceeding 6,000 psi (41 MPa).

(-b) Nonwelded vessels in hydrogen service constructed of materials with actual ultimate tensile strength exceeding 137 ksi (945 MPa)[see KM-230(a) and KM-243] and hydrogen partial pressure exceeding 750 psi (5.2 MPa).

(2) Vessels of welded construction operating at temperatures less than 200°F (95°C).

(-a) Vessels of welded construction with hydrogen partial pressure exceeding 2,500 psi (17 MPa).

(-b) Vessels of welded construction in hydrogen service of materials with actual ultimate tensile strength exceeding 90 ksi (620 MPa) [see KM-230(a) and KM-243] and hydrogen partial pressure exceeding 750 psi (5.2 MPa).

(c) Requirements of this Article are nonmandatory for vessels operating above 200°F (95°C). However, if vessels are exposed to hydrogen at a temperature warmer than 200°F (95°C) and subsequently exposed to service temperatures colder than 200°F (95°C), not including startup and shutdown, the rules of this Article should be considered. Brittle fracture shall be considered as a potential failure mode during startup and shutdown.

(d) The rules of this Article are applicable to the materials listed in Tables KM-400-1 and KM-400-2 (Tables KM-400-1M and KM-400-2M), and to aluminum alloys listed in Table KM-400-4 (Table KM-400-4M).

KD-1001 LIMITATIONS

The maximum design temperature shall be limited by the following:

(a) For carbon and low alloy steels in Table KM-400-1 (Table KM-400-1M) that are included in Figure 1 of API RP 941, the maximum design temperature shall be on or below the applicable curve in Figure 1 of API RP 941 for operating limits in hydrogen service.

The applicable curve in Figure 1 of API RP 941 at 13,000 psi hydrogen partial pressure may be used for hydrogen partial pressures above 13,000 psi (90 MPa), up to and including 15,000 psi (100 MPa). For pressures above 15,000 psi (100 MPa), the temperature shall not exceed 150°F (65°C).

(b) For austenitic stainless steels, the maximum design temperature shall be that specified in Table KM-400-2 (Table KM-400-2M).

(c) For aluminum alloys, the maximum design temperature shall not exceed the temperature specified in Table KM-400-4 (Table KM-400-4M).

(d) For all other materials, the maximum design temperature shall not exceed 400°F (205°C).

(e) Vessel parts in direct contact with hydrogen shall have an ultimate tensile strength not exceeding 137 ksi (950 MPa) unless $K_{I\,\max}^{*} + K_{I\,\mathrm{res}} \le 0$.

KD-1002 TERMINOLOGY

a = a principal planar dimension of a crack, crack depth, in. (mm)

K_{Ic} = plane-strain fracture toughness, ksi-in.$^{1/2}$ (MPa-m$^{1/2}$)

K_{IH} = threshold stress intensity factor for hydrogen-assisted cracking, ksi-in.$^{1/2}$ (MPa-m$^{1/2}$)

l = major axis of the crack, crack length, in. (mm)

LT = the test specimen has a fracture plane whose normal is in the longitudinal direction of a plate, or in the longitudinal direction of a tubular product, and the expected direction of crack propagation is in the direction transverse to the maximum grain flow, or in the width direction of a plate, or in the circumferential direction of a tubular product

t = section thickness, in. (mm)

TL = the test specimen has a fracture plane whose normal is in the transverse direction of a plate, or in the circumferential direction of a tubular product, and the expected direction of crack propagation is in the direction of the maximum

grain flow, or longitudinal direction of the plate, or in the longitudinal direction of a tubular product

KD-1003 USER'S DESIGN SPECIFICATION

The User shall state in the User's Design Specification when the special requirements of this Article shall be met for vessels constructed in accordance with the requirements of this Division after reviewing the requirements of Article KD-10 relative to the specific design. (See KG-311.)

KD-1010 FATIGUE LIFE EVALUATION USING FRACTURE MECHANICS

The design fatigue life shall be determined using a fracture mechanics approach in accordance with Article KD-4, except as modified in (a) and (b) below. In a hydrogen environment, the vessel life shall be evaluated to prevent failure of the vessel due to brittle failure or plastic collapse, and failure due to hydrogen-assisted cracking.

(a) The critical flaw size shall be determined in accordance with KD-401(c). The critical flaw size shall be calculated utilizing the fracture toughness of the material, as defined in KD-1021. The critical flaw size shall be further limited to ensure that the maximum stress intensity applied at the crack tip under design loading ($K^*_{I,\max} + K_{I,\mathrm{res}}$) remains less than the threshold value for hydrogen-assisted cracking, K_{IH} (see KD-1022).

(b) The crack growth rate and the calculated number of design cycles shall be in accordance with Article KD-4, except the crack growth rate factors in Table KD-430 (Table KD-430M) shall be replaced with factors determined in accordance with the rules in KD-1023. The crack growth rate is assumed to be zero when $K^*_{I,\max} + K_{I,\mathrm{res}} \le 0$. Determination of the threshold value for hydrogen-assisted cracking, K_{IH}, and hydrogen fatigue crack growth rate, da/dN, is not required when $K^*_{I,\max} + K_{I,\mathrm{res}} \le 0$.

Vessels constructed of aluminum alloys shall meet the requirements of this Article, except that the environmental effect of hydrogen on fatigue and fracture properties, as specified in KD-1040 and KD-1050, need not be considered.

KD-1020 FRACTURE MECHANICS PROPERTIES

The fracture mechanics properties to be used in the analysis shall be obtained in accordance with KD-1021, KD-1022, and KD-1023.

KD-1021 PLANE-STRAIN FRACTURE TOUGHNESS, K_{IC}

(a) The plain-strain fracture toughness used in the fracture mechanics life assessment in KD-1010 shall be determined as required in KM-250.

(b) As an alternative to the requirements in (a), for aluminum alloys listed in Table KM-400-4 (Table KM-400-4M), notch tensile tests may be used according to KM-270. A value of 23 ksi-in.$^{1/2}$ (25 MPa-m$^{1/2}$) shall be used as K_{Ic} for the fracture mechanics evaluation.

KD-1022 QUALIFICATION TESTS FOR THRESHOLD STRESS INTENSITY FACTOR FOR HYDROGEN-ASSISTED CRACKING, K_{IH}

The purpose of this test is to qualify the construction material by testing three heats of the material. The threshold stress intensity factors for hydrogen-assisted cracking, K_{IH}, shall be obtained from the thickest section from each heat of the material and heat treatment. The test specimens shall be in the final heat-treated condition (if applicable) to be used in the vessel construction. A set of three specimens shall be tested from each of the following locations: the base metal, the weld metal, and the heat-affected zone (HAZ) of welded joints, welded with the same qualified welding procedure specification (WPS) as intended for the vessel construction. A change in the welding procedure requires retesting of welded joints (weld metal and HAZ). The test specimens shall be in the TL direction. If TL specimens cannot be obtained from the weld metal and the HAZ, then LT specimens may be used. The values of K_{IH} shall be obtained by use of the test method described in KD-1040. The lowest measured value of K_{IH} shall be used in the analysis.

KD-1023 FATIGUE-CRACK-GROWTH RATE, da/dN

The purpose of this test is to qualify the construction material by testing three heats of the material per heat treat condition. The values of fatigue-crack-growth rate in the form of $da/dN = c\ (\Delta K)^m$ shall be obtained using the test method described in KD-1050.

The da/dN data shall be obtained from each heat of the material and heat treatment. The test specimens shall be in the final heat treated condition (if applicable) to be used in the vessel construction. A set of three specimens shall be tested from each of the following locations: the base metal, the weld metal, and the heat-affected zone (HAZ) of welded joints. Tests on welded joints (weld metal and HAZ) shall include data for each qualified welding procedure used in the vessel construction. The test specimens shall be in the TL direction. If TL specimens cannot be obtained from the weld metal and the HAZ, then LT specimens may be used. The upper bound data shall be used in the analysis.

KD-1024 USE OF TEST DATA FOR OTHER MATERIALS

The data obtained in KD-1022 or KD-1023 may be used for vessels manufactured from other material as follows:

(a) the same material specification/grade, or

(b) a similar specification/grade meeting the following requirements:

(1) the same nominal chemical composition

(2) the same heat treatment condition

provided the tensile and yield strengths as reported on the material test report do not exceed by more than 5% the average values for the material used in the qualification tests of KD-1022 or KD-1023.

The welded joints shall meet the requirements of the welding procedure specification (WPS) used for qualifying the construction material.

KD-1040 TEST METHOD FOR K_{IH} DETERMINATION

KD-1041 GENERAL

(a) Testing shall be conducted using applicable rules of ASTM E1681 and the additional rules specified in this document.

(b) The fatigue-precracked specimen shall be loaded by a constant load or constant displacement method to a stress-intensity $K_{I\mathrm{APP}}$, to be defined by the User based on fracture mechanics calculations. The specimen shall be kept in the loaded condition for a specified time in pressurized hydrogen gas at room temperature. After the test period, the specimen shall be examined to assess whether subcritical cracking occurred from the initial fatigue crack.

(c) If the subcritical crack growth exhibited by the test specimen does not exceed 0.01 in. (0.25 mm), then the material is characterized as suitable for construction of pressure vessels with respect to the hydrogen assisted cracking (HAC) resistance requirement.

(1) If the test was conducted using the constant load method, the value of $K_{I\mathrm{APP}}$ is designated as K_{IH}.

(2) If the test was conducted using the constant displacement method, K_{IH} is equal to 50% $K_{I\mathrm{APP}}$.

(d) If the subcritical crack growth exhibited by the test specimen is greater than or equal to 0.01 in. (0.25 mm), then the procedure specified in ASTM E1681, paras. 9.2.1 and 9.2.2 shall be used in establishing the K_{IH} value.

KD-1042 TERMINOLOGY

HAC = Hydrogen Assisted Cracking.

$K_{I\mathrm{APP}}$ = Initial applied Elastic Stress-Intensity factor, ksi-in.$^{1/2}$ (MPa-m$^{1/2}$).

KD-1043 SPECIMEN CONFIGURATIONS AND NUMBERS OF TESTS (25)

(a) A specimen geometry described in ASTM E1681 shall be used. All specimens shall meet

(1) the validity requirements of ASTM E1681, para. 9.3.1, or

(2) the validity requirements of ASTM E1681, para. 9.3.2 provided the specimen thickness is greater than or equal to 85% of the design thickness of the vessel

(b) The specimen orientation shall be TL as shown in ASTM E399. In the weld metal tests, the notch shall be machined in the center of the width of the weld and shall be normal to the surface of the material. In the heat-affected zone tests, the notch shall be machined approximately normal to the surface of the material and in such a manner that the precrack shall include as much heat-affected zone material as possible in the resulting fracture.

(c) A set of three K_{IH} measurements shall be made per test.

(d) Three transverse tensile specimens shall be taken adjacent to the compact specimens and shall be tested at room temperature in accordance with SA-370. The measured average value of yield strength shall be used in the specimen validity check specified in (a).

KD-1044 FATIGUE PRECRACKING

Fatigue precracking shall be in accordance with ASTM E1681, paras. 7.3.3 to 7.3.5.

KD-1045 SPECIMEN TESTING PROCEDURE (25)

(a) The specimens may be loaded by a suitable constant displacement or a constant load method.

(1) If the test is conducted using the constant load method, the fatigue-precracked test specimen is loaded to a stress-intensity $K_{I\mathrm{APP}}$ determined from the fracture analysis. The value of $K_{I\mathrm{APP}}$ shall not be less than the value K_{IH} determined from the fracture analysis.

(2) If the test is conducted using the constant displacement method, the fatigue-precracked test specimen shall be loaded to a stress-intensity $K_{I\mathrm{APP}}$ that is at least 1.5 times greater than the estimated K_{IH} but less than 180 ksi-in.$^{1/2}$ (198 MPa-m$^{1/2}$). For ferritic steels, the following table may be used to set $K_{I\mathrm{APP}}$.

Values of $K_{I\mathrm{APP}}$ for Ferritic Steels as a Function of Yield Strength

Yield Strength	$K_{I\mathrm{APP}}$
90 ksi (621 MPa)	145 to 180 ksi-in.$^{1/2}$ (159 to 198 MPa-m$^{1/2}$)
110 ksi (759 MPa)	85 to 145 ksi-in.$^{1/2}$ (93 to 159 MPa-m$^{1/2}$)
130 ksi (897 MPa)	65 to 105 ksi-in.$^{1/2}$ (71 to 115 MPa-m$^{1/2}$)

(b) Constant Displacement Method

(1) K_{IH} shall be established based on evidence of subcritical crack extension from the fatigue precrack (ASTM E1681, para. 9.2.2). If subcritical crack extension is not observed [see KD-1047(b)], then K_{IH} is equal to 50% of $K_{I\mathrm{APP}}$.

(2) In establishing K_{IH} with subcritical crack growth, the ratio of the final crack length (a) to specimen width (W) shall not exceed 0.95.

(c) Constant Load Method. All applicable rules of ASTM E1681 shall be met.

KD-1046 TEST PROCEDURE

(a) Place the test specimens in a high-pressure test chamber.

(b) Evacuate the test chamber to eliminate any traces of air or moisture absorbed by the walls. Scavenging with the test gas followed by vacuum pumping can be used to improve the cleaning efficiency.

(c) Pressurize the test chamber with hydrogen gas to a pressure equal to or greater than the design pressure of the vessel.

(d) Measure the hydrogen gas composition at the termination of the test. The gas shall have the following limits on impurities: $O_2 < 1$ ppm, $CO_2 < 1$ ppm, CO < 1 ppm, and $H_2O < 3$ ppm. The impurity limits can typically be achieved with a supply gas composition of 99.9999% hydrogen.

(e) For ferritic steels [see Table KM-400-1 (Table KM-400-1M)] and for the martensitic stainless steels [see Table KM-400-2 (Table KM-400-2M)], the test specimens shall be subjected to a constant load or constant displacement at least for 1,000 hr during the test at room temperature. For austenitic stainless steels, the test duration shall be at least 5,000 hr.

(f) Oxides on the precrack surface can inhibit hydrogen uptake into the material during testing. The effect of oxides can be circumvented by applying $K_{I\mathrm{APP}}$ in the hydrogen gas environment for constant-load tests (see KD-1045). For constant-displacement tests, the specimen and test chamber shall be located in a glove box with an inert atmosphere containing <5ppm O_2 and < 50 ppm H_2O. After placing the bolt-loaded compact specimens inside the test chamber, the test chamber need not be kept in the glove box during the specified exposure period.

KD-1047 CRACK GROWTH EXAMINATION

(a) After the specified test period, unload the specimen, and mark the HAC advance using one of the following methods:

(1) Heat tinting the specimen at about 570°F (300°C) for 30 min.

(2) Fatigue cycling at maximum stress-intensity factor not exceeding 0.6 $K_{I\mathrm{APP}}$. Advance the crack by at least 1 mm.

(b) Measure the crack growth using a scanning electron microscope. Measurements shall be taken perpendicular to the precrack at 25% B, 50% B, and 75% B locations, where B is the test specimen thickness. Calculate the average of these three values.

(1) If the average measured crack growth does not exceed 0.01 in. (0.25 mm), and the test is conducted using the constant load method, the material's K_{IH} value is equal to the $K_{I\mathrm{APP}}$.

(2) If the average measured crack growth does not exceed 0.01 in. (0.25 mm), and the test is conducted using the constant displacement method, K_{IH} is equal to 50% of $K_{I\mathrm{APP}}$.

(c) Assess extent of subcritical crack extension and evaluate K_{IH} according to ASTM E1681, paras. 9.2.1 and 9.2.2 and KD-1045.

KD-1048 VESSEL MATERIAL QUALIFICATION (25)

The K_{IH} value established for the material shall be qualified for maximum tensile strength equal to the average of the three tensile strength values obtained in KD-1043(d).

KD-1049 REPORT (25)

The information described in ASTM E1681, section 10, shall be reported. The report shall indicate if the validity criteria are met or not and shall include scanning electron microscope micrographs in KD-1047(b). The report shall be kept on file permanently as a record that the vessel material has been tested and found acceptable.

KD-1050 FATIGUE CRACK GROWTH RATE TESTS

KD-1051 FATIGUE CRACK GROWTH RATE TEST METHOD

This test method is provided to measure the fatigue crack growth rate in the form of $da/dN = c(\Delta K)^m$ in gaseous hydrogen at design pressure.

KD-1052 FATIGUE CRACK GROWTH RATE TESTING

Testing shall be conducted in accordance with all applicable rules of ASTM E647 at room temperature in hydrogen at a pressure not less than the design pressure of the vessel.

KD-1053 SPECIMEN CONFIGURATIONS AND NUMBERS OF TESTS

(a) Specimen orientation shall be in the TL direction, as shown in ASTM E399. In the weld metal tests, the notch shall be machined in the center of the width of the weld and shall be normal to the surface of the material. In the heat-affected zone tests, the notch shall be machined approximately normal to the surface of the material

and in such a manner that the precrack shall include as much heat-affected zone material as possible in the resulting fracture.

(b) Three da/dN vs. ΔK data sets shall be generated per test.

KD-1054 TEST PROCEDURE

(a) Evacuate the test chamber to eliminate any traces of air or moisture absorbed by the walls. Scavenging with the test gas followed by vacuum pumping can be used to improve the cleaning efficiency.

(b) Pressurize the test chamber with hydrogen gas to a pressure equal to or greater than the design pressure of the vessel.

(c) Measure the hydrogen gas composition at the termination of the test. The gas shall have the following limits on impurities: O_2 < 1 ppm, CO_2 < 1 ppm, CO < 1 ppm, and H_2O < 3 ppm. The impurity limits can typically be achieved with a supply gas composition of 99.9999% hydrogen.

KD-1055 TEST FREQUENCY

The test frequency shall be established by the User for the intended service; however, the cycle rate shall not exceed 0.1 Hz.

KD-1056 R-RATIO

The R-ratio defined as K_{min}/K_{max} shall not be less than that used in the vessel design.

KD-1057 *da/dN* DATA

The data in the form of $da/dN = c(\Delta K)^m$ shall be obtained for the full range of ΔK of interest used in the fracture analysis.

KD-1058 DATA REPORT

Data report shall be prepared in accordance with Section 10 of ASTM E647.

ARTICLE KD-11
DESIGN REQUIREMENTS FOR WELDED VESSELS

KD-1100 SCOPE

The rules contained in this Article provide for the design of welded vessels.

The special requirements of this Article are additional to the general requirements given in Articles KD-2, KD-3, and KD-4. When requirements of this Article differ from those of Articles KD-2, KD-3, and KD-4, they are specifically delineated.

KD-1101 GENERAL REQUIREMENTS FOR WELDED VESSELS

Welded vessels (see Part KF) may be constructed from forged rings or other wrought material product forms, such as rolled plate, provided

(a) the applicable welding requirements of this Division and those of ASME Section IX, Welding and Brazing Qualifications, are met

(b) all welds meet the fabrication and examination requirement of Part KF and Part KE

(c) the mechanical properties of the weld and heat-affected zone shall be verified to meet the properties of the base metal specified in Part KM after all fabrication and heat treatment has been completed

KD-1110 TYPES OF JOINTS PERMITTED

All joints, except for joints described in Article KD-7, KD-830(b), KD-1131, and KF-821(f), shall be Type No. 1 butt joints (see KF-221).

KD-1111 TRANSITION BUTT JOINTS

An angle joint, with a circumferential butt joint, connecting a transition to a cylinder shall be considered as meeting this requirement provided the angle of the cone relative to the axis of the cylinder does not exceed 30 deg and the requirements of a Type No. 1 butt joint are met. All requirements pertaining to the butt joint shall apply to the angle joint.

KD-1112 FORGED FLAT HEADS WITH HUBS FOR BUTT JOINTS

(a) Hubs for butt welding to the adjacent shell, head, or other pressure parts, such as hubbed and flat heads (see Figure KD-1112), shall not be machined from flat plate.

(b) Hubs shall be forged as shown in Figure KD-1112 to permit Type No. 1 butt welds.

(c) The mechanical properties of the forged lip that is to be welded to the shell shall be subject to the same requirements as the shell. Proof of this shall be furnished by a tension test specimen (subsize, if necessary) taken in this direction and as close to the hub as is practical.[4]

(d) The height of the hub shall be the greater of 1.5 times the thickness of the pressure part to which it is welded or $^{3}/_{4}$ in. (19 mm), but need not be greater than 2 in. (50 mm).

KD-1113 CORNER WELDS

Corner welds consisting of full-penetration groove welds and/or fillet welds are not permitted for the attachment of heads, flanges, etc., to shells.

KD-1120 TRANSITION JOINTS BETWEEN SECTIONS OF UNEQUAL THICKNESS

The requirements of this paragraph do not apply to flange hubs.

KD-1121 SHELL AND HEAD JOINTS

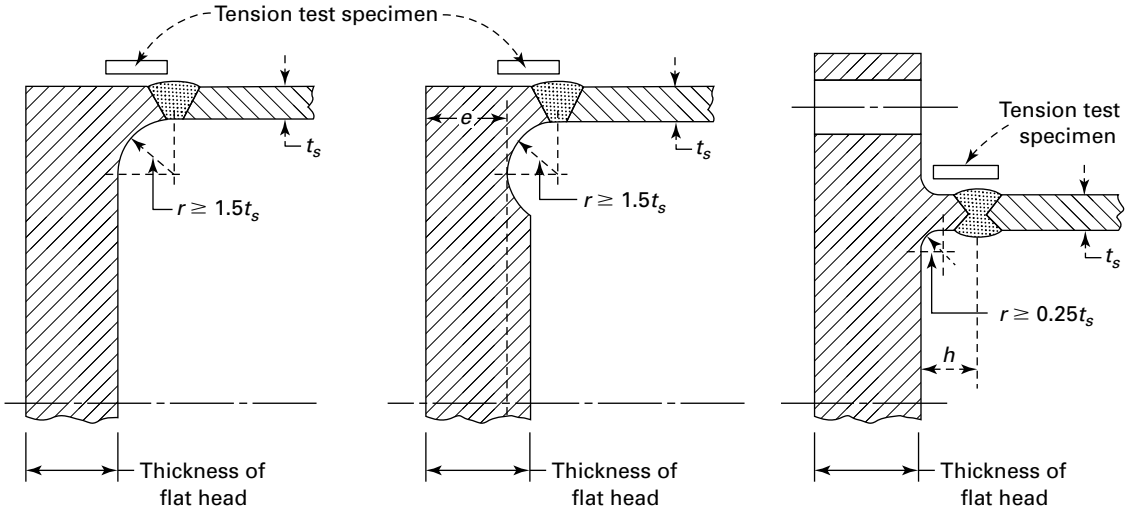
(a) Unless the static and cyclic analyses (see Articles KD-2, KD-3, and KD-4) or experimental analysis (see Article KD-12) indicate otherwise, a tapered transition as shown in Figure KD-1121 shall be provided between sections that differ in thickness by more than one-fourth of the thickness of the thinner section or by more than $^{1}/_{8}$ in. (3.2 mm), whichever is less.

(b) The transition may be formed by any process that will provide a uniform taper. When the transition is formed by adding additional weld metal beyond that which would otherwise be the edge of the weld, such additional weld metal buildup shall meet the weld fabrication requirements of this Division and Section IX.

(c) The butt weld may be partly or entirely in the tapered section as indicated in Figure KD-1121. Unless the results of the static and cyclic analyses (see Articles KD-2, KD-3, and KD-4) or experimental analysis (see Article KD-12) indicate otherwise, the following additional requirements shall also apply:

(1) the length of taper shall be not less than three times the offset between adjacent surfaces

Figure KD-1112
Typical Pressure Parts With Butt-Welded Hubs
(Not Permissible if Machined From Rolled Plates)



GENERAL NOTES:
(a) The tension test specimen may be located inside or outside of the hub.
(b) h is the greater of $^3/_4$ in. (19 mm) or $1.5t_s$.

(2) when a taper is required on any formed head intended for butt-welded attachment, the skirt shall be long enough so that the required length of taper does not extend beyond the tangent line

(3) an ellipsoidal or hemispherical head that has a greater thickness than a cylinder of the same inside diameter may be machined to the outside diameter of the cylinder provided the remaining thickness is at least as great as that required for a shell of the same diameter

KD-1122 NOZZLE NECK TO PIPING JOINTS

In the case of nozzle necks that attach to piping of a lesser wall thickness, a tapered transition from the weld end of the nozzle may be provided to match the piping thickness although the thickness is less than otherwise required by the rules of this Division. This tapered transition shall meet the limitations shown in Figure KD-1122.

KD-1130 NOZZLE ATTACHMENTS

All nozzle attachment welds shall be Type No. 1 butt joints (see Figure KD-1130) unless specifically provided for in KD-1131.

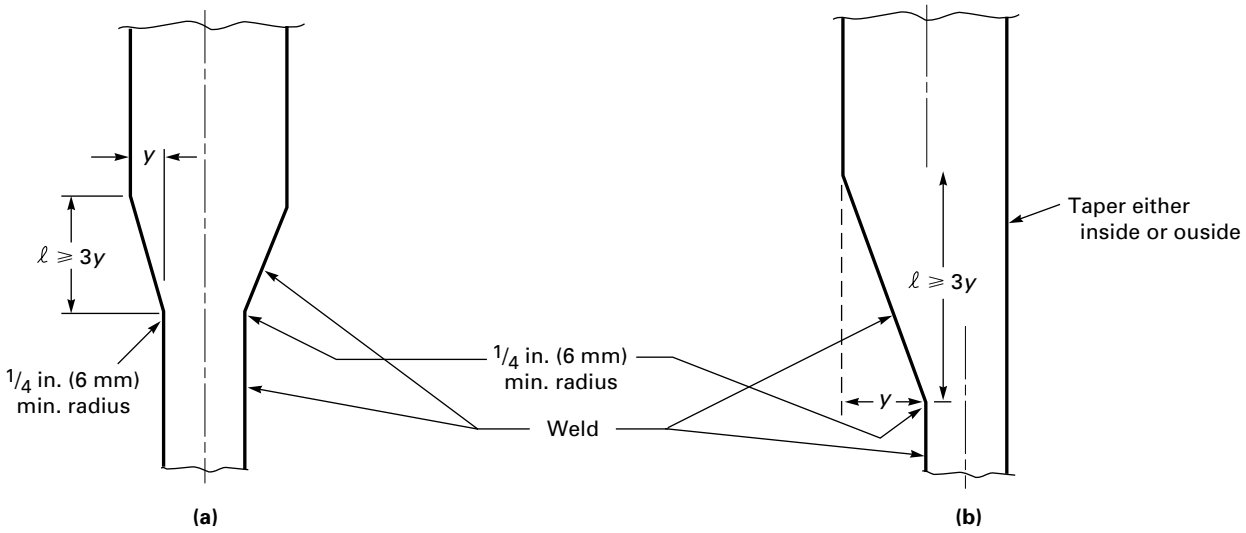
KD-1131 NOZZLE ATTACHMENTS TO VESSEL SURFACES

Nozzles attached to the outside surface of a vessel to form a continuous flow path with a hole cut in the vessel wall shall be attached by a full-penetration groove weld (see Figure KD-1131).

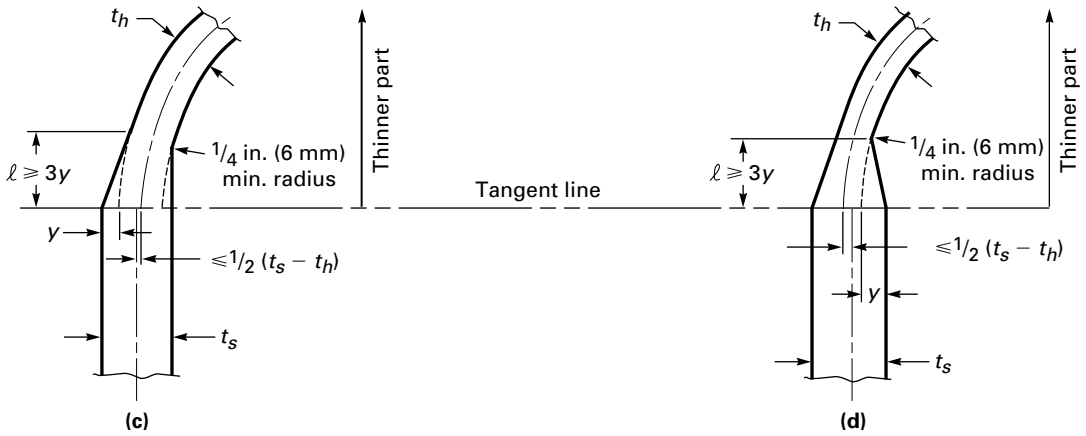
KD-1132 NOZZLE REINFORCEMENT

Nonintegral nozzle reinforcement is not permitted. All reinforcement shall be integral with the nozzle, shell, or both. Additional guidance is provided in Nonmandatory Appendix H.

Figure KD-1121
Joints Between Formed Heads and Shells



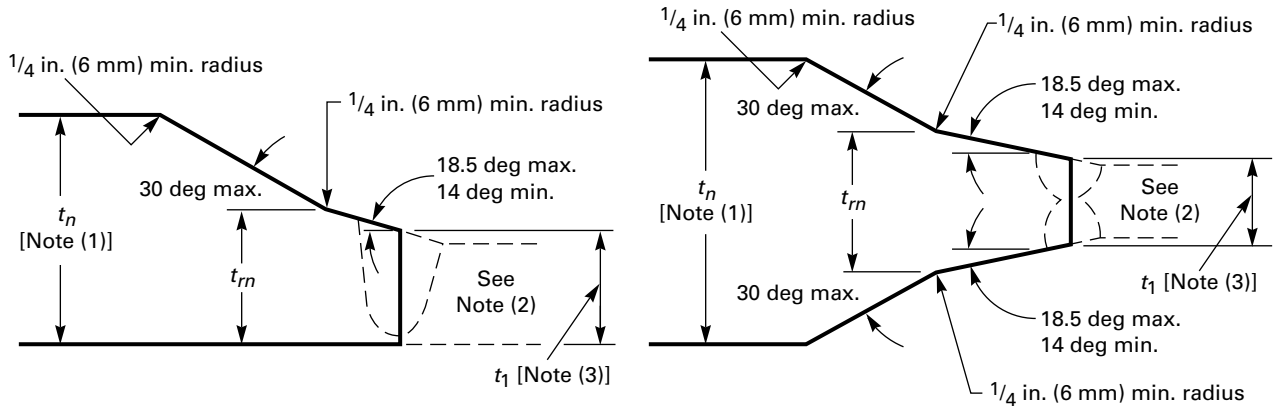
Butt Welding of Sections of Unequal Thickness



Joints Between Formed Heads and Shells

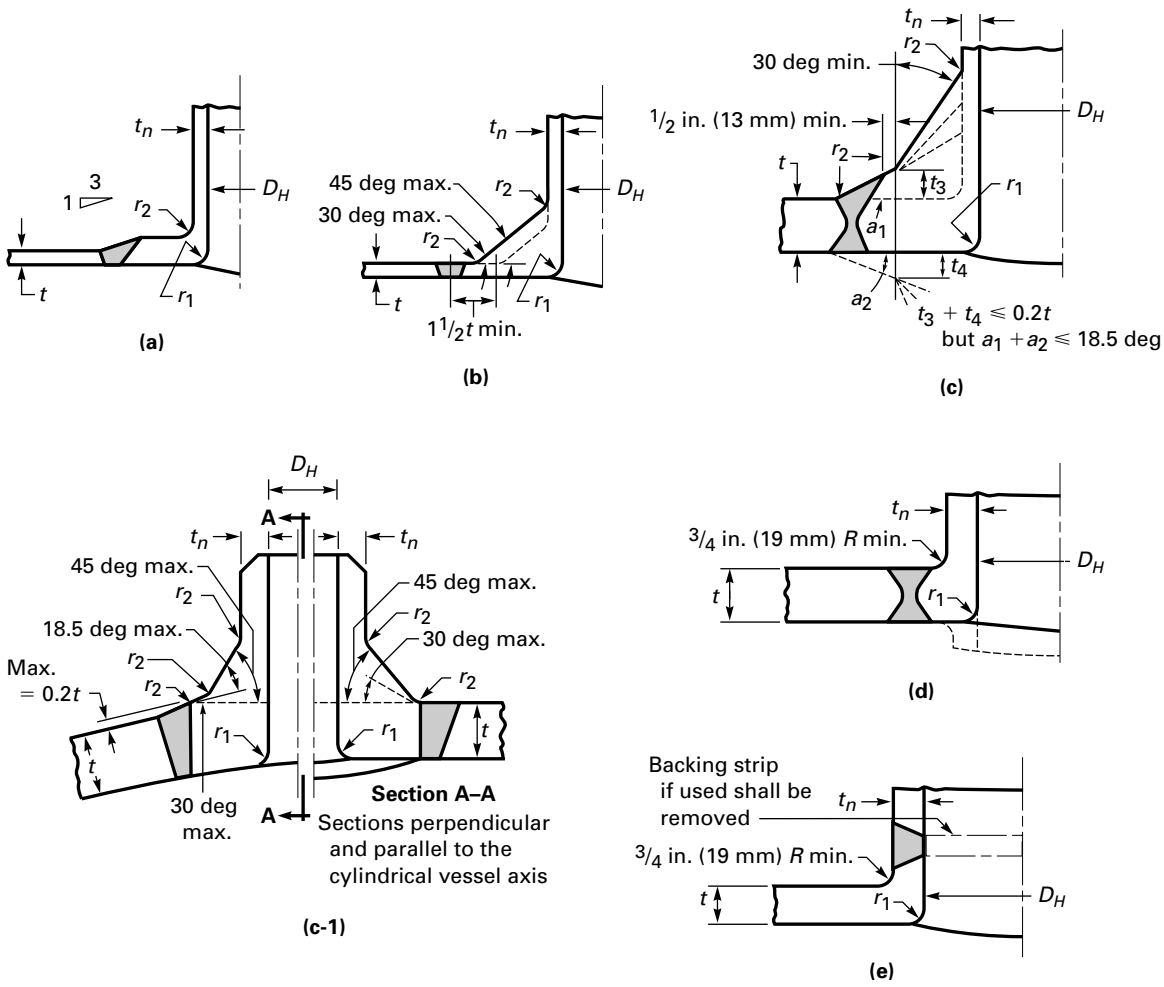
GENERAL NOTES:
(a) Length of required taper, ℓ, may include the width of the weld.
(b) In all cases ℓ shall not be less than 3y, where ℓ is required length of taper and y is the offset between the adjacent surfaces of abutting sections.

Figure KD-1122
Nozzle Necks Attached to Piping of Lesser Wall Thickness



NOTES:
(1) Nominal nozzle thickness.
(2) Weld bevel is shown for illustration only.
(3) t_1 is not less than the greater of
(a) $0.8t_{rn}$ where t_{rn} = required thickness of seamless nozzle wall
(b) minimum wall thickness of connecting pipe

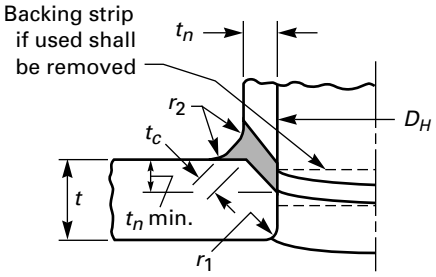
Figure KD-1130
Some Acceptable Welded Nozzle Attachments



Legend:

D_H = diameter of opening in shell or head
r_1 = $\leq \frac{1}{4}t$, $\frac{1}{4}t_n$, $\frac{1}{4}D_H$, or $\frac{3}{4}$ in. (19 mm), whichever is less
r_2 = $\geq \frac{1}{4}$ in. (6 mm)
t = nominal thickness of shell or head
t_n = nominal thickness of nozzle

Figure KD-1131
An Acceptable Full-Penetration Welded Nozzle Attachment Not Readily Radiographable



Legend:

D_H = diameter of opening in part penetrated
r_1 max. = $\frac{1}{4}t$, $\frac{1}{4}t_n$, $\frac{1}{4}D_H$, or $\frac{3}{4}$ in. (19 mm), whichever is less
r_2 = $\frac{1}{4}$ in. (6 mm) min.
t = thickness of part penetrated
t_c min. = $0.7t_n$ or $\frac{1}{4}$ in. (6 mm), whichever is less
t_n = thickness of penetrating part

ARTICLE KD-12
EXPERIMENTAL DESIGN VERIFICATION

KD-1200 GENERAL REQUIREMENTS

KD-1201 WHEN EXPERIMENTAL STRESS ANALYSIS IS REQUIRED

The critical or governing stresses in parts for which theoretical stress analysis is inadequate or for which design values are unavailable shall be substantiated by experimental stress analysis.

KD-1202 WHEN REEVALUATION IS NOT REQUIRED

Reevaluation is not required for configurations for which detailed experimental results, that are consistent with the requirements of this Article, are available.

KD-1203 DISCOUNTING OF CORROSION ALLOWANCE, ETCETERA

The test procedures followed and the interpretation of the results shall be such as to discount the effects of material added to the thickness of members, such as corrosion allowance or other material that cannot be considered as contributing to the strength of the part.

KD-1204 INSPECTION AND REPORTS

Tests conducted in accordance with this Article need not be witnessed by the Inspector. However, a detailed report of the test procedure and the results obtained shall be included with the Manufacturer's Design Report.

KD-1210 TYPES OF TESTS

Tests may be run in order to determine governing stresses, the collapse pressure, or the adequacy of a part for cyclic loading. For determining governing stresses and the collapse pressure, a single test is normally adequate.

KD-1211 TESTS FOR DETERMINATION OF GOVERNING STRESSES

Permissible types of tests for the determination of governing stresses are strain measurement tests and photoelastic tests. Brittle coating tests may be used only for the purpose described in KD-1241. Results of displacement measurement tests and tests to destruction are not acceptable for governing stress determination.

KD-1212 TESTS FOR DETERMINATION OF COLLAPSE PRESSURE CP

Strain measurement tests may be used for the determination of the collapse pressure CP. Distortion measurement tests may be used for the determination of the CP if it can be clearly shown that the test setup and the instrumentation used will give valid results for the configuration on which the measurements are made. Brittle coating tests and tests to destruction shall not be used to determine the CP.

KD-1213 FATIGUE TESTS

Fatigue tests may be used to evaluate the adequacy of a part for cyclic loading, as described in KD-1260.

KD-1220 STRAIN MEASUREMENT TEST PROCEDURE

KD-1221 REQUIREMENTS FOR STRAIN GAGES

Strain gages of any type capable of indicating strains to an accuracy of 0.00005 in./in. (mm/mm) (0.005%) or better may be used. It is recommended that the gage length be such that the maximum strain within the gage length does not exceed the average strain within the gage length by more than 10%. Instrumentation shall be such that both surface principal stresses may be determined at each gage location in the elastic range of material behavior at that gage location. A similar number and orientation of gages at each gage location are required to be used in tests beyond the elastic range of material behavior. The strain gages and cements that are used shall be shown to be reliable for use on the material surface finish and configuration considered to strain values at least 50% higher than those expected.

KD-1222 USE OF MODELS FOR STRAIN OR DISTORTION MEASUREMENTS

Except in tests made for the measurement of the CP, strain gage data may be obtained from the actual component or from a model component of any scale that meets

the gage length requirements of KD-1221. The model material need not be the same as the component material, but shall have an elastic modulus that is either known or has been measured at the test conditions. The requirements of dimensional similitude shall be met.

In the case of CP tests, only full-scale models, prototypical in all respects, are permitted unless the tester can clearly demonstrate the validity of the scaling laws used. The test vessel or component used to determine CP shall be made from material of the same type, grade, and class as the production vessel.

KD-1230 PHOTOELASTIC TEST PROCEDURE

Either two-dimensional or three-dimensional techniques may be used as long as the model represents the structural effects of the loading.

KD-1240 TEST PROCEDURES

KD-1241 LOCATION OF TEST GAGES

(a) In tests for determination of governing stresses, sufficient locations on the vessel shall be investigated to ensure that measurements are taken at the most critical areas. The location of the critical areas and the optimum orientation of test gages may be determined by a brittle coating test.

(b) In tests made for the measurement of CP, sufficient measurements shall be taken so that all areas which have any reasonable probability of indicating a minimum CP are adequately covered. It is noted, however, that the intent of the measurements is to record motion in the vessel due to primary loading effects. Care shall be taken to avoid making measurements at areas of concentrated stress due to secondary or peaking effects. If strain gages are used to determine the CP, particular care should be given to ensuring that strains (either membrane, bending, or a combination) are being measured which are actually indicative of the load-carrying capacity of the structure. If distortion measurement devices are used, care should be given to ensure that it is the change in significant dimensions or deflections that is measured, such as diameter or length extension, or beam or plate deflections that are indicative of the tendency of the structure to reach the CP.

KD-1242 REQUIREMENTS FOR PRESSURE GAGES AND TRANSDUCERS

Pressure gages and transducers shall meet the requirements of Article KT-4.

KD-1243 APPLICATION OF PRESSURE OR LOAD

(a) In tests for determining governing stresses, the internal pressure or mechanical load shall be applied in such increments that the variation of strain with load can be plotted so as to establish the ratio of stress to load in the elastic range. If the first loading results in strains that are not linearly proportional to the load, it is permissible to unload and reload successively until the linear proportionality has been established.

(b) When frozen stress photoelastic techniques are used, only one load value can be applied, in which case the load shall not be so high as to result in deformations that invalidate the test results.

(c) In tests made for the measurement of the CP, the proportional load shall be applied in sufficiently small increments so that an adequate number of data points for each gage are available for statistical analysis in the linear elastic range of behavior. All gages shall be evaluated prior to increasing the load beyond this value. A least square fit (regression) analysis shall be used to obtain the best-fit straight line and the confidence interval shall be compared to preset values for acceptance or rejection of the strain gage or other instrumentation. Unacceptable instrumentation shall be replaced and the replacement instrumentation tested in the same manner.

(d) After all instrumentation has been deemed acceptable, the test shall be continued on a strain- or displacement-controlled basis, with adequate time permitted between load changes for all metal flow to be completed.

KD-1250 INTERPRETATION OF RESULTS

KD-1251 INTERPRETATION TO BE ON ELASTIC BASIS

The experimental results obtained shall be interpreted on an elastic basis to determine the stresses corresponding to the design loads; that is, in the evaluation of stresses from strain gage data, the calculations shall be performed under the assumption that the material is elastic. The elastic constants used in the evaluation of experimental data shall be those applicable to the test material at the test temperature.

KD-1252 REQUIRED EXTENT OF STRESS ANALYSIS

The extent of experimental stress analysis performed shall be sufficient to determine the governing stresses for which design values are unavailable, as described in KD-1201. When possible, combined analytical and experimental methods shall be used to distinguish between primary, secondary, and local stresses so that each combination of categories can be controlled by the applicable stress limit.

KD-1253 DETERMINATION OF COLLAPSE PRESSURE, CP

(a) For distortion measurement tests, the loads are plotted as the ordinate and the measured deflections are plotted as the abscissa. For strain gage tests, the loads are plotted as the ordinate and the maximum principal strains on the surface as the abscissa. The test CP is taken as the pressure that produces a measured strain of no more than 2%. This strain limit shall be based on the actual strain in the test vessel due to primary loading effects. Therefore, strain gages or distortion measuring devices shall be located to obtain results due to primary loading, and to avoid results due to secondary and peak effects (see KD-1241).

(b) If the vessel is destroyed or fails to maintain its pressure boundary before the CP can be determined, the vessel shall be redesigned and retested. The process is repeated until the vessel can sustain pressures that are large enough to obtain the CP in the prescribed manner.

(c) The CP used for design purposes shall be the test CP multiplied by the ratio of the specified material yield strength at design temperature to the actual measured test material yield strength at the test temperature. When the design pressure is based on the CP test, the maximum design pressure shall be determined in accordance with KD-1254. Careful attention shall be given to assuring that proper consideration is given to the actual as-built dimensions of the test model when correlating the CP of the test model to that expected for the actual structure being designed.

KD-1254 DETERMINATION OF MAXIMUM DESIGN PRESSURE AT ROOM TEMPERATURE

The maximum design pressure P when based on the CP testing as described in this paragraph shall be computed by one of the following equations using the actual material yield strength.

(a) If the actual measured yield strength is determined only by the testing required by the material specification,

$$P = \frac{0.8}{1.732}\text{CP}\left(\frac{S_y}{S_{yms}}\right)$$

where

S_y = specified minimum yield strength at room temperature, ksi (MPa)
S_{yms} = actual yield strength based on the testing required by the material specification, ksi (MPa), but not less than S_y

(b) If the actual yield strength is determined in accordance with the additional testing prescribed below,

$$P = \frac{1}{1.732}\text{CP}\left(\frac{S_y}{S_{yact}}\right)$$

where

S_{yact} = actual average yield strength from test specimens at room temperature, ksi (MPa), but not less than S_y

(c) The yield strength of the material in the part tested shall be determined in accordance with ASME SA-370 with the following additional requirements:

(1) Yield strength so determined (S_{yact}) shall be the average of at least three specimens cut from the part tested after the test is completed. The specimens shall be cut from a location where the stress during the test has not exceeded the yield strength. The specimens shall not be flame cut because this might affect the strength of the material.

(2) When excess stock from the same piece of wrought material is available and has been given the same heat treatment as the pressure part, the test specimens may be cut from this excess stock. The specimen shall not be removed by flame cutting or any other method involving sufficient heat to affect the properties of the specimen.

KD-1260 EXPERIMENTAL DETERMINATION OF ALLOWABLE NUMBER OF OPERATING CYCLES

Experimental methods may be used to determine the allowable number of operating cycles of components and vessels as an alternative to the requirements of Article KD-3. This approach shall only be used for vessels or components that have been shown to demonstrate a leak-before-burst mode of failure.

KD-1261 TEST DESCRIPTION

When a fatigue test is used to demonstrate the adequacy of a component or a portion thereof to withstand cyclic loading, a description of the test shall be included in the Design Report. This description shall contain sufficient detail to show compliance with the requirements stated herein.

KD-1262 TEST PROCEDURE

(a) The test component or portion thereof shall be constructed of material having the same composition and subjected to the same mechanical working and heat treating so as to produce mechanical properties equivalent to those of the material in the prototype component. Structural similitude shall be maintained, at least in those portions whose ability to withstand

cyclic loading is being investigated and in those adjacent areas that affect the stresses in the portion under test.

(b) The test component or portion thereof shall withstand the number of cycles as set forth in (c) before failure occurs. *Failure* is herein defined as a propagation of a crack through the entire thickness such as would produce a measurable leak in a pressure-retaining member.

(c) The minimum number of test cycles N_T that the component shall withstand, and the magnitude of the loading P_T [see eqs. (3)(1), (3)(2), and (f)(2)(3)] to be applied to the component during test, shall be determined by multiplying the design service cycles N_D by a specified factor K_{TN}, and the design service loads P_D by K_{TS}. Values of these factors shall be determined by means of the test parameter ratio diagram, the construction of which is as follows and is illustrated in Figure KD-1260.1.

(1) Project a vertical line from the design service cycles N_D on the abscissa of the S_a versus N diagram, to intersect the fatigue design curve S_a of the appropriate figure in Article KD-3, to an ordinate value of K_s times S_{aD}. Label this point A. K_s is a factor that accounts for the effect of several test parameters [see (g)].

(2) Extend a horizontal line through the point D until its length corresponds to an abscissa value of K_n times N_D. Label this point B. Note that $K_n$is a factor that accounts for the effect of several test parameters [see (g)].

(3) Connect points A and B. The segments AB embrace all the allowable combinations of K_{TS} and K_{TN} [see (e) for accelerated testing]. Any point C on this segment may be chosen at the convenience of the tester. Referring to Figure KD-1260.1, the factors K_{TS} and K_{TN} are defined by:

$$K_{TS} = \frac{\text{value of ordinate at point } C}{\text{value of ordinate at point } D}$$

$$K_{TN} = \frac{\text{value of abscissa at point } C}{\text{value of abscissa at point } D}$$

Thus

$$P_T \text{ (test loading)} = K_{TS}P_D \quad (1)$$

$$N_T \text{ (test cycles)} = K_{TN}N_D \quad (2)$$

(d) It should be noted that if the test component is not full size but a geometrically similar model, the value P_T would have to be adjusted by the appropriate scale factor, to be determined from structural similitude principles, if the loading is other than pressure. The number of cycles that the component shall withstand during this test without failure must not be less than N_T, while subjected to a cyclic test loading P_T which shall be adjusted, if required, using model similitude principles if the component is not full size.

(e) Accelerated fatigue testing (test cycles N_D) *may be* conducted if the design cycles N_D are greater than 10^4 and the testing conditions are determined by the following procedures, which are illustrated in Figure KD-1260.2. In this figure, the points A, B, and D correspond to similar labeled points in Figure KD-1260.1.

(1) The minimum number of test cycles $N_{T,\min}$ shall be:

$$N_{T,\,\min} = 10^2\sqrt{N_D}$$

Project a vertical line through $N_{T,\min}$ on the abscissa of the S_a versus N diagram such that it intersects and extends beyond the fatigue design curve.

(2) Construct a curve through the point A and intersect the vertical projection of $N_{T,\min}$ [see (1)] by multiplying every point on the fatigue design curve by the factor K_s [see (c)(1)]. Label the intersection of this curve and the vertical projection of $N_{T,\min}$ as A'.

(3) Any point C on the segment A, A', B determines the allowable combinations of K_{TS} and K_{TN}. The factors K_{TS} and K_{TN} are obtained in the same manner as in (c).

(f) In certain instances, it may be desirable (or possible) in performing the test to increase only the loading or number of cycles, but not both, in which event two special cases of interest result from the above general case.

(1) Case 1 (factor applied to cycles only). In this case, $K_{TS} = 1$ and

$$K_{TN} = \frac{\text{value of abscissa at point } B}{\text{value of abscissa at point } D}$$

The number of test cycles that the component shall withstand during this test must, therefore, not be less than

$$N_T = K_{TN}N_D$$

while subjected to the cyclic design service loading, adjusted as required, if a model is used.

(2) Case 2 (factor applied to loading only). In this case, $K_{TN} = 1$ and

$$K_{TS} = \frac{\text{value of ordinate at point } A}{\text{value of ordinate at point } D}$$

The component must, therefore, withstand a number of cycles at least equal to the number of design service cycles, while subjected to a cyclic test loading

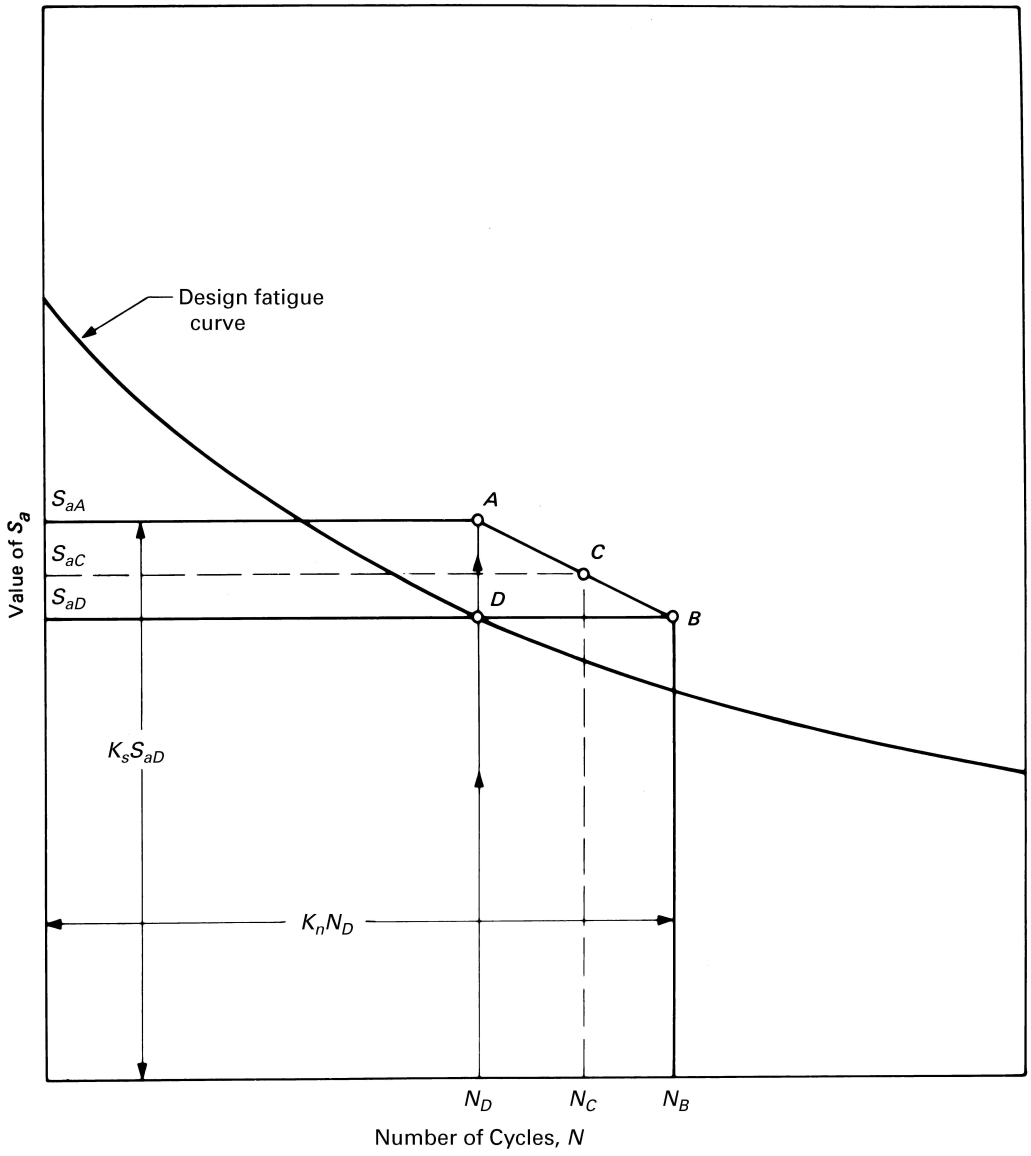
$$P_T = K_{TS}P_D \quad (3)$$

again adjusted as required, if a model is used.

(g) The values of K_s and K_n are the multiples of factors that account for the effects of size, surface finish, cyclic rate, temperature, and the number of replicate tests performed. They shall be determined as follows:

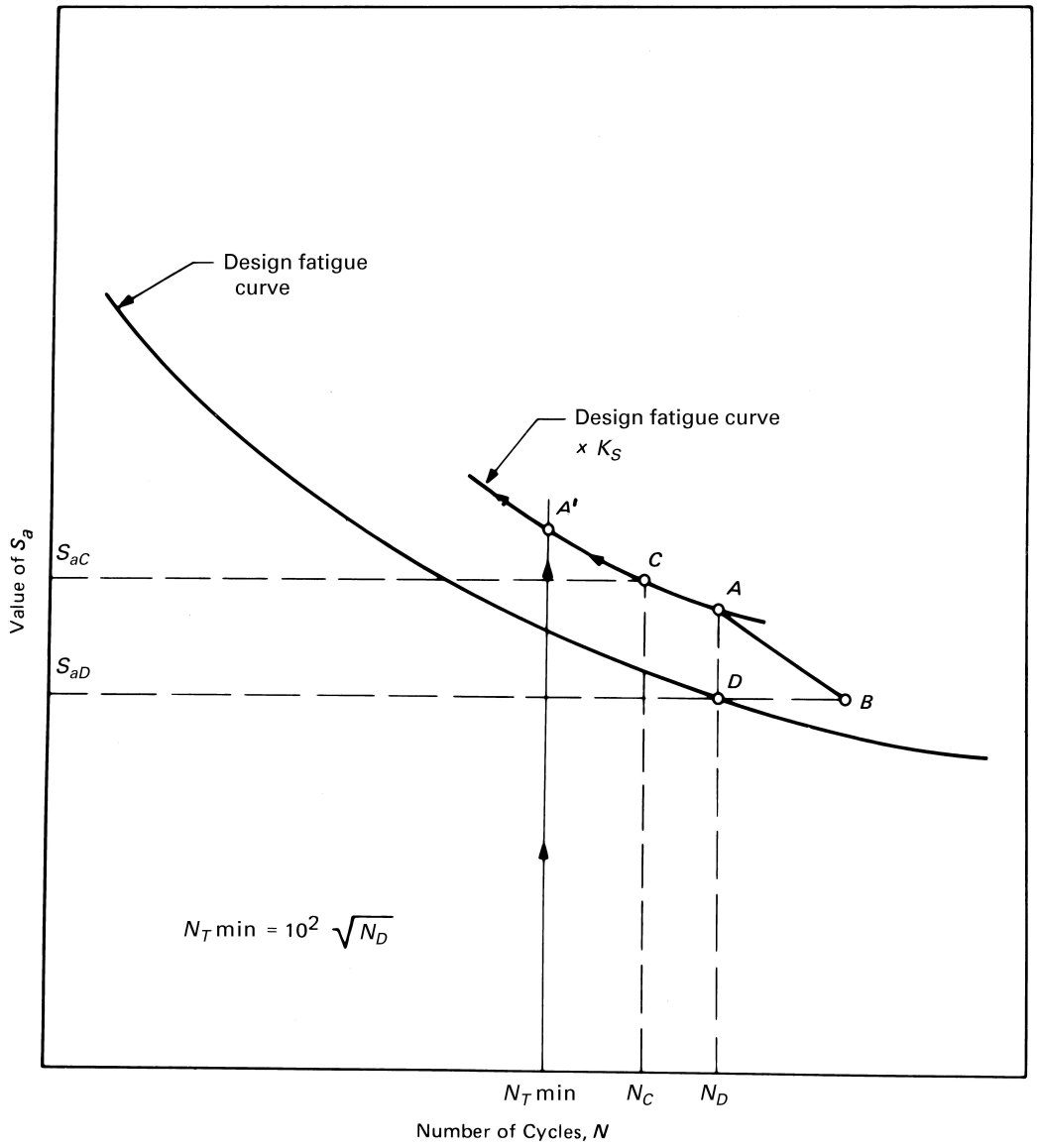
K_n = greater of $(K_s)^{4.3}$ or 2.6
K_s = greater of $K_{sa}K_{sf}K_{sc}K_{st}K_{ss}$ or 1.25

Figure KD-1260.1
Construction of Testing Parameter Ratio Diagram



GENERAL NOTE: For Point C, $K_{TS} = S_{aC}/S_{aD}$ and $K_{TN} = N_C/N_D$.

Figure KD-1260.2
Construction of Testing Parameter Ratio Diagram for Accelerated Tests



GENERAL NOTE: For Point C, $K_{TS} = S_{aC}/S_{aD}$ and $K_{TN} = N_C/N_D$.

K_{sa} = factor for the effect of size of the highly stressed surface area on fatigue life
= greater of $(A_p/A_T)^{1/30}$ or 1.0, where A_p is the size of the highly stressed surface area of the prototype component and A_T is the size of the highly stressed surface area of the test component

K_{sc} = factor for differences in design fatigue curves at various temperatures
= greater of $\frac{(S_aN \text{ at } T_c)(S_a10^n \text{ at } T_t)}{(S_aN \text{ at } T_D)(S_a10^n \text{ at } T_c)}$ or 1.0

K_{sf} = factor for the effect of surface finish
= greater of $K_r(P)/K_r(T)$ or 1.0, where $K_r(P)$ is the surface roughness factor of the prototype and $K_r(T)$ is the surface roughness factor of the test component. The $K_r(P)$ and $K_r(T)$ factors are based on the surface finish and shall be taken from Figure KD-320.6(a) [Figure KD-320.6M(a)] or Figure KD-320.6(b) [Figure KD-320.6M(b)].

K_{ss} = factor for the statistical variation in test results
= greater of 1.470 − (0.044 × number of replicate tests) or 1.0

K_{st} = factor for the effect of test temperature
= greater of (E at T_t)/(E at T_D) or 1.0, where E is the elastic modulus of the component material

S_a10^n = S_a from the applicable fatigue design curve at the maximum number of cycles defined on the curve

T_c = 700°F (370°C) for carbon and low alloy steels, and 800°F (425°C) for austenitic stainless steels and nickel–chromium–iron alloys

T_D = design temperature

T_t = test temperature

KD-1270 DETERMINATION OF FATIGUE STRENGTH REDUCTION FACTORS

(a) Experimental determination of fatigue strength reduction factors shall be in accordance with the following procedures.

(1) The test part shall be fabricated from a material with the same nominal chemistry, mechanical properties, and heat treatment as the component.

(2) The stress level in the specimen shall be such that the linearized primary-plus-secondary equivalent stress ($P_L + P_b + Q$) does not exceed the limit prescribed in Figure 9-200.1 so that failure does not occur in less than 1,000 cycles.

(3) The configuration, surface finish, and stress state of the specimen shall closely simulate those expected in the components. In particular, the stress gradient shall not be more abrupt than that expected in the component.

(4) The cyclic rate shall be such that appreciable heating of the specimen does not occur.

(b) It is recommended that the fatigue strength reduction factor be determined by performing tests on notched and unnotched specimens and calculated as the ratio of the unnotched stress to the notched stress for failure.

ARTICLE KD-13
ADDITIONAL DESIGN REQUIREMENTS FOR COMPOSITE REINFORCED PRESSURE VESSELS (CRPV)

KD-1300 SCOPE

The following Article provides additional design requirements for the Composite Reinforced Pressure Vessels (CRPV) designed in accordance with this Division.

KD-1310 GENERAL

(a) Rules for calculating the static and dynamic strength for CRPV made of a metallic layer with a circumferentially wrapped fiber reinforced plastic layer are given in subsequent paragraphs. The loads resulting from transportation, the regulatory requirements and all vibratory, dynamic, and gravity loads shall be included in the CRPV design.

(b) The circumferential stresses generated in both the metallic layer and the laminate layer are used to resist circumferential loads due to internal pressure. Longitudinal stresses in the metallic layer alone shall be used to resist axial loads due to internal pressure, thermal expansion, and all other longitudinal loads. The longitudinal strength, perpendicular to the fiber winding directions, of the laminate layer shall not be used in the design calculations other than to ensure sufficient strength exists for the transfer of applicable external loads to the metallic layer.

(c) Plastic analysis in accordance with KD-230 and the additional requirements of this Division shall be used to analyze the CRPV. The composite (over wrap) layer shall be assumed to be linear elastic with nominal modulus and minimum strength properties as specified in the Manufacturer's Laminate Procedure Specification (see Section X, Mandatory Appendix 10, 10-303).

(d) The design cycle calculations shall be done in accordance with the fracture mechanics principles of Article KD-4. In the analysis of welded joints, the most unfavorable combination of misalignment, weld peaking, and weld geometry shall be considered.

(e) In determining the stress distribution in the two layers, the appropriate elastic modulus for each layer, at the maximum operating temperature, shall be used. Radial strain compatibility between the layers is achieved when the laminate is applied wet and intimate contact is established between the layers. When intimate contact between the two layers is not achieved or other strain incompatibilities exist, the effect on the stress distribution shall be considered. Changes in the stress distribution in the two layers as a result of temperature changes and differences in the coefficients of thermal expansion shall be considered.

(f) Residual stresses, in the form of a precompression in the metallic layer and a pretension in the laminate layer, are generated during the hydrostatic test. These stresses shall be taken into account in determining the residual and operating stress distributions.

(g) Any relaxation in the residual stress distribution due to long-term creep at operating temperature, or short-term creep at elevated temperatures, shall be considered and the limits shown in (h) shall be adjusted accordingly.

(h) For vessels to be installed at a fixed location, the maximum circumferential stress at any location in the laminate layer shall not exceed 36% of the tensile strength of the glass fiber laminate and 40% of the carbon fiber laminate at the operating pressure as defined in the Manufacturer's Laminate Procedure Specification (see Section X, Mandatory Appendix 10, 10-309). For vessels to be used in transport service, the maximum circumferential stress at any location in the laminate layer shall not exceed 36% of the tensile strength of the glass fiber laminate and 40% of the carbon fiber laminate at the design pressure as defined in the Manufacturer's Laminate Procedure Specification (see Section X, Mandatory Appendix 10, 10-309). For both fixed and transport service, the maximum circumferential stress at any location in the laminate layer shall not exceed 67% of the tensile strength of the laminate under the hydrostatic test load. The Manufacturer’s Design Report shall document the basis for selection of the specified pressure range for the hydrostatic test.

(i) The calculated burst pressure of the liner alone shall be equal to or greater than the design pressure of the vessel. The calculation shall be done using the minimum specified values of yield and tensile strength. Strain hardening shall be considered.

(j) The calculation of stresses shall consider the least favorable effects of geometric irregularities (e.g., out-of-roundness), weld peaking, reinforcement, and offsets as well as mismatches of Categories A and B welds. See KF-1211.

KD-1311 LAMINATE PROCEDURE SPECIFICATION

The Laminate Procedure Specification that specifies the materials and the procedures employed to apply the laminate layer to the metallic layer shall be included in the Manufacturer's Design Report. See Section X, Mandatory Appendix 10, 10-402.

KD-1312 MAXIMUM DESIGN TEMPERATURE

The Maximum Design Temperature of the laminate shall be the same as or higher than the Maximum Design Temperature of the CRPV as specified in the User's Design Specification. The Maximum Design Temperature of the CRPV shall not exceed 150°F (66°C). The Maximum Design Temperature of the laminate is defined as 35°F (19°C) below the glass transition temperature, T_g, or the maximum use temperature of the resin, whichever is lower, and shall be documented in the Laminate Procedure Specification. The maximum use temperature of the resin shall exceed the test temperatures as specified in Section X, Mandatory Appendix 10, 10-300.

KD-1313 MINIMUM DESIGN TEMPERATURE

The Minimum Design Temperature to which a CRPV may be constructed shall not be colder than –65°F (–54°C).

KD-1314 CRPV SUPPORTS

CRPV supports shall be designed to function without damaging the CRPV considering all loads resulting from transportation and operation. Supports shall be welded on the heads only or use laminate stops. Laminate stops shall consist of material built up or applied on the outer surface of the laminate that provides a load-bearing surface, perpendicular to the CRPV surface that will transfer external loads to the CRPV. If laminate stops are used, the shear strength of the laminate shall be adequate to resist the longitudinal static and dynamic loads.

KD-1315 LONGITUDINAL REINFORCEMENT

For the service conditions specified by the User's Design Specification, the designer shall consider the need for longitudinal reinforcement of the laminate to prevent laminate cracking under operating or test conditions.

PART KF
FABRICATION REQUIREMENTS

ARTICLE KF-1
GENERAL FABRICATION REQUIREMENTS

KF-100 GENERAL

(a) Types of fabrication covered by Part KF are not unique to this Division. The uniqueness of this Division lies in the credit that may be taken for favorable residual stresses that are introduced during fabrication when there is no welding and in permitting the Designer to utilize the full capability of high strength materials as primary pressure-retaining boundaries.

(b) Since all vessels conforming to the rules of this Division require fatigue analysis and since most will be heavy wall construction, many of the requirements of this Part are intended to produce vessels which are consistent with the Designer's assumption that no subsurface flaw exists that would be more likely to propagate in fatigue than the assumed surface flaws restricted by the requirements of Part KE.

(c) The Manufacturer must have the ability to control the residual stress distribution and ensure that the material properties and material defects in the vessel and vessel components are consistent with the basis of the design.

KF-101 SCOPE

(a) Article KF-1 gives general fabrication requirements for all vessels in this Division.

(b) Article KF-2 gives supplemental requirements for all welded vessels in the Division. This includes those made of rolled and welded plate and those made of weldable forgings, such as ring forgings joined by circumferential welds and forgings for fully radiographable nozzles. Materials that are permitted for welded construction are listed in Part KM:

(c) Article KF-3 gives supplemental requirements for protective liners.

(d) Article KF-4 gives requirements for the postweld heat treatment of all weldments, including repair welds.

(e) Article KF-5 gives supplemental requirements for autofrettaged vessels.

(f) Article KF-6 gives supplemental requirements for vessels made from either plate or forged materials whose tensile properties have been enhanced by quenching and tempering processes.

(g) Article KF-7 gives supplemental requirements that are specific to materials which are used to fabricate vessels where welded fabrication is not permitted by Part KM.

(h) Article KF-8 gives supplemental requirements for layered vessels. Since the design allowable stresses in this Division are based on yield strength and not limited by tensile properties, the requirements of the Article are more restrictive than the layered vessel requirements in other Divisions of this Code.

(i) Article KF-9 gives requirements for wire-wound vessels and frames.

(j) Article KF-10 gives requirements for aluminum alloys.

KF-110 MATERIAL

KF-111 CERTIFICATION AND EXAMINATION OF MATERIALS

The Manufacturer shall require certification of all materials including weld materials to ensure compliance with the requirements of Part KM. In addition, all materials shall be examined in accordance with Part KE. The certified results of these tests and examinations shall be documented in the Manufacturer's Construction Records (see KG-325).

KF-112 MATERIAL IDENTIFICATION

(a) Where possible, material for pressure parts shall be laid out so that when the vessel is completed, the original identification markings required in the specifications for the material will be plainly visible. In case the original identification markings are unavoidably removed or the material is divided into two or more parts, prior to cutting, the Manufacturer shall accurately transfer one set of markings to a location where the markings will

be visible on the completed vessel. Alternatively, a coded marking, acceptable to the Inspector, shall be used to ensure identification of each piece of material during fabrication and subsequent identification of the markings on the completed vessel. Except as indicated in KF-112.1, material may be marked by any method acceptable to the Inspector. The Inspector need not witness the transfer of the marks, but shall be satisfied that this has been done correctly.

(b) All parts completed elsewhere shall be marked with the part manufacturer's name and the part identification. Should identifying marks be obliterated in the fabrication process and for small parts, other means of identification shall be used.

KF-112.1 Method of Transferring Markings. Where the service conditions prohibit die stamping for material identification, and when so specified by the User, the Material Manufacturer and the Manufacturer shall mark the required data on the material in a manner which will allow positive identification upon delivery. The markings shall be recorded so that each piece of material will be positively identified in its position in the finished vessel to the satisfaction of the Inspector. Transfer of markings for material that is to be divided shall be done in accordance with KF-112(a). See Article KS-1 for allowable types of markings.

KF-112.2 Transfer of Markings by Other Than the Manufacturer. When material is formed into shapes by anyone other than the Manufacturer and the original markings as required by the applicable material specification are unavoidably cut out, or the material is divided into two or more parts, the Manufacturer of the shape shall either:

(a) transfer the original identification markings to another location on the shape, or

(b) provide for identification by the use of a coded marking traceable to the original required marking, using a marking method agreed upon and described in the Quality Control System of the Manufacturer of the completed pressure vessel.

The mill certification of the physical and chemical requirements of this material, in conjunction with the above modified marking requirements, shall be considered sufficient to identify these shapes. Manufacturer's Partial Data Reports and parts stamping shall be as required by KM-102 and KS-120.

KF-112.3 Material Identification Records. An as-built sketch or a tabulation of materials shall be made, identifying the location of each piece of material that is traceable to the material test report or certificate of compliance and the Code marking.

KF-113 REPAIR OF DEFECTIVE MATERIAL

Material in which defects exceeding the limits of Article KE-2 are known or are discovered during the process of fabrication is unacceptable. Unless prohibited by the material specification in Section II, the User's Design Specification, or Part KM, defects may be removed and the material repaired by the Manufacturer or by the Material Manufacturer with the approval of the Manufacturer. All repairs shall be made in accordance with the provisions of Article KE-2 and documented in the Manufacturer's Construction Records.

KF-120 MATERIAL FORMING

All materials for shell sections and for heads shall be formed to the required shape by any process that will not unduly impair the mechanical properties of the material.

KF-121 MATERIAL PREPARATION

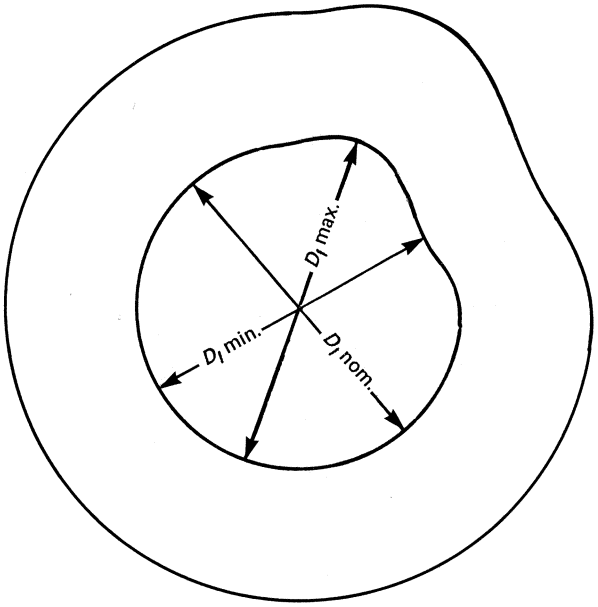
KF-121.1 Examination of Materials. (25)

(a) All materials to be used in constructing the pressure vessel shall be examined before forming or fabrication for the purpose of detecting, as far as possible, defects which exceed the acceptable limits of Article KE-2. All edges cut during fabrication (including the edges of openings cut through the thickness) shall be examined in accordance with KE-310. All defects exceeding the limits of KE-310 shall be documented and repaired.

(b) Cut edges of base materials with thicknesses over $1\frac{1}{2}$ in. (38 mm) shall be examined for discontinuities by a surface examination method in accordance with KE-233. This examination is not required for the cut edges of openings 3 in. (76 mm) in diameter and smaller. However, the material shall be ultrasonically examined over 100% of the area in which the opening is to be cut, in accordance with KE-232. If indications are found which exceed the acceptable limits of KE-232, the indications shall be repaired in accordance with KF-113. Nonlaminar discontinuities and laminar discontinuities are treated differently for plates and forgings. See Article KE-2 for acceptance criteria for each of these. Threaded connections that seal against pressure shall not have any discontinuities.

KF-121.2 Material Cutting. Plates, edges of heads, and other parts may be cut to shape and size by mechanical means such as machining, shearing, grinding, or by thermal cutting. After thermal cutting, all slag and detrimental discoloration of material which has been molten shall be removed by mechanical means suitable to the material, prior to further fabrication or use. When thermal cutting is used, the effect on mechanical properties shall be taken into consideration. The edges to be welded shall be uniform and smooth.

Figure KF-131
Example of the Maximum and Minimum Inside Diameters in a Cylindrical Shell



GENERAL NOTE: $D_{I,\max} - D_{I,\min} \le 0.01(D_{I,\text{nom}})$

KF-121.3 Finish of Exposed Inside Edges of Nozzles. Exposed inside edges of nozzles other than as provided for in Figures KD-1130 and KD-1131 shall be radiused (grinding permitted) to at least $t/4$ or $^3/_4$ in. (19 mm), whichever is less, when the inner end of the nozzle neck is flush with the inside wall of the shell. When the inner end of the nozzle neck protrudes beyond the inside wall of the shell toward the center of curvature, it shall be radiused (grinding permitted) on both inner and outer surfaces of the neck end to at least $t_n/4$ or $^3/_8$ in. (10 mm), whichever is smaller.

KF-130 TOLERANCES FOR CYLINDRICAL AND SPHERICAL SHELLS AND HEADS

Fabrication deviations from the stated tolerances are prohibited, unless provision is made for the deviations in the design calculations and are agreed to by the User, Manufacturer, and Inspector (see Article KD-2).

KF-131 CYLINDRICAL SHELLS

The difference between the maximum and minimum inside diameters at any cross section shall not exceed 1% of the nominal inside diameter at the cross section under consideration (see Figure KF-131). The diameters may be measured on the inside or outside of the vessel. If measured on the outside, the diameters shall be corrected for the material thickness at the cross section under consideration.

KF-132 SPHERICAL SHELLS AND FORMED HEADS

(a) Deviations from the specified shape of the inner surface of spherical shells and formed heads shall not exceed $+1^1/_4$% and $-^5/_8$% of the nominal inside diameter of the vessel. Such deviations shall be measured perpendicular to the specified shape and shall not be abrupt.

(b) Deviation measurements shall be taken on the surface of the base metal and not on welds.

(c) The straight flange or cylindrical end of a formed head or the edge of a spherical shell shall be circular within the tolerance specified in KF-131.

ARTICLE KF-2
SUPPLEMENTAL WELDING FABRICATION REQUIREMENTS

KF-200 GENERAL REQUIREMENTS FOR ALL WELDS

KF-201 WELDING PROCESSES

(a) The welding processes that shall be used for making pressure-containing welds and applying weld metal overlay in the construction of vessels under this Part are listed below.

(1) shielded metal arc
(2) submerged arc
(3) gas metal arc
(4) gas tungsten arc

Definitions are given in Section IX, which include variations of these processes.

(b) The electroslag strip overlay welding process may be used only for application of weld metal overlay.

KF-202 RESTRICTIONS BASED ON CARBON CONTENT

When the carbon content of the material exceeds 0.35% by heat analysis, welded fabrication including attachment welds is not permitted. Repair welding may be permitted under the rules of Article KF-7.

KF-203 EXAMINATION OF WELD EDGE PREPARATION SURFACES

Weld edge preparation surfaces in materials 2 in. (51 mm) or more in thickness shall be examined in accordance with KE-310. Defects shall be repaired in accordance with the rules of Part KE.

KF-204 FINAL WELD FINISH

The finished weld shall be ground or machined to blend with the surfaces of the parts being joined. Both the blend radii and the surface finish of the weld deposit shall be inspected to ensure they comply with the design requirements of the engineering design.

KF-205 IDENTIFICATION, HANDLING, AND STORING OF ELECTRODES AND OTHER WELDING MATERIALS

The Manufacturer is responsible for control of the welding electrodes and other materials which are to be used in the fabrication of the vessel. Suitable identification, storage, and handling of electrodes, flux, and other welding materials shall be maintained. Precautions shall be taken to minimize absorption of moisture by low-hydrogen electrodes and flux.

KF-206 PERMISSIBLE AMBIENT CONDITIONS DURING WELDING

No welding of any kind shall be carried out when the temperature of the metal surface within 3 in. (75 mm) of the point of welding is lower than 60°F (16°C).

No welding shall be done when surfaces are wet or covered with ice, when rain or snow is falling on the surfaces to be welded, or during periods of high wind unless the work is properly protected.

KF-210 WELDING QUALIFICATIONS AND RECORDS

KF-211 MANUFACTURER'S RESPONSIBILITY (25)

Each Manufacturer is responsible for the welding carried out by their organization. The Manufacturer shall establish and qualify welding procedures in accordance with Section IX. The Manufacturer shall also be responsible for the additional requirements of this Division and the qualification of welders and welding operators who apply these procedures and requirements. See KG-420 for requirements for subcontracted services.

The Manufacturer's Quality Control System shall include a requirement, acceptable to the accredited Authorized Inspection Agency, for complete and exclusive administrative and technical supervision and control of all welders and welding operators, whether direct employees or those engaged by contract for their services.

KF-212 QUALIFICATION TEST LIMITATIONS

Welding of all test coupons shall be conducted by the Manufacturer. Testing of all test coupons shall be the responsibility of the Manufacturer. Qualification of welding procedure by one Manufacturer shall not qualify that procedure for use by any other Manufacturer, except as provided for in Section IX, QG-106. A performance qualification test conducted by one Manufacturer shall not qualify a welder or welding operator to do work for any other Manufacturer, except as provided for in Section IX, QG-106.

KF-213 PRODUCTION WELDING PRIOR TO QUALIFICATION

No production welding shall be carried out until after the required welding procedures have been qualified.

KF-214 QUALIFICATION OF WELDING PROCEDURE

(a) Each welding procedure that is to be used shall be recorded in detail by the Manufacturer on forms provided in Section IX, or on other forms which contain the required information.

(b) The procedures used in welding pressure parts and in joining nonpressure parts (attachments) to pressure parts shall be qualified in accordance with Section IX. When tensile specimens are required by Section IX, the yield strength shall also be determined, using the method required for the base metal. The yield strength of each test specimen shall be not less than the lowest specified minimum yield strength for the base metals joined. In addition, impact tests shall be performed in accordance with Article KT-2.

(c) When making procedure qualification test plates for butt welds in accordance with Section IX, consideration shall be given to the effect of angular, lateral, and end restraint on the weldment. It is the responsibility of the Manufacturer to ensure that the procedure qualification test plates simulate the restraints on the production weldments.

KF-215 TEST OF WELDERS AND WELDING OPERATORS

(a) The welders and the welding operators used in welding pressure parts and in joining nonpressure parts (attachments) to pressure parts shall be qualified in accordance with Section IX and Article KT-2. Mechanical testing is required for all performance qualification tests; qualification by NDE is not permitted. See Article KT-2 for additional requirements on weld position testing, weld impact testing, and test plate requirements.

(b) The qualification test for welding operators of machine welding equipment shall be performed on a separate test plate prior to the start of welding or on the first workpiece.

(25) KF-216 MAINTENANCE OF QUALIFICATION AND PRODUCTION RECORDS

The Manufacturer shall maintain records of the welding procedures and the welders and welding operators employed by the Manufacturer, showing the date and results of tests and the identification mark assigned to each welder. These records shall be maintained in accordance with Section IX.

KF-220 WELD JOINTS PERMITTED AND THEIR EXAMINATION

Type No. 1 butt joints as described in KF-221 shall be used for all welded joints except as listed in (a) through (c) below. For further discussion, see KD-1110. Partial penetration welds, such as fillet welds, that are not used in combination with full-penetration welds as described below are not permitted on pressure-retaining parts.

(a) Full-penetration welds are permitted for nozzle attachments under the rules of KD-1130. They are described in KF-222.

(b) Type No. 2 single-welded groove welds are permitted under the rules of Article KF-8 when joining layers other than the innermost shell on welded layer vessels. These welds are described in KF-223.

(c) Welds used for attaching heating and cooling jackets and support clips are permitted under the rules of Article KD-7 and KF-224. These welds are full-penetration groove welds as shown in Figure KD-700, and as described in KF-222. In some cases these welds may be used in combination with fillet welds.

Required weld examination shall be done after all postweld heat treatment and in accordance with Article KE-3. Discussion specific to the four types of joints permitted under the rules of this Division follows.

(d) A welded joint surface may remain in the "as welded" condition, without grinding or machining as required by KF-204, when the weld surface is inaccessible or surface conditioning methods are impractical to apply, provided the following requirements are met:

(1) The weld shall have no concavity or reduction in thickness.

(2) The fatigue analysis shall be done in accordance with Article KD-4.

(3) For use in the fracture mechanics analysis of each weld joint that is not ground or machined, a finite element analysis shall be performed to obtain the through-thickness stress distribution.

(4) The finite element analysis shall incorporate the maximum weld misalignment and peaking, and the profile of the maximum weld reinforcement permitted by Section VIII, Division 3. Alternatively, the values specified in the design or the as-built values for weld misalignment, peaking, and weld reinforcement may be used if documented in the Manufacturer's Design Report and verified by an inspection report.

KF-221 TYPE NO. 1 BUTT JOINTS

Type No. 1 butt joints are those produced by welding from both sides of the joint or by other means that produce the same quality of deposited weld metal on both inside and outside weld surfaces. Welds using backing strips which remain in place do not qualify as Type No. 1 butt joints.

Type No. 1 butt joints shall have complete penetration and full fusion and shall be ground or machined flush with the members joined together. All Type No. 1 butt joints, whether longitudinal or circumferential, shall be completely examined for their entire length in accordance with Article KE-3.

KF-222 FULL-PENETRATION GROOVE WELDS ATTACHING NOZZLES

Nozzle attachments are normally Type No. 1 butt joints, which are covered by the design rules of KD-1130 and shown in Figure KD-1130. Full-penetration groove welds are also permitted for attaching nozzles to shells in accordance with the design rules of KD-1131. These welds are not readily radiographable. Backing strips are not permitted.

(25) **KF-222.1 Weld Procedure Qualifications.** Normally this weld will be a single-welded joint. Consideration shall be given to using a welding procedure such as GTAW capable of producing a high quality of weld on the ID of the nozzle. The suitability of the electrode and procedure, including preheat and postheat, shall be established by making a groove weld specimen as shown in Section IX, Figures QW-461.1 and QW-461.3 in material of the same analysis and of thickness in conformance with Section IX, Tables QW-451.1 through QW-451.4 and Tables QW-452.1(a) through QW-452.6. The specimen before welding shall be in the same condition of heat treatment as the work it represents. After welding, the specimen shall be subjected to heat treatment equivalent to that specified for the final product. Tension and bend specimens, as shown in Section IX, Figures QW-462.1(a) through QW-462.1(e), QW-462.2, and QW-462.3(a), shall be made. These tests shall meet the requirements of Section IX, QW-150 and QW-160. The radius of the mandrel used in the guided bend test shall be as follows:

Specimen Thickness	Radius of Mandrel *B*	Radius of Die *D* [Note (1)]
$\frac{3}{8}$ in. (10 mm)	$1\frac{1}{4}$ in. (32 mm)	$1\frac{11}{16}$ in. (43 mm)
1 in. (25 mm)	$10t/3$	$9t/2 + \frac{1}{16}$ in. (1.5 mm)

NOTE: (1) Corresponds to dimensions *B* and *D* for P-No. 11 material in Section IX, Figure QW-466.1 and other dimensions to be in proportion.

KF-222.2 Weld Examination. In addition to the final examination requirements of Article KE-3, consideration shall be given to intermediate weld examination, such as wet magnetic particle examination, in order to ensure weld soundness after completion of the process.

KF-223 TYPE NO. 2 BUTT JOINTS

Type No. 2 butt joints are only permitted in layers subsequent to the inner shell of welded layered vessels. Design and fabrication rules are listed in Article KD-8 and Article KF-8. See Article KF-8 for specific welding and weld examination requirements.

KF-224 QUALITY AND EXAMINATION REQUIREMENTS FOR FILLET WELDS USED IN COMBINATION WITH FULL-PENETRATION GROOVE WELDS

When fillet welds are used in conjunction with full-penetration groove welds, the groove weld portion shall be qualified and performed under the rules of KF-222 before the fillet weld is made. The fillet weld shall meet the following requirements:

(a) The reduction in thickness of the adjoining surfaces at the root of the fillet weld shall not be greater than $\frac{1}{32}$ in. (0.8 mm) or cause the adjoining material to be below the design minimum required thickness at any point.

(b) The surface finish shall be inspected under the rules of KF-204 and the surface shall be examined under the rules of KE-334.

KF-225 LIQUID PENETRANT EXAMINATION

All austenitic chromium–nickel alloy steel, austenitic–ferritic duplex steel, and nickel alloy welds, both butt and fillet, shall be examined in accordance with the liquid penetrant method (see KE-334). If heat treatment is required, the examination shall be made following heat treatment. All defects shall be repaired and the repair documented in accordance with the provisions of KF-240. The repaired area shall be reexamined by the liquid penetrant method.

KF-226 SURFACE WELD METAL BUILDUP (25)

Construction in which deposits of weld metal are applied to the surface of base metal for the purpose of restoring the thickness of the base metal or modifying the configuration of weld joints in order to meet the tapered transition requirements of KD-1120 or KF-234(b) shall meet the following requirements.

(a) Prior to production welding, a welding procedure shall be qualified for the thickness of weld metal deposited.

(b) All weld metal buildup shall be examined over the full surface of the deposit by a surface examination method in accordance with KE-233.

(c) All weld metal buildup that exceeds $\frac{3}{8}$ in. (10 mm) in thickness shall be examined over the entire deposit by either radiography or ultrasonic methods in accordance with KE-220.

(d) When such surface weld metal buildup is used in welded joints which require volumetric examination, the weld metal buildup shall be included in the examination.

KF-230 REQUIREMENTS DURING WELDING

Parts that are being welded shall be cleaned, aligned, fitted, and retained in position during the welding operation.

KF-231 PREPARATION OF REVERSE SIDE OF DOUBLE-WELDED JOINTS

Before applying weld metal to the reverse side, the reverse side of double-welded joints shall be prepared by chipping, grinding, or gouging in order to secure sound metal at the root of the weld. Removal of root pass weld is not required for any process of welding by which the base of the weld remains free from impurities. Prior to the start of the weld at the reverse side, the cleaned root area shall be examined in accordance with KE-334.

KF-232 CLEANING OF SURFACES TO BE WELDED

The surfaces of the parts to be welded shall be clean and free of scale, rust, oil, grease, and other deleterious foreign material. For all materials, detrimental oxide shall be removed from the weld metal contact area for a distance of at least 2 in. (50 mm) from welding joint preparation. When weld metal is to be deposited over a previously welded surface, all slag shall be removed to prevent inclusion of impurities in the weld metal.

(25) KF-233 ALIGNMENT DURING WELDING

(a) Bars, jacks, clamps, tack welds, or other appropriate means may be used to maintain the alignment of the edges to be welded. Tack welds, if used to maintain alignment, shall either be removed completely when they have served their purpose, or their stopping and starting ends shall be properly prepared by grinding or other suitable means so that they may be satisfactorily incorporated into the final weld. Tack welds shall be made by qualified procedures and welders. Permanent tack welds shall be examined by a surface examination method in accordance with KE-233. Acceptance criteria and repair shall be in accordance with KE-334.

(b) A single-welded joint (i.e., welds made from one side only), as permitted by KF-220, may be used provided the Inspector is satisfied that proper fusion and penetration has been obtained. When using this type of weld, particular care shall be taken in aligning and separating the components to be joined.

KF-234 ALIGNMENT TOLERANCES FOR EDGES TO BE BUTT WELDED

(a) Alignment of sections at edges to be butt welded shall be such that the maximum offset is not greater than allowed in Table KF-234.

(b) All offsets shall be faired at a three-to-one taper over the width of the finished weld or, if necessary, by adding additional weld metal beyond what would have been the edge of the weld. Such additional weld metal buildup shall meet the requirements of KF-226.

(c) For transition joints between sections of unequal thicknesses, see KD-1120.

KF-235 PRECAUTIONS TO BE TAKEN WHEN WELDING IS RESTARTED

If the welding is stopped for any reason, extra care shall be taken in restarting to get the required penetration and fusion.

KF-236 REMOVAL OF TEMPORARY ATTACHMENTS AND ARC STRIKES (25)

The areas from which temporary attachments have been removed or areas of arc strikes shall be ground smooth and examined by a surface examination method in accordance with KE-233. Defects shall be removed and the material shall be examined to ensure that the defects have been removed. If weld repairs are necessary, they shall be made using qualified welding procedures and welders, and shall be examined as outlined in KF-226.

KF-237 PEENING

Controlled peening may be performed to reduce distortion. Peening shall not be used on the initial (root) layer of weld metal, nor on the final (face) layer unless the weld is postweld heat treated.

KF-238 IDENTIFICATION MARKINGS OR RECORDS FOR WELDERS AND WELDING OPERATORS (25)

(a) Each welder and welding operator shall mark the identifying number, letter, or symbol, assigned by the Manufacturer, adjacent to and at intervals of not more than 3 ft (0.9 m) along the welds that the welder or welding operator makes in material $\frac{1}{4}$ in. (6 mm) and over in thickness. Weld marking procedures shall meet the requirements of KF-112 and KF-601. Alternatively, a record shall be kept by the Manufacturer of each joint welded by the welder or welding operator. This record shall be available to the Inspector.

(b) When a multiple number of permanent nonpressure part attachment welds are made on a vessel, the Manufacturer need not identify the welder or welding operator that welded each individual joint, provided

Table KF-234
Maximum Allowable Offset in Welded Joints

Section Thickness	Direction of Joints in Cylindrical Shells	
	Longitudinal	Circumferential
Up to and including $^{15}/_{16}$ in. (24 mm)	Lesser of $t/5$ or $^{3}/_{32}$ in. (2.4 mm)	$t/5$
Greater than $^{15}/_{16}$ in. (24 mm), less than or equal to $1^{1}/_{2}$ in. (38 mm)	$^{3}/_{32}$ in. (2.4 mm)	$^{3}/_{16}$ in. (4.8 mm)
Greater than $1^{1}/_{2}$ in. (38 mm)	$^{3}/_{32}$ in. (2.4 mm)	$t/8$ but not greater than $^{1}/_{4}$ in. (6 mm)

(1) the Manufacturer's Quality Control System includes a procedure that identifies the welders or welding operators that made such welds on each vessel so that the Inspector can verify that the welders or welding operators were all properly qualified

(2) the welds in each category are all of the same type and configuration and are welded with the same welding procedure specification

(c) Permanent identification of welders or welding operators making tack welds that become part of the final pressure weld is not required, provided the Manufacturer's Quality Control System includes a procedure to permit the Inspector to verify that such tack welds were made by qualified welders or welding operators.

KF-240 REPAIR OF WELD DEFECTS

KF-241 REMOVAL OF DEFECTS

Defects detected by the examinations required by Article KE-3 or the hydrostatic test shall be removed by mechanical means or by thermal gouging processes. If thermal gouging is used, the Manufacturer shall ensure the process is not detrimental to the material.

KF-242 REWELDING OF AREAS TO BE REPAIRED

The areas to be repaired shall be rewelded by qualified welders using qualified welding procedures (see KF-210).

KF-243 EXAMINATION OF REPAIRED WELDS

Repaired welds shall be reexamined by the methods of the original examination of the weld. The repaired weld shall not be accepted unless the examination shows the repair to be satisfactory.

KF-244 POSTWELD HEAT TREATMENT OF REPAIRED WELDS

The postweld heat treating rules in Article KF-4 shall apply to all weld repairs.

KF-245 DOCUMENTATION OF REPAIRS

All weld repairs shall be documented in the Manufacturer's Construction Records.

ARTICLE KF-3
FABRICATION REQUIREMENTS FOR MATERIALS WITH PROTECTIVE LININGS

KF-300 SCOPE

This Article applies to materials with protective linings that are applied by integral cladding or weld overlaying. Prestressed liners which are considered part of the shell for strength purposes are not covered by this Article (see Article KF-8).

KF-301 TYPES OF JOINTS PERMITTED

The types of joints and welding procedures used shall be such as to minimize the formation of brittle weld composition by the mixture of metals of corrosion-resistant alloy and base material.[5]

KF-302 WELD METAL COMPOSITION

Welds that are exposed to the corrosive action of the contents of the vessel should have resistance to corrosion that is not substantially less than that of the corrosion-resistant integral or weld metal overlay cladding or lining. The use of filler metal that will deposit weld metal with practically the same composition as the material joined is recommended. Weld metal of different composition may be used provided it has better mechanical properties in the opinion of the Manufacturer, and the User is satisfied that its resistance to corrosion is satisfactory for the intended service. The columbium content of columbium-stabilized austenitic stainless steel weld metal shall not exceed 1.00% except when a higher content is permitted in the material being welded.

KF-303 400 SERIES ALLOY FILLER METALS

400 Series alloy filler metals are not permitted when the filler metal is welded to the base metal.

KF-310 QUALIFICATION OF WELDING PROCEDURES

The specification of the welding procedure that is proposed to be followed in clad, weld overlaid or lined construction shall be recorded in detail.

KF-311 PROCEDURE TO BE QUALIFIED IN ACCORDANCE WITH SECTION IX

All weld procedures associated with protective liners shall be qualified in accordance with the provisions of Section IX, QW-217.

KF-312 QUALIFICATION OF PROCEDURE FOR ATTACHING LININGS

(a) Each welding procedure to be used for attaching lining material to the base material shall be qualified on lining attachment welds made in the form and arrangement to be used in construction and with materials that are within the ranges of chemical composition of the materials to be used, respectively, for the base material, the linings, and the weld metal.

(b) Welds shall be made in each of the positions defined in Section IX, QW-120 that are to be used in construction. One specimen from each position to be qualified shall be sectioned, polished, and etched to show clearly the demarcation between the fusion zone and the base metal.

(c) For the procedure to qualify, the specimen shall show, under visual examination without magnification, complete fusion and complete freedom from cracks in the fusion zone and in the heat-affected metal.

KF-313 REQUIREMENTS FOR COMPOSITE WELDS

KF-313.1 Procedure Qualification for Groove Welds in Base Material With Corrosion-Resistant Integral Cladding or Weld Metal Overlay. The requirements in Section IX, QW-217 for procedure qualification shall be followed. The procedure for groove welds may be qualified as in KF-311, or the weld in the base joint or cladding joint may be qualified individually in accordance with the rules in Section IX.

KF-313.2 Performance Qualification for Composite Welds. The requirements in Section IX, QW-310 and KF-313.1 or KF-313.3 shall be followed for performance qualification.

KF-313.3 Test Plates for Composite Welds. Performance qualification tests shall be made in accordance with Section IX by preparing test material from integral clad or weld overlay material having the same P-Numbers

in Section IX, Table QW/QB-422 as that of the base material. Integral or weld metal overlay cladding materials to be used in the test shall have the same F-Number in Section IX, Table QW-432 as the filler metal that will be used in construction. When the integral clad or weld metal overlay material is not listed in Section IX, Table QW/QB-422, qualification shall be made on the same grade as used in the vessel. Heat treatment is not required but is permitted if the welder's work on construction is to be heat treated. The following conditions shall also be met. A section cut from the test material perpendicular to the welding direction and properly prepared and etched shall show no lack of fusion longer than $\frac{1}{8}$ in. (3.2 mm). The total length of unfused cladding shall not exceed 10% of the length of the test material perpendicular to the direction of welding.

KF-320 INTEGRALLY CLAD MATERIALS

A shear test shall demonstrate a minimum shear strength of 20 ksi (140 MPa) for integral clad materials.

KF-330 POSTWELD HEAT TREATMENT OF LININGS

KF-331 WHEN BASE METAL MUST BE POSTWELD HEAT TREATED[6]

Vessels or parts of vessels constructed of an integrally clad material or weld metal overlay shall be postweld heat treated when the base material is required to be postweld heat treated. In applying these rules, the determining thickness shall be the total thickness of base material. When the thickness of the base material requires postweld heat treatment, it shall be performed after the application of weld metal overlay or clad restoration.

KF-332 REQUIREMENTS WHEN BASE METAL OR LINING IS CHROMIUM-ALLOY STEEL

Vessels or parts of vessels constructed of chromium-alloy stainless steel cladded base material and those lined with chromium-alloy stainless steel applied linings shall be postweld heat treated in all thicknesses, except that vessels clad or lined with Type 405 or Type 410S and welded with an austenitic electrode or non-air-hardening nickel–chromium–iron electrode need not be postweld heat treated unless required by KF-331.

KF-333 HEAT TREATMENT THAT MAY AFFECT VESSEL STRESS REDISTRIBUTION

The Manufacturer shall ensure and document, in accordance with KG-323(e), that any heat treatment given to a vessel or vessel part does not adversely affect the stress distribution required by Articles KD-5, KD-8, KD-9, and KD-10. In addition, for layered or autofrettaged vessels, the Manufacturer shall meet the requirements for heat treatment given in KF-830 or KF-540(b), as applicable.

KF-340 EXAMINATION REQUIREMENTS

KF-341 EXAMINATION OF BASE MATERIALS PROTECTED BY WELDED OVERLAY

The examination required by the rules in Article KE-3 shall be made after the joint, including the corrosion-resistant layer, is complete. The examination may be made on the weld in the base material before the alloy cover weld is deposited, provided the following requirements are met:

(a) the thickness of the base material at the welded joint is not less than that required by the design calculation

(b) the corrosion-resistant alloy weld deposit is non-air-hardening

(c) the completed alloy weld deposit is examined by any method that will detect cracks in accordance with KE-233

KF-342 EXAMINATION OF CHROMIUM-ALLOY CLADDING OVERLAY

The joints between chromium-alloy cladding overlay or loose liner sheets shall be examined for cracks as specified in KF-342.1 and KF-342.2.

KF-342.1 Straight Chromium-Alloy Filler Metal.

(a) Joints welded with straight chromium-alloy filler metal shall be examined throughout their full length. Chromium-alloy welds in continuous contact with the welds in the base metal shall be examined in accordance with Article KE-3.

(b) Liner welds that are attached to the base metal, but merely cross the seams in the base metal, shall be examined in accordance with KE-334.

KF-342.2 Austenitic Chromium–Nickel Steel Filler Metal. Joints welded with austenitic chromium–nickel steel filler metal or non-air-hardening nickel–chromium–iron filler metal shall be dye penetrant examined over their entire length in accordance with KE-334 and spot UT examined over 10% of their length in accordance with Article KE-3.

KF-350 INSPECTION AND TESTS

KF-351 GENERAL REQUIREMENTS

The rules in the following paragraphs shall be used in conjunction with the general requirements for inspection in Part KE, and for testing in Part KE that pertain to the method of fabrication used.

KF-352 LEAK TEST OF PROTECTIVE LINING

A test for pressure tightness of the protective lining that will be appropriate for the intended service is recommended, but the details of the test shall be a matter for agreement between the User and the Manufacturer. The test should not damage the load-carrying baseplate. When rapid corrosion of the base material is to be expected from contact with the contents of the vessel, particular care should be taken in devising and executing the leak test.

KF-360 STAMPING AND REPORTS

The provisions for stamping and reports in Part KS shall apply to vessels that are constructed of integral clad, weld metal overlay, or protective liners and shall include the specification and type of lining material. This information shall be included in the Manufacturer's Data Reports.

ARTICLE KF-4
HEAT TREATMENT OF WELDMENTS

KF-400 HEAT TREATMENT OF WELDMENTS

This section gives requirements for heat treatment of weldments. For heat treatment requirements for quenched and tempered steels, see KF-630.

KF-401 REQUIREMENTS FOR PREHEATING

The welding procedure specification for the material being welded shall specify the minimum preheating requirements in accordance with the weld procedure qualification requirements of Section IX. The need for and temperature of preheat are dependent on a number of factors, such as the chemical analysis, degree of restraint of the parts being joined, elevated temperature physical properties, and material thicknesses.

KF-402 REQUIREMENTS FOR POSTWELD HEAT TREATMENT[7]

Before applying the detailed requirements and exemptions in these paragraphs, satisfactory qualification of the welding procedures to be used shall be performed in accordance with Section IX and the restrictions listed below. Except for nonferrous materials and except as otherwise provided in Table KF-402.1 (Table KF-402.1M) for ferrous materials, all welded pressure vessels or pressure vessel parts shall be given a postweld heat treatment at a temperature not less than that specified in Table KF-402.1 (Table KF-402.1M) when the nominal thickness, including corrosion allowance, of any welded joint in the vessel or vessel parts exceeds the limits in Table KF-402.1 (Table KF-402.1M). Materials in Table KF-402.1 (Table KF-402.1M) are listed by P-Number, which may be found in Section IX, Table QW/QB-422 and in Tables KM-400-1 through KM-400-3 (Tables KM-400-1M through KM-400-3M). When there is a conflict in P-Number or Group Number, the numbers in Section IX govern.

KF-402.1 When Holding Temperatures and Times May Be Exceeded. Except where prohibited in Table KF-402.1 (Table KF-402.1M), holding temperatures and/or holding times exceeding the minimum values given in Table KF-402.1 (Table KF-402.1M) may be used (see KT-112 for additional requirements for time at temperature). A time–temperature recording of all postweld heat treatments shall be provided for review by the Inspector. The total holding time at temperature specified in Table KF-402.1 (Table KF-402.1M) may be an accumulation of time of multiple postweld heat treat cycles.

KF-402.2 Heat Treatment of Pressure Parts When Attached to Different P-Number Groups and Nonpressure Parts. When pressure parts of two different P-Number groups are joined by welding, the postweld heat treatment shall be that specified in Table KF-402.1 (Table KF-402.1M) with applicable notes for the material requiring the higher postweld heat treatment temperature. When nonpressure parts are welded to pressure parts, the postweld heat treatment temperature of the pressure part shall control.

KF-402.3 Definition of Nominal Thickness Governing Postweld Heat Treatment. The nominal thickness in Tables KF-402.1 and KF-630 (Tables KF-402.1M and KF-630M) is the thickness of the welded joint as defined herein. For pressure vessels or parts of pressure vessels being postweld heat treated in a furnace charge, it is the greatest weld thickness in any vessel or vessel part which has not previously been postweld heat treated.

(a) When the welded joint connects parts of equal thickness, using a full-penetration butt weld, the nominal thickness is the total depth of the weld exclusive of any permitted weld reinforcement.

(b) For groove welds, the nominal thickness is the depth of the groove.

(c) For fillet welds, the nominal thickness is the throat dimension. If a fillet weld is used in conjunction with a groove weld, the nominal thickness is the depth of the groove or the throat dimension, whichever is greater.

(d) For stud welds, the nominal thickness shall be the diameter of the stud.

(e) When a welded joint connects parts of unequal thicknesses, the nominal thickness shall be the following:

(1) the thinner of two adjacent butt-welded parts including head-to-shell connections

(2) the thickness of the shell in connections to tubesheets, flat heads, covers, flanges, or similar constructions

(3) in Figures KD-700, KD-1112, KD-1121, KD-1122, KD-1130, and KD-1131, the thickness of the weld across the nozzle neck, shell, head, or attachment fillet weld, whichever is greater

Table KF-402.1
Requirements for Postweld Heat Treatment of Pressure Parts and Attachments (U.S. Customary Units)

Material	Nominal Holding Temperature, °F, min.	Minimum Holding Time at Normal Temperature for Nominal Thickness (See KF-402.1)		
		Up to 2 in.	Over 2 in. to 5 in.	Over 5 in.
P-No. 1 [Notes (1), (2)]	1,100	1 hr/in. (0.25 hr minimum)	2 hr plus 15 min for each additional inch over 2 in.	2 hr plus 15 min for each additional inch over 2 in.
P-No. 3 [Notes (3), (4)]	1,100	1 hr/in. (0.25 hr minimum)	2 hr plus 15 min for each additional inch over 2 in.	2 hr plus 15 min for each additional inch over 2 in.
P-No. 4	1,200	1 hr/in. (1 hr minimum)	1 hr/in.	5 hr plus 15 min for each additional inch over 5 in.
P-No. 5A [Notes (3), (4)]	1,250	1 hr/in. (1 hr minimum)	1 hr/in.	5 hr plus 15 min for each additional inch over 5 in.
P-No. 5C [Notes (3), (4)]	1,250	1 hr/in. (1 hr minimum)	1 hr/in.	5 hr plus 15 min for each additional inch over 5 in.
P-No. 8 [Note (5)]	...	...	...	...
P-No. 10A [Notes (4), (6)]	1,100	1 hr minimum plus 15 min for each additional inch over 1 in.	1 hr minimum plus 15 min for each additional inch over 1 in.	1 hr minimum plus 15 min for each additional inch over 1 in.
P-No. 42 [Note (5)]	...	...	...	...
P-No. 43 [Note (5)]	...	...	...	...
P-No. 44 [Note (5)]	...	...	...	...
P-No. 45 [Note (5)]	...	...	...	...

NOTES:
(1) Postweld heat treatment is mandatory under the following conditions:
(a) for materials over $1\frac{1}{4}$ in. nominal thickness
(b) on material over $\frac{5}{8}$ in. nominal thickness for pressure parts subject to direct firing
(2) For SA-841 plate materials, the holding temperature shall not exceed 1,200°F.
(3) If during the holding period of postweld heat treatment, the maximum time or temperature of any vessel component exceeds the provisions of KT-112, additional test coupons shall be made and tested.
(4) Postweld heat treatment is mandatory under the following conditions:
(a) for all materials over $\frac{3}{8}$ in. nominal thickness
(b) on materials of all thicknesses intended for pressure parts subject to direct firing
(5) Postweld heat treatment is neither required nor prohibited for joints between materials of P-Nos. 8, 42, 43, 44, or 45, or any combination thereof. If postweld heat treatment is performed for P-No. 8 or P-No. 45 materials, the Manufacturer shall consider the steps necessary to avoid embrittlement and the precipitation of deleterious phases. See Section II, Part D, Nonmandatory Appendix A, A-207 through A-210.
(6) Consideration should be given for possible embrittlement of materials containing up to 0.15% vanadium when postweld heat treating at minimum temperatures.

Table KF-402.1M
Requirements for Postweld Heat Treatment of Pressure Parts and Attachments (SI Units)

Material	Nominal Holding Temperature, °C, min.	Minimum Holding Time at Normal Temperature for Nominal Thickness (See KF-402.1)		
		Up to 50 mm	Over 50 mm to 125 mm	Over 125 mm
P-No. 1 [Notes (1), (2)]	595	1 h/25 mm (0.25 h minimum)	2 h plus 15 min for each additional 25 mm over 50 mm	2 h plus 15 min for each additional 25 mm over 50 mm
P-No. 3 [Notes (3), (4)]	595	1 h/25 mm (0.25 h minimum)	2 h plus 15 min for each additional 25 mm over 50 mm	2 h plus 15 min for each additional 25 mm over 50 mm
P-No. 4	650	1 h/25 mm (1 h minimum)	1 h/25 mm	5 h plus 15 min for each additional 25 mm over 125 mm
P-No. 5A [Notes (3), (4)]	675	1 h/25 mm (1 h minimum)	1 h/25 mm	5 h plus 15 min for each additional 25 mm over 125 mm
P-No. 5C [Notes (3), (4)]	675	1 h/25 mm (1 h minimum)	1 h/25 mm	5 h plus 15 min for each additional 25 mm over 125 mm
P-No. 8 [Note (5)]	...	...	...	...
P-No. 10A [Notes (4), (6)]	595	1 h minimum plus 15 min for each additional 25 mm over 25 mm	1 h minimum plus 15 min for each additional 25 mm over 25 mm	1 h minimum plus 15 min for each additional 25 mm over 25 mm
P-No. 42 [Note (5)]	...	...	...	...
P-No. 43 [Note (5)]	...	...	...	...
P-No. 44 [Note (5)]	...	...	...	...
P-No. 45 [Note (5)]	...	...	...	...

NOTES:

(1) Postweld heat treatment is mandatory under the following conditions:
  (a) for materials over 32 mm nominal thickness
  (b) on material over 16 mm nominal thickness for pressure parts subject to direct firing

(2) For SA-841 plate materials, the holding temperature shall not exceed 650°C.

(3) If during the holding period of postweld heat treatment, the maximum time or temperature of any vessel component exceeds the provisions of KT-112, additional test coupons shall be made and tested.

(4) Postweld heat treatment is mandatory under the following conditions:
  (a) for all materials over 10 mm nominal thickness
  (b) on materials of all thicknesses intended for pressure parts subject to direct firing

(5) Postweld heat treatment is neither required nor prohibited for joints between materials of P-Nos. 8, 42, 43, 44, or 45, or any combination thereof. If postweld heat treatment is performed for P-No. 8 or P-No. 45 materials, the Manufacturer shall consider the steps necessary to avoid embrittlement and the precipitation of deleterious phases. See Section II, Part D, Nonmandatory Appendix A, A-207 through A-210.

(6) Consideration should be given for possible embrittlement of materials containing up to 0.15% vanadium when postweld heat treating at minimum temperatures.

(4) the thickness of the nozzle neck at the joint in nozzle neck-to-flange connections

(5) the thickness of the weld at the point of attachment when a nonpressure part is welded to a pressure part

(6) the thickness of the weld in tube-to-tubesheet connections

(f) For repairs, the nominal thickness is the depth of the repair weld.

KF-410 HEATING PROCEDURES FOR POSTWELD HEAT TREATMENT

KF-411 METHODS OF HEATING

The postweld heat treatment shall be performed in accordance with one of the procedures of this paragraph. In the procedures that follow, the soak band is defined as the volume of metal required to meet or exceed the minimum PWHT temperatures listed in Table KF-402.1 (Table KF-402.1M). As a minimum, the soak band shall contain the weld, heat-affected zone, and a portion of base metal adjacent to the weld being heat treated. The minimum width of this volume is the widest width of weld plus 1t or 2 in. (50 mm), whichever is less, on each side or end of the weld. The term t is the nominal thickness as defined in KF-402.3. For additional detailed recommendations regarding implementation and performance of these procedures, refer to Welding Research Council (WRC) Bulletin 452, June 2000, "Recommended Practices for Local Heating of Welds in Pressure Vessels".

KF-411.1 Heating Entire Vessel. Heating the vessel as a whole in a closed furnace is preferred and should be used whenever practical.

KF-411.2 Heating Vessel Portions. Heating the vessel in more than one heat in a furnace is permitted, provided the overlap of the heated sections of the vessel is at least 5 ft (1.5 m). When this procedure is used, the portion outside of the furnace shall be shielded so that the temperature gradient is not harmful (see KF-412). The cross section where the vessel projects from the furnace shall not intersect a nozzle or other structural discontinuity.

KF-411.3 Heating Components and Circumferential Welds.

(a) It is permissible to heat shell sections, heads, and other components of vessels, for postweld heat treatment of longitudinal joints or complicated welded details, before joining any sections to make the completed vessel. Circumferential joints not previously postweld heat treated may be locally postweld heat treated by heating a circumferential band that includes such joints.

(b) This procedure may also be used for local heat treatment of circumferential joints in pipe, tubing, or nozzle necks. In the latter case, proximity to the shell increases thermal restraint, and the designer should provide adequate length to permit heat treatment without harmful gradients at the nozzle attachments. If this is not practical, see KF-411.5.

(c) The width of the heated band on each side of the greatest width of the finished weld shall be not less than two times the shell thickness. The portion outside the heating device shall be protected so that the temperature gradient is not harmful. For such local heating, the soak band shall extend around the full circumference. The portion outside the soak band shall be protected so that the temperature gradient is not harmful. This procedure may also be used to postweld heat treat portions of new vessels after repairs.

KF-411.4 Heating Vessel Internally. The vessel may be heated internally by any appropriate means when adequate temperature indicating and recording devices are utilized to aid in the control and maintenance of a uniform distribution of temperature in the vessel wall. The vessel shall be fully insulated where required prior to heating so the temperature requirements of KF-413 are met.

KF-411.5 Local Heating of Nozzles and External Attachments on Vessels.

(a) Heating a circumferential band containing nozzles or other welded attachments that require postweld heat treatment in such a manner that the entire band shall be brought up uniformly to the required temperature (see KF-413) and held for the specified time. Except as modified in (b), the soak band shall extend around the entire vessel, and shall include the nozzle or welded attachment. The portion of the vessel outside of the circumferential soak band shall be protected so that the temperature gradient is not harmful.

(b) This procedure may also be used for local heat treatment of circumferential joints in pipe, tubing, or nozzle necks. In the latter case, proximity to the shell increases thermal restraint, and the designer should provide adequate length to permit heat treatment without harmful gradients — at the nozzle attachment, or heat a full circumferential band around the shell, including the nozzle.

The circumferential soak band width may be varied away from the nozzle or attachment weld requiring PWHT, provided the required soak band around the nozzle or attachment weld is heated to the required temperature and held for the required time. As an alternate to varying the soak band width, the temperature within the circumferential band away from the nozzle or attachment may be varied and need not reach the required temperature, provided the required soak band around the nozzle or attachment weld is heated

to the required temperature, held for the required time, and the temperature gradient is not harmful throughout the heating and cooling cycle. The portion of the vessel outside of the circumferential soak band shall be protected so that the temperature gradient is not harmful.

(c) The procedure in (a) may also be used to postweld heat treat portions of vessels after repairs.

KF-411.6 Local Area Heating of Double Curvature Heads or Shells. Heating a local area around nozzles or welded attachments in the larger radius sections of a double curvature head or a spherical shell or head in such a manner that the area is brought up uniformly to the required temperature (see KF-413) and held for the specified time. The soak band shall include the nozzle or welded attachment. The soak band shall include a circle that extends beyond the edges of the attachment weld in all directions by a minimum of t or 2 in. (50 mm), whichever is less. The portion of the vessel outside of the soak band shall be protected so that the temperature gradient is not harmful.

KF-411.7 Heating of Other Configurations. Local area heating of other configurations, such as spot or bulls-eye local heating, not addressed in KF-411.1 through KF-411.6 is permitted, provided that other measures (based upon sufficiently similar documented experience or evaluation) are taken that consider the effect of thermal gradients, all significant structural discontinuities (such as nozzles, attachments, head to shell junctures) and any mechanical loads that may be present during PWHT. The portion of the vessel outside of the soak band shall be protected so that the temperature gradient is not harmful.

KF-412 HEAT TREATMENT THAT MAY AFFECT VESSEL STRESS REDISTRIBUTION

The Manufacturer shall ensure, in accordance with KG-323(e), that any heat treatment given to a vessel or vessel part does not adversely affect the stress redistribution required by Articles KD-5, KD-8, and KD-9. In addition, the Manufacturer shall meet the requirements for heat treatment given in KF-830 or KF-540(b), as applicable.

KF-413 HEATING AND COOLING RATES

Postweld heat treatment shall be carried out by one of the methods given in KF-411 in accordance with the following requirements:

(a) The temperature of the furnace shall not exceed 800°F (430°C) at the time the vessel or part is placed in it.

(b) Above 800°F (430°C), the rate of heating shall be not more than 400°F/hr (220°C/h) per inch (25 mm) of the maximum metal thickness of the shell or head plate, but in no case more than 400°F/hr (220°C/h) and in no case need it be less than 100°F/hr (55°C/h). During the heating period, there shall not be a greater variation in temperature throughout the portion of the vessel being heated than 250°F (140°C) within any 15 ft (4.6 m) interval of length.

(c) The vessel or vessel part shall be held at or above the temperature specified in Table KF-402.1 (Table KF-402.1M) for the period of time specified. During the holding period, there shall not be a difference greater than 100°F (55°C) between the highest and lowest temperatures throughout the portion of the vessel being heated, except where the range is further limited in Table KF-402.1 (Table KF-402.1M).

(d) During the heating and holding periods, the furnace atmosphere shall be so controlled as to avoid excessive oxidation of the surface of the vessel. The furnace shall be of such design as to prevent direct impingement of the flame on the vessel.

(e) Unless modified by Article KF-6, above 800°F (430°C) cooling shall be done in a closed furnace or cooling chamber at a rate not greater than 500°F/hr (280°C/h) per inch (25 mm) of the maximum metal thickness of the shell or head plate, but in no case need it be less than 100°F/hr (55°C/h). From 800°F (430°C), the vessel may be cooled in still air.

KF-420 POSTWELD HEAT TREATMENT AFTER REPAIRS

Vessels or parts of vessels that have been postweld heat treated in accordance with the requirements of this Article shall again be postweld heat treated after repairs have been made if the welds made in such repairs required postweld treatment under the requirements of this Article. The Manufacturer shall ensure that any additional heat treatments required shall not adversely affect the vessel material properties.

ARTICLE KF-5
ADDITIONAL FABRICATION REQUIREMENTS FOR AUTOFRETTAGED VESSELS

KF-500 GENERAL

The rules in this Article apply specifically to the fabrication of autofrettaged vessels and shall be used in conjunction with Article KF-1.

KF-510 EXAMINATION AND REPAIR

(a) All base materials to be used in fabrication shall be examined ultrasonically in accordance with KE-232.

(b) The concurrence of the Professional Engineer who certifies the Manufacturer's Design Report shall be obtained prior to making any repairs by welding.

(c) All repairs shall be made by the Material Manufacturer or the Manufacturer in accordance with Article KE-2 and documented in accordance with KE-214.

KF-520 AUTOFRETTAGE PROCEDURES

The Manufacturer shall have a written detailed procedure. The procedure shall contain, as a minimum, the following.

(a) Method of accomplishing autofrettage.

(b) Method of controlling the extent of autofrettage.

(c) Method of recording time, temperature, and pressure during autofrettage.

(d) Method for measuring the extent of autofrettage achieved and for determining that it is within acceptable limits. Article KD-5 contains an equation which relates measured strain to the extent of autofrettage.

(e) Any machining after autofrettage shall be documented. The influence of machining after autofrettage is discussed in KD-520(b).

KF-521 DOCUMENTATION OF NUMBER OF PRESSURIZATIONS

The effect on crack initiation and ultimate fatigue life of multiple autofrettage attempts which exceed 1.25 times the design pressure shall be documented by the Designer. The Vessel Manufacturer shall document all such attempts and submit them to the Professional Engineer who certified the Manufacturer's Design Report for approval.

KF-530 EXAMINATION AFTER AUTOFRETTAGE

Surfaces which are expected to undergo plastic deformation during autofrettage and which will not be accessible during the final surface examination required in KE-400 shall be examined by one of the methods in KE-230 as appropriate.

KF-540 REPAIR OF DEFECTS AFTER AUTOFRETTAGE

(a) Defects may be removed and the vessel repaired by the Manufacturer in accordance with KF-510.

(b) If repair by welding is performed, no credit for the favorable effects of autofrettage in the area of the weld repair shall be taken in the fatigue analysis required in Part KD. Repair welding shall be done in accordance with the requirements of Article KE-2. If postweld heat treatment is required, the effects of this heat treatment on the residual stress distribution shall be documented by the Manufacturer in the Manufacturer's Construction Report.

KF-550 STAMPING AND REPORTS

The provisions for stamping and reports in Part KS shall apply to pressure vessels fabricated in accordance with this Article. In addition to the required marking, the letters PS shall be applied below the Certification Mark and U3 Designator (see KF-601).

ARTICLE KF-6
ADDITIONAL FABRICATION REQUIREMENTS FOR QUENCHED AND TEMPERED STEELS

KF-600 GENERAL

The following supplementary rules are applicable to steels suitable for welded vessel parts, the material properties of which have been enhanced by quenching and tempering heat treatment. The provisions of KM-240 shall also apply to materials whose properties are enhanced by quenching and tempering heat treatment.

KF-601 MARKING ON PLATES AND OTHER MATERIALS

Any steel stamping shall be done with low stress stamps. Steel stamping of all types may be omitted on material with a thickness of ½ in. (13 mm) or less. For the use of other markings in lieu of stamping, see KF-112.

KF-602 REQUIREMENTS FOR HEAT TREATING AFTER FORMING

(a) Parts formed after quenching and tempering, and which are formed at a temperature lower than the final tempering temperature, shall be heat treated in accordance with Table KF-630 (Table KF-630M) when the extreme fiber elongation from forming exceeds 5% as determined by eqs. (1) or (2).

(1) For double curvature (for example, heads):

$$\% \text{ extreme fiber elongation} = \frac{75t}{R_f}\left(1 - \frac{R_f}{R_o}\right) \quad (1)$$

(2) For single curvature (for example, cylinders):

$$\% \text{ extreme fiber elongation} = \frac{50t}{R_f}\left(1 - \frac{R_f}{R_o}\right) \quad (2)$$

where

R_f = final centerline radius, in. (mm)
R_o = original centerline radius (equals infinity for flat plate), in. (mm)
t = plate thickness, in. (mm)

(b) Parts formed at temperature equal to or higher than the original tempering temperature shall be requenched and tempered in accordance with the applicable material specifications either before or after welding into the vessel.

KF-603 MINIMUM THICKNESS AFTER FORMING

The minimum thickness after forming of any section subject to pressure shall be ¼ in. (6 mm).

KF-610 WELDING REQUIREMENTS

KF-611 QUALIFICATION OF WELDING PROCEDURES AND WELDERS

The qualification of the welding procedure and the welders shall conform to the requirements of Section IX and any additional requirements of this Section.

KF-612 FILLER METAL

Filler metal containing more than 0.08% vanadium shall not be used for weldments subject to postweld heat treatment.

KF-613 PREPARATION OF BASE METAL

Preparation of plate edges, welding bevels, and chamfers, and similar operations involving the removal of metal, shall be by machining, chipping, grinding, or by gas cutting or air arc gouging, as provided in KF-613.1.

KF-613.1 Precautions Necessary When Using Gas Cutting or Gouging. When metal removal is accomplished by methods involving melting, such as gas cutting or arc air gouging, etc., it shall be done with due precautions to avoid cracking. Where the cut surfaces are not to be subsequently eliminated by fusion with weld deposits, they shall be removed by machining or grinding to a depth of at least 1/16 in. (1.6 mm) followed by inspection by a surface examination method in accordance with KE-233. (25)

KF-614 WELD FINISH

All weld deposits shall merge smoothly into the base metal without abrupt transitions.

(25) KF-615 TOUGHNESS REQUIREMENTS FOR WELDS

The deposited weld metal and the heat-affected zone shall meet the impact test values of KM-234 when tested in accordance with Article KT-2.

(25) KF-620 TEMPORARY WELDS WHERE NOT PROHIBITED

(a) Temporary welds for pads, lifting lugs, and other nonpressure parts, as well as temporary lugs for alignment, shall be made by qualified welders and procedures in accordance with KF-210.

(b) Temporary welds shall be removed and the metal surface shall be restored to a smooth contour. The area shall be examined by a surface examination method in accordance with KE-233. If repair welding is required, it shall be documented in accordance with KE-210. Temporary welds and repair welds shall be considered the same as all other welds insofar as requirements for qualified operators and procedures and for heat treatment are concerned.

(25) KF-630 POSTWELD HEAT TREATMENT

(a) Vessels or parts of vessels constructed of quenched and tempered steels shall be postweld heat treated when required in Table KF-630 (Table KF-630M). When determining the thickness requiring postweld heat treatment in Table KF-630 (Table KF-630M) for clad or weld deposit overlayed vessels or parts of vessels, the total thickness of the base material shall be used.

(b) Postweld heat treatment shall be performed in accordance with Article KF-4, as modified by the requirements of Table KF-630 (Table KF-630M). In no case shall the PWHT temperature exceed the tempering temperature. PWHT and tempering may be accomplished concurrently. Where accelerated cooling from the tempering temperature is required by the material specification, the same minimum cooling rate shall apply to PWHT.

(c) All welding of connections and attachments shall be postweld heat treated whenever required by Table KF-630 (Table KF-630M), based on the greatest thickness of material at the point of attachment to the head or shell (see KF-402.1 and KF-402.2).

(d) Furnaces shall be provided with suitable equipment for the automatic recording of temperatures. The metal temperature of the vessel or vessel part during the holding period shall be recorded and shall be controlled within ±25°F (±14°C).

(e) Parts or entire vessels may be rapidly cooled after PWHT by spraying or immersion when temper embrittlement is of concern. See KM-240 for heat treatment certification requirements.

(f) The P-Numbers and Group Numbers listed for some of the materials in these tables are for reference only. For welded construction in this Division, Section IX, Table QW/QB-422 shall be consulted for P-Numbers and Group Numbers. When there is a conflict in P-Number or Group Number, the numbers in Section IX govern.

KF-640 EXAMINATION AND TESTING

KF-641 EXAMINATION AFTER HEAT TREATMENT

After final heat treatment, such vessels shall be examined for the presence of cracks on the outside surface of the shell and heads and on the inside surface where practicable. This examination shall be made in accordance with KE-233.

KF-642 CHECK OF HEAT TREATMENT BY HARDNESS TESTING

After final heat treatment, quenched and tempered materials shall be subjected to Brinell hardness tests. The readings shall be taken at a minimum of three locations representing the approximate center and each end of the components. The axial interval between each location shall not exceed 5 ft (1.5 m). Four readings shall be taken equally spaced around the circumference at each of these locations. The average Brinell hardness at any location where hardness is measured shall not vary by more than 40 HB.[8]

KF-650 STAMPING AND REPORTS

The provisions for stamping and reports in Part KS shall apply to pressure vessels constructed in whole or in part of quenched and tempered steels, except that the use of nameplates is mandatory for shell thicknesses below ½ in. (13 mm). Nameplates are preferred on vessels of quenched and tempered steels in thicknesses above $^1/_2$ in. (13 mm) instead of stamping. In addition to the required marking, the letters UQT shall be applied below the Certification Mark and U3 Designator (see KF-601).

Table KF-630
Postweld Heat Treatment Requirements for Quenched and Tempered Materials in Table KM-400-1
(U.S. Customary Units)

Spec. No.	Grade or Type	P-No. and Group No.	Thickness Requiring PWHT, in.	Postweld Heat Treatment Temp., °F	Holding Time	
					hr/in.	min./hr
Plate Steels						
SA-517	Grade A	11B Gr. 1	Over 0.58	1,000–1,100	1	1/4
SA-517	Grade B	11B Gr. 4	Over 0.58	1,000–1,100	1	1/4
SA-517	Grade E	11B Gr. 2	Over 0.58	1,000–1,100	1	1/4
SA-517	Grade F	11B Gr. 3	Over 0.58	1,000–1,100	1	1/4
SA-517	Grade J	11B Gr. 6	Over 0.58	1,000–1,100	1	1/4
SA-517	Grade P	11B Gr. 8	Over 0.58	1,000–1,100	1	1/4
SA-533	Grades B & D, Cl. 3	11A Gr. 4	Over 0.58	1,000–1,050	1/2	1/2
SA-543	Type B & C, Cl. 1	11A Gr. 5	[Note (2)]	1,000–1,050	1	1
SA-543	Type B & C, Cl. 2	11B Gr. 10	[Note (2)]	1,000–1,050	1	1
SA-724	Grades A & B	1 Gr. 4	None	NA [Note (1)]	NA [Note (1)]	NA [Note (1)]
SA-724	Grade C	1 Gr. 4	Over 1.5	1,050–1,150	1	1/2
Forgings						
SA-372	Grade E, Cl. 70	...	See Section II, Part A, SA-372 for heat treating requirements			
SA-372	Grade F, Cl. 70	...	See Section II, Part A, SA-372 for heat treating requirements			
SA-372	Grade J, Cl. 110	...	See Section II, Part A, SA-372 for heat treating requirements			
SA-508	Grade 4N, Cl. 1	11A Gr. 5	[Note (2)]	1,000–1,050	1	1
SA-508	Grade 4N, Cl. 2	11B Gr. 10	[Note (2)]	1,000–1,050	1	1
SA-508	Grade 4N, Cl. 3	3 Gr. 3	[Note (2)]	1,000–1,050	1	1

NOTES:
(1) NA indicates not applicable.
(2) PWHT is neither required nor prohibited. Consideration should be given to the possibility of temper embrittlement. The cooling rate from PWHT, when used, shall not be slower than that obtained by cooling in still air.

Table KF-630M
Postweld Heat Treatment Requirements for Quenched and Tempered Materials in Table KM-400-1M (SI Units)

Spec. No.	Grade or Type	P-No. and Group No.	Thickness Requiring PWHT, mm	Postweld Heat Treatment Temp., °C	Holding Time	
					h/25 mm	min./h
Plate Steels						
SA-517	Grade A	11B Gr. 1	Over 14.7	540–590	1	¼
SA-517	Grade B	11B Gr. 4	Over 14.7	540–590	1	¼
SA-517	Grade E	11B Gr. 2	Over 14.7	540–590	1	¼
SA-517	Grade F	11B Gr. 3	Over 14.7	540–590	1	¼
SA-517	Grade J	11B Gr. 6	Over 14.7	540–590	1	¼
SA-517	Grade P	11B Gr. 8	Over 14.7	540–590	1	¼
SA-533	Grades B & D, Cl.3	11A Gr. 4	Over 14.7	540–570	½	½
SA-543	Types B & C, Cl.1	11A Gr. 5	[Note (2)]	538–566	1	1
SA-543	Types B & C, Cl.2	11A Gr. 10	[Note (2)]	538–566	1	1
SA-724	Grades A & B	1 Gr. 4	None	NA [Note (1)]	NA [Note (1)]	NA [Note (1)]
SA-724	Grade C	1 Gr. 4	Over 38	565–620	1	½
Forgings						
SA-372	Grade E, Cl. 70	...	See Section II, Part A, SA-372 for heat treating requirements			
SA-372	Grade F, Cl. 70	...	See Section II, Part A, SA-372 for heat treating requirements			
SA-372	Grade J, Cl. 110	...	See Section II, Part A, SA-372 for heat treating requirements			
SA-508	Grade 4N, Cl. 1	11A Gr. 5	[Note (2)]	540–590	1	1
SA-508	Grade 4N, Cl. 2	11B Gr. 10	[Note (2)]	540–565	1	1
SA-508	Grade 4N, Cl. 3	3 Gr. 3	[Note (2)]	540–590	1	1

NOTES:
(1) NA indicates not applicable.
(2) PWHT is neither required nor prohibited. Consideration should be given to the possibility of temper embrittlement. The cooling rate from PWHT, when used, shall not be slower than that obtained by cooling in still air.

ARTICLE KF-7
SUPPLEMENTARY REQUIREMENTS FOR MATERIALS WITH WELDING RESTRICTIONS

KF-700 SCOPE

This Article gives additional requirements for forged vessels and vessel components fabricated of materials in which welding is restricted.

KF-710 REPAIR OF DEFECTS

KF-711 LOCALIZED THIN AREAS

Surface defects may be removed by blend grinding subject to the restrictions of KE-211.

KF-712 REPAIR OF DEFECTS BY WELDING

Materials not permitted by Part KM for welded construction may be repaired by welding if *all* of the following conditions are met:

(a) The carbon content is less than or equal to 0.40% by heat analysis.

(b) Repair welding is not prohibited by either Part KM or the material specification listed in Section II, Part A.

(c) Both the user and Material Manufacturer or the Manufacturer agree to repair welding.

(d) The repair welding is in accordance with a qualified welding procedure specification and performed by welders or welding operators qualified in accordance with Section IX.

(e) The suitability of the electrode and procedure, including preheat and postheat, shall be established by making a groove weld specimen as shown in Section IX, Figures QW-461.2 and QW-461.3 in material of the same analysis and of thickness in conformance with Section IX, Tables QW-451.1 through QW-451.4 and Tables QW-452.1(a) through QW-452.6. Before welding, the specimen shall be in the same condition of heat treatment as the work it represents, and after welding, the specimen shall be subjected to heat treatment equivalent to that contemplated for the work. Tension and bend specimens, as shown in Section IX, Tables QW-462.1(a) through QW-462.1(e), QW-462.2, and QW-462.3(a) shall be made. These tests shall meet the requirements of Section IX, QW-150 and QW-160. The radius of the mandrel used in the guided bend test shall be in accordance with KF-222.1.

(f) For allowable depth of repairs, see Article KE-2.

(g) The finished welds shall be postweld heat treated or given a further heat treatment as required by the applicable material specification. This welding shall be performed prior to final heat treatment except for seal welding of threaded openings, which may be performed either before or after final treatment.

(h) The finished welds shall be examined after postweld heat treatment in accordance with the requirements of Article KE-3.

KF-720 METHODS OF FORMING FORGED HEADS

Except for integral heads as described in KD-640, heads shall be made as separate forgings or by closing the extremities of a hollow forged body to such shape and dimensions as may be required to produce the final form desired.

ARTICLE KF-8
SPECIFIC FABRICATION REQUIREMENTS FOR LAYERED VESSELS

KF-800 SCOPE

(a) The rules of this Division apply to all layered vessels except as specifically modified by this Article. The rules in this Article apply specifically to layered vessels, layered shells, and layered heads.

(b) This Division provides rules for two basic types of layered vessels: those constructed by shrink fitting fabricated layers, and those constructed by fitting and welding concentrically wrapped layers together. For a further discussion of these types of layered vessels, refer to Article KD-8.

(c) Fabrication rules for these two vessel types differ. Paragraphs KF-810 through KF-814 give rules for vessels of shrink-fit construction, while KF-820 through KF-827 give rules for concentrically wrapped, welded layered vessels.

(d) Paragraph KF-830 gives rules for postweld heat treatment that apply to both types of vessel construction.

KF-810 RULES FOR SHRINK-FIT VESSELS

KF-811 FABRICATION OF INDIVIDUAL LAYERS

Prior to the shrink-fit assembly process, each layer shall be individually fabricated, heat treated as applicable, and examined in accordance with the rules given for vessels in this Division. If a layer is autofrettaged prior to the shrink-fit process, the rules of Article KF-5 shall apply to the autofrettaged layer. If a layer is rolled and welded, the requirements of Articles KF-2 and KF-4 shall apply to the layer prior to the assembly process. The examination rules of Part KE shall apply to each layer where applicable.

KF-812 SHRINK-FIT PROCESS TEMPERATURES

The temperatures needed to produce the design interference fit shall not exceed the tempering temperature of the material. The Manufacturer shall ensure that there will be no loss in the material properties due to the heating process.

KF-813 ASSEMBLY PROCEDURE AND REPORT

The Manufacturer shall provide a written procedure that describes in detail the fabrication process steps that will be used to produce the design residual stress distribution. This procedure shall address but is not limited to the following:

(a) The method for accomplishing the stress redistribution shall be identified, together with the necessary process controls.

(b) Variables that are to be controlled to accomplish the design residual stress distribution shall be identified, together with changes in their values necessary to ensure adequate control of the process.

(c) The methods used to measure the amount of residual stress distribution that is achieved, with precision consistent with the criteria of (b), shall be identified. Reliability of measuring devices shall be ensured through redundancy or other means. If thermally compensated resistance strain gages are used, a minimum of four gages shall be provided.

(d) All measured data from (a), (b), and (c) shall be documented and reported to the Designer who signs the Manufacturer's Design Report. A copy of the shrink-fitting assembly procedure shall also be given to the Designer with this data.

KF-814 EXAMINATION OF VESSELS WITH THREE OR MORE LAYERS

In addition to the examinations required by KF-811 and KE-400, for vessels containing three or more layers the following examinations are also required. After each shrink-fitting operation is completed, the entire surface of the subassembly that will be covered by the next layer in the assembly process shall be given a surface examination in accordance with KE-233.

KF-820 RULES FOR CONCENTRICALLY WRAPPED WELDED LAYERED VESSELS

KF-821 WELDING FABRICATION REQUIREMENTS

(a) The inner layer shall be seamless or contain Type No. 1 butt joints (see KF-221). Welds attaching the inner shell layer to the inner head layer shall be Type No. 1 butt joints. The use of permanent backing strips is prohibited.

(b) Type No. 2 butt joints are single-welded butt joints which use the previous layer for backing. These types of joints shall be staggered. They shall not be used as full thickness welds to attach layered section to layered section. Where Type No. 2 butt joints are used, particular care shall be taken in aligning and separating the components to be joined so that there will be complete penetration and fusion at the bottom of the joints for their full length.

(c) Weld joints shall be ground to ensure contact between the weld area and the succeeding layer, before application of the layer.

(d) Category A weld joints in layered shell sections shall be in an offset pattern such that the centers of the welded longitudinal joints of adjacent layers are separated circumferentially by a distance of at least five times the layer thickness in the joint to be welded. Weld categories are described in KE-321.

(e) Category A weld joints in layered heads may be in an offset pattern; if offset, the joints of adjacent layers shall be separated by a distance of at least five times the layer thickness in the joint to be welded.

(f) Category A, B, C, or D weld joints that attach a layered section to a solid section and category A or B weld joints that attach a layered section to a layered section shall be Type No. 1 butt joints. See Figures KD-830.5 and KD-830.6 for some acceptable configurations.

The offset pattern circumferential welds as shown in Figure KD-830.5, illustrations (d), (e) and (f) and circumferential weld using an insert as shown in Figure KD-830.5, illustration (b) are acceptable when the inner layers are designed as Type No.1 butt joints.

Offset pattern welds shall be such that the centers of the adjacent weld joints are separated by a minimum of 5 times the layer thickness to be joined.

KF-822 WELDING PROCEDURE QUALIFICATION

Requirements for welding qualification and records shall be in accordance with KF-210, except that the layered test plate welding procedure qualification shall be modified as follows:

(a) The minimum and maximum thicknesses qualified by procedure qualification test plates shall be as shown in Section IX, Tables QW-451.1 through QW-451.4, except that

(1) for category A welds in the layer section of the shell, the qualification shall be based upon the thickness of the thickest individual layer exclusive of the inner shell or inner head

(2) for category B weld procedure qualification, the thickness of the layered test plate need not exceed 3 in. (75 mm), shall consist of at least two layers, but shall not be less than 2 in. (50 mm) in thickness

(3) for category B weld joints made individually for single layers and spaced at least one layer thickness apart, the procedure qualification for category A welds applies

(b) The longitudinal weld joint of the inner shell or inner head and the longitudinal weld joint of layered shell or layered head shall be qualified separately unless it is of the same P-Number material. The weld gap of the longitudinal layer weld joint shall be the minimum width used in the procedure qualification for layers $^{7}/_{8}$ in. (22 mm) and less in thickness.

(c) Circumferential layer-to-layer weld joints, or the layer-to-solid weld joints in a solid head, flange, or end closure, shall be qualified with a simulated layer test plate as shown in Figure KF-822(a) for layer thicknesses $^{7}/_{8}$ in. (22 mm) and under. A special type of joint tensile specimen shall be made from the layer test coupon as shown in Figure KF-822(b). Face and root bend specimens shall be made of both the inner and outer weld to the thickness of the layer by cutting the weld to the layer thickness.

KF-823 WELDER PERFORMANCE QUALIFICATION

Welding shall be performed only by welders and welding operators who have been qualified in accordance with Section IX. The minimum and maximum thicknesses qualified by any welder test plate shall be as shown in Section IX, Tables QW-452.1(a) through QW-452.6.

KF-824 VENTING BETWEEN LAYERS

Vent holes shall be provided to detect leakage of the inner shell and to prevent buildup of pressure within the layers as follows:

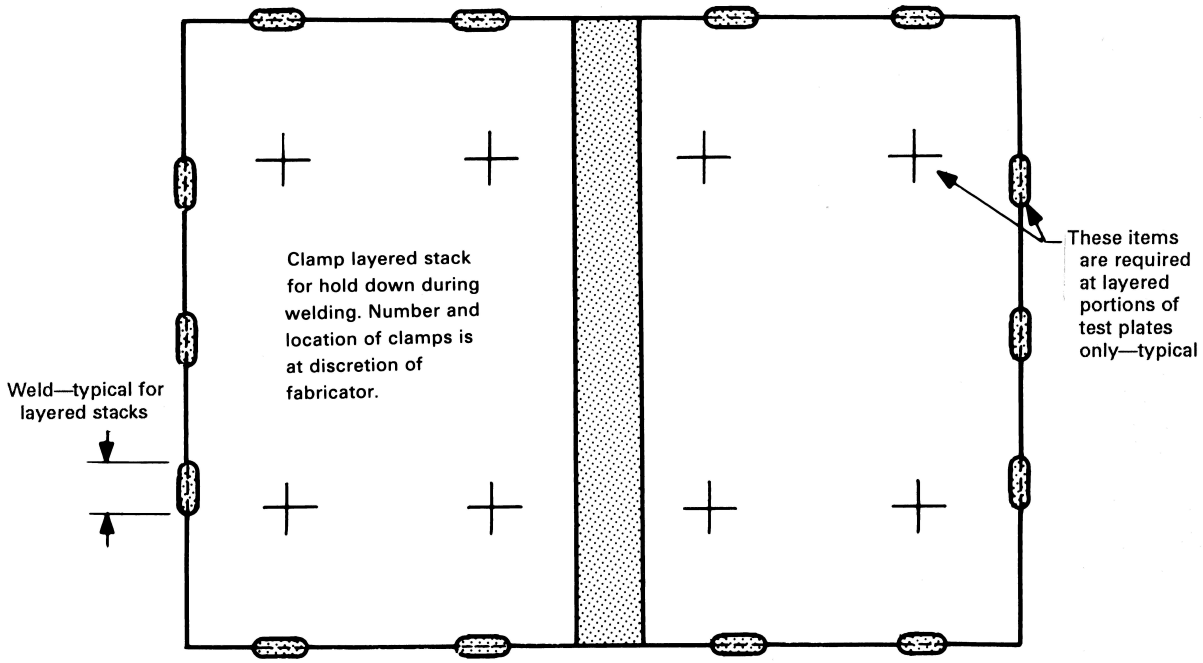
(a) In each shell course or head segment, a layer may be made up of one or more plates. Each layer plate shall have at least two vent holes $^{1}/_{4}$ in. (6 mm) diameter or larger. Holes may be drilled radially through the multiple layers or may be staggered in individual layer plates.

(b) Vent holes shall not be obstructed. If a monitoring system is used, it shall be designed to prevent buildup of pressure within the layers.

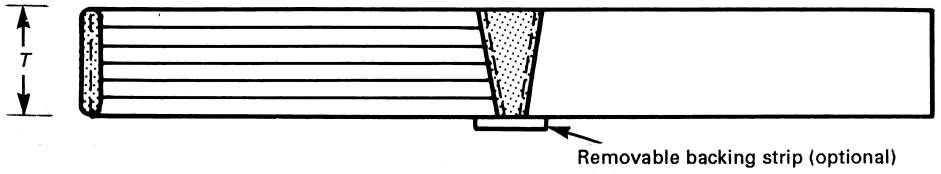
KF-825 NONDESTRUCTIVE EXAMINATION OF WELDED JOINTS

The rules of the following paragraphs supplement and modify the requirements of Part KE. They apply specifically to the nondestructive examination of pressure vessels and vessel parts that are fabricated using layered construction.

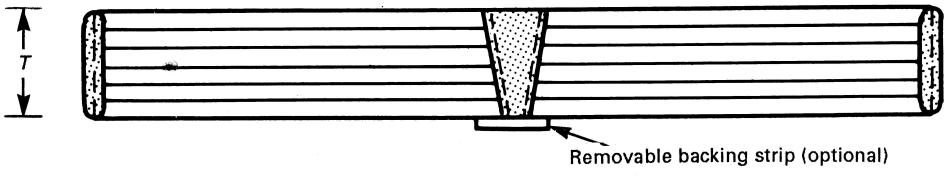
Figure KF-822(a)
Solid-to-Layered and Layered-to-Layered Test Plates



(a) Plan-View of Solid-to-Layered and Layered-to-Layered Test Plates



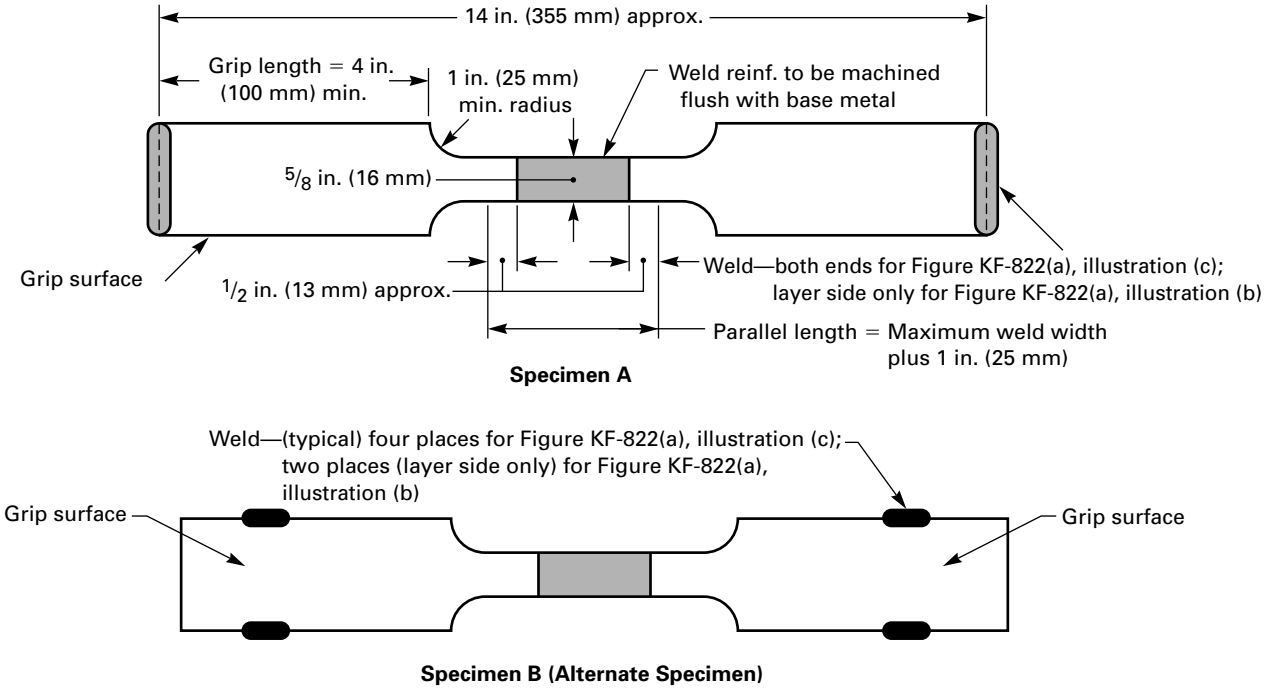
(b) Layered-to-Solid Test Plate



(c) Layered-to-Layered Test Plate

GENERAL NOTE: For T > 1 in. (25 mm), multiple specimens in accordance with Section IX, QW-151 may be used.

Figure KF-822(b)
Test Specimens for Weld Procedure Qualification



GENERAL NOTE: Specimens A and B are plan views of Figure KF-822(a), illustrations (b) and (c), and are identical except for locations of grip surfaces and welds. All grip surfaces are to be machined flat.

KF-825.1 Inner Shells and Inner Heads. Categories A and B joints in the inner shells of layered shell sections and in the inner heads of layered heads shall be examined throughout their entire length in accordance with Article KE-3 before application of subsequent layers.

(25) **KF-825.2 Category A Weld Joints in Layers.**

(a) Category A joints in layers 1/4 in. (6 mm) through 5/16 in. (8 mm) in thickness welded to the previous surface shall be examined for 100% of their length in accordance with Article KE-3 a surface examination method in accordance with KE-233.

(b) Category A joints in layers over 5/16 in. (8 mm) in thickness welded to the previous layer shall be examined for 100% of their length by both a surface and a volumetric examination in accordance with Article KE-3. For the ultrasonic method, the distance amplitude correction curve or reference level shall be raised by 6 dB for the bottom 10% of the weld thickness.

(25) **KF-825.3 Step Welded Girth Joints in Layers.**

(a) Category B joints in layers 1/4 in. (6 mm) through 5/16 in. (8 mm) in thickness shall be spot examined over a minimum of 10% of their length in accordance with Article KE-3 by a surface examination method in accordance with KE-233. The random spot examination shall be performed as specified in KF-825.8.

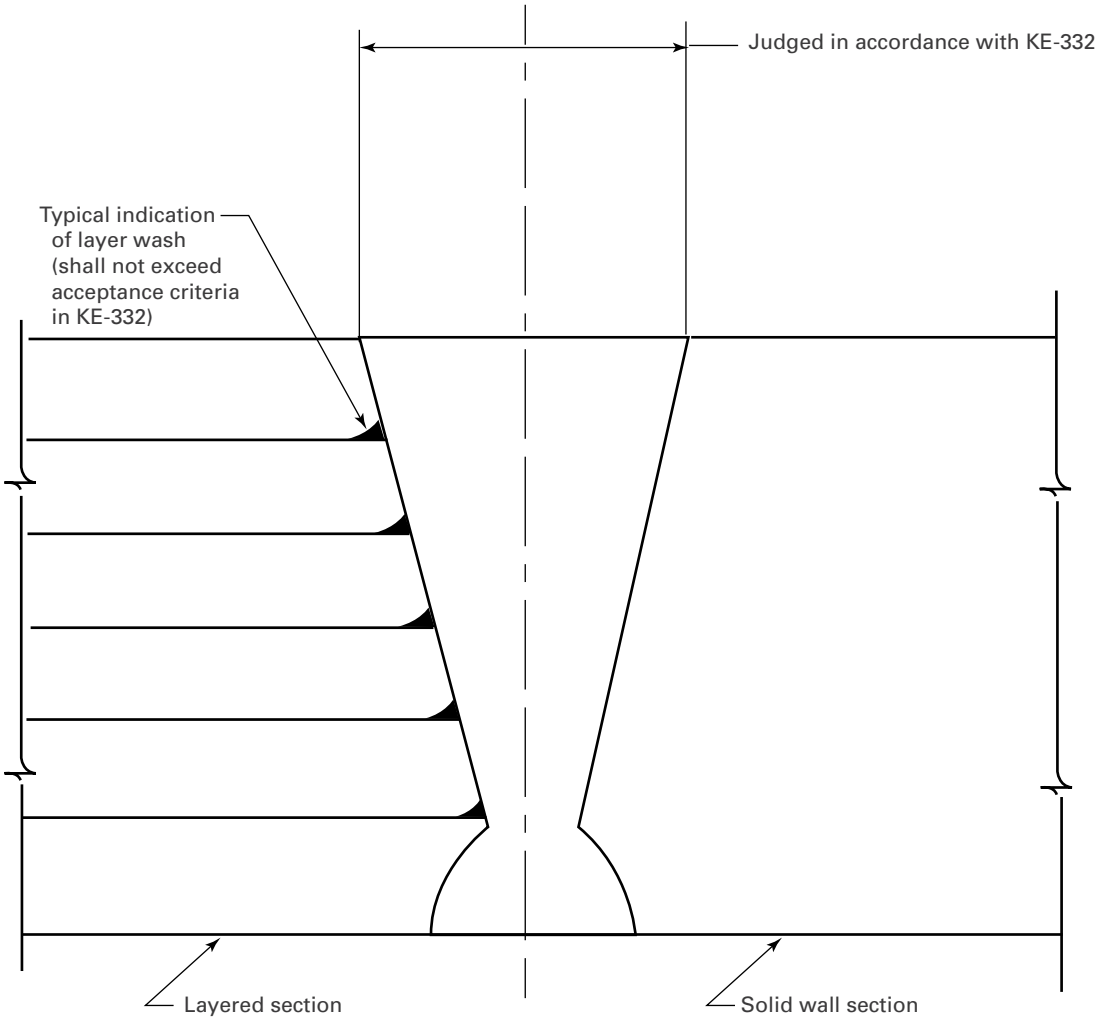
(b) Category B joints in layers over 5/16 in. (8 mm) through 7/8 in. (22 mm) in thickness shall be examined for 100% of their length in accordance with Article KE-3 by a surface examination method in accordance with KE-233. In addition, these joints shall be spot examined over a minimum of 10% of their length by the ultrasonic method in accordance with Article KE-3, except that the distance amplitude correction curve or reference level shall be raised by 6 dB for the bottom 10% of the weld thickness. The random spot examination shall be performed as specified in KF-825.8.

(c) Category B joints in layers over 7/8 in. (22 mm) in thickness shall be examined for 100% of their length by both a surface and volumetric means in accordance with Article KE-3. For ultrasonic examination, the distance amplitude correction curve or reference level shall be raised by 6 dB for the bottom 10% of the weld thickness.

KF-825.4 Through-Thickness Butt Joints.

(a) Categories B and D joints attaching a solid section to a layered section or a layered section to a layered section shall be examined over their entire length in accordance with Article KE-3.

Figure KF-825.4
Indications of Layer Wash



NOTE: (1) Any indication not in line with layer interface shall be interpreted in accordance with KF-825.4.

(b) It is recognized that layer wash[9] or acceptable gaps (see KF-826) may show as indications difficult to distinguish from slag on radiographic film. Acceptance shall be based on reference to the weld geometry as shown in Figure KF-825.4 and acceptance criteria in KE-332.

KF-825.5 Flat Head and Tubesheet Weld Joints. Category C joints attaching layered shell or layered heads to flat heads and tubesheets shall be examined to the same requirements as specified for Category B joints in KF-825.3.

(25) **KF-825.6 Welds Attaching Nonpressure Parts and Stiffeners.** All welds attaching supports, lugs, brackets, stiffeners, and other nonpressure attachments to pressure parts (see Article KD-7) shall be examined on all exposed surfaces by a surface examination method in accordance with the requirements of Article KE-3. However, the examination required in KF-224 shall be made after any postweld heat treatment.

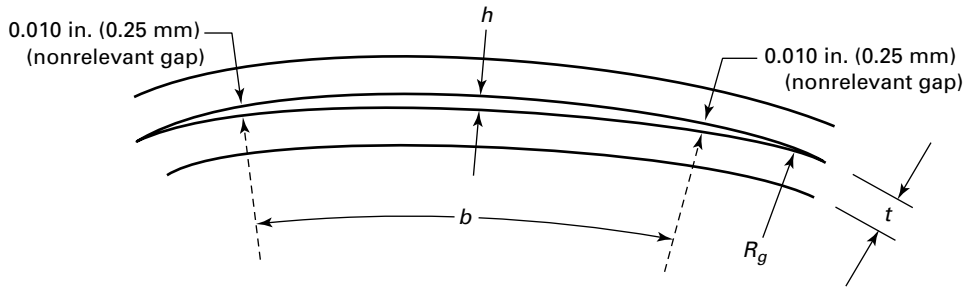
KF-825.7 Transition Welds. (25)

(a) All weld metal buildup in solid wall sections in layered transitions shall be examined over the full surface of the deposit by a surface examination method in accordance with Article KE-3.

(b) When such surface weld metal buildup is used in welded joints which require radiographic or ultrasonic examination, the weld metal buildup shall be included in the examination.

KF-825.8 Random Spot Examination and Repair of Weld. (25) The random surface examinations required by KF-825.3(a), and the ultrasonic examinations required by KF-825.3(b), shall be performed as follows:

Figure KF-826
Gap Area Between Layers



Legend:
A_g = area of gap (approx.) = $^2/_3hb$, in.^{2} (mm)^2
b = arc length of relevant radial gap, in. (mm)
h = radial gap, in. (mm)
R_g = radius of vessel at gap, in. (mm)
t = layer thickness, in. (mm)

(a) The location of the random spot shall be chosen by the Inspector, except that when the Inspector has been duly notified in advance and cannot be present or otherwise make the selection, the Manufacturer may exercise judgment in selecting the random spot or spots. The minimum length of a spot shall be 6 in. (150 mm).

(b) When any random spot examination discloses welding which does not comply with the minimum quality requirements of the applicable paragraphs of Article KE-3, two additional spots of equal length shall be examined in the same weld unit at locations away from the original spot. The locations of these additional spots shall be determined by the Inspector or Manufacturer as provided for in the original spot examination.

(c) If either of the two additional spots examined shows welding which does not comply with the minimum quality requirements of the applicable paragraphs of Article KE-3, the entire unit of weld represented shall be rejected. The entire rejected weld shall be removed and the joint shall be rewelded or, at the Manufacturer's option, the entire unit of weld represented shall be completely examined and defective welding only need be corrected.

(d) Repair welding shall be performed using a qualified procedure and in a manner acceptable to the Inspector. The rewelded joint or the weld repaired areas shall be random spot examined at one location in accordance with the requirements of KF-825.3(a) and KF-825.3(c).

KF-826 GAPS BETWEEN LAYERS

KF-826.1 Contact Between Layers. The following requirements shall be satisfied:

(a) After weld preparation and before welding circumferential seams, the height of the radial gaps between any two adjacent layers shall be measured at the ends of the layered shell section or layered head section at right angles to the vessel axis, and also the length of the relevant radial gap in inches shall be measured, neglecting radial gaps of less than 0.010 in. (0.25 mm) as nonrelevant. An approximation of the area of the gap shall be calculated as indicated in Figure KF-826.

(b) In the case of layered spheres or layered heads, if the gaps cannot be measured as required in (a), measurement of gap heights shall be taken through vent holes (see KF-824) in each layer course to ensure that the height of gaps between any two layers does not exceed the gap permitted in (c). The spacing of the vent holes shall be such that gap lengths can be determined. In the event an excessive gap height is measured through a vent hole, additional vent holes shall be drilled as required to determine the gap length. There shall be at least two vent holes per layer segment.

(c) The maximum number and size of gaps permitted in any cross section of a layered vessel shall be limited by the most stringent conditions given in (1) through (5).

(1) Maximum gap between any two layers shall not exceed the value of h evaluated in KF-826.2 or $^3/_{16}$ in. (5 mm), whichever is less.

(2) Maximum permissible number of gaps and their corresponding arc lengths at any cross section of a layered vessel shall be calculated as follows. Measure each gap and its corresponding length throughout the cross section, h and b; then calculate the value of F for each of the gaps using eq. (1):

$$F = 0.109\frac{bh}{R_g^2} \quad (1)$$

where

b = length of gap, in. (mm)
F = gap value (dimensionless)

h = gap between any two layers, in. (mm)
R_g = outside radius of layer above which the gap is located, in. (mm)

(3) The total sum of the values of F calculated above shall be evaluated in accordance with KF-826.3.

(4) The gap area, A_g, between any two adjacent layers shall not exceed the thickness of the thinner of the two adjacent layers expressed in area units.

(5) The maximum length of any single gap shall not exceed the inside diameter of the vessel. Where more than one gap exists between any two adjacent layers, the sum of the gap lengths between these layers shall not exceed the inside diameter of the vessel.

(d) All measured data from (a), (b), and (c) shall be documented and reported to the Designer who signs the Manufacturer's Design Report.

KF-826.2 Evaluation for Maximum Gap. The maximum gap between any layers based on number of design cycles shall be evaluated as follows:

(a) The longitudinal stress of the shell and the bending stress due to pressure and the gap can be calculated respectively as:

$$\sigma_{ml} = \frac{{R_I}^2}{{R_O}^2 - {R_I}^2} P \tag{2}$$

$$\sigma_{bl} = \frac{1.812Eh}{R_g} \tag{3}$$

σ_{ml} and σ_{bl} may be obtained by analysis using analysis model with maximum gap.

(b) The maximum gap shall be evaluated in accordance with KD-340. The allowable cycle for maximum gap and design pressure shall be equal to or greater than design cycle, where

E = modulas of elasticity, ksi (MPa)
h = maximum gap between any two layers, in. (mm)
P = design pressure, ksi (MPa)
R_g = outside radius of layer above which the gap is indicated, in. (mm)
R_I = inside diameter, in. (mm)
R_O = outside diameter, in. (mm)
σ_{bl} = longitudinal bending stress due to gap between any two layers, in. (mm)
σ_{ml} = longitudinal membrane stress due to pressure, ksi (MPa)

KF-826.3 Evaluation for Maximum Permissible Number of Circumferential Gaps. The maximum permissible number of circumferential gaps and their corresponding lengths due to pressure can be evaluated as follows:

(a) The circumferential stress of the cylindrical shell due to pressure and gaps can be calculated as follows:

$$\sigma_{tp} = \frac{{R_O}^2 + {P_I}^2}{{R_O}^2 - {R_I}^2} P \tag{4}$$

$$\sigma_{tg} = \frac{E}{1 - \nu^2} \Sigma F \tag{5}$$

σ_{tp} and σ_{tg} may be obtained by analysis using analysis model with maximum permissible number of circumferential gaps.

(b) σ_{tg} shall be satisfied as follows:

$$\sigma_{tg} \le \left(\Delta\sigma_N - \sigma_{tp} \right) \tag{6}$$

where

E = modulas of elasticity, ksi (MPa)
P = design pressure
R_I = inside diameter, in. (mm)
$\Delta\sigma_N$ = structural stress range corresponding to design cycle per KD-340
ν = poisson's ratio
$\sum F$ = total sum of the value of F [all of the accumulated gap strain, see KF-826.1(c)(2)]
σ_{tg} = circumferential stress in a layer due to all the accumulated gap strains
σ_{tp} = circumferential stress due to pressure

The structural stress range $\Delta\sigma_N$ corresponding to design cycle shall be obtained in accordance with KD-340.

KF-827 CIRCUMFERENTIAL EXPANSION DURING HYDROTEST

The following measurements shall be taken at the time of the hydrostatic test to check on the contact between successive layers, and the effect of gaps which may or may not be present between layers:

(a) The circumference shall be measured at the midpoint between adjacent circumferential joints, or between a circumferential joint and any nozzle in a shell course. Two sets of measurements are to be taken. The first is to be taken at zero pressure prior to hydrotest. The second set is to be taken during the hydrotest (see KT-330). After the hydrotest pressure has been successfully maintained for a minimum of 5 min, the measurements shall be made while the hydrotest pressure is maintained. The difference in measurements shall be averaged for each course in the vessel and the results recorded as average middle circumferential expansion e_m in inches.

(b) The theoretical circumferential expansion e_{th} of a solid vessel shall be calculated in accordance with KD-822.

(c) Acceptance criteria for circumferential expansion at the hydrotest pressure shall be in accordance with KD-822.

(d) All measured data from (a), (b), and (c) shall be documented and reported to the Designer who signs the Manufacturer's Design Report.

KF-830 HEAT TREATMENT OF WELDMENTS

(a) Postweld heat treatments of layers after the shrink-fit assembly process will cause the residual stress distribution obtained by the shrink-fitting operation to be reduced. The residual stress will not be known within the tolerance required in KD-810(a). Therefore, if a postweld heat treatment is given to shrink-fitted layers, no credit shall be taken for the beneficial effects of the prestress obtained by shrink fitting. For alternative rules pertaining to postweld heat treatment of layered vessels, refer to (b).

(b) When required, pressure parts shall be postweld heat treated in accordance with Articles KF-4 and KF-6; however, completed layered vessels or layered sections need not be postweld heat treated provided all welded joints connect a layered section to a layered section, or a layered section to a solid wall, and all of the following conditions are met.

(1) The thickness referred to in Table KF-402.1 and Table KF-630 (Table KF-630M) is the thickness of one layer. Should more than one thickness of layer be used, the thickness of the thickest layer shall govern.

(2) The finished joint preparation of a solid section or solid nozzle which is required to be postweld heat treated under the provisions of Table KF-402.1 or Table KF-630 (Table KF-630M) shall be provided with a buttered layer of at least $\frac{1}{4}$ in. (6 mm) thick welding material not requiring postweld heat treatment. Solid sections of P-No. 1 materials need not have this buttered layer. Postweld heat treatment of the buttered solid section shall then be performed prior to attaching to the layered sections. Postweld heat treatment following attachment to the layered section is not required unless the layered section is required to be postweld heat treated.

(3) A multipass welding technique shall be used and the weld layer thickness shall be limited to $\frac{1}{4}$ in. (6 mm) maximum. When materials listed in Table KF-630 (Table KF-630M) is used, the last pass shall be given a temper bead[10] technique treatment.

(4) The postweld heat treating rules in Article KF-4 shall apply to all weld repairs.

ARTICLE KF-9
SPECIAL FABRICATION REQUIREMENTS FOR WIRE-WOUND VESSELS AND FRAMES

KF-900 SCOPE

The requirements of this Article apply specifically to pressure vessels consisting of an inner cylindrical shell (or a number of concentric shells) prestressed by a surrounding winding. The end load is not carried by the cylinder(s) or the winding. The winding consists of a wire helically wound in pretension in a number of turns and layers around the outside of the cylinder. These requirements also apply to additional frames used to carry the load from the closures.

The rules of this Article shall be used as a supplement to or in lieu of applicable requirements given in Articles KF-1 through KF-7. When requirements of this Article differ from those of Articles KF-1 through KF-7, they are specifically delineated.

KF-910 FABRICATION REQUIREMENTS

The general and special requirements stated in Articles KF-1, KF-6, KF-7, and KF-8 shall be valid when applicable. The welding fabrication requirements stated in Articles KF-2 through KF-8 shall be replaced by the requirements in KF-911.

KF-911 WELDING FABRICATION REQUIREMENTS

Welds and repair welds are not permitted in parts that are prestressed by wire winding and carry pressure loads. However, an exception is made for the welded joints that are necessary to lengthen the wire in order to get an uninterrupted winding. The requirements for these welded wire joints are stated in KF-912.

(25) KF-912 WELDED WIRE JOINTS

When it is necessary to get a winding consisting of an uninterrupted length of wire, butt-welded joints may be used to join wire lengths. The minimum distance between these joints shall not be less than 6,500 ft (2 000 m), and the average distance not less than 12,000 ft (3 700 m). Welded joints are not permitted in the outermost winding layer. The welded joint shall be carefully ground in order to get a smooth surface and thereby reestablish the original cross-section shape.

The Manufacturer shall measure the reduction in strength of welded wire joints obtained by the Manufacturer's welding procedure. The wire force shall be reduced to a corresponding lower level for a minimum of two turns before and after the welded joint.

After welding and before proceeding with fabrication, each joint shall be subjected to a tensile stress level of not less than two-thirds of the specified minimum tensile strength of the nonwelded wire. If the joint breaks, the welding shall be repeated until the strength requirement specified above is fulfilled.

KF-913 WINDING PROCEDURE REQUIREMENTS

Each wire-wound vessel shall be wound in accordance with a detailed wire winding procedure. This procedure shall provide all details relevant to winding, including a description of the winding machine and how tensile force in the wire is applied, controlled, and measured. All winding shall be carried out in accordance with this procedure.

The application of the winding onto the cylinder or the frame shall be carried out in a special winding machine equipped with devices that make it possible to control and measure the tensile force used for applying the wire. This force shall also be recorded on a diagram that shall be filed by the Manufacturer. The measuring devices shall be calibrated at least every 6 months, or at any time there is reason to believe that the measuring devices are erroneous.

The winding procedure shall include a calculated wire force (see KD-912) that shall be used for each winding layer. Measurements shall be made of the compression at intervals specified in the program and the results compared with the calculations. The measurements shall be made using methods that guarantee a result with adequate accuracy. If differences are noted between specified and measured compression at these checkpoints and there is reason to presume that the specified final compression will not be reached if the original program is followed, a change may be made in the remaining program by increasing the specified wire

force by not more than 10%. The final difference between originally specified and measured compression shall not exceed 5%.

The wire end shall be properly locked to prevent unwrapping.

ARTICLE KF-10
ADDITIONAL FABRICATION REQUIREMENTS FOR ALUMINUM ALLOYS

(a) Vessels and components may be manufactured from sheet, plate bar, rod, drawn seamless tube, and seamless extruded tube conforming to Table KM-400-4 (Table KM-400-4M) specifications. Finished vessels and components shall be heat treated in accordance with the requirements of the specifications listed in Table KM-400-4 (Table KM-400-4M) and shall meet the specified mechanical properties for T6 or T651 temper, as applicable.

(b) Welding and thermal cutting are not permitted.

ARTICLE KF-11
ADDITIONAL FABRICATION REQUIREMENTS FOR WELDING AGE-HARDENING STAINLESS STEELS

KF-1100 SCOPE

The following supplementary rules are applicable to age-hardening stainless steels, SA-705 and SA-564, found in Table KM-400-2 (Table KM-400-2M), used for welded vessels and vessel components.

KF-1110 WELDING REQUIREMENTS

KF-1111 QUALIFICATION OF WELD PROCEDURES AND WELDERS

(a) The qualification of weld procedures and the welders shall conform to the requirements of this Article and Part KF.

(b) Weld coupons shall be impact tested as required by Article KM-2 and shall meet the impact test values of KM-234.

(c) Impact test specimens shall be taken from both the deposited weld material and heat-affected zone.

KF-1112 FILLER METALS

(a) Components constructed of age-hardening stainless steels, SA-705 and SA-564, Grades XM-12, XM-25, and 630 shall be welded using a filler metal of same nominal composition as UNS S17400.

(b) Age-hardening stainless steels, SA-705 and SA-564, Grades 631, XM-13, and XM-16 shall be welded using a filler metal of the same nominal composition as the base metal.

KF-1120 BASE METAL HEAT TREATMENT CONDITION

All material shall be heat treated prior to welding to the solution annealed condition or to a yield strength of 105 ksi or less, in accordance with the heat treatment requirements of the applicable materials specification.

(25) KF-1130 TEMPORARY WELDS WHERE NOT PROHIBITED

(a) Temporary welds for pads, lifting lugs, and other nonpressure parts, as well as temporary lugs for alignment, shall be made by qualified welders and procedures in accordance with the requirements of this Article and KF-210.

(b) Temporary welds and repair welds shall be considered the same as all other welds insofar as requirements for qualified operators and procedures and for heat treat are concerned.

(c) Temporary welds shall be removed and the metal surface shall be restored to a smooth contour. The area shall be examined by a surface examination method in accordance with KE-233. Defects shall be removed and the materials shall be examined to ensure that all defects have been removed.

(d) If repairs are necessary, they shall be made using qualified weld procedures and welders in accordance with this Article.

KF-1140 POSTWELD HEAT TREATMENT

After completion of all welding, the vessel or component shall be fully solution annealed and aged to the desired heat treat condition in accordance with the requirements of the applicable materials specification.

KF-1150 PRODUCTION WELD TESTING

(a) A production weld sample shall be made by using a piece of material of sufficient size and geometry to allow the conditions of production welding to be maintained on the test sample, but should not be less than 6 in. by 6 in. The material used for production test coupon shall be of the same heat of material used to make the actual production vessel or component.

(b) A minimum of one production weld test coupon shall be made for each heat of material and each welding process used to fabricate the production vessel or component.

(c) The production weld test coupon shall be heat treated at the same time and same conditions as the vessel or component.

(d) The production weld test coupon shall be tested in accordance with the requirements of KF-1111.

(25) KF-1160 EXAMINATION AND TESTING

After final heat treatment of the components, all welds shall be examined on the outside surface and inside surface where accessible by a surface examination method in accordance with KE-233, and shall also be examined in accordance with Article KE-3.

KF-1170 REPAIR WELDING

If repair welding is required, it shall be performed in accordance with this Article and documented in accordance with KE-210.

KF-1180 POSTWELD HEAT TREATMENT AFTER WELD REPAIRS

Components heat treated to the solution annealed and aged heat treatment condition in accordance with the requirements of this Article shall be given a full postweld solution anneal and aging heat treatment after completion of all weld repairs.

ARTICLE KF-12
ADDITIONAL FABRICATION REQUIREMENTS FOR COMPOSITE REINFORCED PRESSURE VESSELS (CRPV)

KF-1200 SCOPE

The following Article provides additional fabrication requirements for the Composite Reinforced Pressure Vessels (CRPV) fabricated in accordance with this Division.

KF-1210 WELDING

The surfaces of the external welds and all other welds and surfaces shall be designed, fabricated, and finished in accordance with the requirements of this Division before laminate application.

KF-1211 FINAL WELD FINISH FOR CRPV

Weld surfaces may be left unground inside the CRPV provided a fatigue analysis, including experimental verification, is undertaken for the specific Welding Procedure Specification and Procedure Qualification Record, see KF-1210. The outer surface of the weld shall be finished in accordance with KF-204. Experimental verification shall be accomplished by the pressure cycle tests of CRPV required to qualify and requalify the Laminate Procedure Specification, see Section X, Mandatory Appendix 10, 10-402 and 10-600, Laminate Procedure Qualification. For the unfinished weld surfaces on the internal surface of the CRPV, the maximum permitted weld reinforcement shall be in accordance with Table KF-1211.

KF-1212 LAMINATE PROCEDURE SPECIFICATION QUALIFICATION

(a) General Requirements. For vessels to be installed at a fixed location, a hydrostatic test to a pressure at least 1.25 times the design pressure shall be performed on each CRPV Prototype Vessel. For vessels to be used in transport service, a hydrostatic test to a pressure at least 1.25 times the design pressure or 1.5 times the service or working pressure, whichever is greater, shall be performed on each CRPV Prototype Vessel. This test may be combined with any hydrostatic pressurization procedure used to provide a prestress in the individual layers, provided the minimum test pressure is reached. This hydrostatic test shall be done after the tests and examinations in Section X, Mandatory Appendix 10, 10-503(a)(1), 10-608, and 10-609 but before tests and examinations in (b)(1) and Section X, Mandatory Appendix 10, 10-613 through 10-616.

(b) Specific Requirements

(1) Volumetric Expansion Tests. Each CRPV Prototype Vessel shall be subjected to a volumetric expansion test using a test fluid that complies with the requirements of KT-320.

(-a) The volume of liquid used to fill the CRPV at atmospheric pressure and temperature shall be compared with that required to fill it at the design pressure and at the same temperature. Care shall be taken to eliminate air pockets to ensure accuracy. The volume of liquid used in each instance shall be determined by any appropriate means, such as a weigh tank that has been calibrated to an accuracy of ±0.2%. The percent expansion shall be subsequently used in the production volumetric expansion test.

(-b) Alternatively, the volumetric expansion may be determined by measuring the overall length of the CRPV and its circumference at 5 ft (1.5 m) intervals along its length, with a minimum of three such determinations being made; all measurements shall be made with instruments that have been calibrated to an accuracy of ±0.05%. These measurements shall be taken with the CRPV filled with liquid at atmospheric pressure and at design pressure, both at the same temperature. The percent volumetric expansion calculated from these measurements shall be subsequently used in the production volumetric expansion test.

(-c) Acceptance criteria shall be in accordance with KT-510(b).

(2) Laminate Acoustic Emission Examination. An acoustic emission examination of the laminate shall be conducted in accordance with Section X, Mandatory Appendix 10, 10-503(a)(7). The acoustic emission examination report shall be included in the Qualification Test Report and referenced on Form CRPV-2A.

Table KF-1211
Permitted Weld Reinforcement

Weld Thickness, in. (mm)	Max. Reinforcement, in. (mm)
1/4 to 1/2 (6.0 to 12.7), incl.	1/8 (3.2)
Over 1/2 (12.7)	5/32 (4.0)

(3) Cyclic Pressure Qualification Test. At least one CRPV Prototype Vessel shall be subjected to a cyclic pressure test in accordance with KD-1260, followed by a hydrostatic qualification pressure test, as follows:

(-a) The vessel to be tested shall have the same diameter and wall thickness as the production vessels, but the length between girth welds may be reduced to no less than $10\sqrt{Rt}$, where R is the overall outside radius of the composite vessel and t is the overall wall thickness.

(-b) The test fluid shall comply with the requirements of KT-320.

(-c) Portions of the cyclic pressure test may be done at different temperatures and pressure ranges. When this is done, the number of test cycles shall be calculated as follows:

Step 1. Determine the test temperature, test pressure range, and number of test cycles for the first portion of the test (test cycle 1). The test pressure range shall not be less than the operating pressure range as defined in the User's Design Specification. The test temperature shall not be warmer than the minimum design metal temperature specified in the User's Design Specification. The number of test cycles shall not be less than the number calculated using the requirements of KD-1260 based on the number of operating pressure cycles that will occur at a metal or composite temperature colder than 30°F (0°C) specified in the User's Design Specification. If no cycles colder than 30°F (0°C) are specified in the User's Design Specification because the vessel is operating in ambient conditions, the number of test cycles shall be calculated using the requirements of KD-1260 based on 10% of the total number of cycles. Designate the number of test cycles n_{t1}.

Step 2. Calculate the number of test cycles that would be required if the entire test was done at the test temperature and test pressure range for the first portion of the test using the requirements of KD-1260. Designate the required number of cycles N_{t1}.

Step 3. Calculate the fraction of the total cyclic test requirement, T_{f1}, that will be achieved in the first portion of the test as $T_{f1} = n_{t1}/N_{t1}$.

Step 4. Determine the test temperature, test pressure range, and number of test cycles for the second portion of the test (test cycle 2). The test pressure range shall not be less than the operating pressure range as defined in the User's Design Specification. The test temperature shall not be colder than the design metal temperature specified in the User's Design Specification. The number of test cycles shall not be less than the number calculated using the requirements of KD-1260 based on the number of operating pressure cycles that will occur at a metal or composite temperature warmer than 110°F (45°C) specified in the User's Design Specification. If no cycles warmer than 110°F (45°C) are specified in the User's Design Specification because the vessel is operating in ambient conditions, the number of test cycles shall be calculated using the requirements of KD-1260 based on 10% of the total number of cycles. Designate the number of test cycles n_{t2}.

Step 5. Calculate the fraction of the total cyclic test requirement, T_{f1}, that will be achieved in the second portion of the test as $T_{f2} = n_{t2}/N_{t2}$.

Step 6. Repeat Steps 1 through 3 for each additional portion of the test (test cycles 1 through n).

Step 7. Add the fractions of the total cyclic test requirement for each portion of the test (each test cycle), $T_{ft} = T_{f1} + T_{f2} + \ldots T_{fn}$. Adjust the number of cycles to be achieved in each portion of the test until T_{ft} equals or exceeds 1.0.

(4) Hydrostatic Pressure Qualification Test. The Qualification Test Pressure is a pressure designated by the Manufacturer that shall be at least two times the design pressure for vessels to be installed at a fixed location. For vessels to be used in transport service, the Qualification Test Pressure shall be at least two times the design pressure or 2.5 times the service or working pressure, whichever is greater. This pressure shall be reported in the Qualification Test Report and recorded on Form CRPV-2A. At least one CRPV Prototype Vessel shall be subjected to hydrostatic pressure qualification tests after the cyclic pressure qualification tests as follows:

(-a) The test fluid shall be applied at a uniform rate to the Qualification Test Pressure, so that it is reached in not less than 60 sec and then it shall be held at this pressure for at least 60 sec. No leakage is permitted.

(-b) After the Qualification Test Pressure is held for a minimum of 60 sec the pressure shall be increased at a rate that is not greater than specified in (-a) until burst. The mode(s) of failure shall be characterized and the burst pressure and mode(s) of failure shall be reported in the Qualification Test Report and recorded on Form CRPV-2A.

PART KOP
OVERPRESSURE PROTECTION

ARTICLE KOP-1
GENERAL REQUIREMENTS

(25) KOP-100 GENERAL REQUIREMENTS

NOTE: Beginning with the 2021 Edition of Division 3, pressure relief device requirements were transferred from Part KR to Section XIII and the remaining Division 3 overpressure protection requirements were restructured within Part KOP. A complete cross-reference list of the changes between the 2019 and 2021 Editions is available in the Nonmandatory Appendix M of the 2021 Edition.

(a) This Part provides the acceptable methods and requirements for overpressure protection for pressure vessels constructed to the requirements of this Division. Acceptable methods include pressure relief devices and overpressure protection by system design (see Section XIII, Part 13). This Part establishes the type, quantity, and settings of acceptable pressure relief devices and relieving capacity requirements including maximum allowed relieving pressures. Unless otherwise specified, the required pressure relief devices shall be constructed, capacity certified, and bear the ASME Certification Mark in accordance with ASME BPVC, Section XIII. In addition, this Part provides requirements for installation of pressure relief devices.

(b) All pressure vessels within the scope of this Division shall be provided with protection against overpressure according to the requirements of this Part. Combination units (such as heat exchangers with shells designed for lower pressures than the tubes) shall be protected against overpressure from internal failures.

(c) In the case where a vessel is pressurized by an intensifier system whose output pressure to the vessel is a fixed multiple of the supply pressure, the pressure relief device may be located on the low pressure supply side of the intensifier if all the following requirements are met:

(1) There shall be no intervening stop valves or check valves between the driving chamber(s) and the relief device(s).

(2) Heating of the discharge fluid shall be controlled to prevent further pressure increase, which would exceed vessel design conditions.

(3) The discharge fluid shall be stable and nonreactive (water, hydraulic fluid, etc.).

(4) The material being processed in downstream equipment is stable and nonreactive or is provided with a suitable secondary vent system, which will effectively prevent transfer of secondary energy sufficient to overpressure the vessel.

The Designer is cautioned to consider the effects of leaking check valves in such systems.

KOP-110 DEFINITIONS

Unless otherwise defined in this Division, the definitions relating to pressure relief devices in Section XIII shall apply.

KOP-120 RESPONSIBILITIES (25)

(a) It is the responsibility of the User or the User's designated agent to identify all potential overpressure scenarios and the method of overpressure protection used to mitigate each scenario.

(b) It is the responsibility of the user to ensure that the required overpressure protection system is properly installed prior to initial operation.

(c) If a pressure relief device(s) is to be installed, it is the responsibility of the User or the User's designated agent to size and select the pressure relief device(s) based on its intended service. Intended service considerations shall include, but not necessarily be limited to, the following:

(1) normal operating and upset conditions
(2) fluids
(3) fluid phases

(d) The overpressure protection system need not be supplied by the vessel Manufacturer.

(e) The User or the User's designated agent shall be responsible for establishing a procedure for sizing, flow capacity calculations for the device, and associated flow paths, as well as changes in fluid conditions and properties as appropriate. These calculations shall be based on the most severe credible combinations of final compositions and resulting temperature. Alternatively, sizing shall be determined on an empirical basis by actual capacity

tests with the process in question at expected relieving conditions. The User shall be responsible for providing or approving the assumptions used in all flow capacity calculations. The User is cautioned that some fluids (e.g., ethylene) in the supercritical state behave more like liquids than gasses, so liquid or combination liquid/vapor trim values should be considered.

(25) KOP-130 DETERMINATION OF PRESSURE-RELIEVING REQUIREMENTS

(a) It is the responsibility of the User or the User's designated agent to identify all potential overpressure scenarios and the method of overpressure protection used to mitigate each scenario.

(b) The aggregate capacity of the pressure relief devices connected to any vessel or system of vessels for the release of a liquid, air, steam, or other vapor shall be sufficient to remove the maximum quantity that can be generated or supplied to the attached equipment without permitting a rise in pressure within the vessel of more than that specified in KOP-140.

(c) The rated pressure-relieving capacity of a pressure relief valve for other than steam or air shall be determined by the method of conversion given in Section XIII, Mandatory Appendix IV.

(25) KOP-140 OVERPRESSURE LIMITS

The aggregate capacity of the safety relief devices or vents shall be sufficient to prevent overpressures in excess of 10% above the design pressure of the vessel when the safety relief devices are discharging. The Designer shall consider the effects of the pressure drop in the overpressure protection system piping during venting when specifying the set pressures and flow capacities of pressure relief valves and rupture disk devices. When multiple pressure relief devices can discharge through a common stack or vent path, the maximum back pressure that can exist during simultaneous releases at the exit of each pressure relief device shall not impair its operation

KOP-150 PERMITTED PRESSURE RELIEF DEVICES AND METHODS

(25) KOP-151 GENERAL

Pressure relief valves, rupture disk devices, overpressure protection by system design, or a combination of protection methods may be used to protect against overpressure.

KOP-152 RUPTURE DISK DEVICES

(a) Because of the high pressures associated with this Division, it may be impractical to accomplish full-scale flow capacity performance testing and certification of pressure-relieving devices. For this reason, rupture disk devices may be the more commonly used means of overpressure protection for vessels within the scope of this Division.

The use of rupture disk devices may be advisable when very rapid rates of pressure rise could be encountered, or where the relief device must have intimate contact with the process stream. Intimate contact may be required to overcome inlet line fouling problems or to ensure that the temperature of the disk is the same as the interior temperature of the vessel.

(b) Rupture disk devices bearing the Certification Mark with the "UD3" Designator in accordance with Section XIII may be used.

(c) Rupture disk devices bearing the Certification Mark with the "UD" Designator in accordance with Section XIII may be used, provided the applicable requirements of Section XIII, Part 4 are met, including the specific requirements for Section VIII, Division 3.

(d) Rupture disk devices bearing the Certification Mark with the "UD3" Designator in accordance with Section XIII may incorporate a Manufacturer's standard rupture disk holder manufactured by a Manufacturer other than the rupture disk Manufacturer.

(e) The flow capacity of the rupture disk device shall be demonstrated by calculation to meet the requirements of KOP-140.

(1) The calculated capacity rating of the rupture disk device shall not exceed a value based on the applicable theoretical formula multiplied by a coefficient of discharge, *KD*, where *KD* = 0.62

(2) The Designer is responsible to evaluate the rupture disk and holder design to determine the applicable area to be used in the theoretical formula. The Designer is cautioned that normal capacity calculations may not be applicable for supercritical fluids and should consider the critical point and nonlinear thermodynamic properties of the fluid used in service. Flow through the entire relieving system shall be analyzed with due consideration for the wide variation in physical properties, which will occur due to the wide range of flowing pressures.

(3) Rupture disks may be certified as to burst pressure provided the test stand has enough volume to provide a complete burst. Flow coefficient (*Cp*, *K*, *LEQ*, percent open area) may be established at a lower pressure using any suitable fluid.

KOP-153 PRESSURE RELIEF VALVES (25)

(a) Pressure relief valves bearing the Certification Mark with the "UV3" Designator in accordance with Section XIII may be used. Pressure relief valves

bearing the Certification Mark with the "UV" Designator in accordance with Section XIII may be used, provided the applicable requirements of Section XIII, Part 3 are met, including specific requirements for Section VIII, Division 3. If the valve is the primary relief device [see KOP-154(c)], the requirements of Section XIII, Parts 9 and 10 for accreditation of testing laboratories and acceptance of Authorized Observers shall be met.

(b) All pressure relief valves shall meet the requirements of Section XIII, and shall be flow capacity performance tested and certified in accordance with Section XIII, Part 9, except in the case where their opening is not required to satisfy the overpressure limits given in KOP-140. See KOP-154(c) for further discussion about the use of relief valves in parallel with rupture disks.

(c) Pressure relief valves shall be the direct spring-loaded type.

KOP-154 COMBINATION DEVICES

A rupture disk device used in combination with a pressure relief valve may be advisable on vessels containing substances that may render a pressure relief valve inoperative by fouling, or where a loss of valuable material by leakage should be avoided, or where contamination of the atmosphere by leakage of noxious, flammable, or hazardous fluids must be avoided.

(a) Multiple rupture disk devices in parallel shall not be used on the inlet side of a pressure relief valve.

(b) When a combination device is used, both the rupture disk device and the pressure relief valve shall meet the applicable requirements of Part KOP and Section XIII. The rupture disk device shall be installed to prevent fragments from the rupture disk from interfering with the proper operation of the pressure relief valve. For additional requirements, see Section XIII, Part 8.

(c) A rupture disk device may be used in parallel with a pressure relief valve whose set pressure is lower than the rupture disk when it is important to limit the quantity of a release or it is impractical to certify the flow capacity of the pressure relief valve under the rules of this Division. The calculated flow capacity of the rupture disk device acting alone shall be adequate to meet the requirements of KOP-140, and the rupture disk device shall meet all the applicable requirements of this Part. With the exception of the flow capacity certification, the pressure relief valve shall meet all the requirements of this Part.

KOP-155 POWER-ACTUATED PRESSURE RELIEF SYSTEMS

Power-actuated pressure relief systems may be used in accordance with Article KOP-2.

KOP-156 OVERPRESSURE PROTECTION BY SYSTEM DESIGN (25)

Overpressure protection by system design in accordance with Section XIII, Part 13 is permitted.

(a) For vessels with overpressure protection by system design where the pressure is self-limited at or below the vessel design pressure (see Section XIII, 13.2), there shall be no credible overpressure scenario in which the pressure exceeds the design pressure of the pressurized equipment at the coincident temperature.

(b) For vessels with overpressure protection by system design where the pressure is not self-limited at or below the vessel design pressure (see Section XIII, 13.3), there shall be no credible overpressure scenario in which the pressure exceeds 110% of the design pressure times the ratio of the allowable stress value at the temperature of the overpressure scenario to the allowable stress value at the vessel design temperature. The overpressure limit shall not exceed the vessel test pressure.

KOP-160 PRESSURE SETTINGS AND PERFORMANCE REQUIREMENTS

(a) A single safety relief device shall open at a nominal pressure not exceeding the design pressure of the vessel at the operating temperature, except as permitted in (b) below.

Users are cautioned that certain types of rupture disks have manufacturing ranges that can result in a marked burst pressure greater than the specified burst pressure.

(b) If the required discharging capacity is supplied by more than one device, only one need be set to operate at a pressure not exceeding the design pressure of the vessel. The additional device or devices may be set at a higher pressure but not to exceed 105% of the design pressure of the vessel. The requirements of KOP-140 shall also apply.

(c) For CRPV in transport service, a single safety relief device may be set to open at a nominal pressure not exceeding 110% of the design pressure of the vessel at the operating temperature in lieu of the requirements in (a) above. The requirements of KOP-140 shall also apply.

(d) The pressure at which any device is set shall include the effects of superimposed back pressure through the pressure relief device and the vent system (see KOP-140).

(e) The set pressure tolerance of pressure relief valves shall not exceed ±3%.

(f) Rupture disk devices shall burst within a tolerance of ±5% of the marked burst pressure.

KOP-170 INSTALLATION

KOP-171 SIZE OF OPENINGS AND NOZZLES

The flow characteristics of the entire pressure-relieving system shall be part of the relieving capacity calculations. The size of nozzles and openings shall not adversely affect the proper operation of the pressure-relieving device.

KOP-172 INTERVENING STOP VALVES

There shall be no intervening stop valves between the vessel and any overpressure protection device associated with the vessel, except as permitted in KOP-173.

A full-area stop valve may be placed on the discharge side of a pressure-relieving device when its discharge is connected to a common header with other discharge lines from other pressure relief devices on vessels that are in operation, so that this stop valve when closed will prevent a discharge from any connected operating vessels from backing up beyond the valve so closed. Such a stop valve shall be so arranged that it can be locked or sealed in either the open or closed position by an authorized person. Under no condition shall this valve be closed while the vessel is in operation.

KOP-173 DUAL OVERPRESSURE PROTECTION

Where it is desirable to perform maintenance on pressure relief devices without shutting down the process, a full-area three-way transfer valve may be installed on the inlet of the pressure relief device(s). The design of the transfer valve and pressure relief devices must be such that the requirements of KOP-140 are met at any position of the transfer valve. Alternatively, the User may elect to install stop valves in each branch, but so controlled that one branch is open at all times and the requirements of KOP-140 are always met while the process is in operation.

ARTICLE KOP-2
REQUIREMENTS FOR POWER-ACTUATED PRESSURE RELIEF SYSTEMS

(25) KOP-200 GENERAL REQUIREMENTS

In accordance with the rules provided in this Article, a pressure vessel may be provided with overpressure protection by a power-actuated pressure relief system in lieu of a pressure relief valve, rupture disk, or other pressure relief devices if all provisions of Section XIII, Part 13 and KOP-140 are satisfied.

KOP-201 USER RESPONSIBILITIES

The User's Design Specification shall

(a) require overpressure protection by a power-actuated pressure relief system

(b) certify that the User will demonstrate the functioning of the system prior to initial operation and at least four times per year

KOP-202 MANUFACTURER'S RESPONSIBILITIES

(a) The Manufacturer's Design Report shall contain instructions for demonstration of the functioning of the system.

(b) The Manufacturer shall ensure that the Authorized Inspector witnesses the initial setting and verification of the functionality of each power-actuated pressure relief device.

(c) Overpressure protection provided by this Article shall be shown in the Manufacturer's Data Report.

(d) A detailed schematic of the control system shall be supplied with the vessel documentation.

(25) KOP-210 SYSTEM REQUIREMENTS

(a) The output from three independent devices shall be processed by an automated system. These devices shall be a combination of pressure transducers and elongation (strain) measuring devices as described in (1) and (2) below.

(1) Two pressure transducers and one elongation measuring device.

(2) Two elongation measuring devices and one pressure transducer.

(b) Any elongation measuring device shall be provided to continuously indicate the elongation (strain) of the vessel in a location where the elastic elongation (strain) of the vessel is linearly proportional to the pressure.

(1) Any elongation (strain) measuring device shall be designed and installed such that temperature does not affect the results.

(2) Means shall be provided to automatically reset the zero of the elongation measuring device(s) at the beginning of each pressurization cycle to maintain calibration.

(c) The pressure vessel shall be automatically depressurized under any of the following conditions:

(1) Any outputs (pressure transducer or elongation device) indicate that the pressure exceeds the limits in KOP-160(a) and KOP-160(b).

(2) Any of the three input signals are lost or fail for duration of 2 sec or more.

(3) Any pressure or elongation output deviates from any other output by more than 5%.

(d) There shall be at least two normally opened (NO) valves that are kept closed by the use of hydraulic or pneumatic pressure, so that both valves open (thereby lowering the vessel pressure) when the electrical signal to the valve is lost.

(e) The power-actuated pressure relief valves shall be designed to fail open, relieving the pressure in the pressure vessel in case of an electric, hydraulic, or pneumatic failure.

(f) The set pressure tolerance for the power-actuated pressure relief valves shall not exceed ±5% of the set pressure.

(g) The material for the portion of the valve that is exposed to the high-pressure fluid shall meet the material requirements in Part KOP.

(h) The stems of valves used in conjunction with power-actuated pressure relief systems that meet the requirements of Article KOP-2 may use materials meeting the requirements of Section XIII, 3.3.1(b), provided the following requirements are met:

(1) Failure of the valve stem shall result in depressurization of the system

(2) Any fluid that is released as a result of valve stem failure shall be directed away from personnel.

(3) Fluid released shall be nonhazardous

KOP-220 FLOW CAPACITY TESTING

(a) As an alternative to the flow capacity testing requirements of Section XIII, Part 9, the capacity of the power-actuated pressure relief valve may be demonstrated by tests on a prototype system. If any of the essential system design variables change, a new demonstration shall be required. The essential variables are

(1) an increase in vessel volume

(2) an increase in heating capacity

(3) an increase in pressure generator capacity

(4) a change in the relief flow path configuration that could reduce the flow capacity

(5) a change in the valve size or model number

(6) a change in any other variables that could increase the required relief capacity or reduce the furnished relief capacity of the system

The system shall be tested using most severe identifiable conditions in such a way that it can be demonstrated that the pressure will be limited to the overpressure required by KOP-140. The demonstration shall be witnessed by the Authorized Inspector.

(b) The results of the flow capacity demonstration and the setting and verification tests shall be documented in the Manufacturer's Design Report.

(c) Because the actual flow capacity test is performed on the entire system, the 10% derating factor required in Section XIII, 9.7.4 shall not apply.

ARTICLE KOP-3
OVERPRESSURE PROTECTION FOR IMPULSIVELY LOADED VESSELS

(25) KOP-300 GENERAL

Since impulsive pressure loading durations are short in comparison to the reaction time of overpressure protection systems, overpressure protection requirements for impulsively loaded vessels are provided in the following paragraphs. The User or the User's designated agent shall specify overpressure protection by administrative controls and system design, and shall reference this Article in writing in the purchase documents. The Manufacturer is responsible only for verifying that the User or the User's designated agent has specified overpressure protection by administrative controls and system design, and for listing this Article on the Manufacturer's Data Report.

(a) The User or the User's designated agent shall conduct a detailed analysis that examines all credible scenarios that could result in an overpressure condition. The "Causes of Overpressure" described in Section 4 of API Standard 521, "Pressure-Relieving and Depressurizing Systems" shall be considered. An organized, systematic approach by a multidisciplinary team employing one or more of the following methodologies shall be used:

(1) Hazards and Operability Analysis (HazOp)

(2) Failure Modes, Effects, and Criticality Analysis (FMECA)

(3) Fault Tree Analysis

(4) Event Tree Analysis

(5) "What-If" Analysis

In all cases, the User's or the User's designated agent shall determine the potential for overpressure due to all credible operating and upset conditions, including equipment and instrumentation malfunctions.

(b) The analysis described in (a) shall be conducted by an engineer experienced in the applicable analysis methodology. Any overpressure concerns that are identified shall be evaluated by an engineer experienced in pressure vessel design and analysis. The results of the analysis shall be documented and signed by the individual in charge of operation of the vessel. The documentation shall include

(1) detailed Process and Instrument Flow Diagrams (P&IDs), showing all pertinent elements of the system associated with the vessel

(2) a description of all credible operating and upset scenarios, including scenarios involving fire, and those that result from equipment and instrumentation malfunctions

(3) an analysis showing the maximum short-term impulsive loading and long-term pressure that can result from each of the scenarios examined in (2) above

(4) a detailed description of any administrative controls, or instrumentation and control system, or combination thereof, that is used to limit the impulsive loading and long-term pressure to the system, including the identification of all truly independent redundancies and a reliability evaluation (qualitative or quantitative) of the overall safety system

(c) The documentation shall be made available to the regulatory and enforcement authorities having jurisdiction at the site where the vessel will be installed. The User of this Article is cautioned that prior jurisdictional acceptance may be required.

(d) This Article shall be shown on the Manufacturer's Data Report for pressure vessels that will be provided with overpressure protection by administrative controls and system design, and it shall be noted on the Data Report that prior jurisdictional acceptance may be required.

PART KE
EXAMINATION REQUIREMENTS

ARTICLE KE-1
REQUIREMENTS FOR EXAMINATION PROCEDURES AND PERSONNEL QUALIFICATION

KE-100 GENERAL

Nondestructive examinations shall be conducted in accordance with the examination methods of Section V, except as modified by the requirements of this Article.

KE-101 RADIOGRAPHIC EXAMINATION

Radiographic examination shall be in accordance with Section V, Article 2, except that fluorescent screens are not permitted, the geometric unsharpness shall not exceed the limits of Section V, Article 2, T-285, and the image quality indicators of Table KE-101 (Table KE-101M) shall be used in lieu of those shown in Section V, Article 2, Table T-276.

KE-102 ULTRASONIC EXAMINATION

Ultrasonic examination shall be in accordance with Section V, Article 5.

KE-103 MAGNETIC PARTICLE EXAMINATION

Magnetic particle examination shall be in accordance with Section V, Article 7. If prods are used, the procedure shall include precautions that shall be taken to prevent arc strikes. This procedure shall also contain steps to be followed to remove arc strikes, which may occur so that all affected material has been removed. See KE-210.

KE-104 LIQUID PENETRANT EXAMINATION

Liquid penetrant examination shall be in accordance with Section V, Article 6.

(25) KE-105 EDDY CURRENT EXAMINATION

Eddy current examination shall be in accordance with Section V, Article 8 and Mandatory Appendix IV, Mandatory Appendix VI, Mandatory Appendix VII, Mandatory Appendix IX, or Mandatory Appendix X.

KE-106 NONDESTRUCTIVE EXAMINATION PROCEDURES (25)

(a) Except for nondestructive examination of material that is required by the referenced material specifications, all nondestructive examinations required by this Division shall be conducted in accordance with detailed written procedures that have been demonstrated to the satisfaction of the Inspector. The procedures shall comply with the appropriate article of Section V for the particular examination method. Written procedures and records of demonstration of procedure capability and records of personnel qualification to these procedures shall be made available to the Inspector and included in the Manufacturer's Construction Records (see KS-320).

(b) Following any nondestructive examination in which examination materials are applied to the part, the part shall be thoroughly cleaned in accordance with applicable material or procedure specifications.

KE-110 QUALIFICATION AND CERTIFICATION OF NONDESTRUCTIVE EXAMINATION PERSONNEL

KE-111 GENERAL

(a) Organizations performing and evaluating nondestructive examinations required by this Division shall use personnel qualified to the requirements of KE-112 through KE-115.

(b) When these services are subcontracted by the certificate holder (see KG-322), the certificate holder shall verify the qualification of personnel to the requirements of KE-112 through KE-115. All nondestructive examinations required by this subsection shall be performed by, and the results evaluated by, qualified nondestructive examination personnel.

(c) For nondestructive examination methods that consist of more than one operation or type, it is permissible to use personnel qualified to perform one or more

Table KE-101
Thickness, Image Quality Indicator Designations, Essential Holes, and Wire Diameters (U.S. Customary Units)

	Image Quality Indicator					
	Source Side			Film Side		
Single Wall Material Thickness Range, in.	Designation	Essential Hole	Wire Diameter, in.	Designation	Essential Hole	Wire Diameter, in.
Up to 1/4, incl.	8	2*T*	0.005	8	2*T*	0.005
Over 1/4 to 3/8	12	2*T*	0.008	10	2*T*	0.006
Over 3/8 to 1/2	15	2*T*	0.010	12	2*T*	0.008
Over 1/2 to 5/8	15	2*T*	0.010	12	2*T*	0.008
Over 5/8 to 3/4	17	2*T*	0.013	15	2*T*	0.010
Over 3/4 to 7/8	17	2*T*	0.013	15	2*T*	0.010
Over 7/8 to 1	20	2*T*	0.016	17	2*T*	0.013
Over 1 to 1 1/4	20	2*T*	0.016	17	2*T*	0.013
Over 1 1/4 to 1 3/8	25	2*T*	0.020	20	2*T*	0.016
Over 1 3/8 to 1 1/2	30	2*T*	0.025	25	2*T*	0.020
Over 1 1/2 to 2	35	2*T*	0.032	30	2*T*	0.025
Over 2 to 2 1/2	40	2*T*	0.040	35	2*T*	0.032
Over 2 1/2 to 3	40	2*T*	0.040	35	2*T*	0.032
Over 3 to 4	50	2*T*	0.050	40	2*T*	0.040
Over 4 to 6	60	2*T*	0.063	45	2*T*	0.040
Over 6 to 8	80	2*T*	0.100	50	2*T*	0.050
Over 8 to 10	100	2*T*	0.126	60	2*T*	0.063
Over 10 to 12	120	2*T*	0.160	80	2*T*	0.100
Over 12 to 16	160	2*T*	0.250	100	2*T*	0.126
Over 16 to 20	200	2*T*	0.320	120	2*T*	0.160

operations. As an example, one person may be used who is qualified to conduct radiographic examination and another may be used who is qualified to interpret and evaluate the radiographic film.

KE-112 QUALIFICATION PROCEDURE

(25) **KE-112.1 Qualification.** Personnel performing nondestructive examination in accordance with KE-112 and KE-113 shall be qualified and certified in accordance with the requirements of Section V, Article 1, T-120(e), T-120(f), T-120(g), T-120(i), T-120(j), or T-120(k), as applicable.

(a) Qualification of Level III nondestructive examination personnel shall be by examination.

(b) The written practice and the procedures used for examination of personnel shall be referenced in the Employer's Quality Control System.

(c) For visual examination, the Jaeger Number 1 letters shall be used as specified in Section V, Article 9, T-923. The use of equivalent type and size letters is permitted.

(d) A Level I individual shall be qualified to perform specified setups, calibrations, and tests, and to record and evaluate data by comparison with specific acceptance criteria defined in written instructions. The Level I individual shall implement these written NDE instructions under the guidance of a Level II or Level III individual. A Level I individual may independently accept the results of nondestructive examinations when the specific acceptance criteria are defined in the written instructions.

KE-112.2 Qualification to Perform Other NDE Methods. For nondestructive examination methods not covered by the referenced qualification documents, personnel shall be qualified to comparable levels of competency by subjection to comparable examinations on the particular method involved. The emphasis shall be on the individual's ability to perform the nondestructive examination in accordance with the applicable procedure for the intended application.

Table KE-101M
Thickness, Image Quality Indicator Designations, Essential Holes, and Wire Diameters (SI Units)

Single Wall Material Thickness Range, mm	Image Quality Indicator					
	Source Side			Film Side		
	Designation	Essential Hole	Wire Diameter, mm	Designation	Essential Hole	Wire Diameter, mm
Up to 6, incl.	8	2*T*	0.13	8	2*T*	0.13
Over 6 to 10	12	2*T*	0.20	10	2*T*	0.15
Over 10 to 13	15	2*T*	0.25	12	2*T*	0.20
Over 13 to 16	15	2*T*	0.25	12	2*T*	0.20
Over 16 to 19	17	2*T*	0.33	15	2*T*	0.25
Over 19 to 22	17	2*T*	0.33	15	2*T*	0.25
Over 22 to 25	20	2*T*	0.41	17	2*T*	0.33
Over 25 to 32	20	2*T*	0.41	17	2*T*	0.33
Over 32 to 35	25	2*T*	0.51	20	2*T*	0.41
Over 35 to 38	30	2*T*	0.64	25	2*T*	0.51
Over 38 to 50	35	2*T*	0.8	30	2*T*	0.64
Over 50 to 64	40	2*T*	1.0	35	2*T*	0.8
Over 64 to 76	40	2*T*	1.0	35	2*T*	0.8
Over 76 to 100	50	2*T*	1.3	40	2*T*	1.0
Over 100 to 150	60	2*T*	1.60	45	2*T*	1.0
Over 150 to 200	80	2*T*	2.5	50	2*T*	1.3
Over 200 to 250	100	2*T*	3.2	60	2*T*	1.60
Over 250 to 300	120	2*T*	4.0	80	2*T*	2.5
Over 300 to 400	160	2*T*	6.4	100	2*T*	3.20
Over 400 to 500	200	2*T*	8.1	120	2*T*	4.1

KE-113 CERTIFICATION OF PERSONNEL

(a) The Employer retains responsibility for the adequacy of the program and is responsible for certification of Levels, I, II, and III nondestructive examination personnel.

(b) When ASNT is the outside agency administering the Level III basic and method examinations, the Employer may use a letter from ASNT as evidence on which to base the certification.

(c) When an outside agency is the examining agent for Level III qualification of the Employer's personnel, the examination results shall be included with the Employer's records in accordance with KE-115.

KE-114 VERIFICATION OF NONDESTRUCTIVE EXAMINATION PERSONNEL CERTIFICATION (25)

The certificate holder has the responsibility to verify the qualification and certification of nondestructive examination personnel employed by Material Manufacturers and Material Suppliers and subcontractors who provide nondestructive examination services.

KE-115 RECORDS (25)

Personnel qualification records identified in the referenced qualification documents shall be retained by the Employer. See additional requirements in KE-106.

ARTICLE KE-2
REQUIREMENTS FOR EXAMINATION AND REPAIR OF MATERIAL

KE-200 GENERAL REQUIREMENTS

(a) Pressure-retaining material shall be examined by nondestructive methods applicable to the material and product form as required by the rules of this Article.

(b) The requirements of this Article for repair by welding, including examination of the repair welds, shall be met wherever repair welds are made to pressure-retaining material.

(c) The requirements of this Article shall apply to both Material Manufacturer and Manufacturer.

KE-201 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 Article for each product form after the quenching and tempering phase of the heat treatment.

KE-210 GENERAL REQUIREMENTS FOR REPAIR OF DEFECTS

(25) KE-211 ELIMINATION OF DEFECTS BY BLEND GRINDING

(a) Imperfections exceeding the acceptance criteria of KE-233.2 shall be considered defects. Such defects shall be removed or reduced to an acceptable sized imperfection. Defects may be removed by grinding or machining, provided the requirements of (1) through (4) are met.

(1) The remaining thickness of the section is not reduced below that required by Part KD, except as noted in (b).

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

(3) After defect elimination, the area is reexamined by a surface examination method in accordance with KE-233 to ensure that the imperfection has been removed or reduced to an acceptable size.

(4) Areas ground to remove oxide scale or other mechanically caused impressions for appearance or to facilitate proper ultrasonic testing need not be examined by a surface examination method in accordance with KE-233.

(b) Reduction in thickness due to blend grinding, below the minimum required by Part KD, is permitted within the limits stated below.

(1) Repair cavity diameter:

$$\mathrm{COD} = 0.2\sqrt{R_m t}$$

(2) Cavity depth below required thickness:

$$C_{\mathrm{depth}} = 0.02\sqrt{R_m t}$$

KE-212 REPAIR BY WELDING

(a) Except for materials in which welding is prohibited or restricted in Part KM, the Material Manufacturer may repair the material by welding after the defects have been removed. For restricted materials, see Article KF-7.

(b) The permitted depth of repair is given separately in this Article by product form.

(c) Prior approval of the certificate holder shall be obtained for the repair.

KE-212.1 Defect Removal. The defect shall be removed (25) by suitable mechanical, thermal cutting, or gouging methods and the cavity shall be prepared for repair. After thermal cutting, all slag and detrimental discoloration of material which has been molten shall be removed by mechanical means suitable for the material prior to weld repair. When thermal cutting is used, the effect on mechanical properties shall be taken into consideration. The surface to be welded shall be uniform and smooth. The cavity shall be examined by a surface examination method in accordance with KE-233.

KE-212.2 Qualification of Welding Procedures and Welders. The welding procedure and welders or welding operators shall be qualified in accordance with the requirements of Article KF-2 and Section IX, and meet the toughness requirements of Article KT-2.

KE-212.3 Blending of Repaired Areas. After repair, the surface shall be blended uniformly into the surrounding surface.

KE-212.4 Examination of Repair Welds. Each repair (25) weld shall be examined a surface examination method in accordance with KE-233. In addition, when the depth of the repair cavity exceeds the lesser of $^3/_8$ in. (10 mm) or 10% of the section thickness, the repair weld shall be ultrasonically examined after repair in

accordance with KE-102 and to the acceptance standards of KE-333.

KE-212.5 Heat Treatment After Repairs. The product shall be heat treated after repair in accordance with the heat treatment requirements of Article KF-4.

(25) KE-213 REPAIRS OF CLADDING

The Material Manufacturer may repair defects in cladding by welding provided the requirements of (a) through (c) are met.

(a) The welding procedure and the welders or welding operators shall be qualified in accordance with Article KF-2 and Section IX.

(b) The defect shall be removed, and the cavity prepared for repair shall be examined by a surface examination method in accordance with KE-233.

(c) The repaired area shall be examined by a surface examination method in accordance with KE-233.

KE-214 MATERIAL REPORT DESCRIBING DEFECTS AND REPAIRS

Each defect repair shall be described in the Material Test Report for each piece, including a chart which shows the location and size of the repair, the welding material identification, welding procedure, heat treatment, and examination results. The location of repairs shall be traceable to the completed vessel.

KE-220 EXAMINATION AND REPAIR OF PLATE

(25) KE-221 TIME OF EXAMINATION

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

(a) Ultrasonic examination shall be performed after rolling to size and after heat treatment, except postweld heat treatment.

(b) When radiographic examination of repair welds to plate is required, it shall be performed after postweld heat treatment.

(c) Surface examination of repair welds to plate shall be performed after final heat treatment (see KE-212.4).

KE-222 EXAMINATION PROCEDURES FOR SUBSURFACE IMPERFECTIONS

All plates shall be examined by the straight beam ultrasonic method in accordance with Section V, Article 23, SA-578, Standard Specification for Straight-Beam Ultrasonic Examination of Plain and Clad Steel Plates for Special Applications, except that the extent of examination and the acceptance standards to be applied are given in (a) and (b).

(a) Extent of Examination. One hundred percent of each major plate surface shall be covered by moving the search unit in parallel paths with not less than a 10% overlap. The location of all recordable indications as defined in Section V shall be documented.

(b) Acceptance Criteria

(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 1 in. (25 mm) shall be unacceptable.

(2) In addition, two or more imperfections smaller than described in (1) shall be unacceptable if they are separated by a distance less than the diameter of the larger imperfection or they may be collectively encompassed by the circle described in (1).

KE-223 REPAIR BY WELDING

The depth of the repair cavity shall not exceed one-third the nominal thickness of the plate and the repair shall be in accordance with KE-210.

KE-230 EXAMINATION AND REPAIR OF FORGINGS AND BARS (25)

(a) Forgings and bars shall be examined by the ultrasonic method in accordance with KE-232, except configurations which do not yield meaningful examination results by ultrasonic methods shall be examined by radiographic methods in accordance with Section V, Article 2 using the acceptance standards of KE-332. In addition, all external surfaces and accessible internal surfaces shall be examined by a surface examination method in accordance with KE-233.

(b) Forged flanges and fittings, such as elbows, tees, and couplings, shall be examined in accordance with the requirements of KE-240.

(c) Bar material used for bolting shall be examined in accordance with KE-260.

(d) Forgings and forged or rolled bars which are to be bored to form tubular products or fittings shall be examined in accordance with the requirements of KE-240 after boring.

KE-231 TIME OF EXAMINATION (25)

Acceptance examination, including those for repair welds, shall be performed at the time of manufacture as required in (a) through (d).

(a) Ultrasonic examination may be performed at any time after forging [see KE-230(d)] and the maximum practical volume shall be examined after final heat treatment, excluding postweld heat treatment.

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

(c) A surface examination method in accordance with KE-233 shall be performed in the finished condition. A welded joint surface may not require examination

when the weld surface is inaccessible [see KE-241(b), KE-251(a), and KE-502(a)].

(d) Forgings and rolled bars which are to be bored or turned to form tubular parts or fittings shall be examined after boring or turning, except for threading.

KE-232 ULTRASONIC EXAMINATION

KE-232.1 Examination Procedure. All forgings in the rough forged or finished condition, and bars, shall be examined in accordance with one of the following specifications: Section V, Article 23, SA-745, Standard Practice for Ultrasonic Examination of Austenitic Steel Forgings or Section V, Article 23, SA-388, Standard Practice for Ultrasonic Examination of Heavy Steel Forgings. Either contact, immersion, or water column coupling is permissible. The techniques of (a) through (d) are required, as applicable.

(a) All forgings and bars shall be examined by the ultrasonic method using the straight beam technique.

(b) Ring forgings and other hollow forgings shall, in addition, be examined using the angle beam technique in two circumferential directions, unless wall thickness or geometric configuration makes angle beam examination impractical.

(c) In addition to (a) and (b), ring forgings made to fine grain melting practices and used for vessel shell sections shall also be examined by the angle beam technique in two axial directions.

(d) Forgings may be examined by the use of alternative ultrasonic methods which utilize distance amplitude corrections, provided the acceptance standards are shown to be equivalent to those listed in KE-232.2.

KE-232.2 Acceptance Standards.

(a) Straight Beam General Rule. A forging shall be unacceptable if the results of straight beam examinations show one or more reflectors which produce indications accompanied by a complete loss of back reflection not associated with or attributable to geometric configurations. Complete loss of back reflection is assumed when the back reflection falls below 5% of full calibration screen height.

(b) Angle Beam Rule. A forging shall be unacceptable if the results of angle beam examinations show one or more reflectors which produce indications exceeding in amplitude the indication from the appropriate calibration notches (see KE-232.1).

(25) KE-233 SURFACE EXAMINATION

Surface examination of ferromagnetic materials shall be performed using a wet magnetic particle method or an eddy current method. A liquid penetrant method may be used for those portions of surfaces of ferromagnetic materials where it cannot be demonstrated that a wet magnetic particle method is capable of finding relevant surface defects.

Surface examination of nonferromagnetic material shall be performed using a liquid penetrant method or an eddy current method.

It shall be demonstrated that the inspections to be performed are capable of finding relevant surface indications as defined in KE-233.2(a).

KE-233.1 Evaluation of Indications. (25)

(a) For magnetic particle examinations, alternating current methods are prohibited. When utilizing magnetic particle examination, mechanical discontinuities at or near the surface will be indicated by the retention of the examination medium. However, all indications are not necessarily imperfections, since certain metallurgical discontinuities and magnetic permeability variations may produce similar indications which are not relevant to the detection of unacceptable discontinuities.

(b) When utilizing liquid penetrant examination, mechanical discontinuities at the surface will be indicated by bleeding out of the penetrant; however, localized surface imperfections, such as may occur from machining marks, surface conditions, or an incomplete bond between base metal and cladding, may produce similar indications which are not relevant to the detection of imperfections. Any indication in excess of the KE-233.2 acceptance standards which is believed to be nonrelevant shall be regarded as a defect and shall be reexamined by the same or other nondestructive examination methods to verify whether or not actual defects are present. Surface conditioning may precede the reexamination. Nonrelevant indications that would mask indications of defects are unacceptable.

(c) When eddy current examination is used, the method shall be in accordance with KE-105.

(d) Linear indications are indications in which the length is more than three times the width. Rounded indications are indications which are circular or elliptical with the length less than three times the width.

KE-233.2 Acceptance Standards.

(a) Only indications with major dimensions greater than $^{1}/_{16}$ in. (1.6 mm) shall be considered relevant.

(b) The relevant indications of (1) through (4) are unacceptable. More stringent acceptance criteria may be specified in the User's Design Specification. See KG-311.

(1) any linear indications greater than $^{1}/_{16}$ in. (1.6 mm) long for material less than $^{5}/_{8}$ in. (16 mm) thick, greater than $^{1}/_{8}$ in. (3.2 mm) long for material from $^{5}/_{8}$ in. (16 mm) thick to under 2 in. (50 mm) thick, and $^{3}/_{16}$ in. (4.8 mm) long for material 2 in. (50 mm) thick and greater

(2) rounded indications with dimensions greater than $^{1}/_{8}$ in. (3.2 mm) for thicknesses less than $^{5}/_{8}$ in. (16 mm) and greater than $^{3}/_{16}$ in. (4.8 mm) for thicknesses $^{5}/_{8}$ in. (16 mm) and greater

(3) four or more rounded indications in a line separated by $\frac{1}{16}$ in. (1.6 mm) or less, edge-to-edge

(4) ten or more rounded indications in any 6 in.^{2} (3 900 mm^2) of area whose major dimension is no more than 6 in. (150 mm), with the dimensions taken in the most unfavorable location relative to the indications being evaluated

KE-234 REPAIR BY WELDING

When repair by welding is not prohibited by Part KM or the product specification, the depth of repair is not limited except as by the product specification and shall be in accordance with KE-210.

KE-240 EXAMINATION AND REPAIR OF SEAMLESS AND WELDED (WITHOUT FILLER METAL) TUBULAR PRODUCTS AND FITTINGS

(25) KE-241 REQUIRED EXAMINATION

(a) Wrought seamless and welded (without filler metal) pipe and tubing shall be examined over the entire volume of the material in accordance with the applicable paragraph (1), (2), or (3). Tubular products may require both outside and inside surface conditioning prior to examination.

(1) Pipe and tubing smaller than 2$\frac{1}{2}$ in. (64 mm) O.D. shall be examined by the ultrasonic method in accordance with KE-242.1(a) in two opposite circumferential directions[11] and by the eddy current method in accordance with KE-244, provided the product is limited to sizes, materials, and thicknesses for which meaningful results can be obtained by eddy current examination. Each method shall be calibrated to the appropriate standard; that is, the ultrasonic method shall be calibrated to the axial notches or grooves of KE-242.2(b), and the eddy current method shall be calibrated to the circumferential notches and grooves as well as the radial hole of KE-244.2. As an alternative to the eddy current examination or when the eddy current examination does not yield meaningful results, an axial scan ultrasonic examination in two opposite axial directions in accordance with KE-242.1(b) shall be made.

(2) Pipe and tubing 2$\frac{1}{2}$ in. (64 mm) O.D. through 6$\frac{3}{4}$ in. (170 mm) O.D. shall be examined by the ultrasonic method in accordance with KE-242.1(a) in two opposite circumferential directions and in accordance with KE-242.1(b) in two opposite axial directions.

(3) Pipe and tubing larger than 6$\frac{3}{4}$ in. (170 mm) O.D. shall be examined by the ultrasonic method in two opposite circumferential directions in accordance with KE-242.1(c) or the radiographic method in accordance with KE-243. Alternatively, for welded without filler metal pipe larger than 6$\frac{3}{4}$ in. (170 mm) O.D., the plate shall be examined by the ultrasonic method in accordance with KE-220 prior to forming and the weld shall be examined by the radiographic method in accordance with KE-243. Radiographic examination of welds, including repair welds, shall be performed after final rolling and forming and may be performed prior to any required postweld heat treatment.

(b) Wrought seamless and welded without filler metal fittings (including pipe flanges and fittings machined from forgings and bars) shall be examined in accordance with the material specification and in addition by a surface examination method in accordance with KE-233 on all external surfaces and all accessible internal surfaces.

(c) Tubular products used for vessel nozzles shall be examined over the entire volume of material by either the ultrasonic method in two opposite circumferential directions in accordance with KE-242 or the radiographic method in accordance with KE-243, and shall be examined on all external and all accessible internal surfaces by a surface examination method in accordance with KE-233.

KE-242 ULTRASONIC EXAMINATION

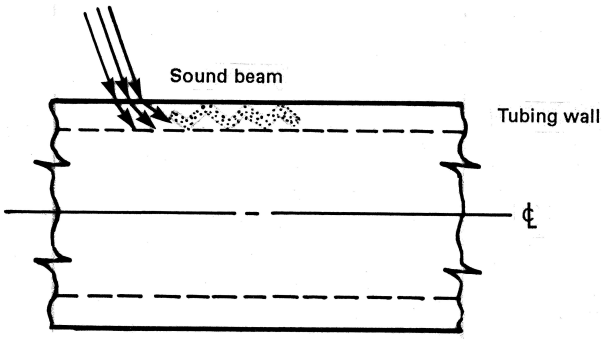
KE-242.1 Examination Procedure for Pipe and Tubing. Independent channels or instruments shall be employed for axial and circumferential scans.

(a) Circumferential Direction — 6$\frac{3}{4}$ in. (170 mm) O.D. and Smaller. The procedure for ultrasonic examination of pipe and tubing in the circumferential direction shall be in accordance with Section V, Article 23, SE-213, Standard Practice for Ultrasonic Inspection of Metal Pipe and Tubing, except as required in KE-241(a)(1) and KE-241(a)(2), and the requirements of this paragraph. The procedure shall provide a sensitivity which will consistently detect defects that produce indications equal to, or greater than, the indications produced by standard defects included in the reference specimens specified in KE-242.2.

(b) Axial Direction — 6$\frac{3}{4}$ in. (170 mm) O.D. and Smaller. When required by KE-241, the ultrasonic examination of pipe and tubing shall include angle beam scanning in the axial direction. The procedure for the axial scans shall be in accordance with SE-213 in Section V, except that the propagation of sound in the tube or pipe wall shall be in the axial direction instead of the circumferential direction and as required in KE-241(a). Figure KE-242.1 illustrates the characteristic oblique entry of sound into the pipe or tube wall in the axial direction of ultrasonic energy propagation to detect transverse notches.

(c) Pipe and Tubing Larger Than 6$\frac{3}{4}$ in. (170 mm) O.D. The procedure for ultrasonic examination of pipe and tubing larger than 6$\frac{3}{4}$ in. (170 mm) O.D. shall be in accordance either with the requirements of Section II, SA-388 for angle beam scanning in the circumferential direction or with the requirements of Section V, Article 23, SE-213, except as required in KE-241(a)(3). The reference standard shall be in accordance with KE-242.2.

Figure KE-242.1
Axial Propagation of Sound in Tube Wall



(d) Acceptance Standards. Products with defects that produce indications in excess of the indications produced by the standard defects in the referenced specimen are unacceptable.

KE-242.2 Reference Specimens. The reference specimen shall be of the same nominal diameter and thickness, and of the same nominal composition and heat-treated condition, as the product which is being examined.

(a) For circumferential scanning, the standard defects shall be axial notches or grooves on the outside and inside surfaces of the reference specimen and shall have a length of approximately 1 in. (25 mm) or less, a width not to exceed $\frac{1}{16}$ in. (1.6 mm) for a square notch or U-notch, a width proportional to the depth for a V-notch, and depth not greater than the larger of 0.004 in. (0.10 mm) or 3% of the nominal wall thickness.

(b) For axial scanning in accordance with Section V, Article 23, SE-213, a transverse (circumferential) notch shall be introduced on the inner and outer surfaces of the standard. Dimensions of the transverse notch shall not exceed those of the longitudinal notch. The reference specimen may be the product being examined.

(c) The reference specimen shall be long enough to simulate the handling of the product being examined through the examination equipment. When more than one standard defect is placed in a reference specimen, the defects shall be located so that indications from each defect are separate and distinct without mutual interference or amplification. All upset metal and burrs adjacent to the reference notches shall be removed.

KE-242.3 Checking and Calibration of Equipment. The proper functioning of the examination equipment shall be checked and the equipment shall be calibrated by the use of the reference specimens, as a minimum

(a) at the beginning of each production run of a given size and thickness of given material

(b) after each 4 hr or less during the production run;

(c) at the end of the production run

(d) at any time that malfunctioning is suspected

If, during any check, it is determined that the testing equipment is not functioning properly, all of the product that has been tested since the last valid equipment calibration shall be reexamined.

KE-243 RADIOGRAPHIC EXAMINATION

The radiographic examination shall be performed in accordance with Section V, Article 2, as modified by KE-101, using the acceptance requirements of KE-332.

KE-244 EDDY CURRENT EXAMINATION

The requirements for eddy current examination are given in KE-244.1 through KE-244.3.

KE-244.1 Examination Procedure. The procedure for eddy current examination shall provide a sensitivity that will consistently detect defects by comparison with the standard defects included in the reference specimen specified in KE-244.2. Products with defects that produce indications in excess of the reference standards are unacceptable unless the defects are eliminated or repaired in accordance with KE-246.

KE-244.2 Reference Specimen. The reference specimen shall be a piece of, and shall be processed in the same manner as, the product being examined. The standard defects shall be circumferential or tangential notches or grooves on the outside and the inside surfaces of the product and shall have a length of approximately 1 in. (25 mm) or less, a width not to exceed $\frac{1}{16}$ in. (1.6 mm), a depth not greater than the larger of 0.004 in. (0.10 mm) or 5% of the wall thickness, and a radial hole having a nominal diameter of $\frac{1}{16}$ in. (1.6 mm) or less. The size of reference specimens shall be as specified in KE-242.2.

KE-244.3 Checking and Calibration of Equipment. The checking and calibration of examination equipment shall be the same as in KE-242.3.

KE-245 TIME OF EXAMINATION

Time of acceptance examination, including that of repair welds, shall be in accordance with KE-231.

KE-246 REPAIR BY WELDING

When repair by welding is not prohibited by Part KM or the product specification, the depth of repair is not limited except as by the product specification and shall be in accordance with KE-210.

KE-250 EXAMINATION AND REPAIR OF TUBULAR PRODUCTS AND FITTINGS WELDED WITH FILLER METAL

(25) KE-251 REQUIRED EXAMINATION

(a) All welds shall be examined 100% by radiography in accordance with the method and acceptance requirements of the material specification. All external weld surfaces and accessible internal weld surfaces shall be examined by a surface examination method in accordance with KE-233. When radiographic examination of welds is not specified in the material specification, the welds shall be examined by radiography in accordance with the requirements of Section V, Article 2, as modified by KE-111 using the acceptance standards of KE-332. The radiographic film and a radiographic report showing film locations shall be provided with the Material Test Report.

(b) Plate for these products shall be examined by ultrasonic methods in accordance with KE-220 or the finished product shall be examined in accordance with KE-242.

(25) KE-252 TIME OF EXAMINATION

Acceptance examinations, including those for repair welds, shall be performed at the time of manufacture as specified in (a) through (c).

(a) Ultrasonic examination of plate shall be performed at the time as specified in KE-221, or, if the finished product is examined, the time of examination shall be after final rolling and forming.

(b) Radiographic examination of welds, including repair welds, shall be performed after final rolling and forming and may be performed prior to any required postweld heat treatment.

(c) A surface examination of welds in accordance with KE-233, including repair welds, shall be performed after heat treatment, except the examination may be performed prior to postweld heat treatment of P-No. 1 material.

KE-253 REPAIR BY WELDING

When repair by welding is not prohibited by Part KM, or the product specification, the depth of repair is not limited except as by the product specification and shall be in accordance with KE-210.

KE-260 EXAMINATION OF BOLTS, STUDS, AND NUTS

KE-261 REQUIRED EXAMINATION

(a) All bolting materials shall be visually examined.

(b) Nominal sizes greater than 1 in. (25 mm) shall be examined by either the magnetic particle or liquid penetrant method.

(c) Nominal sizes greater than 2 in. (50 mm) shall be examined by ultrasonic methods in accordance with KE-264 and KE-265.

KE-262 VISUAL EXAMINATION

The areas of threads, shanks, and heads of final machined parts shall be visually examined. Harmful discontinuities such as laps, seams, or cracks that would be detrimental to the intended service are unacceptable.

KE-263 MAGNETIC PARTICLE OR LIQUID PENETRANT EXAMINATION (25)

All bolts, studs, and nuts greater than 1 in. (25 mm) nominal bolt size shall be examined by a surface examination method in accordance with KE-233. Such examination shall be performed on the finished bolting after threading, or on the material stock at approximately the finished diameter before threading, and after heading, if this process is used. Any indications shall be unacceptable.

KE-264 ULTRASONIC EXAMINATION FOR SIZES GREATER THAN 2 IN. (50 MM)

All bolts, studs, and nuts greater than 2 in. (50 mm) nominal size shall be ultrasonically examined over the entire surface prior to threading in accordance with the requirements of KE-264.1 through KE-264.4.

KE-264.1 Ultrasonic Method. Examination shall be carried out by the straight beam, radial scan method.

KE-264.2 Examination Procedure. Examination shall be performed at a nominal frequency of 2.25 MHz with a search unit not to exceed 1 in.^{2} (650 mm^2) in area.

KE-264.3 Calibration of Equipment. Calibration sensitivity shall be established by adjustment of the instrument so that the first back screen reflection is 75–90% of full screen height.

KE-264.4 Acceptance Standards. Any discontinuity which causes an indication in excess of 20% of the height of the first back reflection or any discontinuity which prevents the production of a first back reflection of 50% of the calibration amplitude is not acceptable.

KE-265 ULTRASONIC EXAMINATION FOR SIZES OVER 4 IN. (100 MM)

In addition to the requirements of KE-264, all bolts, studs, and nuts over 4 in. (100 mm) nominal size shall be ultrasonically examined over an entire end surface before or after threading in accordance with the requirements of KE-265.1 through KE-265.4.

KE-265.1 Ultrasonic Method. Examination shall be carried out by the straight beam, longitudinal scan method.

KE-265.2 Examination Procedure. Examination shall be performed at a nominal frequency of 2.25 MHz with a search unit not to exceed 0.5 in.^{2} (320 mm^2).

KE-265.3 Calibration of Equipment. Calibration shall be established on a test bar of the same nominal composition and diameter as the production part and a minimum of one-half of the length. A $\frac{3}{8}$ in. (10 mm) diameter × 3 in. (76 mm) deep flat bottom hole shall be drilled in one end of the bar and plugged to full depth. A distance amplitude correction curve shall be established by scanning from both ends of the test bar.

KE-265.4 Acceptance Standards. Any discontinuity which causes an indication in excess of that produced by the calibration hole in the reference specimen as corrected by the distance amplitude correction curve is not acceptable.

KE-266 REPAIR BY WELDING

Weld repair of bolts, studs, and nuts is not permitted.

(25) KE-270 EXAMINATION OF CASTINGS

KE-271 GENERAL REQUIREMENTS

Nondestructive examination shall be conducted in accordance with the examination methods of Section V except as modified by the requirements of KE-271 and KE-272.

Castings shall be examined by the ultrasonic method in accordance with KE-272. Configurations that do not yield meaningful examination results by ultrasonic methods shall be examined by radiographic methods in accordance with Section V, Article 2 using acceptance standards of KE-332. In addition, all external surfaces shall be examined by a surface examination method in accordance with KE-233.

KE-272 ULTRASONIC EXAMINATION REQUIREMENTS

KE-272.1 Examination Procedure. All castings shall be examined on all external surfaces and all accessible internal surfaces in accordance with SA-609/SA-609M as shown in Section V, Article 23, both by the straight beam technique and the angle beam technique. The angle beam examination shall be in two circumferential directions and two axial directions.

KE-272.2 Acceptance Criteria. The casting wall thickness shall be divided into thirds: Zone A covers the thirds adjacent to the external and internal surfaces, and Zone B covers the central third.

(a) Straight Beam Rule. A casting shall be unacceptable if the results of straight beam examinations show one or more reflectors of measurable length that produce indications, accompanied by a complete loss of back-wall reflection not associated with or attributable to geometric configurations. Complete loss of back-wall reflection is assumed when the back-wall reflection falls below 5% of full calibration screen height. A casting shall also be unacceptable if the results of the straight beam examinations show one or more reflectors that either

(1) produce a 75% or greater loss of back-wall reflection that has been determined to be caused by a discontinuity, or

(2) show a response equal to or greater than the dynamic amplitude correction curve over an area specified by quality level 1 in Zone A and quality level 2 in Zone B, where the quality levels are as defined in SA-609/SA-609M, Table 2.

(b) Angle Beam Rule. A casting shall be unacceptable if the results of angle beam examinations show one or more reflectors that produce indications exceeding in amplitude the indication from the appropriate calibration notches over an area specified by quality level 1 in Zone A and quality level 2 in Zone B, where the quality levels are as defined in SA-609/SA-609M, Table 2.

More stringent acceptance criteria may be specified in the User's Design Specification.

KE-273 REMOVAL OF FLAWS

(a) It will generally be necessary to machine external surfaces to remove surface casting imperfections. Any remaining surface flaws more than $\frac{1}{8}$ in. (3 mm) in height shall be removed by grinding and blending.

(b) Reduction in thickness due to blending is permitted to the extent given in KE-211. Any greater blending shall be included in the component structural assessment as a change in geometry, but such blending shall not exceed one-quarter of the thickness or extend over a length greater than 4 in. (100 mm). After defect elimination, the area is to be reexamined by the magnetic particle method or the liquid penetrant method in accordance with KE-233 to ensure that the imperfection has been removed or reduced to an acceptable size.

ARTICLE KE-3
EXAMINATION OF WELDS AND ACCEPTANCE CRITERIA

(25) KE-300 EXAMINATION OF WELDS AND WELD OVERLAY

Acceptance examinations of welds and weld overlay shall be performed at the times stipulated in (a) through (f) during fabrication and installation, except as otherwise specified in KE-310 and KE-400.

(a) All butt joints shall be ultrasonically examined after completion of all required heat treatment. Where ultrasonic examination cannot resolve embedded flaws in the performance qualification block, or weld joint and/or vessel geometry prohibits ultrasonic examination, radiographic examination shall be performed.

(b) A surface examination of welds in accordance with KE-233, including plate weld repair, shall be performed after any required postweld heat treatment, except that welds in P-No. 1 material may be examined either before or after postweld heat treatment. The surface examination of welds at progressive states of welding may be performed before PWHT. A welded joint surface may not require examination when the weld surface is inaccessible [see KE-241(b), KE-251(a), and KE-502(a)].

(c) The surface examination of weld surfaces that are to be covered with weld overlay shall be performed before the weld overlay is deposited. The surface examination of weld surfaces that are not accessible after a postweld heat treatment shall be performed prior to postweld heat treatment. These examinations may be performed before PWHT.

(d) Weld overlay shall be examined after completion of all required heat treatment by a surface examination method in accordance with KE-233.

(e) All of the joints in austenitic stainless steel and nonferrous material shall be examined by the liquid penetrant method after final postweld heat treatment, if any, is performed. A welded joint surface may not require examination when the weld surface is inaccessible [see KE-241(b), KE-251(a), and KE-502(a)].

(f) Examination of weld joints when required in ferritic steels with tensile properties enhanced by quenching and tempering shall be made after all weld overlay has been deposited, and all required heat treatment has been performed.

KE-301 REQUIREMENTS FOR ULTRASONIC EXAMINATIONS OF WELDS (25)

(a) For welds in wrought product forms, both straight beam and angle beam examinations shall be required. The ultrasonic examination area shall include the volume of the weld, plus 2 in. (50 mm) on each side of the weld. The straight beam examinations shall include the volume of the base metal through which subsequent shear wave shall pass. These examinations shall be performed in accordance with procedures agreed upon by the Manufacturer and User, and shall meet the requirements of Section V, Article 4.

(b) A documented examination strategy or scan plan shall be provided showing transducer placement, movement, and component coverage that provides a standardized and repeatable methodology for weld acceptance. The scan plan shall include ultrasonic beam angle used, beam directions with respect to weld centerline, and vessel volume examined for each weld. The documentation shall be made available to the purchaser upon request.

(c) The ultrasonic examination shall be performed in accordance with a written procedure conforming to the requirements of Section V, Article 4, Mandatory Appendix VIII or Mandatory Appendix XI. The procedure shall have been demonstrated to perform acceptably on qualification blocks. Acceptable performance is defined as response from the maximum allowable flaw and other flaws of interest demonstrated to exceed the reference level. Alternatively, for techniques that do not use amplitude recording levels, acceptable performance is defined as demonstrating that all imaged flaws with recorded lengths, including the maximum allowable flaws, have an indicated length equal to or greater than the actual length of the flaws in the qualification block.

(d) The ultrasonic examination shall be performed using a device employing automatic computer based data acquisition. The initial straight beam material examination (Section V, Article 4, T-472) for reflectors that could interfere with the angle beam examination shall be performed

(1) manually,

(2) as part of a previous manufacturing process, or

(3) during the automatic UT examination provided detection of these reflectors is demonstrated in accordance with (c).

(e) Data shall be recorded in unprocessed form. A complete data set with no gating, filtering, or thresholding for response from examination of the volume in (a) above shall be included in the data record.

(f) Personnel performing and evaluating UT examinations shall be qualified and certified in accordance with their employer's written practice as specified in Section V, Article 1, T-120(e) or T-120(f). Only Level II or Level III personnel shall analyze the data or interpret the results.

(g) When the UT examination is contracted by others, contractor qualification records of certified personnel shall be approved by the Certificate Holder and maintained by their employer.

(h) Personnel who acquire and analyze UT data shall be trained using the equipment in (d) above, and shall participate in the demonstration of (c) above.

(i) Data analysis and acceptance criteria shall be as follows:

(1) Data Analysis Criteria. Reflectors exceeding the limits in either (-a) or (-b) below, as applicable, shall be investigated to determine whether the indication originates from a flaw or is a geometric indication in accordance with (2) below. When a reflector is determined to be a flaw, it shall be evaluated for acceptance in accordance with KE-333.

(-a) For amplitude-based techniques, the location, amplitude, and extent of all reflectors that produce a response greater than 20% of the reference level shall be investigated.

(-b) For nonamplitude-based techniques, the location and extent of all images that have an indicated length greater than the limits in (-1), (-2), or (-3) below, as applicable, shall be investigated.

(-1) For welds in material equal to or less than 1½ in. (38 mm) thick at the weld, images with indicated lengths greater than 0.150 in. (3.8 mm) shall be investigated.

(-2) For welds in material greater than 1½ in. (38 mm) thick but less than 4 in. (100 mm) thick at the weld, images with indicated lengths greater than 0.200 in. (5 mm) shall be investigated.

(-3) For welds in material greater than 4 in. (100 mm) thick at the weld, images with indicated lengths greater than 0.05t or 0.75 in. (19 mm), whichever is smaller, shall be investigated (t = nominal material thickness adjacent to the weld).

(2) Geometric. Ultrasonic indications of geometric and metallurgical origin shall be classified as follows:

(-a) Indications that are determined to originate from the surface configurations (such as weld reinforcement or root geometry) or variations in metallurgical structure of materials (such as cladding to base metal interface) may be classified as geometric indications, and

(-1) need not be characterized or sized in accordance with (3) below;

(-2) need not be compared to allowable flaw acceptance criteria listed in Table KE-301-1 or Table KE-301-2 or developed in accordance with KD-450;

(-3) shall have the maximum indication amplitude and location recorded, for example: internal attachments, 200% DAC maximum amplitude, 1 in. (25 mm) above the weld centerline, on the inside surface, from 90 deg to 95 deg.

(-b) The following steps shall be taken to classify an indication as geometric:

(-1) Interpret the area containing the reflector in accordance with the applicable examination procedure.

(-2) Plot and verify the reflector coordinates, provide a cross-sectional display showing the reflector position and surface discontinuity such as root or counterbore.

(-3) Review fabrication or weld prep drawings.

(-c) Alternatively, other NDE methods or techniques may be applied to classify an indication as geometric (e.g., alternative UT beam angles, radiography, I.D. profiling, or O.D. profiling).

(3) Flaw Sizing. Flaws shall be sized in accordance with a procedure demonstrated to size similar flaws at similar material depths. Alternatively, a flaw may be sized by a supplemental manual technique as long as it has been qualified by the demonstration of (c) above. The dimensions of the flaw shall be determined by the rectangle that fully contains the area of the flaw. (Refer to Figures KE-301-1 through KE-301-7.)

(-a) The length (l) of the flaw shall be drawn parallel to the inside pressure-retaining surface of the component.

(-b) The depth of the flaw shall be drawn normal to the inside pressure-retaining surface and shall be denoted as "a" for a surface flaw or "2a" for a subsurface flaw.

(-c) Subsurface flaw(s) close to a surface shall be considered surface flaw(s) if the distance between the flaw and the nearest surface is equal to or less than one-half the flaw through-wall dimension as shown in Figure KE-301-1.

(-d) Subsurface flaws with S/a greater than 1.0 and surface flaws shall be evaluated for acceptance in accordance with the criteria of Table KE-301-1 or Table KE-301-2 (or Figure KE-301-2 or Figure KE-301-3) or criteria for smaller flaws as specified by the Manufacturer performing an analysis in accordance with KD-411.

(-e) Alternative weld flaw size acceptance criteria may be generated by a Manufacturer using the methods of KD-450 in lieu of the requirements of (-d).

(-1) Interpolation between aspect ratios in the table generated in accordance with KD-451 is permitted.

(-2) All flaws with aspect ratios larger or smaller than those in the table generated shall be considered relevant by the examiner and documented.

(-3) Any flaws detected with aspect ratios larger or smaller than those in the table generated in accordance with KD-451 shall be evaluated using a specific fracture

Table KE-301-1
Flaw Acceptance Criteria for 1 in. (25 mm) to 12 in. (300 mm) Thick Weld

	1 in. (25 mm) ≤ t ≤ 2½ in. (64 mm)		4 in. (100 mm) ≤ t ≤ 12 in. (300 mm)	
Aspect Ratio, a/ℓ	Surface Flaw, a/t	Subsurface Flaw, a/t	Surface Flaw, a/t	Subsurface Flaw, a/t
0.00	0.031	0.034	0.019	0.020
0.05	0.033	0.038	0.020	0.022
0.10	0.036	0.043	0.022	0.025
0.15	0.041	0.049	0.025	0.029
0.20	0.047	0.057	0.028	0.033
0.25	0.055	0.066	0.033	0.038
0.30	0.064	0.078	0.038	0.044
0.35	0.074	0.090	0.044	0.051
0.40	0.083	0.105	0.050	0.058
0.45	0.085	0.123	0.051	0.067
0.50	0.087	0.143	0.052	0.076

GENERAL NOTES:
(a) See Figure KE-301-2, illustration (a) and Figure KE-301-3, illustration (a).
(b) t = thickness of the weld excluding any allowable reinforcement. For a buttweld joining two members having different thickness at the weld, t is the thinner of these two thicknesses. If a full penetration weld includes a fillet weld, the thickness of the throat of the fillet weld shall be included in t.
(c) S is the distance of the indication from the nearest surface of the component (see Figure KE-301-1).
(d) For intermediate flaw aspect ratio a/ℓ, and thickness t [2½ in. (64 mm) < t < 4 in. (100 mm)], linear interpolation is permissible.
(e) If the acceptance criteria in this table results in a flaw length, ℓ, less than 0.25 in. (6.4 mm), a value of 0.25 in. (6.4 mm) may be used.
(f) This table is only applicable to a material thickness of 8 in. (200 mm) or thinner if the specified minimum tensile strength is greater than 95 ksi (655 MPa).
(g) This table is only applicable to a material thickness of 8 in. (200 mm) or thinner if PWHT is not undertaken.

Table KE-301-2
Flaw Acceptance Criteria for 16 in. (400 mm) Thick Weld

	Surface Flaw, a		Subsurface Flaw, a	
Aspect Ratio, a/ℓ	in.	mm	in.	mm
0.00	0.228	5.79	0.240	6.10
0.05	0.240	6.10	0.264	6.71
0.10	0.264	6.71	0.300	7.62
0.15	0.300	7.62	0.348	8.84
0.20	0.336	8.53	0.396	10.1
0.25	0.396	10.1	0.456	11.6
0.30	0.456	11.6	0.528	13.4
0.35	0.528	13.4	0.612	15.5
0.40	0.612	15.5	0.696	17.7
0.45	0.618	15.7	0.804	20.4
0.50	0.624	15.9	0.912	23.6

GENERAL NOTES:
(a) See Figure KE-301-2, illustrations (b) and (c) and Figure KE-301-3, illustrations (b) and (c).
(b) For intermediate flaw aspect ratio, a/ℓ linear interpolation is permissible.
(c) t = the thickness of the weld excluding any allowable reinforcement. For a buttweld joining two members having different thickness at the weld, t is the thinner of these two thicknesses. If a full penetration weld includes a fillet weld, the thickness of the throat of the fillet weld shall be included in t.
(d) S is the distance of the indication from the nearest surface of the component (see Figure KE-301-1).
(e) This table is applicable to materials with specified minimum tensile strength no greater than 95 ksi (655 MPa).
(f) If a thickness is larger than 16 in. (400 mm), flaw acceptance values for a thickness of 16 in. (400 mm) shall be used.
(g) When the thickness is larger than 12 in. (300 mm) and less than 16 in. (400 mm), linear interpolation between values for 12 in. (300 mm) in Table KE-301-1 and those for 16 in. (400 mm) in Table KE-301-2 is permissible.
(h) This table is not applicable if PWHT is not undertaken.

mechanics calculation to determine whether they are acceptable.

(25) KE-302 REQUIREMENTS FOR PERFORMANCE QUALIFICATION BLOCK

The qualification blocks shall be prepared by welding and shall contain at least three flaws, oriented to simulate flaws parallel to the production weld's fusion line as follows:

(a) The qualification block shall contain at least three planar flaws. The primary weld preparation angle shall be represented by at least two embedded flaws oriented with ±10 deg of the weld preparation angle. One flaw shall be located near the midpoint of the top one-third of the qualification block (representing the O.D.), one flaw shall be located near mid-thickness of the qualification block, and one flaw shall be located near the midpoint of the bottom one-third of the qualification block (representing I.D.).

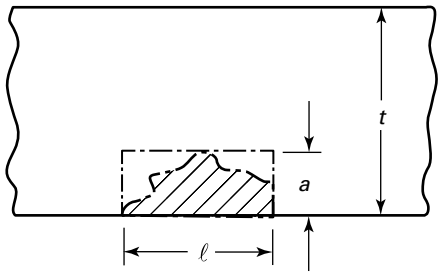
(b) The material of the qualification block shall meet the P-Number requirements of Section V, Article 5.

(c) The thickness of the qualification block shall be within ±25% of the actual final thickness of the thickest weld to be examined in the pressure vessel.

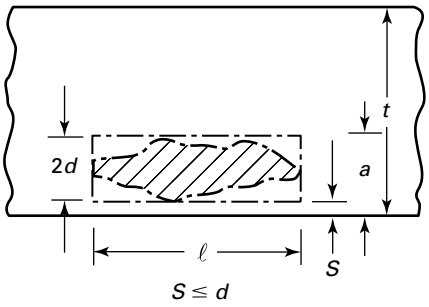
(d) The embedded planar flaws in the qualification block may be natural or artificial and must be fully characterized in location, orientation (angular rotation in horizontal and vertical axis), and reflecting area.

(e) Flaw size shall be no larger than the flaw sizes listed in Table KE-301-1 or Table KE-301-2 or developed in accordance with KD-450 for the thickness to be examined.

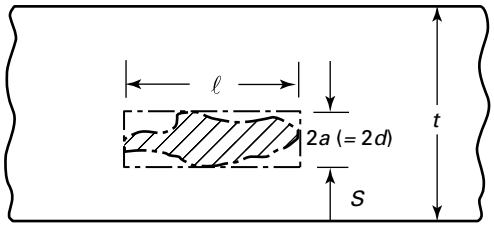
Figure KE-301-1
Flaw Classification of Single Indication



(a) Surface Indication



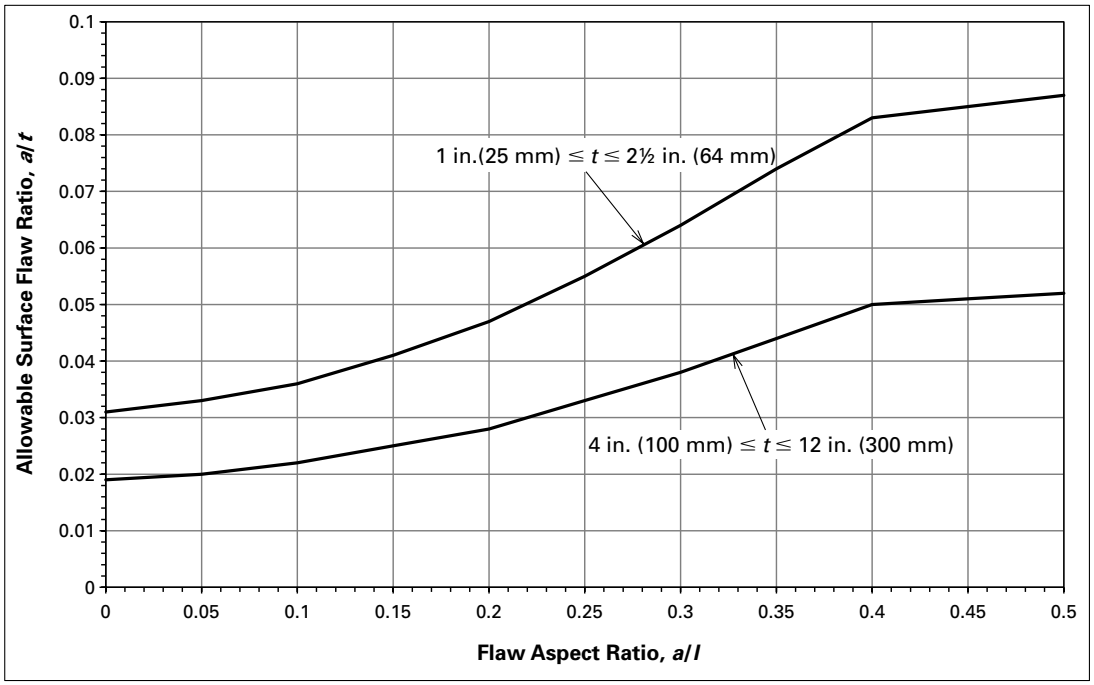
(b) Surface Indication



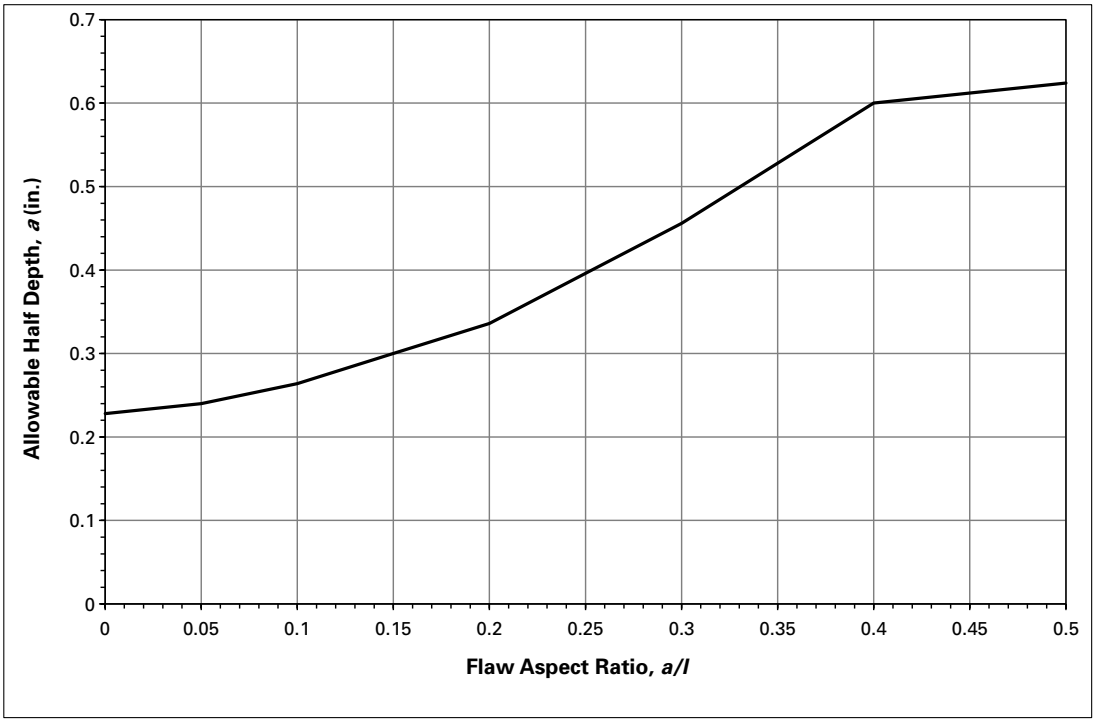
$S > a$

(c) Subsurface Indication

Figure KE-301-2
Surface Flaw Acceptance Criteria

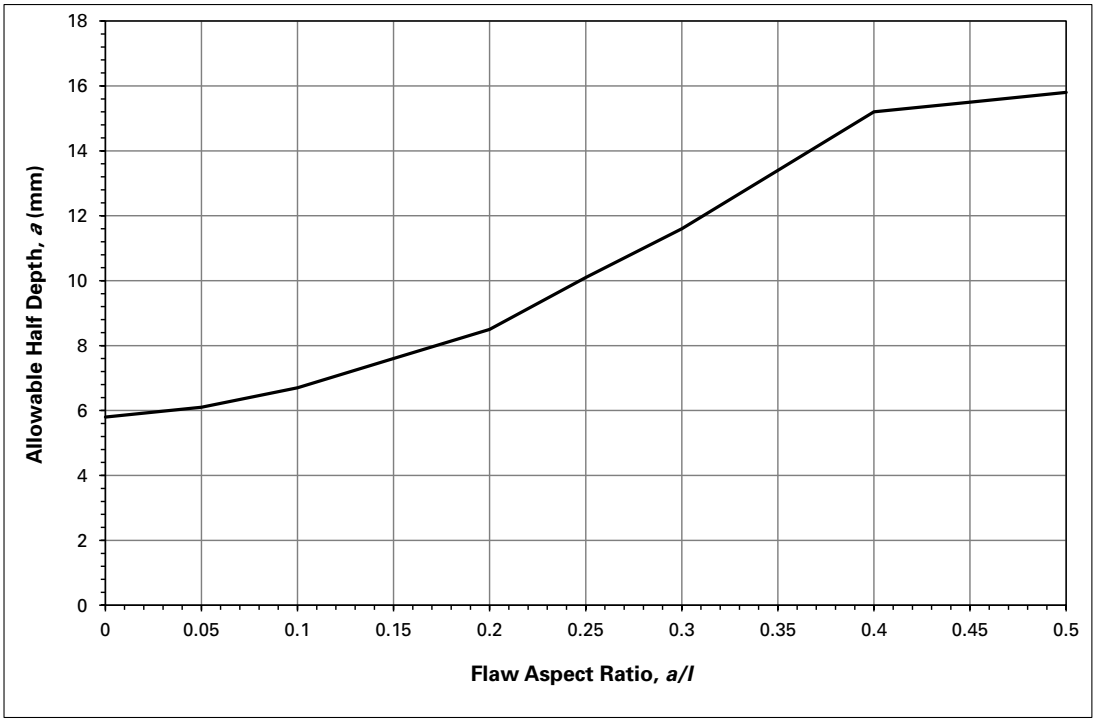


(a) For Weld Thickness 1 in. (25 mm) ≤ *t* ≤ 2½ in. (64 mm) and 4 in. (100 mm) ≤ *t* ≤ 12 in. (300 mm) [Note (1)]



(b) For Weld Thickness *t* = 16 in. (400 mm) [Note (2)]

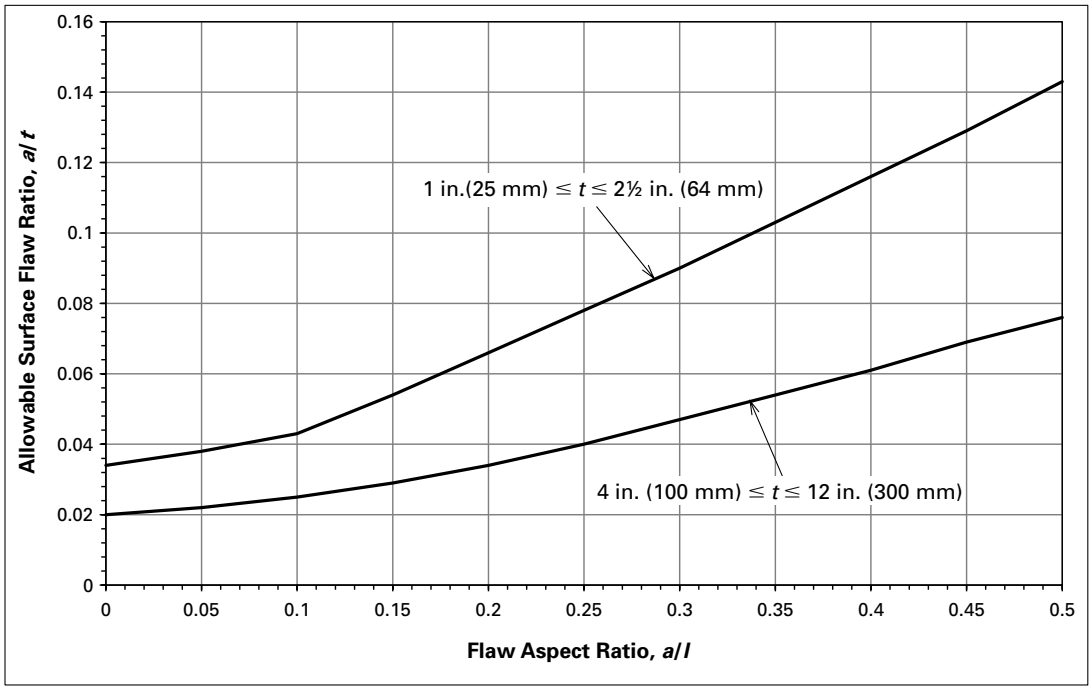
Figure KE-301-2
Surface Flaw Acceptance Criteria (Cont'd)



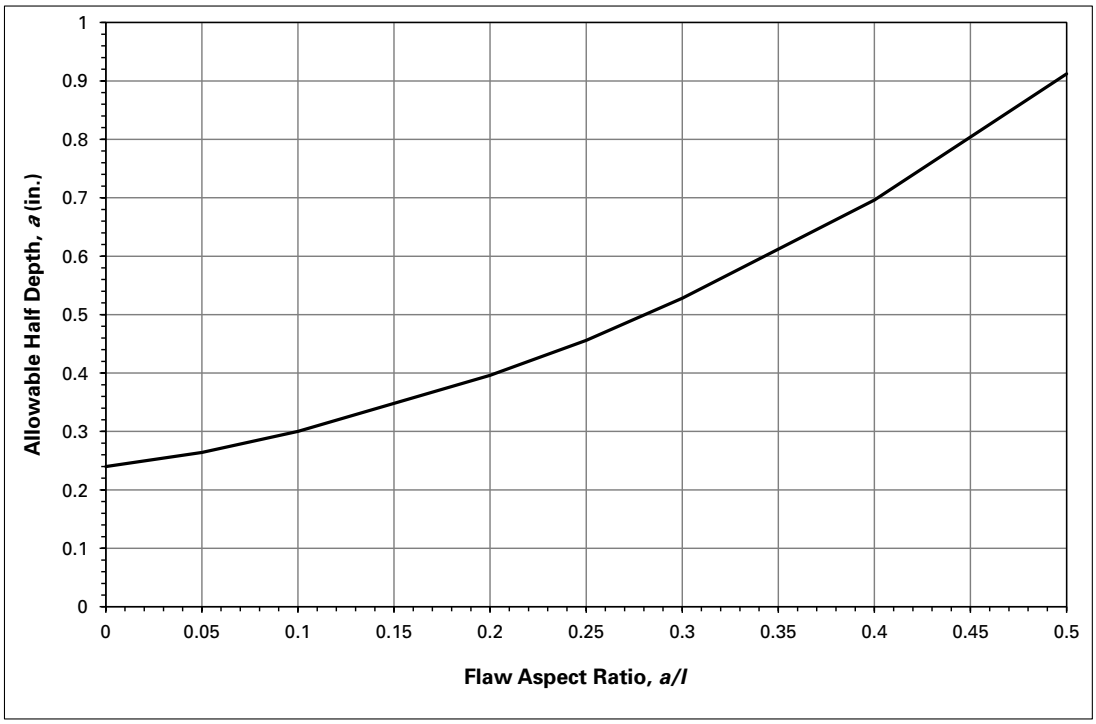
(c) For Weld Thickness t = 400 mm (16 in.) [Note (3)]

NOTES:
(1) This graph obtained from acceptance criteria for surface flaw for 1 in. (25 mm) ≤ t ≤ 2½ in. (64 mm) and 4 in. (100 mm) ≤ t ≤ 12 in. (300 mm) in Table KE-301-1.
(2) This graph obtained from acceptance criteria for surface flaw for t = 16 in. in Table KE-301-2.
(3) This graph obtained from acceptance criteria for surface flaw for t = 400 mm in Table KE-301-2.

Figure KE-301-3
Subsurface Flaw Acceptance Criteria

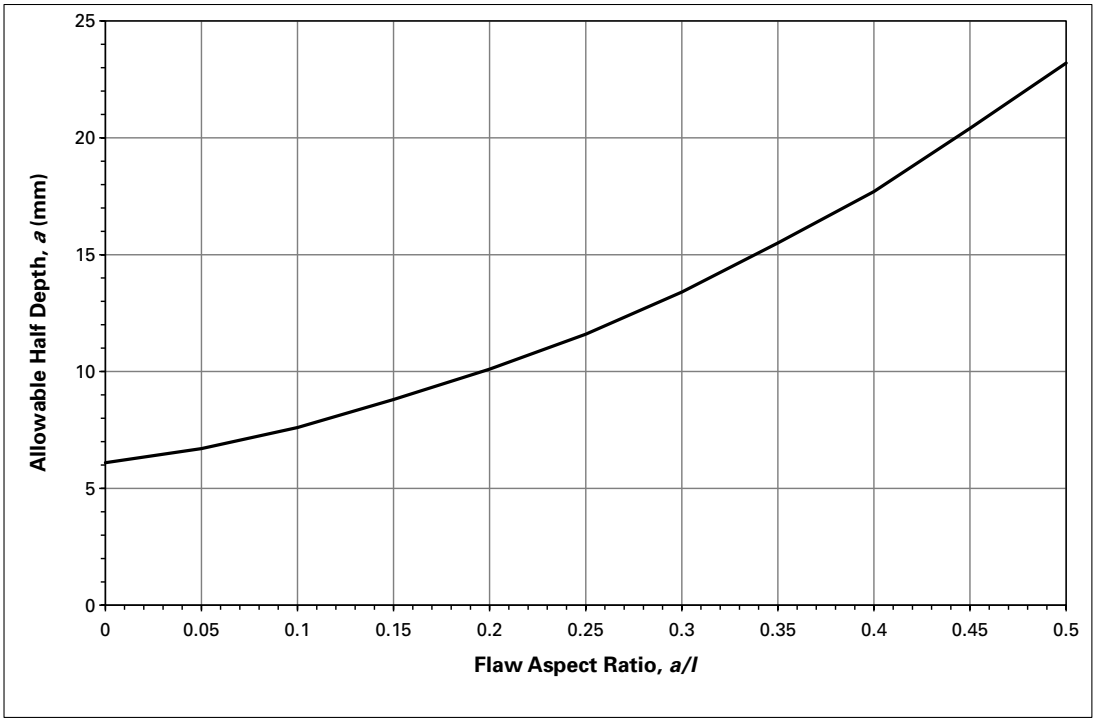


(a) For Weld Thickness 1 in. (25 mm) ≤ *t* ≤ 2½ in. (64 mm) and 4 in. (100 mm) ≤ *t* ≤ 12 in. (300 mm) [Note (1)]



(b) For Weld Thickness *t* = 16 in. (400 mm) [Note (2)]

Figure KE-301-3
Subsurface Flaw Acceptance Criteria (Cont'd)



(c) For Weld Thickness t = 400 mm (16 in.) [Note (3)]

NOTES:
(1) This graph obtained from acceptance criteria for subsurface flaw for 1 in. (25 mm) ≤ t ≤ 2½ in. (64 mm) and 4 in. (100 mm) ≤ t ≤ 12 in. (300 mm) in Table KE-301-1.
(2) This graph obtained from acceptance criteria for subsurface flaw for t = 16 in. in Table KE-301-2.
(3) This graph obtained from acceptance criteria for subsurface flaw for t = 400 mm in Table KE-301-2.

Figure KE-301-4
Multiple Planar Flaws Oriented in Plane Normal to Pressure-Retaining Surface

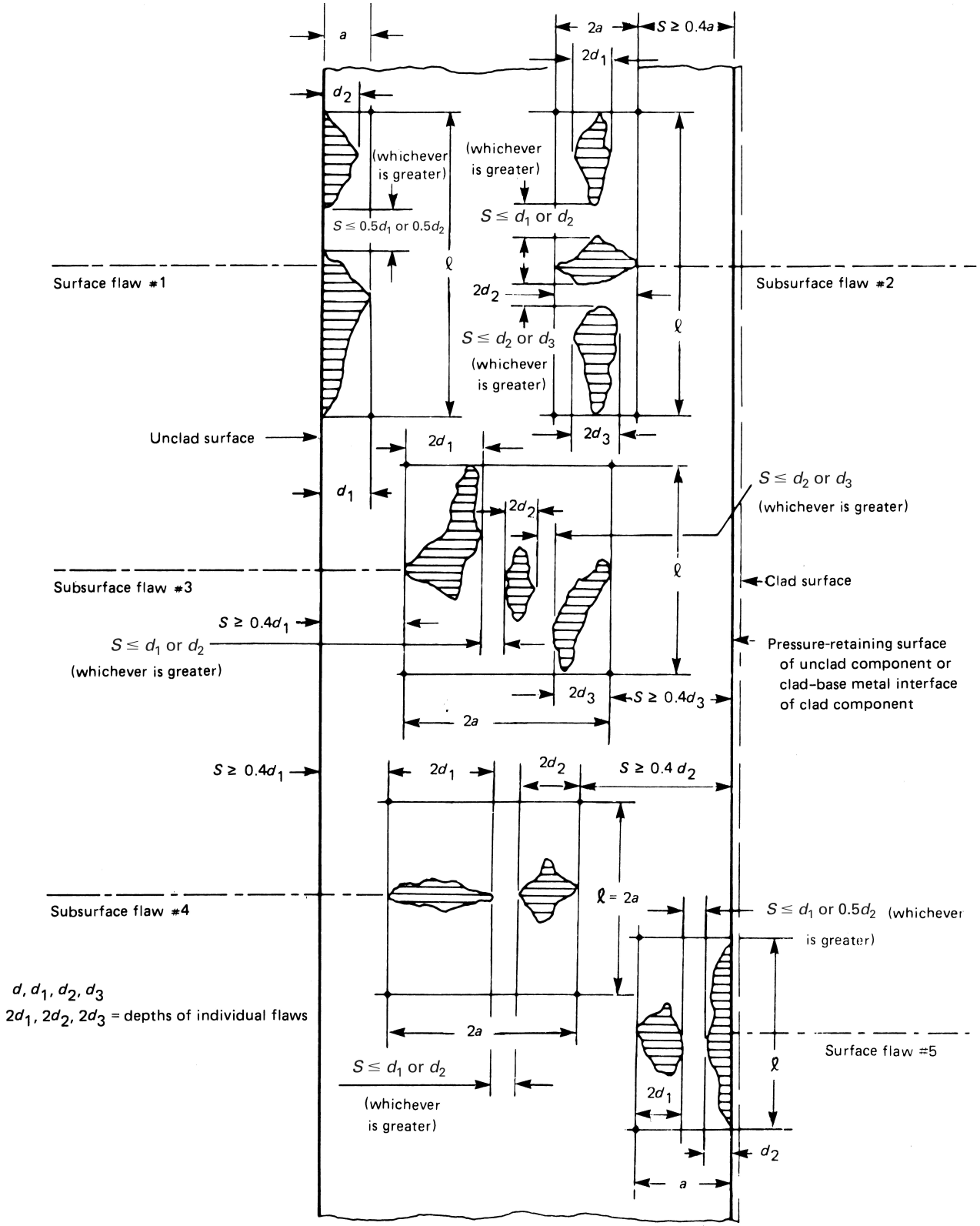


Figure KE-301-5
Parallel Planar Flaws

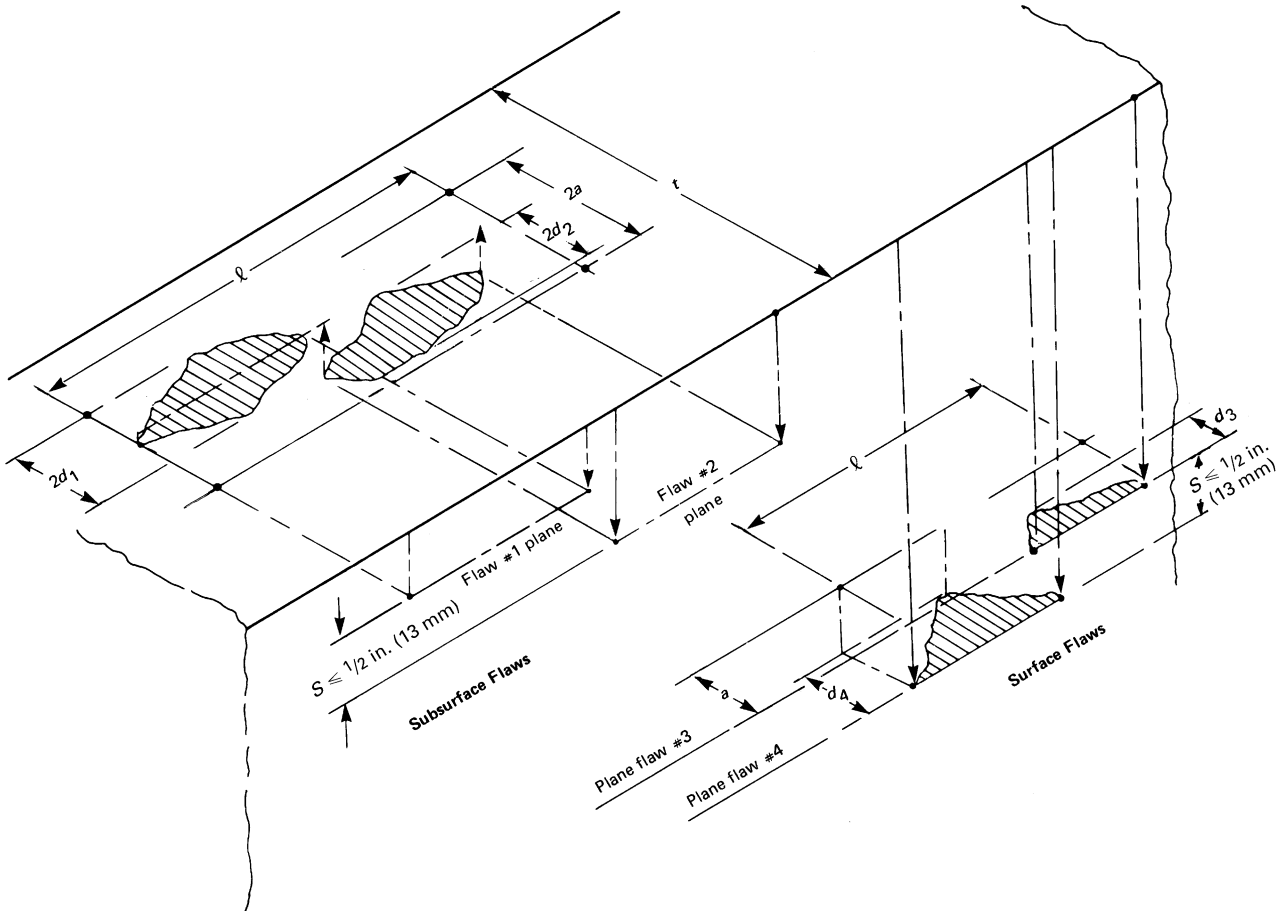


Figure KE-301-6
Nonaligned Coplanar Flaws in Plane Normal to Pressure-Retaining Surface (Illustrative Flaw Configurations)

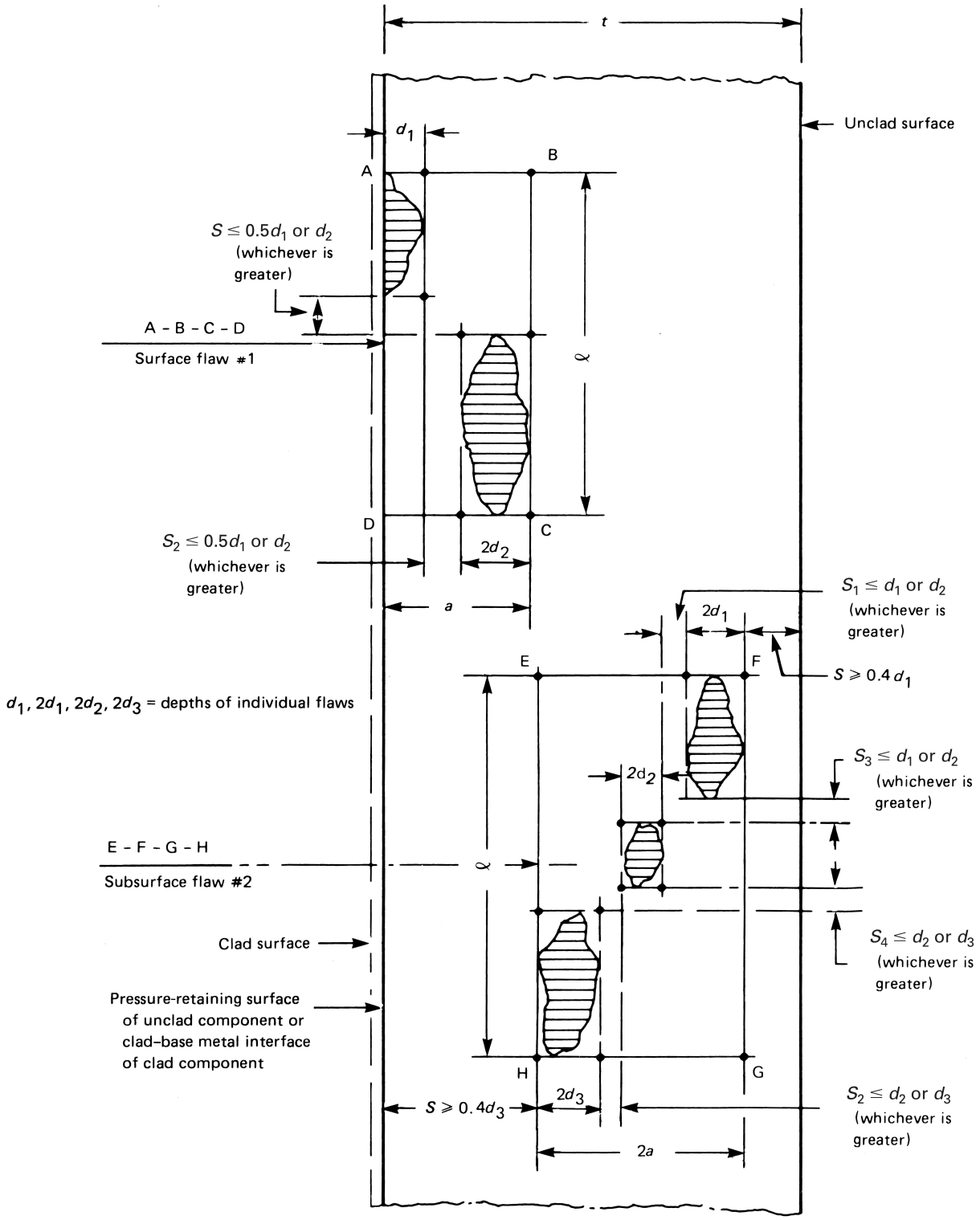


Figure KE-301-7
Multiple Aligned Planar Flaws

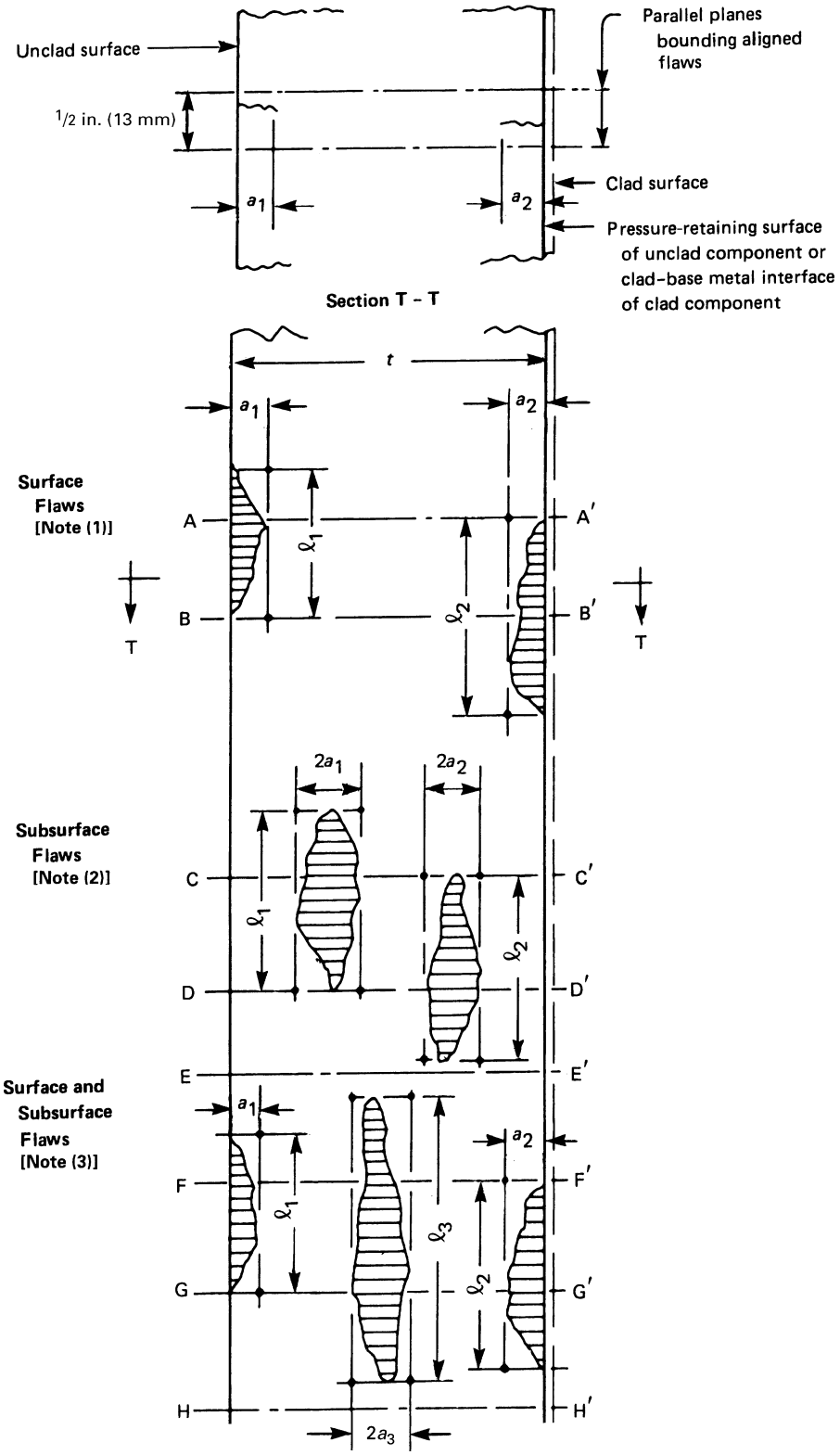


Figure KE-301-7
Multiple Aligned Planar Flaws (Cont'd)

NOTES:
(1) This illustration indicates two surface flaws. The first, a_1, is on the outer surface of the component, and the second, a_2, is on the inner surface:
$(a_1 + a_2) \le (a_s + a'_s)/2$ within planes $A–A'$ and $B–B'$
(2) This illustration indicates two subsurface flaws:
$(a_1 + a_2) \le (a_e + a'_e)/2$ within planes $C–C'$ and $D–D'$
(3) This illustration indicates two surface flaws and one subsurface flaw:
(a) $(a_1 + a_3) \le (a_s + a'_e)/2$ within planes $E–E'$ and $F–F'$
(b) $(a_1 + a_2 + a_3) \le (a_s + a_e + a'_s)/3$ within planes $F–F'$ and $G–G'$
(c) $(a_2 + a_3) \le (a'_s + a_e)/2$ within planes $G–G'$ and $H–H'$
(d) a_s for first surface flaw, a'_s for second surface flaw, a_e for first subsurface flaw, and a'_e for second subsurface flaw are acceptable flaw depth dimensions, respectively.

(25) KE-310 EXAMINATION OF WELD EDGE PREPARATION SURFACES

All weld edge preparation surfaces in materials 2 in. (51 mm) or more in thickness shall be examined by a surface examination method in accordance with KE-233. Weld repairs made to the weld edge preparation surfaces shall also be inspected by a surface examination method before the surface becomes inaccessible.

Indications shall be evaluated in accordance with the acceptance standards in (a), (b), and (c). The location of all relevant indications shall be documented.

(a) Only indications with major dimensions greater than $^1/_{16}$ in. (1.6 mm) shall be considered relevant.

(b) Laminar type indications are acceptable without repair if they do not exceed $^1/_4$ in. (6 mm) in length. The extent of all laminar type indications exceeding $^1/_4$ in. (6 mm) in length shall be determined by ultrasonic examination. Indications exceeding $^1/_4$ in. (6 mm) in length shall be repaired by welding to a depth of $^3/_8$ in. (10 mm) or the depth of the indication, whichever is less, unless the ultrasonic examination reveals that additional depth of repair is required to meet the ultrasonic examination requirement for the product form.

(c) Other nonlaminar relevant indications that are unacceptable are:

(1) any linear indications greater than $^3/_{16}$ in (4.8 mm) long

(2) rounded indications with dimensions greater than $^3/_{16}$ in. (4.8 mm)

(3) four or more rounded indications in a line separated by $^1/_{16}$ in. (1.6 mm) or less, edge-to-edge

KE-320 TYPES OF WELDS AND THEIR EXAMINATION

KE-321 WELDED JOINT CATEGORIES

The term category as used herein defines the location of a joint in a vessel, but not the type of joint. The categories established by this paragraph are for use in this Division in specifying special requirements regarding joint type and degree of examination for certain welded pressure joints. Since these special requirements, which are based on service and thickness, do not apply to every welded joint, only those joints to which special requirements apply are included in categories. The joints included in each category are designated as joints of Categories A, B, C, and D below. Figure KE-321 illustrates typical joint locations included in each category.

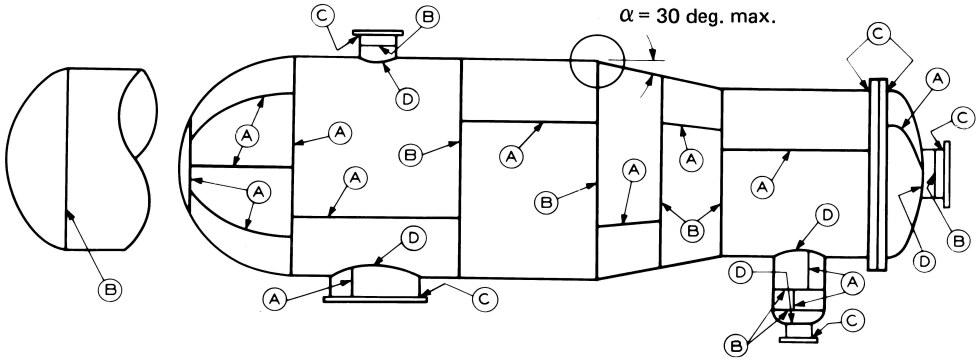
(a) Category A Locations. Category A locations are longitudinal welded joints within the main shell, communicating chambers,[12] transitions in diameter, or nozzles; any welded joint within a sphere, within a formed or flat head, or within the side plates[13] of a flat-sided vessel; and circumferential welded joints connecting hemispherical heads to main shells, to transitions in diameter, to nozzles, or to communicating chambers.

(b) Category B Locations. Category B locations are circumferential welded joints within the main shell, communicating chambers, nozzles, or transitions in diameter, including joints between the transition and a cylinder at either the large or small end; and circumferential welded joints connecting formed heads other than hemispherical to main shells, to transitions in diameter, to nozzles, or to communicating chambers.

(c) Category C Locations. Category C locations are welded joints connecting flanges, tubesheets, or flat heads to the main shell, to formed heads, to transitions in diameter, to nozzles, or to communicating chambers; and any welded joint connecting one side plate to another side plate of a flat-sided vessel.

(d) Category D Locations. Category D locations are welded joints connecting communicating chambers or nozzles to main shells, to spheres, to transitions in diameter, to heads, or to flat-sided vessels; and nozzles at the small end of a transition in diameter and those joints connecting nozzles to communicating chambers.

Figure KE-321
Illustration of Welded Joint Locations Typical of Categories A, B, C, and D



KE-322 WELD JOINTS (25)

The entire length of all Categories A, B, C, and D weld joints shall be ultrasonically examined in accordance with KE-300. Where ultrasonic examination test results cannot be conclusively interpreted, radiographic examination of that area shall be carried out in accordance with KE-101. The external and accessible internal weld surfaces and adjacent base material for at least $\frac{1}{2}$ in. (13 mm) on each side of the weld shall be examined by a surface technique in accordance with KE-233.

KE-323 WELD BUILDUP DEPOSITS AT OPENINGS FOR NOZZLES, BRANCH, AND PIPING CONNECTIONS

When weld buildup deposits are made to a surface, the weld buildup deposit, the fusion zone, and the parent metal beneath the weld buildup deposit shall be ultrasonically examined. See KE-333 for acceptance standards.

KE-324 ATTACHMENT WELDS (25)

Attachment welds made to pressure-retaining material shall be examined by a surface technique in accordance with KE-233. See KE-233 for acceptance standards.

KE-325 WELDS FOR MEMBRANE SEALS (25)

Membrane seal welds shall be examined by a surface technique in accordance with KE-233.

KE-330 ACCEPTANCE STANDARDS

KE-331 GENERAL REQUIREMENTS

Acceptance standards for welds shall be as stated in the following paragraphs, while the acceptance standards for material adjacent to the weld or beneath the weld or weld buildup shall be as stated in Article KE-2.

KE-332 RADIOGRAPHIC ACCEPTANCE STANDARDS

Welds that are shown by radiography to have any of the following types of imperfections are unacceptable:

(a) any type of crack or zone of incomplete fusion or penetration

(b) any other linear indication which has a length greater than

(1) $\frac{1}{4}$ in. (6 mm) for t up to $\frac{3}{4}$ in. (19 mm), inclusive (where t is the thickness of the thinner portion of the plate being welded)

(2) $t/3$ for t over $\frac{3}{4}$ in. (19 mm) to $2\frac{1}{4}$ in. (57 mm), inclusive

(3) $\frac{3}{4}$ in. (19 mm) for t over $2\frac{1}{4}$ in. (57 mm)

(c) internal root weld conditions are acceptable when the density change as indicated in the radiograph is not abrupt (such that radiographs can be interpreted); linear indications on the radiograph at either edge of such conditions shall be unacceptable as provided in (b)

(d) any group of aligned, rounded indications having an aggregate length greater than t in a length of $12t$, unless the minimum distance between successive indications exceeds $6L$, in which case the aggregate length is unlimited, L being the length of the largest indication

(e) rounded indications in excess of those shown as acceptable in Table KE-332 and Mandatory Appendix 6.

KE-333 ULTRASONIC ACCEPTANCE STANDARDS (25)

Flaws shall be evaluated for acceptance using the applicable criteria listed in Table KE-301-1 or Table KE-301-2 or developed in accordance with KD-450 with the following additional requirements:

(a) Surface Connected Flaws. Flaws identified as surface flaws during the UT examination may or may not be surface connected. Therefore, unless the UT data analysis confirms that that flaw is not surface connected, it shall be considered surface connected or a flaw open to the surface, and is unacceptable unless a surface examination

Table KE-332
Radiographic Acceptance Standards for Rounded Indications (Examples Only)

Thickness t, in. (mm)	Maximum Size of Acceptable Rounded Indications, in. (mm)		Maximum Size of Nonrelevant Indication, in. (mm)
	Random	Isolated	
Less than $\frac{1}{8}$ (3)	$\frac{1}{4}t$	$\frac{1}{3}t$	$\frac{1}{10}t$
$\frac{1}{8}$ (3)	0.031 (0.8)	0.042 (1.1)	0.015 (0.4)
$\frac{3}{16}$ (5)	0.047 (1.2)	0.063 (1.6)	0.015 (0.4)
$\frac{1}{4}$ (6)	0.063 (1.6)	0.083 (2.1)	0.015 (0.4)
$\frac{5}{16}$ (8)	0.078 (2.0)	0.104 (2.6)	0.031 (0.8)
$\frac{3}{8}$ (9.5)	0.091 (2.3)	0.125 (3.2)	0.031 (0.8)
$\frac{7}{16}$ (11)	0.109 (2.8)	0.146 (3.7)	0.031 (0.8)
$\frac{1}{2}$ (13)	0.125 (3.2)	0.168 (4.3)	0.031 (0.8)
$\frac{9}{16}$ (14)	0.142 (3.6)	0.188 (4.8)	0.031 (0.8)
$\frac{5}{8}$ (16)	0.156 (4.0)	0.210 (5.3)	0.031 (0.8)
$\frac{11}{16}$ (17.5)	0.156 (4.0)	0.230 (5.8)	0.031 (0.8)
$\frac{3}{4}$ (19) to 2 (50), incl.	0.156 (4.0)	0.250 (6.4)	0.031 (0.8)
Over 2 (50)	0.156 (4.0)	0.375 (9.5)	0.063 (1.6)

is performed in accordance with (1), (2), or (3) below. If the flaw is surface connected, the requirements above still apply; however, in no case shall the flaw exceed the acceptance criteria in KE-233.

Acceptable surface examination techniques are

(1) magnetic particle examination (MT) in accordance with Section VIII, Division 1, Mandatory Appendix 6; Section VIII, Division 2, Part 7, 7.5.6; Section I, Mandatory Appendix A, A-260 as applicable; or Section XII, Mandatory Appendix V, or

(2) liquid penetrant examination (PT) in accordance with Section VIII, Division 1, Mandatory Appendix 8; Section VIII, Division 2, Part 7, 7.5.7; Section I, Mandatory Appendix A, A-270 as applicable; or Section XII, Mandatory Appendix VI, or

(3) eddy current examination (ET) in accordance with KE-105. All relevant ET indications that are open to the surface are unacceptable regardless of length.

(b) Multiple Flaws

(1) Discontinuous flaws shall be considered a singular planar flaw if the distance between adjacent flaws is equal to or less than S as shown in Figure KE-301-4.

(2) Discontinuous flaws that are oriented primarily in parallel planes shall be considered a singular planar flaw if the distance between the adjacent planes is equal to or less than $\frac{1}{2}$ in. (13 mm). (Refer to Figure KE-301-5.)

(3) Discontinuous flaws that are coplanar and nonaligned in the through-wall thickness direction of the component shall be considered a singular planar flaw if the distance between adjacent flaws is equal to or less than S as shown in Figure KE-301-6.

(4) Discontinuous flaws that are coplanar in the through-wall direction within two parallel planes $\frac{1}{2}$ in. (13 mm) apart (i.e., normal to the pressure-retaining surface of the component) are unacceptable if the additive flaw depth dimension of the flaws exceeds those shown in Figure KE-301-7.

(c) Subsurface Flaws. Flaw length (l) shall not exceed $4t$.

(d) The final data package shall be reviewed by a UT Level III individual. The review shall include:

(1) the ultrasonic data record

(2) data interpretations

(3) flaw evaluations/characterizations performed by another qualified Level II or III individual.

The data review may be performed by another individual from the same organization.

Alternatively, the review may be achieved by arranging for a data acquisition and initial interpretation by a Level II individual qualified in accordance with KE-301(f) and trained in accordance with KE-301(h), and a final interpretation and evaluation shall be performed by a Level III individual qualified similarly. The Level III individual shall have been qualified in accordance with KE-301(f) above, including a practical examination on flawed specimens.

(e) The nameplate shall be marked under the Certification Mark and Designator by applying UT, to indicate ultrasonic examination of welded seams required to be examined in accordance with this Division.

KE-334 SURFACE EXAMINATION OF WELDS (25)

Welds shall be examined by a surface examination method in accordance with KE-233. A welded joint surface may not require examination when the weld surface is inaccessible [see KE-241(b), KE-251(a) and KE-502(a)].

ARTICLE KE-4
FINAL EXAMINATION OF VESSELS

KE-400 SURFACE EXAMINATION AFTER HYDROTEST

All surfaces of pressure boundary components including internal and external surfaces and weld metal shall be examined after hydrotest or autofrettage as permitted by Article KT-3, unless accessibility prevents meaningful interpretation and characterization of defects, or, if the component would be damaged as a result of such an examination. The surfaces shall be examined in accordance with KE-233. Components or surfaces of components that are not accessible or would potentially be damaged shall be examined at the latest point in which meaningful results can be obtained without damage to the component. Acceptance criteria shall be in accordance with KE-233.2.

KE-410 INSPECTION OF LINED VESSEL INTERIOR AFTER HYDROTEST

When the test fluid leaks behind the protective liner, there is danger that the fluid will remain in place when the vessel is put in service. In cases where the operating temperature of the vessel is above the boiling point of the test fluid, the vessel should be heated slowly for sufficient time to drive out all test fluid from behind the protective liner without damage to the liner. This heating operation shall be performed at the vessel manufacturing plant or at the plant where the vessel is being installed. After the test fluid is driven out, the lining should be repaired. Repetition of the examination, the heat treatment, or the hydrostatic test of the vessel after lining repairs is not required except when there is reason to suspect that the repair welds may have defects that penetrate into the base material, in which case the Inspector shall decide which one or more of these operations shall be repeated.

ARTICLE KE-5
ADDITIONAL EXAMINATION REQUIREMENTS FOR COMPOSITE REINFORCED PRESSURE VESSELS (CRPV)

KE-500 SCOPE

The following Article provides examination requirements for the Composite Reinforced Pressure Vessels (CRPV) manufactured in accordance with this Division.

KE-501 QUALIFICATION OF NONDESTRUCTIVE EXAMINATION PERSONNEL FOR CRPV

(a) The Manufacturer shall certify that each examiner performing acoustic emission testing according to the Division has attended a dedicated training course on the subject, passed a written examination, and has the recommended experience level. The training course shall be appropriate for specific NDT Level II qualification according to Section V, Article 1, T-120(e) or T-120(f).

(b) The manufacturer shall certify that each examiner performing visual tests according to the Division has been qualified to the requirements of Section V, Article 9.

KE-502 WELD EXAMINATION

(a) For Categories A and B welds, the internal surface may not be ground nor examined with magnetic particle or liquid penetrant. The performance of the external ultrasonic examination method of the welds shall be demonstrated using a performance demonstration test block that has been prepared using the welding procedure to be used in production and having similar weld geometry and containing simulated flaws equal to or smaller in size than the initial flaw size in the fracture mechanics calculations. The examination method shall meet the requirements of KE-333.

(b) The external surfaces of all welds shall be examined in accordance with the requirements of this Division before laminate application.

KE-503 ADDITIONAL EXAMINATION REQUIREMENTS FOR CRPV

(a) The Manufacturer completing a CRPV or vessel part shall be responsible for conducting the examinations required by this paragraph.

(b) Each CRPV shall be subjected to the examinations required by this paragraph, and the examinations in Article KT-5, and shall conform to the specified requirements, with results recorded in Production Test Reports. Examinations detailed in (1), (2), and (4) shall be carried out before the hydrostatic test. The CRPV Production Test Report shall become part of the Manufacturer's Construction Records.

(1) Design Dimensions Examination. CRPV shall be examined for conformance with dimensions and tolerances shown on the design drawings.

(2) Repair of Imperfections and Replacement of the Laminate During Construction. Requirements for the repair of imperfections, visual inspection of repaired areas, and replacement of the laminate during construction are found in Section X, Mandatory Appendix 10, 10-406, 10-503(a)(3), and 10-407.

(3) Acoustic Emission Examination. An acoustic emission examination in accordance with the requirements of Section V, Article 11 shall be performed on each CRPV in accordance with KF-1212(b)(2). The acoustic emission examination shall not be conducted until all other tests and examinations required by this Division have been conducted. All repairs that are required as a result of the other tests and examinations shall be completed prior to the acoustic emission examination.

(4) Metallic Surface Examination After Hydrostatic Test. The requirements of KE-400 do not apply to CRPV as examination of internal surfaces and external surfaces under the laminate are not practical. It shall be demonstrated by a fracture mechanics approach that the minimum detectable flaw size will not grow during the hydrostatic test to a size not accounted for in the analysis, see KF-1210 and KE-502.

PART KT
TESTING REQUIREMENTS

ARTICLE KT-1
TESTING REQUIREMENTS

KT-100 SCOPE

The testing of vessels within the scope of this Division shall be performed in accordance with the rules in this Part.

KT-110 REQUIREMENTS FOR SAMPLE TEST COUPONS

KT-111 OBTAINING SAMPLE TEST COUPONS

When material is subjected to heat treatment during fabrication, the test specimens required by the applicable specification shall be obtained from sample coupons which have been heat treated in the same manner as the material, including such heat treatments as were applied by the Material Producer before shipment. The required tests shall be performed by either the material producer or Manufacturer (see KM-220).

KT-112 HEAT TREATING OF SAMPLE TEST COUPONS

The material used in a vessel or a component shall be represented by test specimens which have been subjected to the same manner of heat treatment, including postweld heat treatment, as the vessel. The kind and number of tests, and test results, shall be those required by the material specification. The Manufacturer shall specify the temperature, time, and cooling rates that the material will be subjected to during fabrication. Material from which the specimens are prepared shall be heated at the specified temperature within the tolerances established by the Manufacturer for use in actual fabrication. The total time at temperature shall be at least 80% of the total time at temperature during actual heat treatment of the product and may be performed in a single cycle. Simulation of postweld heat treatment may be applied to the test specimen blanks. Local heating such as flame or arc cutting, preheating, or welding shall not be considered as part of the heat treatment.

KT-113 EXCEPTION FOR STANDARD PRESSURE PARTS

An exception to the requirements of KT-111 and KT-112 shall apply to standard items such as described in KM-102. These may be subjected to postweld heat treatment with the vessel or vessel part without the same treatment being required of the test specimens. This exception shall not apply to specially designed wrought fittings.

ARTICLE KT-2
IMPACT TESTING FOR WELDED VESSELS

KT-200 IMPACT TESTS

(a) For vessels of welded construction, the toughness of welds and heat-affected zones of procedure qualification test plates and vessel production test plates shall be determined as required in this Article.

(b) Test plates shall be subjected to heat treatment, including cooling rates and aggregate time at temperature or temperatures, essentially the same as established by the Manufacturer for use in actual manufacture. The total time at temperature shall be at least 80% of the total time at temperature during actual heat treatment of the product and may be performed in a single cycle.

(c) The test temperature for welds and heat-affected zones shall not be higher than for the base materials.

(d) Impact values shall be at least as high as those required for the base materials [see Table KM-234.2(a)].

KT-210 LOCATION AND ORIENTATION OF SPECIMENS

All weld impact specimens for both weld procedures and production tests shall comply with the following requirements:

(a) One set of weld metal impact specimens shall be taken across the weld with the notch in the weld metal. Each specimen shall be oriented so that the notch is normal to the surface of the material, and one face of the specimen shall be within $\frac{1}{16}$ in. (1.6 mm) of the surface of the material. When tests are made on material over $1\frac{1}{2}$ in. (38 mm) in thickness, two sets of impact specimens shall be taken from the weld, with one set located within $\frac{1}{16}$ in. (1.6 mm) of the surface of one side of the material, and one set taken as near as practical midway between the surface and the center of thickness of the opposite side as described above.

(b) One set of heat-affected zone impact specimens shall be taken across the weld and of sufficient length to locate, after etching, the notch in the affected zone. The notch shall be cut approximately normal to the material surface in such a manner as to include as much heat-affected zone material as possible in the resulting fracture.

KT-220 IMPACT TESTS FOR WELDING PROCEDURE QUALIFICATIONS

Impact tests shall be required on weld and heat-affected zones for all welding procedure qualifications.

KT-221 VARIABLES FOR IMPACT TESTING PROCEDURES

See Section IX, QW-250.

KT-222 THICKNESS QUALIFIED WHEN LOWER CRITICAL TEMPERATURE IS EXCEEDED

For test plates or pipe receiving a postweld heat treatment in which the lower critical temperature is exceeded, the maximum thickness qualified is the thickness of the test plate or pipe.

KT-230 IMPACT TEST OF PRODUCTION TEST PLATES

Impact tests of welds and heat-affected zones shall be made in accordance with KT-210 for each qualified welding procedure used for pressure-retaining welds (i.e., Category A, B, C, or D) on each vessel. Base material of production test plates shall be taken from one of the heats of material used for the vessel production of Category A, B, C, or D weld joints.

(a) The production test plates shall be welded as an extension to the end of the production weld joint where practical.

(b) Alternatively, the production test plates shall be welded immediately prior to the start of production or welded concurrently with the production weld and following requirements shall be met:

(1) Use welding materials and procedures that are to be used on the production joint.

(2) The welding equipment shall be of the same type as used for production.

(3) The location of the test plate welding shall be immediately adjacent to the production welding.

(c) In addition, the following requirements shall apply:

(1) If automatic or semiautomatic welding is performed, a test plate shall be made in each position employed in the vessel welding.

(2) If manual welding is to be employed in the flat position only, a test plate shall be made in the flat position. A vertical test plate with the major portions of the layers of welds deposited in the vertical upward position shall be used to qualify the welding procedure when manual welds are made in any other position. The vertically welded test plate will qualify the manual welding in all positions.

(3) Impact tests shall be valid only if the thickness of the vessel test plate meets the requirements of Section IX, Table QW-451.1, except that, if the thickness is less than $^{5}/_{8}$ in. (16 mm), the thickness of the test material shall be the minimum thickness qualified.

KT-240 BASIS FOR REJECTION

If the vessel test plate fails to meet the impact requirements, the welds represented by the test plate shall be unacceptable. Reheat treatment in accordance with Part KM and retesting are permitted.

ARTICLE KT-3
HYDROSTATIC TESTS

KT-300 SCOPE

Each completed vessel shall be subjected to a hydrostatic test pressure which, at every point in the vessel, is within the range specified in KT-310. Vessels designed for vacuum conditions do not require an additional external pressure hydrotest.

KT-301 LAYERED VESSELS

See additional requirements for hydrotest of layered, and wire-wound vessels in Articles KF-8 and KF-9.

KT-302 NONMETALLIC LINED VESSELS

Vessels which are to be lined with a nonmetallic material shall be pressure tested before the application of such lining.

KT-303 AUTOFRETTAGED VESSELS

Autofrettaged vessels may be exempt from hydrostatic testing. See KT-340.

(25) KT-304 JACKETED VESSELS

(a) For jacketed portions of vessels where the internal vessel is designed to operate at atmospheric pressure or vacuum conditions only, the pressure test need only be applied to the jacket volume. In such cases, the MAWP shall be set as the differential pressure between the jacket and the internal vessel for the purposes of determining the test pressure.

(b) If the jacket is designed to operate under vacuum conditions, it shall be subjected to a pressure test in accordance with KT-3. The internal test pressure shall not be less than 1.25 times the difference between normal atmospheric pressure and the minimum design internal absolute pressure.

(c) If the jacket is designed to operate under both pressure and vacuum conditions, then it shall be tested at the greater of the pressures determined in accordance with (a) or (b).

(25) KT-305 COMBINATION UNITS

(a) Independent Pressure Chambers. Pressure chambers of combination units that have been designed to operate independently shall be hydrostatically tested as separate vessels; that is, each chamber shall be tested without pressure in the adjacent chamber. If the common elements of a combination unit are designed for a larger differential design pressure than the higher maximum allowable working pressure to be marked on the adjacent chambers, the hydrostatic test shall subject the common elements to at least their design differential pressure, corrected for temperature as described in KT-311, as well as meet the requirements in KT-310 for each independent chamber.

(b) Dependent Pressure Chambers. When pressure chambers of combination units have their common elements designed for the maximum differential pressure that can possibly occur during startup, operation (including upset conditions) and shutdown, and the differential pressure is less than the higher pressure in the adjacent chambers, then the common elements shall be subjected to a hydrostatic test pressure calculated using KT-3111 where the MAWP is the differential pressure to be marked on the unit.

(1) Following the test of common elements as required in (a), and their inspection, the adjacent chambers shall be simultaneously tested at the test pressure required for internal pressure. Care must be taken to limit the differential pressure between the chambers to the pressure used when testing common elements.

(2) The vessel stamping and vessel Data Report shall describe the common elements and their limiting differential pressure.

KT-310 LIMITS OF HYDROSTATIC TEST PRESSURE

KT-311 LOWER LIMIT (25)

The test pressure shall not be less than 1.25 times the design pressure to be marked on the vessel, multiplied by the lowest ratio (for materials of which the vessel is constructed, excluding bolting materials) of the specified yield strength value S_y for the test temperature of the vessel to the specified yield strength value S_y for the design temperature.

KT-312 UPPER LIMIT

Except for the provision in KT-312.4, the test pressure shall not exceed the limits in KT-312.1 through KT-312.3, as applicable. The designer is cautioned that hydrostatic

pressure corresponding to design pressure calculated using eqs. (KD-221.1) through (KD-221.6), as applicable, may result in through-thickness yielding and excessive component distortion when the ratio of hydrostatic test pressure to design pressure is greater than 1.25. The designer should use caution that the suitability and integrity of non-cylindrical vessels, end closures, and all other components of the pressure boundary are not adversely affected by the application of the hydrotest pressure (see 9-100 and KT-312.3).

(25) **KT-312.1 For Single Wall Vessels.** Open-end cylindrical shell for $Y \le 2.85$:

$$P_t = 3.732K_{ut}\left(S_y\right)\left(Y^{0.268} - 1\right)$$

Closed-end cylindrical shell and open-end cylindrical shell for $Y > 2.85$:

$$P_t = 1.155K_{ut}\left(S_y\right)\ln(Y)$$

The definitions of open-end and closed-end are shown in KD-221.

Sphere:

$$P_t = 2K_{ut}\left(S_y\right)\ln(Y)$$

where

D_O = outside diameter
D_I = inside diameter
K_{ut} = hydrostatic test pressure upper limit factor
= 0.95 for $S_y/S_u \le 0.7$
= 1.244 – 0.42(S_y/S_u) for $0.7 < S_y/S_u \le 0.9$
= 0.866 for $S_y/S_u > 0.9$
S_u = specified tensile strength at test temperature
S_y = specified yield strength at test temperature
Y = D_O/D_I diameter ratio

(25) **KT-312.2 For Layered Vessels.** Open-end cylindrical shell for $Y \le 2.85$:

$$P_t = \sum_{j=1}^{n} 3.732K_{utj}\left(S_{yj}\right)\left(Y_j^{0.268} - 1\right)$$

Closed-end cylindrical shell and open-end cylindrical shell for $Y > 2.85$:

$$P_t = \sum_{j=1}^{n} 1.155K_{utj}\left(S_{yj}\right)\ln\left(Y_j\right)$$

Sphere:

$$P_t = \sum_{j=1}^{n} 2K_{utj}\left(S_{yj}\right)\ln\left(Y_j\right)$$

where S_{uj}, S_{yj}, and Y_j are the specified tensile strength at test temperature, specified yield strength, and diameter ratio for each individual layer. K_{utj} is the hydrostatic test pressure upper limit factor for each individual layer obtained by equations for K_{ut} in KT-312.1 by giving S_{yj}/S_{uj} instead of S_y/S_u.

(25) **KT-312.3 For Noncylindrical Vessel, End Closure, and Other Components.** The upper limit shall be verified by elastic analysis or elastic–plastic analysis.

(a) Elastic Analysis

$$P_m \le K_{ut}S_y$$

(1) For $P_m \le 0.67S_y$

$$P_m + P_b \le \left(1.5K_{ut}\right)S_y$$

(2) For $0.67S_y < P_m \le K_{ut}S_y$

$$P_m + P_b \le \left[\left(1.5K_{ut} + 1\right)S_y - 1.5P_m\right]$$

(b) Elastic–Plastic Analysis. The elastic–plastic analysis shall be conducted to determine the upper limit of hydrostatic test pressure in accordance with KD-236. This procedure may be used for the cylindrical shell instead of those in KT-312.1 through KT-312.3.

KT-312.4 Pressures beyond Code Limit. If the hydrostatic test pressure exceeds the value determined as prescribed in KT-312.1 through KT-312.3, as applicable, the suitability and integrity of the vessel shall be evaluated by the Designer and the results of this evaluation shall be included in the Manufacturer's Design Report (see KD-236).

KT-320 FLUID MEDIA FOR HYDROSTATIC TESTS[14]

Only fluid which is liquid at the hydrotest temperature and pressure and is not corrosive to the vessel parts shall be used for the hydrostatic test. The Manufacturer shall consider the effect of increase in fluid viscosity with pressure. To minimize the risk of brittle fracture, the test temperature shall be a minimum of 30°F (17°C) higher than the material impact test temperature, but below the boiling point of the pressurized fluid. The test pressure shall not be applied until the vessel and the pressurizing fluid are within 10°F (5.6°C) of each other.

KT-330 TEST PROCEDURE

(a) The test pressure shall be increased in increments of not more than 20% of the test pressure. The pressure shall be stabilized at each increment and maintained without the aid of the pump. If the pressure drops more than 5% at any increment, the pressure shall be released to a safe level. Following the release of the hydrostatic test pressure to a safe level, examination for leakage shall be made of all joints, connections, and regions of high stress, such as head knuckles, regions around openings, and thickness transition sections. The examination shall be made immediately after pressure is released and shall be witnessed by the Inspector. Any evidence of leaks shall be investigated and leaks corrected, after which the vessel shall be retested in accordance with these requirements.

(b) After the test pressure has been maintained without the aid of the pump for a minimum of 5 min, the pressure shall be reduced to the design pressure. A thorough inspection for leakage shall be conducted in accordance with (a). If no leaks are found or if leaks are found to be from a fitting or other attachment, external to the vessel itself, the test may be accepted as satisfactory.

KT-340 EXEMPTION FOR AUTOFRETTAGED VESSELS

Autofrettaged vessels may be exempt from hydrostatic testing if all the following conditions are met:

(a) the vessel, when autofrettaged, is in its final assembled form

(b) no access ports or nozzles will be cut or attached after the autofrettage

(c) the heads, closures, seal carriers, or other sealing members but not necessarily the seals that will be used in the completed vessel are used as sealing members during the autofrettage process

(d) the autofrettage pressure equals or exceeds the requirements of KT-311 as limited by KT-312

KT-350 ADDITIONAL REQUIREMENTS FOR IMPULSIVELY LOADED VESSELS

KT-351 HYDROSTATIC TEST

For impulsively loaded vessels, the hydrostatic pressure shall be as determined in accordance with KT-310 using the design basis quasi-static pressure (QSP).

KT-352 DYNAMIC TEST

(a) For multiple-event detonation vessels, a dynamic (i.e., impulsive) test shall be conducted at 125% of the design basis impulse loading for the worst case operational load combination resulting at the limiting section of the vessel.

(b) Single-event detonation vessels are exempt from the dynamic test, provided that a representative vessel from the same material lot is tested in accordance with (a).

ARTICLE KT-4
PRESSURE TEST GAGES AND TRANSDUCERS

KT-400 TYPE AND NUMBER OF GAGES OR TRANSDUCERS

At least two pressure test gages or transducers shall be used in testing high pressure vessels. All pressure gages and transducer readouts shall be readily visible to the operator controlling the pressure applied.

KT-410 PRESSURE RANGE OF TEST GAGES AND TRANSDUCERS

Dial reading pressure gages used in testing shall have dials graduated over a range of not less than 1.5 and not greater than 4 times the pressure being tested. The transducers used shall have a range not less than 1.5 times and not greater than 4 times the pressure being tested.

KT-420 CALIBRATION OF TEST GAGES AND TRANSDUCERS

All gages or transducers shall be calibrated against a standard deadweight tester or a calibrated master gage at least every 6 months or at any time there is reason to believe that they are in error.

ARTICLE KT-5
ADDITIONAL TESTING REQUIREMENTS FOR COMPOSITE REINFORCED PRESSURE VESSELS (CRPV)

KT-500 RESPONSIBILITY

The Manufacturer completing a CRPV or vessel part shall be responsible for conducting the tests required by this Division.

KT-510 TESTING REQUIREMENTS

Each CRPV shall be subjected to the tests required by this paragraph and shall conform to the specified requirements, with results recorded on Production Test Reports.

(a) Hydrostatic Test. For vessels to be installed at a fixed location, a hydrostatic test to a pressure at least 1.25 times the design pressure shall be performed on each CRPV. For vessels to be used in transport service, a hydrostatic test to a pressure at least 1.25 times the design pressure or 1.5 times the service or working pressure, whichever is greater, shall be performed on each CRPV, see KT-310. This test may be combined with any hydrostatic pressurization procedure used to provide a prestress in the individual layers. The hydrostatic test shall be performed. The CRPV Production Test Report shall become part of the Manufacturer's Construction Records.

(b) Volumetric Expansion Test. A volumetric expansion test shall be performed on every CRPV in accordance with the requirements of the Laminate Procedure Specification Qualification, see KF-1212(b)(1). The results of these tests shall not differ by more than 5% from the values recorded in the original Qualification Test Report and Laminate Procedure Specification after correcting for any variance in material properties.

PART KS
MARKING, STAMPING, REPORTS, AND RECORDS

ARTICLE KS-1
CONTENTS AND METHOD OF STAMPING

KS-100 REQUIRED MARKING FOR VESSELS

(a) Each pressure vessel to which the Certification Mark with U3 Designator is applied shall be marked with the following:

(1) The official Certification Mark with U3 Designator, as shown in Figure KS-100, shall be stamped on vessels certified in accordance with this Division.

(2) Name or identifying acronym of Manufacturer of the pressure vessel as it is shown on the Certificate of Authorization, preceded by "Certified by." Trademark is not considered to be sufficient identification for vessels or parts constructed to this Division.

(3) Manufacturer's serial number (MFG SER). Also, as applicable, Canadian Registration Number (CRN), National Board Registration Number (NB or NATL BD).

(4) Design pressure at coincident design metal temperature. When a vessel is specified to operate at more than one pressure and temperature condition, such values of coincident pressure and design temperature shall be added to the required markings.

(5) Minimum design metal temperature in accordance with KG-311.4(c).

(6) Year built.

(7) Construction type:

CR = composite reinforced pressure vessel construction
F = forged
HT = heat treated
M = monobloc (solid wall)
PHT = partially heat treated
PS = prestressed (autofrettaged or shrink fitted)
UQT = quenched and tempered
W = welded
WL = welded layered
WW = wire wound

(8) When examination of the welds is done using UT in accordance with KE-301, the nameplate shall be marked under the Certification Mark and Designator by applying UT, to indicate ultrasonic examination of welded seams required to be examined in accordance with this Division.

(b) Except for bolting, removable pressure parts shall be permanently marked with a serial number or other identifying mark such that the pressure parts can be traced to the vessel assembly.

Figure KS-100
Official New Certification Mark to Denote the American Society of Mechanical Engineers' Standard

U3

KS-101 METHODS OF MARKING VESSELS WITH TWO OR MORE INDEPENDENT CHAMBERS

One of the following arrangements shall be used in marking vessels having two or more independent pressure chambers designed for the same or different operating conditions. Each detachable chamber shall be marked to identify it positively with the combined unit.

KS-101.1 If Markings Are Grouped in One Location. The markings may be grouped in one location on the vessel provided they are arranged to indicate clearly the data applicable to each chamber, including the maximum differential pressure for the common elements, when this pressure is less than the higher pressure in the adjacent chambers.

KS-101.2 If Each Independent Chamber Is Marked. The complete required marking may be applied to each independent pressure chamber, provided additional marking, such as name of principal chamber (e.g., process chamber, jacket, tubes) is used to indicate clearly to which chamber the data apply.

KS-102 MARKING OF IMPULSIVELY LOADED VESSELS

Impulsively loaded vessel marking shall follow KS-100(a) using the QSP as the design pressure. In addition, the vessel shall be marked with

(a) the central equivalent impulsive load (CEIL) which may be expressed as the maximum allowable TNT-equivalent spherical explosive charge weight with its center placed at a distance of at least the vessel inside radius from any vessel boundary, or

(b) the design basis impulse loading (DBIL) which may be expressed as the TNT-equivalent explosive charge for the limiting configuration as given in the User's Design Specification. Limitations on the placement of the charge(s) should be defined in that document and should also be in the Manufacturer's Design Report

KS-110 APPLICATION OF CERTIFICATION MARK

The Certification Mark with U3 Designator shall be applied by the Manufacturer only with the approval of the Inspector, and after the hydrostatic test has been satisfactorily made and all other required inspection and testing have been satisfactorily completed. Such application of the Certification Mark with U3 Designator, together with final certification in accordance with the rules of this Division, shall confirm that all applicable requirements of this Division and the User's Design Specification have been fulfilled.

KS-120 PART MARKING

(a) See below.

(1) Parts of pressure vessels for which Partial Data Reports with a nameplate or stamping are required shall be marked by the Parts Manufacturer with the following:

(-a) the Certification Mark with appropriate Designator shown in Figure KS-100 above the word "PART"

(-b) the name of the manufacturer of the part, preceded by the words "Certified by"

(-c) the manufacturer's serial number assigned to the part

(-d) design pressure(s) and coincident design metal temperature(s) [see KG-311.4(a) and KG-311.4(b)]

(-e) minimum design metal temperature at the maximum design pressure

Parts may be stamped with the Certification Mark without being pressure tested prior to shipment. If testing was not performed, this shall be indicated in the Remarks section of the K-2 Manufacturer's Partial Data Reports. (See Nonmandatory Appendix A Form K-2.)

(2) No accessory or part of a pressure vessel may be marked "ASME" or "ASME Std." unless so specified in this Division.

(b) The requirements for part marking in accordance with (a)(1)(-d) and (a)(1)(-e) do not apply for parts for which the Parts Manufacturer does not prepare a Manufacturer's Design Report. When pressure part weldments are supplied to the vessel Manufacturer by a subcontractor that possesses a certificate of authorization for a Certification Mark with U or U2 Designator [see KG-420(c)], and the subcontractor submits to the Manufacturer Partial Data Reports, Form U-2, U-2A, or A-2, as appropriate.

KS-130 APPLICATION OF MARKINGS

Markings required in KS-100 through KS-120 shall be applied by one of the following methods.

KS-130.1 Nameplate. A separate corrosion-resistant nameplate, at least 0.02 in. (0.5 mm) thick, shall be permanently attached to the vessel or to an intervening support bracket. The attachment weld to the vessel shall not adversely affect the integrity of the vessel. Attachment by welding shall not be permitted on materials enhanced by heat treatment or on vessels that have been prestressed.

(a) Only the Certification Mark need be stamped on the nameplate.

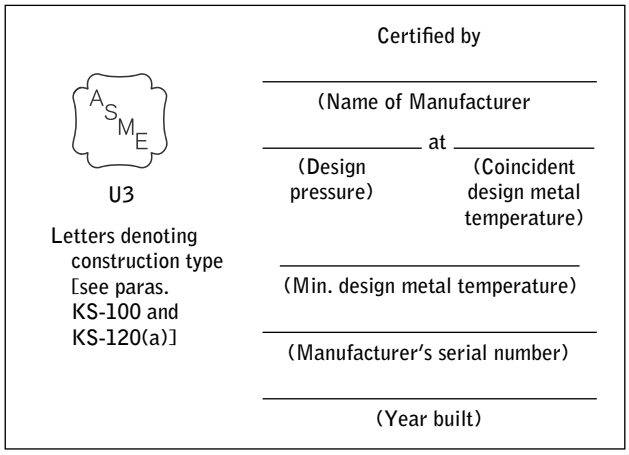
(b) All other data may be stamped, etched, or engraved on the nameplate. See KS-132.

KS-130.2 Directly on Vessel Shell. Markings shall be stamped, with low stress type stamps, directly on the vessel, located on an area designated as a low stress area by the Designer (see KG-330) in the Manufacturer's Design Report (see KG-323). Markings made directly on the vessel shall not be made by the electro-etch method.

KS-130.3 Permanently Attached Tag. When the surface area of small parts is too small to permit the attachment of a nameplate or bracket, or by stamping directly on the part, the required markings shall be located on a permanently attached tag, subject to the prior agreement of the Inspector and the User. The method of attachment shall be described in the Manufacturer's Design Report and traceable to the Form K-2 Manufacturer's Partial Data Report. Such marking shall be of a type that will remain visible until the parts are installed. The Certification Mark is not required.

KS-130.4 Adhesive Attachment. Nameplates may be attached with pressure-sensitive acrylic adhesive systems in accordance with Mandatory Appendix 5.

Figure KS-132
Form of Stamping



KS-131 DUPLICATE NAMEPLATE

A duplicate nameplate may be attached on the support, jacket, or other permanent attachment to the vessel. All data on the duplicate nameplate, including the Certification Mark with U3 Designator, shall be cast, etched, engraved, or stamped. This marking need not be witnessed by the Inspector. The duplicate nameplate shall be marked "DUPLICATE." The use of duplicate nameplates, and the marking of the Certification Mark on the duplicate nameplate, shall be controlled as described in the Manufacturer's Quality Control System.

KS-132 SIZE AND ARRANGEMENTS OF CHARACTERS

(a) The data shall be in characters not less than $^{5}/_{16}$ in. (8 mm) high and shall be arranged substantially as shown in Figure KS-132.

(b) Where space limitations do not permit the requirements of (a) to be met, such as for parts with outside diameters of $3^{1}/_{2}$ in. (90 mm) or smaller, the required character size to be stamped directly on the vessel may be $^{1}/_{8}$ in. (3.2 mm).

(c) The parenthetical supporting information below the data lines in Figure KS-132 may be added as shown in the figure to the nameplate information for clarity. This parenthetical information may be either stamped, etched, or engraved. The characters may be smaller than other stamped information, but not less than $^{1}/_{8}$ in. (3.2 mm). These markings shall be applied with low stress-type stamps if applied directly to the vessel shell.

KS-140 ATTACHMENT OF NAMEPLATE OR TAG (25)

If all or part of the data is marked on the nameplate or tag before it is attached to the vessel, the Manufacturer shall ensure that the nameplate with the correct marking has been attached to the vessel to which it applies as described in the Manufacturer's Quality Control System. The Inspector shall verify that this has been done.

KS-150 SPECIAL STAMPING REQUIREMENTS FOR COMPOSITE REINFORCED PRESSURE VESSELS (CRPV)

(a) The year of vessel expiration shall be shown on the Manufacturer's Data Report and the CRPV nameplate.

(b) Nameplates may be attached to a metallic head or to the composite reinforcement portion of the vessel. Nameplates attached to the composite reinforcement portion of the vessel shall be attached in accordance with the requirements of Section X, RS-130.

(c) For CRPV in transport service, a supplementary nameplate shall be affixed to the CRPV in the immediate vicinity of the connection that will be used for filling that shows the service or the working pressure.

ARTICLE KS-2
OBTAINING AND USING CERTIFICATION MARKS

KS-200 CERTIFICATION MARK BEARING OFFICIAL SYMBOL

A Certificate of Authorization to use the Certification Mark with U3 Designators (see https://www.asme.org/shop/certification-accreditation) shown in Figure KS-100 will be granted by the Society pursuant to the provisions of the following paragraphs. Stamps for applying the Certification Mark shall be obtained from the Society.

KS-210 APPLICATION FOR CERTIFICATE OF AUTHORIZATION

Any organization desiring a Certificate of Authorization shall apply to ASME in accordance with the certification process of ASME CA-1. Authorization to use Certification Marks may be granted, renewed, suspended, or withdrawn as specified in ASME CA-1.

KS-220 ISSUANCE OF AUTHORIZATION

Certificate of Authorization shall be issued in accordance with ASME CA-1 (see https://www.asme.org/shop/certification-accreditation).

KS-230 DESIGNATED OVERSIGHT

The Manufacturer shall comply with the requirements of ASME CA-1 for designated oversight by use of an Authorized Inspection Agency.

KS-240 QUALITY CONTROL SYSTEM

Any Manufacturer holding or applying for a Certificate of Authorization shall demonstrate a Quality Control System that meets the requirements of ASME CA-1 and Mandatory Appendix 2.

(25) KS-250 EVALUATION OF THE QUALITY CONTROL SYSTEM

(a) The issuance or renewal of a Certificate of Authorization is based upon ASME's evaluation and approval of the Quality Control System, and shall be in accordance with ASME CA-1.

(b) Before issuance or renewal of a Certificate of Authorization for use of the Certification Mark with U3 Designator, the Manufacturer's facilities and organization are subject to a joint review by a representative of the Manufacturer's Authorized Inspection Agency and an individual certified as an ASME designee who is selected by the concerned legal jurisdiction.

(c) For those areas where there is no jurisdiction or where a jurisdiction does not choose to select an ASME designee to review a Manufacturer's facility, that function shall be performed by an ASME designee selected by ASME. Where the jurisdiction is the Manufacturer's inspection agency, the joint review and joint report shall be made by the jurisdiction and the ASME designee.

KS-260 CODE CONSTRUCTION BEFORE RECEIPT OF CERTIFICATE OF AUTHORIZATION (25)

When used to demonstrate the Manufacturer's Quality Control System, the Manufacturer may start fabricating Code items before receipt of a Certificate of Authorization to use a Certification Mark under the conditions specified in ASME CA-1.

KS-270 SPECIAL REQUIREMENTS REGARDING MANUFACTURER'S CERTIFICATES FOR MANUFACTURE OF COMPOSITE REINFORCED PRESSURE VESSELS (CRPV)

The Manufacturer shall prepare, implement, and use a quality program that includes the specific technical issues related to the manufacture of CRPV. The level of detail shall be sufficient to satisfy all requirements listed in Mandatory Appendix 2 of this Division, and Section X, Appendix 1.

ARTICLE KS-3
REPORT FORMS AND MAINTENANCE OF RECORDS

(25) KS-300 MANUFACTURER'S DATA REPORTS

(a) A Data Report shall be completed (see Form K-1) by the Manufacturer and the Inspector for each pressure vessel to be marked with the Certification Mark.

(1) For sample report forms and guidance in preparing Data Reports, see Nonmandatory Appendix A.

(2) A Data Report shall be filled out on Form K-1 or Form K-3 by the Manufacturer and shall be signed by the Manufacturer and the Inspector for each pressure vessel marked with the Certification Mark with U3 Designator. Same-day production of vessels may be reported on a single form provided all of the following requirements are met:

(-a) vessels must be identical

(-b) vessels must be manufactured for stock or for the same User or User's designated agent

(-c) serial numbers must be in uninterrupted sequence

(-d) the Manufacturer's written Quality Control System includes procedures to control the development, distribution, and retention of the Data Reports

The number of lines on the Data Report used to describe multiple components (e.g., nozzles, shell courses) may be increased or decreased as necessary to provide space to describe each component. If addition of lines used to describe multiple components results in the Data Report exceeding one page, space must be provided for the Manufacturer and Authorized Inspector to initial and date each of the additional pages. Horizontal spacing for information on each line may be altered as necessary. All information must be addressed; however, footnotes described in the remarks block are acceptable, e.g., for multiple cases of "none" or "not applicable."

(3) Size shall be standard size, 8.5 in. × 11 in. (A4, 210 mm × 297 mm), white bond paper.

(4) Forms may be reprinted, typed, or computer generated.

(5) Forms shall not contain advertising slogans, logos, or other commercial matter. Use only black ink.

(6) Method of completing the Data Report shall be consistent. The report shall be typed or handwritten using legible printing. Handwritten additions or corrections shall be initialed and dated by the Manufacturer's representative and the Authorized Inspector.

(7) Samples of the Manufacturer's Data Reports that the Manufacturer will use shall be submitted to the Inspector for review and approval before use.

(b) The Manufacturer shall

(1) furnish a copy of the Manufacturer's Data Report to the User and to the Inspector

(2) submit a copy of the Manufacturer's Data Report to the appropriate enforcement authority in the jurisdiction in which the vessel is to be installed where required by law

KS-301 PARTIAL DATA REPORTS (25)

(a) The Parts Manufacturer shall indicate under "Remarks" whether or not the Parts Manufacturer has performed any or all of the design functions. For guidance in preparing Partial Data Reports, see Nonmandatory Appendix A.

(b) Partial Data Reports for pressure vessel parts requiring examination under this Division, which are furnished to the Manufacturer responsible for the completed vessel, shall be executed by the Parts Manufacturer's Inspector in accordance with this Division (see KG-322). The vessel shall not be stamped until the Authorized Inspector has reviewed and accepted all Partial Data Reports pertinent to the vessel. All Partial Data Reports, Forms U-2 and U-2A (see Section VIII, Division 1), Form A-2 (see Section VIII, Division 2), and Form K-2, as appropriate, shall be attached to the Manufacturer's Data Report, Form K-1.

KS-302 REPLACEMENT PARTS (25)

Partial Data Reports for those parts of a pressure vessel which are furnished by a Parts Manufacturer to the User of an existing Code vessel, as replacement parts, shall be executed on Form K-2 by the Parts Manufacturer and the Parts Manufacturer's Inspector in accordance with the requirements of this Division. A copy of the Parts Manufacturer's Partial Data Report shall be furnished to the User or the User's designated agent and a copy shall be maintained in accordance with KS-320.

KS-303 MANUFACTURER'S DATA REPORT FOR COMPOSITE REINFORCED PRESSURE VESSELS (CRPV)

(a) A Manufacturer's Data Report shall be completed for each CRPV on Form CRPV-1A, instead of Form K-1 and shall be signed by the Manufacturer and the Authorized Inspector. See Nonmandatory Appendix A for a sample Form CRPV-1A. Instructions for completing Form CRPV-1A are in Nonmandatory Appendix A, Table A-100.1.

(b) A Qualification Test Report Form CRPV-2A shall be used for the record of qualification (or requalification) for the laminate design and Laminate Procedure Specification as part of the Qualification Test Report.

(c) The latest applicable Qualification Test Report shall be referenced on the Data Report and Form CRPV-1A for each CRPV constructed.

KS-310 MAINTENANCE OF RADIOGRAPHS

A complete set of radiographs as described in Section V, Article 2, paras. T-291 and T-292, for each vessel or vessel part, shall be retained by the Manufacturer in accordance with KS-320. Reports of examinations shall be included in the Manufacturer's Construction Records (see KS-320).

(25) KS-320 MAINTENANCE OF RECORDS

The Manufacturer shall furnish to the User the records listed below:

(a) User's Design Specification complete with all reference documents (see KG-311)

(b) Manufacturer's Data Report (see KS-300)

(c) Manufacturer's Design Report (see KG-323)

(d) Manufacturer's Construction Records:

(1) as-built drawings

(2) materials certifications, all Material Test Reports, record of repairs

(3) pressure parts documentation and certifications

(4) Welding Procedures (see KF-216)

(5) weld repair reports (see KF-245)

(6) NDE Examination Procedures, Records of Procedure Qualification, and Records of Personnel Qualifications (see KE-106)

(7) record of all heat treatments (these records may be either the actual heat treatment charts or a certified summary description of heat treatment time and temperature)

(8) prestressing procedures and verification data

(9) NDE reports and as-built sketches showing all relevant NDE indications

(10) record of nonconformances and disposition

In addition, the Manufacturer shall maintain the required radiographs and a copy of all of the above data for a period of not less than 5 yr. These records shall be made available upon request to AI Supervisors or review teams designated by ASME. Deterioration of radiographic film is not a violation of the requirement for the maintenance of the records.

KS-321 ADDITIONAL MANUFACTURER'S CONSTRUCTION RECORDS TO BE SUPPLIED WITH COMPOSITE REINFORCED PRESSURE VESSELS (CRPV)

The Manufacturer's Construction Records supplied to the User shall also include:

(a) material supplier's certifications and specification sheets for resin, fiber reinforcement, promoters, catalyst, and other components used in laminate construction

(b) the records of the laminate material tests

KS-322 RETENTION OF DATA REPORTS FOR COMPOSITE REINFORCED PRESSURE VESSELS (CRPV)

The Manufacturer shall keep a copy of the Manufacturer's Data Report until the date of expiration of the CRPV or register the CRPV with the National Board of Pressure Vessel Inspectors, 1055 Crupper Avenue, Columbus, Ohio 43229 (see KS-300).

MANDATORY APPENDIX 1
NOMENCLATURE

(25) 1-100 NOMENCLATURE

A = interference pressure factor (see KD-811)
= actual discharge area of relief device (see Section XIII, Mandatory Appendix IV)
= nozzle or opening reinforcement area (see H-120)
A_B = cross-sectional area of a vessel normal to the vessel axis through female threads (see E-210)
A_b = total cross-sectional area of the bolts per clamp lug (see G-300)
A_C = cross-sectional area of a closure normal to the vessel axis through female threads (see E-210)
A_c = cross-sectional area of closure (see E-210)
= total cross-sectional area of the clamp (see G-300)
A_{c1} = partial clamp area (see G-300)
A_{c2} = partial clamp area (see G-300)
A_{c3} = partial clamp area (see G-300)
A_{cs} = cross-sectional area (see KD-502)
A_g = gap area (see Figure KF-826)
A_m = required cross-sectional area of the bolts per clamp (see G-300)
A_{m1} = cross-sectional area of the bolts, gasket seating (see G-300)
A_{m2} = cross-sectional area of the bolts, operating (see G-300)
A_o = outside diameter of the hub (see G-300)
A_{or} = outside bearing diameter of the hub (see G-300)
A_1 = curve fitting constant for the elastic region of the stress–strain curve (see KM-620)
A_2 = curve fitting constant for the plastic region of the stress–strain curve (see KM-620)
A_3 = lesser of A_{3a} and A_{3b} (see G-300)
A_{3a} = hub longitudinal shear area based on straight shear (see G-300)
A_{3b} = hub longitudinal shear area based on 45 deg conical (see G-300)
A_5 = minimum clamp cross-sectional area, radial–tangential (see G-300)
A_{5b} = maximum clamp bolt hole cutout area (see G-300)
A_{5i} = individual clamp bolt hole cutout area (see G-300)
A_6 = minimum clamp cross-sectional area, tangential–longitudinal (see G-300)
A_{6b} = maximum clamp bolt hole cutout area (see G-300)
A_{6i} = individual clamp bolt hole cutout area (see G-300)
A_7 = clamp lip longitudinal shear area, lesser of A_{7a} and A_{7b} (see G-300)
A_{7a} = clamp lip longitudinal shear area, straight shear surface (see G-300)
A_{7b} = clamp lip longitudinal shear area, 45 deg conical (see G-300)
a = crack depth or flaw depth (see KD-411 and KD-1002)
= the depth of a flaw at a weld toe [see KD-342(b)]
B = inside diameter of hub (see G-300)
B_c = radial distance from connection centerline to center of bolts (see G-300)
b = length of gap between layers (see KF-826)
C = fatigue crack growth coefficient (see KD-430)
= coefficient based on geometry of a blind end (see E-120)
= diameter of effective clamp–hub reaction circle (see G-300)
C_{depth} = cavity depth below required thickness (see KE-211)
C_g = effective clamp gap (see G-300)
C_i = inside bearing diameter of clamp (see G-300)
C_{ir} = inside bearing diameter of clamp with corner radius (see G-300)
C_M = combined flexibility factor of the body and closure (see E-210)
C_n = inside diameter of neck of the clamp (see G-300)
C_o = room-temperature fatigue crack growth coefficient (see KD-430)
C_r = thread factor (see E-210)
C_T = flexibility factor of the threads (see E-210)
C_t = effective clamp thickness (see G-300)
C_{us} = conversion factor, C_{us} = 1.0 for units of stress in ksi and C_{us} = 6.894757 for units of stress in MPa
C_w = clamp width (see G-300)

C_6 = tangential bending stress moment arm (see G-300)
COD = repair cavity diameter (see KE-211)
CP = collapse pressure (see KD-1212, KD-1222, KD-1241, KD-1243, KD-1253)
CTOD = crack tip opening displacement (see KM-250)
CVN = Charpy V-notch impact strength (see KM-250)
D = any referenced diameter in a cylinder or sphere (see KD-502, KD-802)
= dead weight of the vessel, contents, and appurtenances at the location of the interest (see KD-230)
D_f = cumulative fatigue damage
$D_{f,k}$ = fatigue damage for the kth cycle
D_H = diameter of cross-bored hole (see J-110)
D_I = diameter at inside surface (see KD-502, KD-802, KD-811, KD-911, E-210)
D_{if} = diameter at interface of layers (see KD-802, KD-811, KD-911)
D_n = diameter of outside surface of layer n, (see KD-802)
D_O = outside diameter (see KD-502, KD-802, KD-811, KD-822, KD-911, E-210)
= width across square section of block (see J-110)
D_{op} = diameter of opening in a blind end (see E-110)
D_p = elastic–plastic interface diameter in autofrettage (see KD-502)
= pitch diameter of thread (see E-210)
D_w = outside diameter of winding (see KD-911)
D_Z = autofrettage depth (see KD-502, KD-522)
d = diameter in given plane of finished opening (see H-120)
d_{op} = maximum opening diameter (see E-110, Figure E-110)
d_S = root diameter of a stud (see KD-623)
E = Young's modulus, material property
= earthquake loads (see KD-230)
E_{ACS} = modulus of elasticity of carbon steel at ambient temperature or 21°C (70°F)
E_B = modulus of elasticity of the body (see E-210)
E_C = modulus of elasticity of the closure (see E-210)
E_I = inner layer Young's modulus (see KD-802)
E_O = outer layer Young's modulus (see KD-802)
E_T = modulus of elasticity of the material under evaluation at the average temperature of the cycle being evaluated
E_y = modulus of elasticity evaluated at the temperature of interest, see ASME Section II, Part D
$E_{ya,k}$ = value of modulus of elasticity of the material at the point under consideration, evaluated at the mean temperature of the kth cycle
e = constant = 2.718
e_b = radial distance from bolts to centroid of clamp (see G-300)
e_m = actual circumferential growth (see KD-802, KD-822, KD-824, KF-827)
e_{th} = theoretical circumferential expansion (see KD-802, KD-822, KD-824)
F = peak stress (see KD-210, 9-200, Figure 9-200.1)
= gap value (see KF-826)
= reinforcing area reduction factor for axis angle (see H-120)
F_b = correction factor for the Bauschinger effect (see KD-502, KD-522.2, KD-523)
F_c = permissible layer gap factor (see KD-802)
F_i = nodal force resultant for element location position i
= load on ith thread (see E-210)
F_l = force in the longitudinal direction (see KD-502)
F_n = load on thread n (see E-210)
F_T = total load on threads (see E-210)
F_1 = magnification factor for calculating stress intensity of internal radial–circumferential cracks (see D-403)
F_2 = magnification factor for calculating stress intensity of internal radial–circumferential cracks (see D-403)
F_3 = magnification factor for calculating stress intensity of internal radial–circumferential cracks (see D-403)
F_4 = magnification factor for calculating stress intensity of internal radial–circumferential cracks (see D-403)
$F(\delta)$ = a fatigue modification factor based on the out-of-phase angle between $\Delta\sigma_k$ and $\Delta\tau_k$
f = hub stress correction factor (see G-300)
f_E = environmental correction factor to the welded joint fatigue curve
f_I = fatigue improvement method correction factor the welded joint fatigue curve
f_i = line force at element location point i
$f_{M,k}$ = mean stress correction factor for the kth cycle
f_{MT} = material and temperature correction factor to the welded joint fatigue curve
G = material property (see KD-430)
= gasket load reaction diameter (see G-300)
$\overline{g}$ = radial distance from hub inside diameter to centroid hub shoulder ring (see G-300)
g_0 = thickness of hub at small end (see G-300)
g_1 = thickness of hub at neck (see G-300)
g_2 = height of hub shoulder (see G-300)
H = specific stiffness (see D-405)
= total end force on hub for operating or assembly (see G-300)
H_D = hydrostatic end force on bore area (see G-300)
H_e = total hydrostatic end force (see G-300)

H_G = difference between hub preload and required forces (see G-300)
H_m = gasket seating requirements (see G-300)
H_p = joint-contact surface compression load (see G-300)
H_T = difference between total hydrostatic end force and on bore (see G-300)
H_2 = correction factor for bending stress (see D-401)
h = distance from flange face to end of skirt [see Figure KD-830.3, illustration (c)]
= gap between two layers (see KF-826)
h_D = radial distance clamp–hub reaction circle to H_D (see G-300)
h_G = radial distance clamp–hub reaction circle to H_G (see G-300)
h_n = hub neck length (see G-300)
h_T = radial distance clamp–hub reaction circle to H_T (see G-300)
h_2 = average thickness of hub shoulder (see G-300)
I = material property (see KD-430)
= correction factor used in the structural stress evaluation
I_c = moment of inertia of clamp (see G-300)
I_h = moment of inertia of hub shoulder (see G-300)
I_5 = minimum clamp moment of inertia in any radial–tangential plane (see G-300)
I_{5b} = maximum reduction clamp moment of inertia bolt holes (see G-300)
I_6 = minimum clamp moment of inertia in any tangential–longitudinal plane (see G-300)
I_{6b} = maximum reduction clamp moment of inertia bolt holes (see G-300)
I_τ = correction factor used in the structural shear stress evaluation
J_{crit} = critical value of the J-integral (see KM-253)
K = stress concentration factor (see Figure 9-200.1)
= 0.73 times transition radius r_2 (see H-142)
K_{css} = material parameter for the cyclic stress-strain curve model
$K_{c\delta}$ = equivalent K_{Ic} computed from CTOD data (see KM-252)
K_f = fatigue strength reduction factor used to compute the cyclic stress amplitude or range
K_I = stress intensity factors in a crack (see KD-420, KD-440)
$K_{I\max}$ = maximum stress intensity factor in a crack (see KD-430)
$K_{I\min}$ = minimum stress intensity factor in a crack (see KD-430)
$K_{I\text{res}}$ = residual stress intensity in a crack (see KD-420, KD-430)
K_{Ic} = critical stress intensity factor for crack (see KM-250)
= fracture toughness (see KD-401)
K_{Jc} = equivalent K_{Ic} computed from J_{crit} (see KM-253)
$K_{J\text{REF}}$ = crack tip stress intensity factor (see D-405)
K_N = wire factor (see KD-932)
K_n = greater of 2.6 or $(K_s)^{4.3}$ (see KD-1262)
K_r = surface roughness factor (see KD-322)
K_S = wire factor (see KD-932)
K_{SL} = wire factor (see KD-932)
K_{SS} = wire factor (see KD-932)
K_s = greater of 1.25 or $K_{sa}K_{sf}K_{sc}K_{st}K_{ss}$ (see KD-1262)
K_{sa} = factor for size of highly stressed fatigue area (see KD-1262)
K_{sc} = factor for fatigue curves at varying temperatures (see KD-1262)
K_{sf} = factor for fatigue surface finish (see KD-1262)
K_{ss} = factor for statistical variation in fatigue tests (see KD-1262)
K_{st} = factor for fatigue test temperature (see KD-1262)
K_{th} = threshold stress intensity (see KD-430)
K_T = hoop stress concentration factor for cross-bored holes (see J-110)
K_{TN} = test life ratio (see KD-1262)
K_{TS} = test stress ratio (see KD-1262)
= length along nozzle with thickness t_n plus transition (see H-142)
K_{ut} = hydrostatic test pressure upper limit factor (see KD-221, KT-312)
K_{utj} = hydrostatic test pressure upper limit factor for each individual layer (see KD-221, KT-312)
k = C_p/C_v ratio of specific heats
k_{c1} = design correction factor with S_y/S_u (see 9-210, 9-220, Table 9-100.1, Figure 9-200.1)
L = appurtenance live loading (see KD-230)
L_A = floating transporter acceleration loads due to spectral motion response determined in KD-237
L_a = distance from clamp bolt centerline to where clamp lug joins body (see G-300)
L_h = clamp lug height (see G-300)
L_T = length of wire pieces in fatigue test (see KD-932.3)
L_W = average distance between wire cracks (see KD-932.3)
L_w = clamp lug width (see G-300)
L_1 = measured length of vessel at test pressure
ℓ = length of required taper (see Figure KD-1121)
= surface length of crack (see D-401)
ℓ_c = effective clamp lip length (see G-300)
= circumferential separation of nozzle centerlines (see H-101)
ℓ_ℓ = longitudinal separation of nozzle centerlines (see H-101)
ℓ_m = effective clamp lip moment arm (see G-300)

M = correction factor for membrane stress (see D-401)
= mean flexibility of vessel body and end closure (see E-210)
M_D = moment due to H_D (see G-300)
M_F = offset moment (see G-300)
M_G = moment due to H_G (see G-300)
M_H = reaction moment at hub neck (see G-300)
M_i = nodal moment resultant for element location position i
M_o = total rotational moment on hub (see G-300)
M_p = pressure moment (see G-300)
M_R = radial clamp equilibrating moment (see G-300)
M_T = moment due to H_T (see G-300)
M_5 = clamp longitudinal stress bending moment (see G-300)
M_6 = clamp tangential stress bending moment (see G-300)
m = crack growth rate exponent [see KD-430, Table KD-430 (see Table KD-430M)]
= gasket factor (see G-300)
m_i = line moment at element location position i
m_{ss} = exponent used in a fatigue analysis based on structural stress
${}^{m}N$ = specified number of repetitions of the event associated with time point ${}^{m}t$
${}^{m}P_k$ = component crack face pressure at time point ${}^{m}t$ for the kth cycle. The crack face pressure should be specified if the maximum value of the membrane plus bending stress used in the analysis occurs on a surface that is exposed to the fluid pressure. A conservative approach is to always specify the crack face pressure. The crack face pressure is based on the actual or operating pressure defined in the loading time history.
${}^{m}t$ = time point under consideration with the highest peak or lowest valley
${}^{mn}\Delta\sigma_{ij}$ = stress component range between time points ${}^{m}t$ and ${}^{n}t$
${}^{mn}\Delta\sigma_{11}$ = stress range associated with the normal stress component in the 1-direction between time points ${}^{m}t$ and ${}^{n}t$
${}^{mn}\Delta\sigma_{12}$ = stress range associated with the shear stress component in the 1-direction between time points ${}^{m}t$ and ${}^{n}t$
${}^{mn}\Delta\sigma_{13}$ = stress range associated with the shear stress component in the 2-direction between time points ${}^{m}t$ and ${}^{n}t$
${}^{mn}\Delta\sigma_{22}$ = stress range associated with the normal stress component in the 2-direction between time points ${}^{m}t$ and ${}^{n}t$
${}^{mn}\Delta\sigma_{23}$ = stress range associated with the shear stress component in the 3-direction between time points ${}^{m}t$ and ${}^{n}t$
${}^{mn}\Delta\sigma_{33}$ = stress range associated with the normal stress component in the 3-direction between time points ${}^{m}t$ and ${}^{n}t$
${}^{m}\sigma^{e}_{b,k}$ = elastically calculated bending stress at the point under evaluation for the kth cycle at the m point
${}^{m}\sigma^{e}_{m,k}$ = elastically calculated membrane stress at the point under evaluation for the kth cycle at the m point
${}^{m}\sigma_{ij}$ = stress tensor at the point under evaluation at time point ${}^{m}t$
${}^{m}\tau^{e}_{b,k}$ = elastically calculated bending component of shear stress distribution at the point under evaluation for the kth cycle at the m point
${}^{m}\tau^{e}_{m,k}$ = elastically calculated membrane component of shear stress distribution at the point under evaluation for the kth cycle at the m point
N = number of layers (see KD-802)
= number of allowable design cycles
N_D = design number of alternating stress cycles (see KD-932, KD-1262)
N_f = design limit number of alternating stress cycles (see KD-320)
N_H = outside diameter of hub neck (see G-300)
N_i = allowable number of cycles for vessel service life (see KD-330)
N_k = permissible number of cycles for the kth cycle
N_p = design operating cycles to one-fourth critical crack depth (see KD-440)
N_T = number of test cycles (see KD-1262)
$N_{T\min}$ = minimum number of test cycles (see KD-1262)
NF_{ij} = nodal force at node j, normal to the section, for element location position i
NF_j = nodal force at node j, normal to the section
NM_j = in-plane nodal moment at node j, normal to the section, for a shell element
n = number of layer (see KD-802)
= number of fully engaged threads (see E-210)
= number of nodes in the through-wall thickness direction
= number of threads (see E-210)
n_{css} = material parameter for the cyclic stress-strain curve model
n_i = number of applied alternating stress cycles (see KD-330)
n_k = actual number of repetitions for the kth cycle
${}^{n}N$ = specified number of repetitions of the event associated with time point ${}^{n}t$
${}^{n}P_k$ = component crack face pressure at time point ${}^{n}t$ for the kth cycle. The crack face pressure should be specified if the maximum value of the membrane plus bending stress used in the analysis occurs on a surface that is exposed to the fluid pressure. A conservative

approach is to always specify the crack face pressure. The crack face pressure is based on the actual or operating pressure defined in the loading time history.

^{n}t = time point under consideration that forms a range with time point ^{m}t

$^{n}\sigma^{e}_{b,k}$ = elastically calculated bending stress at the point under evaluation for the kth cycle at the n point

$^{n}\sigma^{e}_{m,k}$ = elastically calculated membrane stress at the point under evaluation for the kth cycle at the n point

$^{n}\sigma_{ij}$ = stress tensor at the point under evaluation at time point $^{n}1$

$^{n}\tau^{e}_{b,k}$ = elastically calculated bending component of shear stress distribution at the point under evaluation for the kth cycle at the n point

$^{n}\tau^{e}_{m,k}$ = elastically calculated membrane component of shear stress distribution at the point under evaluation for the kth cycle at the n point

P = design pressure (see KD-802, G-300)
= fluid pressure acting in a crack (see D-401)

P_A = maximum autofrettage pressure (see KD-502)

P_b = bending stress (see 9-200, Figure 9-200.1)

P_D = design pressure (see KD-220)

P_{if} = interface pressure (see KD-802)

P_L = local membrane stress (see KD-210, 9-200)

P_m = general membrane stress (see 9-200)

P_n = pressure at layer interface (see KD-802)

P_O = operating pressure (see Table KD-230.2, Table 9-100.1)

P_s = static head from liquid or bulk materials (e.g., catalyst) (see KD-230)

P_T = cyclic test loading (see KD-1262)
= thread pitch (see E-210)

P_t = hydrostatic test pressure (see KD-231, KD-824, KT-312)

Q = secondary membrane plus bending stress (see 9-200, Figure 9-200.1)
= reaction shear force at hub neck (see G-300)

Q_c = percent of theoretical circumferential growth measured on outside (see KD-802)
= acceptance criteria (see KD-822, KD-823)

q = parameter used to determine the effect equivalent structural stress range on the fatigue improvement factor

$R_{b,k}$ = ratio of the bending stress to the membrane plus bending stress

$R_{bL,k}$ = ratio of the bending component of the shear stress to the membrane plus bending component of the shear stress

R_c = corner radius (see E-110)

R_f = final centerline radius of formed head (see KF-602)

R_g = outside radius of layer below gap (see Figure KF-826)

R_I = radius to inside surface of innermost layer (see KF-826)

R_K = stress intensity factor ratio (see KD-430)

R_k = stress ratio for the kth cycle

R_m = radius of midsurface of head or shell (see 9-220, KD-721, KE-211)

R_O = outside radius of vessel (see KF-826)

R_o = original centerline radius of formed plate (see KF-602)

r = radius between flat head and shell (see Figure KD-830.3, KD-1112)
= clamp or hub cross-section corner radius (see G-300)
= inside radius of nozzle (see H-142)

r_c = clamp inside corner radius (see G-300)

r_h = hub outside corner radius (see G-300)

r_j = radial coordinate of node j for an axisymmetric element

r_m = mean radius of nozzle (see H-142)

r_2 = transition radius inside nozzle to vessel wall (see H-142)

S = equivalent stress (see KD-623, KD-631, KD-700, KD-723, KD-922, KD-1270, 9-100, 9-200, 9-210, 9-220, 9-260, 9-270, 9-300)
= stress intensity (see KD-210, KD-623)
= number of loaded segments in one pitch (see E-210)

S_a = allowable fatigue strength (see KD-120)
= allowable bolt stress, room temperature (see G-300)

S_{a10^n} = stress intensity at design load (see KD-1262)

S'_a = allowable amplitude of alternating stress (see KD-312.4)

S_{aD} = design stress, allowable (see KD-1262)

S_{alt} = alternating stress intensity (see KD-302, KD-312)

S_b = allowable bolt stress, design temperature (see G-300)

S_e = computed equivalent stress

S_{eq} = equivalent calculated alternating stress intensity (see KD-312.4)

S_i = segment load (see E-210)

S_M = combined flexibility factor of the body and closure (see E-210)

S_s = snow loads (see KD-230)

S_T = flexibility factor of the threads (see E-210)

S_u = ultimate tensile strength (see Section II, Part D, Table U)

S_{uj} = tensile strength for each layer (see Section II, Part D, Table U)

$S_w(x)$ = stress in wire (see KD-911)

S_y = yield strength (see KD-120, KD-221, KD-623, KD-1254)

$S_{y,k}$ = yield strength of the material evaluated at the mean temperature of the kth cycle
S_{yj} = yield strength for each layer (see Section II, Part D, Table Y-1)
S_{yact} = actual yield stress (see KD-1254)
S_{yms} = actual yield strength per material specification (see KD-1254)
S_{YAC} = yield stress for clamp material, room temperature (see G-300)
S_{YAH} = yield stress for hub material, room temperature (see G-300)
S_{YOC} = yield stress for clamp material, design temperature (see G-300)
S_{YOH} = yield stress for hub material, design temperature (see G-300)
S_1 = hub longitudinal stress on outside hub neck (see G-300)
S_2 = maximum Lamé hoop stress at hub bore (see G-300)
S_3 = hub shear stress at shoulder (see G-300)
S_4 = hub radial stress in hub neck (see G-300)
S_5 = clamp longitudinal stress at clamp body inner diameter (see G-300)
S_6 = clamp tangential stress at clamp body outer diameter (see G-300)
S_7 = maximum shear stress in clamp lips (see G-300)
S_8 = clamp lip bending stress (see G-300)
S_9 = clamp lug bending stress (see G-300)
S_{10} = maximum clamp lug shear stress (see G-300)
S_{11} = effective bearing stress between clamp and hub (see G-300)
s_j = local coordinate, parallel to the stress classification line, that defines the location of nodal force NF_j relative to the mid-thickness of the section
T = absolute temperature
= thickness (see KM-201, KM-210, KM-211.1)
= maximum heat-treated thickness (see KM-211)
= self-restraining load case (see KD-230)
= thickness of hub shoulder (see G-300)
T_c = critical temperature (see KD-1262)
= clamp lip thickness below outside edge hub (see G-300)
T_h = hub shoulder thickness below inside edge hub (see G-300)
T_t = test temperature (see KD-1262)
t = twice the greatest possible distance between an interior location and the nearest heat-treated surface (see KM-211.2)
= wall thickness, nominal vessel thickness (see 9-220, KD-802, H-142)
= minimum wall thickness in the region under consideration, or the thickness of the vessel, as applicable
t_b = thickness of blind end (see E-110)
t_{ess} = structural stress effective thickness
t_H = thickness of head at joint (see Figure KD-830.2)
t_j = thickness of each layer (see KD-221)
t_L = thickness of layer at joint (see Figure KD-830.2)
t_n = thickness of layer n (see KD-802)
= nominal thickness of nozzle wall less corrosion allowance (see Figure KD-830.6)
= thickness of nozzle wall (see Figure KD-1130)
t_p = thickness of attached pipe wall (see H-142)
t_r = minimum wall thickness without opening (see H-120)
t_{rn} = required thickness of seamless nozzle wall (see Figure KD-1122)
t_S = shell thickness (see Figure KD-830.2)
t_w = thickness of vessel wall (see E-110)
U = cumulative usage factor (see KD-330)
V_{REF} = longitudinal crack displacement (see D-405)
W = wind load (see KD-230)
= total design bolt load (see G-300)
W_A = assembly loads (e.g., shrink fit, wire winding, sealing preload) (see KD-230)
W_c = total effective clamping preload on one lip (see G-300)
W_{m1} = minimum operating bolt load (see G-300)
W_{m2} = minimum gasket seating bolt load (see G-300)
W_{pt} = pressure test wind load case (see KD-230)
w = width of the element to determine structural stresses from Finite Element Analysis
X = absolute value of the range (load or stress) under consideration using the Rainflow Cycle Counting Method
X_b = basic clamp dimension to neutral axis (see G-300)
X_g = global X axis
X_i = average radial distance from bolt cutout area (see G-300)
X_L = local X axis, oriented parallel to the stress classification line
X_5 = modified clamp dimension to neutral axis (see G-300)
X_6 = modified clamp dimension to neutral axis (see G-300)
x = diameter at any point (see KD-911)
= through-wall thickness coordinate
x_1 = any diameter of cylinder (see KD-911)
x_2 = any diameter of winding (see KD-911)
Y = wall ratio or D_O/D_I of a shell (see KD-220, KD-502)
= weld offset (see Figure KD-830.2)
= absolute value of the adjacent range (load or stress) to previous X using the Rainflow Cycle Counting Method
Y_g = global Y axis

Y_i = ratio of outside diameter to inside diameter of inner layer (see KD-802)
Y_j = ratio of outside diameter to inside diameter of each layer (see KD-220, KT-312)
Y_L = local Y axis, oriented normal to the stress classification line
Y_o = ratio of outside diameter to inside diameter of outer layer (see KD-802)
y = radial offset in buttwelding of unequal section thicknesses (see Figure KD-1121)
Z = D_O/D, where D can be any point in the wall (see KD-220)
= clamp-hub taper angle (see G-300)
α = shape factor [see 9-100, 9-220(d), Figure 9-200.1]
= angle, maximum angle (see Figure KE-321)
= maximum rake angle (see E-110)
α_r = thermal expansion of reinforcing metal (see H-150)
α_v = thermal expansion of vessel wall (see H-150)
β = factor in equivalent alternating stress intensity (see KD-312)
= factor = 0.2 (see KD-932)
γ_1 = true strain in the micro-strain region of the stress–strain curve (see KM-620)
γ_2 = true strain in the macro-strain region of the stress–strain curve (see KM-620)
Δ = difference, increment
ΔK = range of stress intensity factor (see KD-430)
$\Delta S_{\mathrm{ess},k}$ = equivalent structural stress range parameter for the kth cycle (see KD-341 and KD-372)
$\overline{\Delta s}$ = average relative standard deviation of fatigue strength (see KD-932.3)
ΔT = operating temperature range (see H-150)
$\Delta\varepsilon_{\mathrm{k}}$ = local nonlinear structural strain range at the point under evaluation for the kth cycle
$\Delta\varepsilon^e{}_k$ = elastically calculated structural strain range at the point under evaluation for the kth cycle
$\Delta\varepsilon_{p,ij}$ = the range of plastic strain component, ij, at the point under evaluation for the cycle under evaluation. Note that the shear strains are the engineering strain values that are typically output from a finite element analysis (i.e., not tensor strains) (see KD-323)
$\Delta\varepsilon_{p,ij,k}$ = the range of plastic strain component, ij, at the point under evaluation for the kth loading condition or cycle. Note that the shear strains are the engineering strain values that are typically output from a finite element analysis (i.e., not tensor strains) (see KD-232)
$\Delta\sigma_k$ = local nonlinear structural stress range at the point under evaluation for the kth cycle
$\Delta\sigma_s$ = structural stress range
$\Delta\sigma^e{}_{b,k}$ = elastically calculated structural bending stress range at the point under evaluation for the kth cycle
$\Delta\sigma^e{}_k$ = elastically calculated structural stress range at the point under evaluation for the kth cycle
$\Delta\sigma^e{}_{m,k}$ = elastically calculated structural membrane stress range at the point under evaluation for the kth cycle
$\Delta\tau_{\mathrm{k}}$ = structural shear stress range at the point under evaluation for the kth cycle
$\Delta\tau^e{}_{b,k}$ = elastically calculated bending component of the structural shear stress range at the point under evaluation for the kth cycle
$\Delta\tau^e{}_{m,k}$ = elastically calculated membrane component of the structural shear stress range at the point under evaluation for the kth cycle
δ = any difference, diametral interference (see KD-802)
= out-of-phase angle between $\Delta\sigma_k$ and $\Delta\tau_k$ for the kth cycle
δ_{crit} = critical crack tip opening displacement CTOD (see KM-252)
ϵ_m = average tangential strain, autofrettaged outside diameter (see KD-502)
ϵ_p = average tangential strain, autofrettaged bore (see KD-502)
= stress–strain curve fitting parameter (see KM-620)
ϵ_{ta} = true total strain amplitude
ϵ_{tr} = true total strain range
ϵ_{ts} = true total strain (see KM-620)
ϵ_{ys} = 0.2% engineering offset strain (see KM-620)
ϵ_1 = true plastic strain in the micro-strain region of the stress–strain curve (see KM-620)
ϵ_2 = true plastic strain in the macro-strain region of the stress–strain curve (see KM-620)
μ = viscosity
= friction angle (see G-300)
ν = Poisson's ratio (see KD-802); also sometimes viscosity
ν_{i} = inner layer Poisson's ratio (see KD-802)
ν_{o} = outer layer Poisson's ratio (see KD-802)
π = constant = 3.14159
Σ = summation
σ = normal or principal stresses, with various subscripts
σ_{AD} = value of σ_{tRA} at $D = D_I$ (see KD-502)
σ_a = total stress amplitude
σ_b = bending stress
σ_{bi} = bending stress for element location position i
σ_{CD} = residual tangential stress at bore, including the Bauschinger effect (see KD-502)
σ_e = equivalent stress
σ_{ij} = stress tensor at the point under evaluation
$\sigma_{ij,b}$ = bending stress tensor at the point under evaluation

$\sigma_{ij,F}$ = peak stress component
$\sigma_{ij,in}$ = stress tensor on the inside surface of the shell
$\sigma_{ij,m}$ = membrane stress tensor at the point under evaluation
$\sigma_{ij,\text{out}}$ = stress tensor on the outside surface of the shell
σ_m = membrane stress
σ_{mi} = membrane stress for element location position i
$\sigma_{\text{max},k}$ = maximum stress in the kth cycle
$\sigma_{\text{mean},k}$ = mean stress in the kth cycle
$\sigma_{\text{min},k}$ = minimum stress in the kth cycle
σ_{nm} = associated mean stress (see KD-302.2)
σ_R = radial stress component at radius r (see KD-802)
σ_r = total stress range
σ_{rR} = radial stress at bore, including the Bauschinger effect (see KD-522)
σ_{rr} = residual radial stress (see KD-802)
σ_{rRA} = first approximation of residual radial stress after autofrettage (see KD-522)
σ_s = structural stress
σ_t = tangential stress component at radius r (see KD-802)
= true stress at which the true strain will be evaluated (see KM-620)
σ_{tR} = residual tangential stress, including the Bauschinger effect (see KD-522)
σ_{tRA} = first approximation of residual tangential stress after autofrettage (see KD-522)
σ_{tr} = residual tangential stress (see KD-802)
σ_{uts} = engineering ultimate tensile stress evaluated at the temperature of interest (see KM-620)
σ_{ys} = engineering yield stress evaluated at the temperature of interest (see KM-620)
$\sigma_{uts,t}$ = true ultimate tensile stress evaluated at the true ultimate tensile strain
σ_1 = principal stress in the 1-direction
σ_2 = principal stress in the 2-direction
σ_3 = principal stress in the 3-direction
τ = shear stresses, with various subscripts
Φ = flaw shape parameter (see D-401)
ϕ = clamp shoulder angle (see G-300)

MANDATORY APPENDIX 2
QUALITY CONTROL SYSTEM

(25) 2-100 GENERAL

The Manufacturer shall have and maintain a Quality Control System which will establish that all Code requirements, including material, design, fabrication, examination (by the Manufacturer), and inspection of vessels and vessel parts (by the Inspector), will be met. Provided that Code requirements are suitably identified, the system may include provisions for satisfying any requirements by the Manufacturer, or user which exceed minimum Code requirements and may include provisions for quality control of non-Code work. In such systems, the Manufacturer of vessels and vessel parts may make changes in parts of the system which do not affect the Code requirements without securing acceptance by the Inspector (see KG-300).

The system that the Manufacturer uses to meet the requirements of this Division must be one suitable for the Manufacturer's own circumstances. The necessary scope and detail of the system shall depend on the complexity of the work[15] performed and on the size and complexity of the Manufacturer's organization.[16] A written description of the system the Manufacturer will use to produce a Code item shall be available for review. Depending upon the circumstances, the description may be brief or voluminous.

The written description may contain information of a proprietary nature relating to the Manufacturer's processes. Therefore, the Code does not require any distribution of this information except for the Inspector's or ASME designee's copy as covered by 2-123(c). It is intended that information learned about the system in connection with the evaluation will be treated as confidential and that all loaned descriptions will be returned to the Manufacturer upon completion of the evaluation.

2-110 OUTLINE OF FEATURES TO BE INCLUDED IN THE WRITTEN DESCRIPTION OF THE QUALITY CONTROL SYSTEM

The following is a guide to some of the features which should be covered in the written description of the Quality Control System and is equally applicable to work performed at the shop or field or intermediate sites.

(a) See Article KE-1.

(b) The complexity of the work includes factors such as design simplicity versus complexity, the types of materials and welding procedures used, the thickness of materials, the types of nondestructive examinations applied, and whether heat treatments are applied.

(c) The size and complexity of the Manufacturer's organization includes factors such as the number of employees, the experience level of employees, the number of vessels produced, and whether the factors defining the complexity of the work cover a wide or narrow range.

2-111 AUTHORITY AND RESPONSIBILITY

The authority and responsibility of those in charge of the Quality Control System shall be clearly established. Persons performing quality control functions shall have sufficient and well-defined responsibility, the authority, and the organizational freedom to identify quality control problems and to initiate, recommend, and provide solutions.

2-112 ORGANIZATION (25)

An organization chart showing the relationship between management and engineering, purchasing, manufacturing, field construction, inspection, and quality control is required to reflect the actual organization. The purpose of this chart is to identify and associate the various organizational groups with the particular function for which each group is responsible. The Code does not intend to encroach on the Manufacturer's right to establish, and from time to time to alter, whatever form of organization the Manufacturer considers appropriate for its Code work.

2-113 DRAWINGS, DESIGN CALCULATIONS, AND SPECIFICATION CONTROL

The Manufacturer's Quality Control System shall provide procedures which will assure that the latest applicable drawings, design calculations, specifications, and instructions, required by the Code, as well as authorized changes, are used for manufacture, examination, inspection, and testing. The system shall insure that authorized changes are included, when appropriate, in the User's Design Specification and/or in the Manufacturer's Design Report.

2-114 MATERIAL CONTROL

The Manufacturer shall include a system of receiving control which will insure that the material received is properly identified and has documentation including required material certifications or material test reports to satisfy Code requirements as ordered. The system material control shall insure that only the intended material is used in Code construction.

2-115 EXAMINATION AND INSPECTION PROGRAM

The Manufacturer's Quality Control System shall describe the fabrication operations, including examination, sufficiently to permit the Inspector or ASME designee to determine at what stages specific inspections are to be performed.

2-116 CORRECTION OF NONCONFORMITIES

There shall be a system agreed upon with the Inspector for correction of nonconformities. A nonconformity is any condition which does not comply with the applicable rules of this Division. Nonconformities must be corrected or eliminated in some way before the completed component can be considered to comply with this Division.

2-117 WELDING

The Quality Control System shall include provisions for indicating that welding conforms to requirements of Section IX as supplemented by this Division.

2-118 NONDESTRUCTIVE EXAMINATION

The Quality Control System shall include provisions for identifying nondestructive examination procedures the Manufacturer will apply to conform with the requirements of this Division.

(25) 2-119 HEAT TREATMENT

The Quality Control System shall provide controls to ensure that heat treatments as required by the rules of this Division are applied. Means shall be indicated by which the Inspector or ASME designee can be satisfied that these Code heat treatment requirements are met. This may be by review of furnace time–temperature records or by other methods as appropriate.

2-120 CALIBRATION OF MEASUREMENT AND TEST EQUIPMENT

The Manufacturer shall have a system for the calibration of examination, measuring, and test equipment used in fulfillment of requirements of this Division.

2-121 RECORDS RETENTION

The Manufacturer shall have a system for the maintenance of Data Reports and records as required by this Division.

2-122 SAMPLE FORMS

The forms used in this Quality Control System and any detailed procedures for their use shall be available for review. The written description shall make necessary references to these forms.

2-123 INSPECTION OF VESSELS AND VESSEL PARTS (25)

(a) Inspection of vessels and vessel parts shall be by the Inspector as defined in Article KG-4.

(b) The written description of the Quality Control System shall include reference to the Inspector.

(c) The Manufacturer shall make available to the Inspector, at the Manufacturer's plant or construction site, a current copy of the written description of the Quality Control System.

(d) The Manufacturer's Quality Control System shall provide for the Inspector at the Manufacturer's plant to have access to the User's Design Specification, the Manufacturer's Design Report, and all drawings, calculations, specifications, procedures, process sheets, repair procedures, records, test results, and any other documents as necessary for the Inspector to perform the Inspector's duties in accordance with this Division. The Manufacturer may provide such access either to the Manufacturer's own files of such documents or by providing copies to the Inspector.

2-124 CERTIFICATIONS

(a) Methods other than written signature may be used for indicating certifications, authorizations, and approvals where allowed and as described elsewhere in this Division.

(b) Where other methods are employed, controls and safeguards shall be provided and described to ensure the integrity of the certification, authorization, and approval.

MANDATORY APPENDIX 5
ADHESIVE ATTACHMENT OF NAMEPLATES

5-100 SCOPE

This Appendix covers the qualification of procedures for the adhesive attachment of nameplates. The use of adhesive systems for the attachment of nameplates is permitted only under the following conditions:

(a) The adhesive used is a pressure-sensitive acrylic adhesive that has been preapplied by the nameplate manufacturer to a nominal thickness of at least 0.005 in. (0.13 mm).

(b) The adhesive is protected with a moisture-stable liner.

(c) The vessel(s) to which the nameplate is being attached has a design temperature within the range of −40°F to 300°F (−40°C to 150°C), inclusive.

(d) The nameplate is applied to a clean, bare metal surface with attention being given to removal of anti-weld-spatter compound which may contain silicone.

(e) The nameplate application procedure is qualified as outlined in 5-200.

(f) The preapplied adhesive is used within 2 yr after initial adhesive application.

(25) 5-200 NAMEPLATE APPLICATION PROCEDURE QUALIFICATION

(a) The Manufacturer's Quality Control System (see Mandatory Appendix 2) shall define that written procedures, acceptable to the Inspector, for the application of adhesive-backed nameplates shall be prepared and qualified.

(b) The application procedure qualification shall include the following essential variables, using the adhesive and nameplate manufacturers' recommendations where applicable:

(1) description of the pressure-sensitive acrylic adhesive system employed, including generic composition.

(2) the qualified temperature range [the cold box test temperature shall be −40°F (−40°C) for all applications].

(3) materials of nameplate and substrate when the mean coefficient of expansion at design temperature of one material is less than 85% of that for the other material.

(4) finish of the nameplate and substrate surfaces.

(5) the nominal thickness and modulus of elasticity at application temperature of the nameplate when nameplate preforming is employed. A change of more than 25% in the quantity: [(nameplate nominal thickness)^2 × nameplate modulus of elasticity at application temperature] will require requalification.

(6) the qualified range of preformed nameplate and companion substrate contour combinations when preforming is employed.

(7) cleaning requirements for the substrate.

(8) application temperature range and application pressure technique.

(9) application steps and safeguards.

(c) Each procedure used for nameplate attachment by pressure-sensitive acrylic adhesive systems shall be qualified for outdoor exposure in accordance with Standard UL-969, Marking and Labeling Systems, with the following additional requirements:

(1) Width of nameplate test strip shall not be less than 1 in.

(2) Nameplates shall have an average adhesion of not less than 8 lbf/in. (1.4 N/mm) of width after all exposure conditions, including low temperature.

(d) Any change in (b) shall require requalification.

(e) Each lot or package of nameplates shall be identified with the adhesive application date.

MANDATORY APPENDIX 6
ROUNDED INDICATIONS CHARTS ACCEPTANCE STANDARD FOR RADIOGRAPHICALLY DETERMINED ROUNDED INDICATIONS IN WELDS

6-100 APPLICABILITY OF THESE STANDARDS

These standards are applicable to ferritic, austenitic, and nonferrous materials, in cases where radiography is required.

6-110 TERMINOLOGY

(a) Rounded Indications. Indications with a maximum length of three times the width or less on the radiograph are defined as rounded indications. These indications may be circular, elliptical, conical, or irregular in shape and may have tails. When evaluating the size of an indication, the tail shall be included. The indication may be from any source in the weld, such as porosity, slag, or tungsten.

(b) Aligned Indications. A sequence of four or more rounded indications shall be considered to be aligned when they touch a line parallel to the length of the weld drawn through the center of the two outer rounded indications.

(c) Thickness, t. t is the thickness of the weld, excluding any allowable reinforcement. For a butt weld joining two members having different thicknesses at the weld, *t* is the thinner of these two thicknesses. If a full penetration weld includes a fillet weld, the thickness of the throat of the fillet shall be included in *t*.

6-120 ACCEPTANCE CRITERIA

(a) Image Density. Density within the image of the indication may vary and is not a criterion for acceptance or rejection.

(b) Relevant Indications (See Table KE-332 for Examples). Only those rounded indications which exceed the following dimensions shall be considered relevant:

(1) $\frac{1}{10}t$ for t less than $\frac{1}{8}$ in. (3.2 mm)

(2) $\frac{1}{64}$ in. (0.4 mm) for t $\frac{1}{8}$ in. (3.2 mm) to $\frac{1}{4}$ in. (6 mm), inclusive

(3) $\frac{1}{32}$ in. (0.8 mm) for t greater than $\frac{1}{4}$ in. (6 mm) to 2 in. (50 mm), inclusive

(4) $\frac{1}{16}$ in. (1.6 mm) for t greater than 2 in. (50 mm)

(c) Maximum Size of Rounded Indications (See Table KE-332 for Examples). The maximum permissible size of any indication shall be $\frac{1}{4}t$ or $\frac{5}{32}$ in. (4 mm), whichever is smaller, except that an isolated indication separated from an adjacent indication by 1 in. (25 mm) or more may be $\frac{1}{3}t$ or $\frac{1}{4}$ in. (6 mm), whichever is less. For t greater than 2 in. (50 mm), the maximum permissible size of an isolated indication shall be increased to $\frac{3}{8}$ in. (10 mm).

(d) Aligned Rounded Indications. Aligned rounded indications are acceptable when the summation of the diameters of the indications is less than t in a length of $12t$ (see Figure 6-1). The length of groups of aligned rounded indications and the spacing between the groups shall meet the requirements of Figure 6-2.

(e) Spacing. The distance between adjacent rounded indications is not a factor in determining acceptance or rejection, except as required for isolated indications or groups of aligned indications.

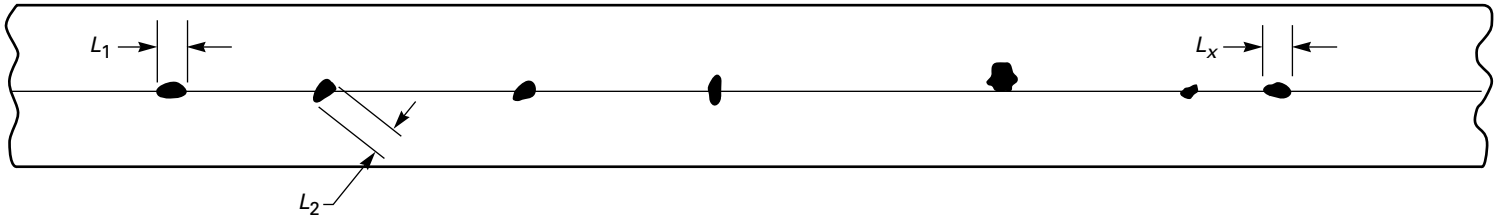
(f) Rounded Indications Charts. The rounded indications as determined from the radiographic film shall not exceed that shown in the charts.

The charts in Figures 6-3.1 through 6-3.6 illustrate various types of assorted, randomly dispersed and clustered rounded indications for different weld thicknesses greater than $\frac{1}{8}$ in. (3.2 mm). These charts represent the maximum acceptable concentration limits for rounded indications.

The chart for each thickness range represents full-scale 6 in. (150 mm) radiographs, and shall not be enlarged or reduced. The distributions shown are not necessarily the patterns that may appear on the radiograph, but are typical of the concentration and size of indications permitted.

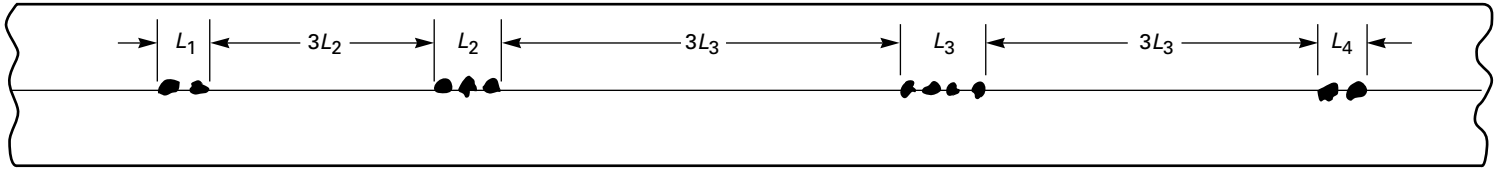
(g) Clustered Indications. The illustrations for clustered indications show up to four times as many indications in a local area as that shown in the illustrations for random indications. The length of an acceptable cluster shall not exceed the lesser of 1 in. (25 mm) or $2t$. Where more than one cluster is present, the sum of the lengths of the clusters shall not exceed 1 in. (25 mm) in a 6 in. (150 mm) length of weld.

Figure 6-1
Aligned Rounded Indications



GENERAL NOTE: The sum of L_1 to L_x shall be less than t in a length of $12t$.

Figure 6-2
Groups of Aligned Rounded Indications



GENERAL NOTE: The sum of the group lengths shall be less than t in a length of $12t$.

(1) Maximum group length:

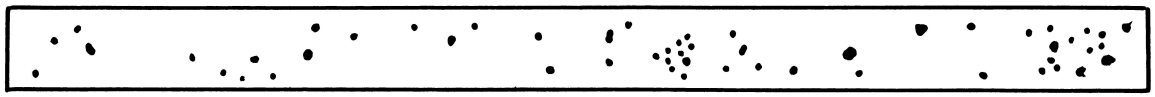
L = 1/4 in. (6 mm) for t < 3/4 in. (19 mm)

L = 1/3t for t 3/4 in. (19 mm) to 2 1/4 in. (57 mm)

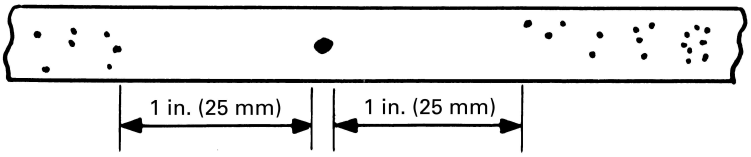
L = 3/4 in. (19 mm) for t > 2 1/4 in. (57 mm)

(2) Minimum group spacing: $3L$, where L is the length of the longest adjacent group being evaluated.

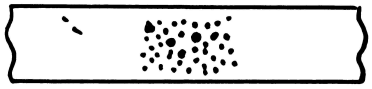
Figure 6-3.1
Charts for t $\frac{1}{8}$ in. (3 mm) to $\frac{1}{4}$ in. (6 mm), Inclusive



Random Rounded Indications
[Note (1)]



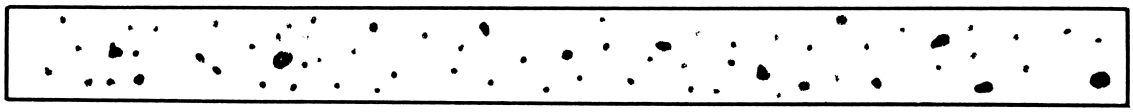
Isolated Indication
[Note (2)]



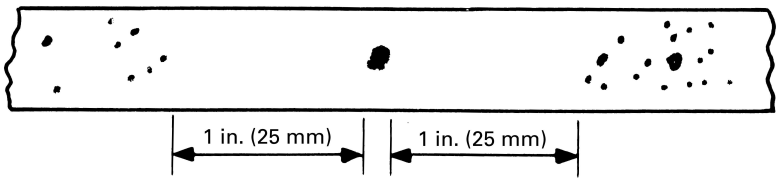
Cluster

NOTES:
(1) Typical concentration and size permitted in any 6 in. (150 mm) length of weld.
(2) Maximum size per Table KE-332.

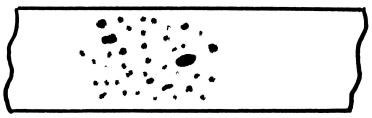
Figure 6-3.2
Charts for t Over $\frac{1}{4}$ in. (6 mm) to $\frac{3}{8}$ in. (10 mm), Inclusive



Random Rounded Indications
[Note (1)]



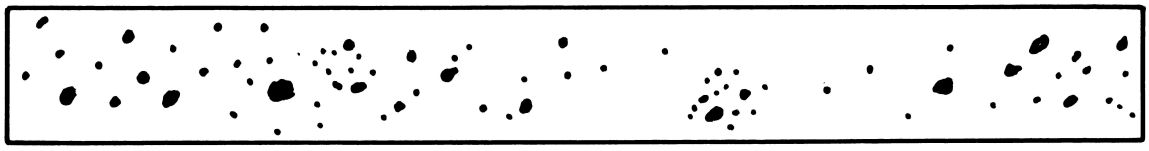
Isolated Indication
[Note (2)]



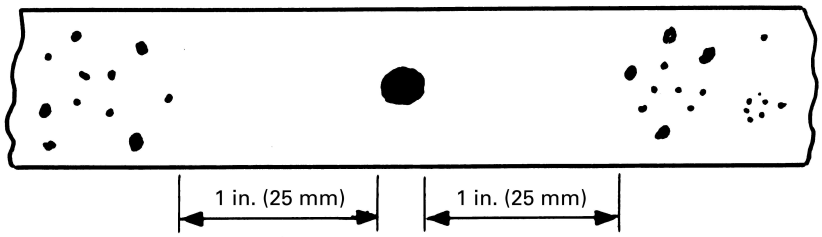
Cluster

NOTES:
(1) Typical concentration and size permitted in any 6 in. (150 mm) length of weld.
(2) Maximum size per Table KE-332.

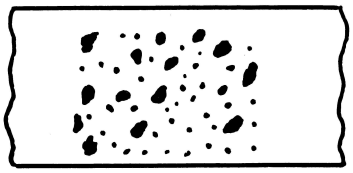
Figure 6-3.3
Charts for t Over $^3/_8$ in. (10 mm) to $^3/_4$ in. (19 mm), Inclusive



Random Rounded Indications
[Note (1)]



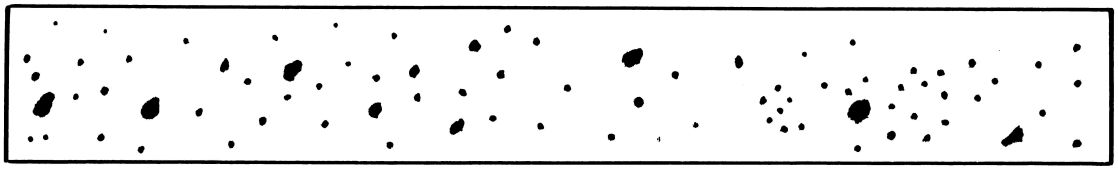
Isolated Indication
[Note (2)]



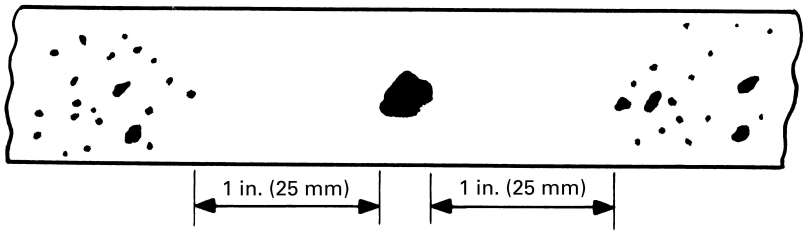
Cluster

NOTES:
(1) Typical concentration and size permitted in any 6 in. (150 mm) length of weld.
(2) Maximum size per Table KE-332.

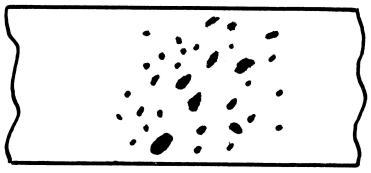
Figure 6-3.4
Charts for *t* Over $^{3}/_{4}$ in. (19 mm) to 2 in. (50 mm), Inclusive



Random Rounded Indications
[Note (1)]



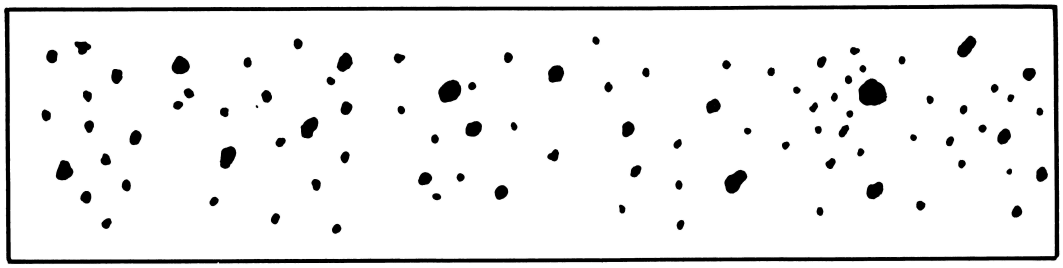
Isolated Indication
[Note (2)]



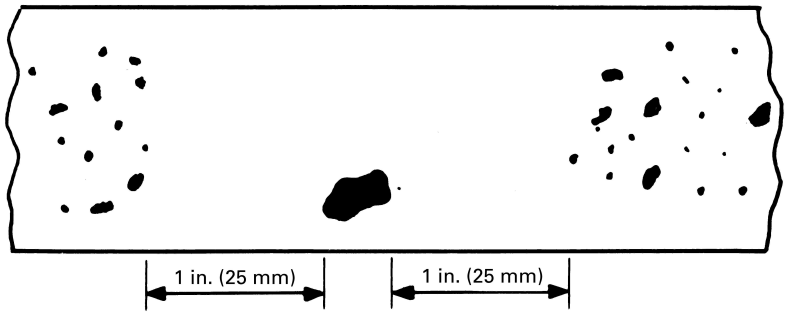
Cluster

NOTES:
(1) Typical concentration and size permitted in any 6 in. (150 mm) length of weld.
(2) Maximum size per Table KE-332.

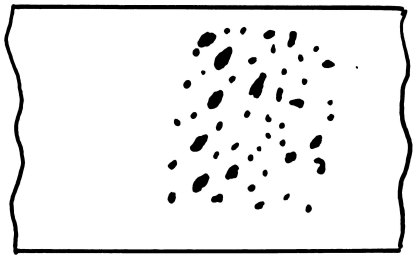
Figure 6-3.5
Charts for *t* Over 2 in. (50 mm) to 4 in. (100 mm), Inclusive



Random Rounded Indications
[Note (1)]



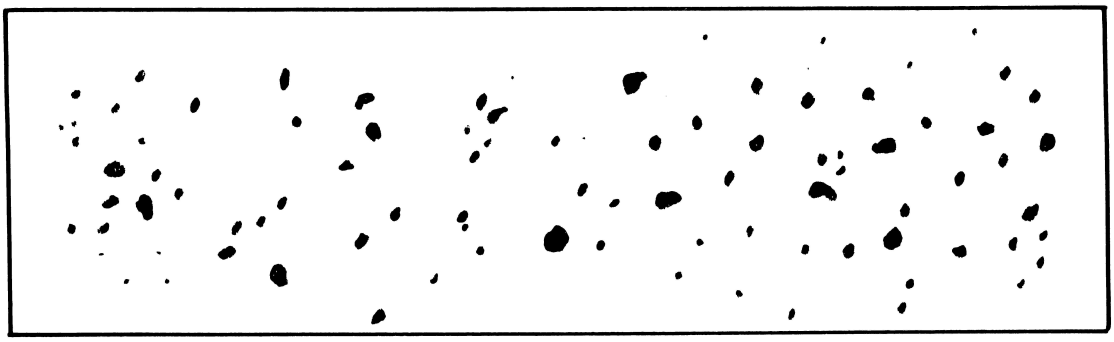
Isolated Indication
[Note (2)]



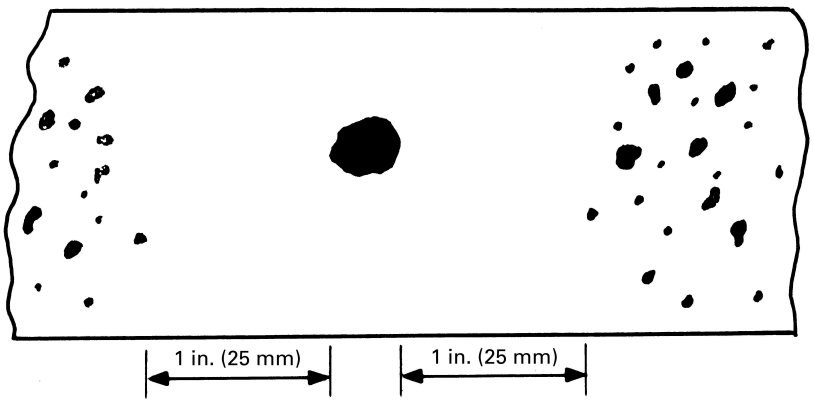
Cluster

NOTES:
(1) Typical concentration and size permitted in any 6 in. (150 mm) length of weld.
(2) Maximum size per Table KE-332.

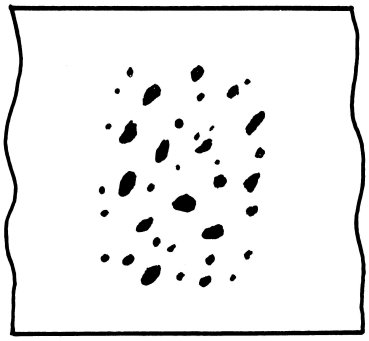
Figure 6-3.6
Charts for *t* Over 4 in. (100 mm)



Random Rounded Indications
[Note (1)]



Isolated Indication
[Note (2)]



Cluster

NOTES:
(1) Typical concentration and size permitted in any 6 in. (150 mm) length of weld.
(2) Maximum size per Table KE-332.

MANDATORY APPENDIX 8
ESTABLISHING GOVERNING CODE EDITIONS AND CASES FOR PRESSURE VESSELS AND PARTS

8-100 GENERAL

(a) After Code revisions are approved by ASME, they may be used beginning with the date of issuance shown on the Code. Except as noted below, revisions become mandatory six months after the date of issuance. Code Cases are permissible and may be used beginning with the date of approval by ASME. Only Code Cases that are specifically identified as being applicable to this Section may be used. At the time a Code Case is applied, only the latest revision may be used. Code Cases that have been incorporated into this Section or have been annulled shall not be used.

(b) Changes in the Code and Code Cases that have been published prior to completion of the pressure vessel or part may include details critical to the intended service conditions of the pressure vessel, which should be considered by the Manufacturer. Application of such changes shall be a matter of agreement between the Manufacturer and the user. Specific incorporated Code provisions from later editions that have been applied to construction shall be noted in the "Remarks" section of the Manufacturer's Data Report.

8-200 CONSTRUCTION

(a) The Manufacturer of any complete vessel or part that is to be stamped with the ASME Certification Mark required by this Section (see KG-324) has the responsibility of assuring through proper Code certification that all work performed complies with the effective Code Edition as follows:

(1) Vessels. The Code Edition used for construction of a pressure vessel shall be either the Edition that is mandatory on the date the pressure vessel is contracted for by the Manufacturer, or a published Edition issued by ASME prior to the contract date, which is not yet mandatory [refer to 8-100(a)].

(2) Subcontracted Parts. When a vessel Manufacturer subcontracts some of the construction to another Certificate Holder, the part Manufacturer shall construct the part to the Code Edition established for the entire pressure vessel.

(3) Parts Built for Stock. Parts built for stock shall be constructed to either the Edition that is mandatory at the time of Code certification, or a published Edition issued by ASME prior to Code certification, that is not yet mandatory [refer to 8-100(a) above].

(4) Parts Used From Stock. When a vessel Manufacturer uses a part from stock, the vessel Manufacturer shall ensure that the part fully satisfies all applicable Code requirements for the Code Edition used for construction of the complete vessel.

(b) It is permitted to use overpressure protection requirements from the Edition in effect when the vessel is placed in service.

8-300 MATERIALS

For parts subject to stress due to pressure, the Manufacturer shall use material conforming to one of the specifications listed as approved for use in the Edition specified for construction, or listed as approved for use in the Guideline for Acceptable ASTM Editions or in the Guideline for Acceptable Non-ASTM Editions in Section II, Part A or Part B.

MANDATORY APPENDIX 9
LINEAR ELASTIC ANALYSIS

9-100 GENERAL

This Mandatory Appendix describes the procedure for the linear elastic calculation of the equivalent stress that are subject to specified limits. This procedure may only be used when permitted by KD-200(d). The steps in the procedure are given in the following subparagraphs. When linear elastic analysis is being used, the Designer shall use all paragraphs of this Appendix as applicable.

Section VIII, Division 2, Annex 5-A gives a procedure that may be used to find the calculated value of stresses for comparisons to the limits in 9-210 through 9-280 when a detailed analysis using the finite element method is used.

9-110 LOAD COMBINATIONS

The load combinations as shown in Table 9-100.1 shall be considered in the analysis. Typical load descriptions are provided in Table KD-230.2. In evaluating load cases involving the pressure term P_D, the effects of the pressure being equal to zero shall be considered. The applicable load case combinations shall be considered in addition to any other combinations defined in the User's Design Specification.

9-200 DERIVATION OF EQUIVALENT STRESS

(a) At the point on the vessel that is being investigated, choose an orthogonal set of coordinates, such as tangential, longitudinal, and radial, and designate them the subscripts t, l, and r. The stress components in these directions are then designated σ_t, σ_l, and σ_r for direct (normal) stresses, and τ_{tl}, τ_{tr}, and τ_{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 categories below (see Figure 9-200.1):

(1) general primary membrane stress, P_m
(2) local primary membrane stress, P_L
(3) primary bending stress, P_b
(4) secondary stress, Q
(5) peak stress, F

(c) Use Figure 9-200.1 to provide assistance in assigning the stress values to the appropriate category. Consider each box in Figure 9-200.1. For each of the three normal stress components and each of the three shear components, calculate the algebraic sum of the values which results from the different types of loadings. The result is a set of six stress components in each box.

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

(e) Calculate the stress differences S_{12}, S_{23}, and S_{31} from eqs. (9-200.1) through (9-200.3):

$$S_{12} = \sigma_1 - \sigma_2 \tag{9-200.1}$$

$$S_{23} = \sigma_2 - \sigma_3 \tag{9-200.2}$$

$$S_{31} = \sigma_3 - \sigma_1 \tag{9-200.3}$$

The maximum distortion energy shall be used to establish the equivalent stress. In this case, the equivalent stress is equal to the von Mises equivalent stress S given by eq. (9-200.4)

$$S = \frac{1}{\sqrt{2}}\left({S_{12}}^2 + {S_{23}}^2 + {S_{31}}^2\right)^{0.5} \tag{9-200.4}$$

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

9-210 STRESS LIMITS

Designs shall satisfy applicable requirements for the most severe combination of loadings and limits of equivalent stress. For spherical and cylindrical shells, the limits of design pressure in KD-221 shall be satisfied. The evaluation of P_m in Table 9-100.1 and Figure 9-200.1 for spherical and cylindrical shells need not be satisfied. For all components except spherical and cylindrical monobloc shells remote from discontinuities, those requirements are as specific in Figure 9-200.1 and the subparagraphs that follow. The equivalent stress calculated in accordance with 9-200(e) from the stress components in any box in Figure 9-200.1 shall not exceed the stress limits that are shown in the circle adjacent to each equivalent stress category in Figure 9-200.1. Designs shall include the load combinations and maximum stress limits under the conditions of design and operation.

Table 9-100.1
Load Case Combinations and Allowable Stresses for an Elastic Analysis

Load Combinations [Note (1)]	Stress Assessment and Allowable Stress [Notes (2), (4)]				
	General Primary Membrane	Local Primary Membrane	Local Primary Membrane Plus Bending	Range of Primary Plus Secondary	Range of Primary Plus Secondary Plus Peak
	P_m	P_L	$P_L + P_b$	$P_L + P_b + Q$	$P_L + P_b + Q + F$
Design					
(1) $P_D + P_s + D$	$k_{c1}S_y/1.5$	$k_{c1}S_y$	$\alpha k_{c1}S_y/1.5$	Not applicable	
(2) $P_D + P_s + D + L + L_A$					
(3) $P_D + P_s + D + L + L_A + T$					
(4) $P_D + P_s + D + S_s$					
(5) $0.6D$ + ($0.6W$ or $0.7E$) [Note (3)]					
(6) $P_O + P_s + D$ + ($0.6W$ or $0.7E$)					
(7) $P_O + P_s + D + 0.75\ (L + L_A + T) + 0.75S_s$					
(8) $P_O + P_s + D + 0.75\ (0.6W$ or $0.7E) + 0.75\ (L + L_A) + 0.75S_s$					
(9) Other design load combinations as defined in the User's Design Specification					
Operating					
Use same load case combinations for design with maximum operating loads instead of design loads.	Not applicable			$2S_y$	S_{eq}
Pressure Test					
(18) $P_T + P_s + D + 0.6W_{pt}$	KT-312.3	Not applicable	KT-312.3	Not applicable	

GENERAL NOTE: Loads listed herein shall be considered to act in the combinations described above; whichever produces the most unfavorable effect in the component being considered. Effects of one or more loads not acting shall be considered.

NOTES:
(1) The parameters used in the Load Combinations column are defined in Table KD-230.2.
(2) See Figure 9-200.1 for additional guidance on stress categories and limits on equivalent stress.
(3) This load combination addresses an overturning condition for foundation design. It does not apply to design of anchorage (if any) to the foundation. Refer to ASCE/SEI 7, 2.4.1, Exception 2 for an additional reduction to W that may be applicable.
(4) k_{c1} is design correction factor (see 9-210). k_{c1} is not applicable for bolts and wire (i.e., k_{c1} = 1.0 for bolts and wire) (see KD-623 and KD-922).

The yield strength values, S_y, used in the calculations shall be taken from the tables in Section II, Part D for the design temperature, except as indicated in Figure 9-200.1, Note (3).

The design correction factor k_{c1} using S_y/S_u shall be obtained as follows:

$$k_{c1} = 1.0 \text{ for } S_y/S_u \le 0.76$$
$$= 0.433\left(1 + \frac{1}{S_y/S_u}\right) \text{ for } 0.76 < S_y/S_u < 1.0 \quad (9\text{-}210.1)$$

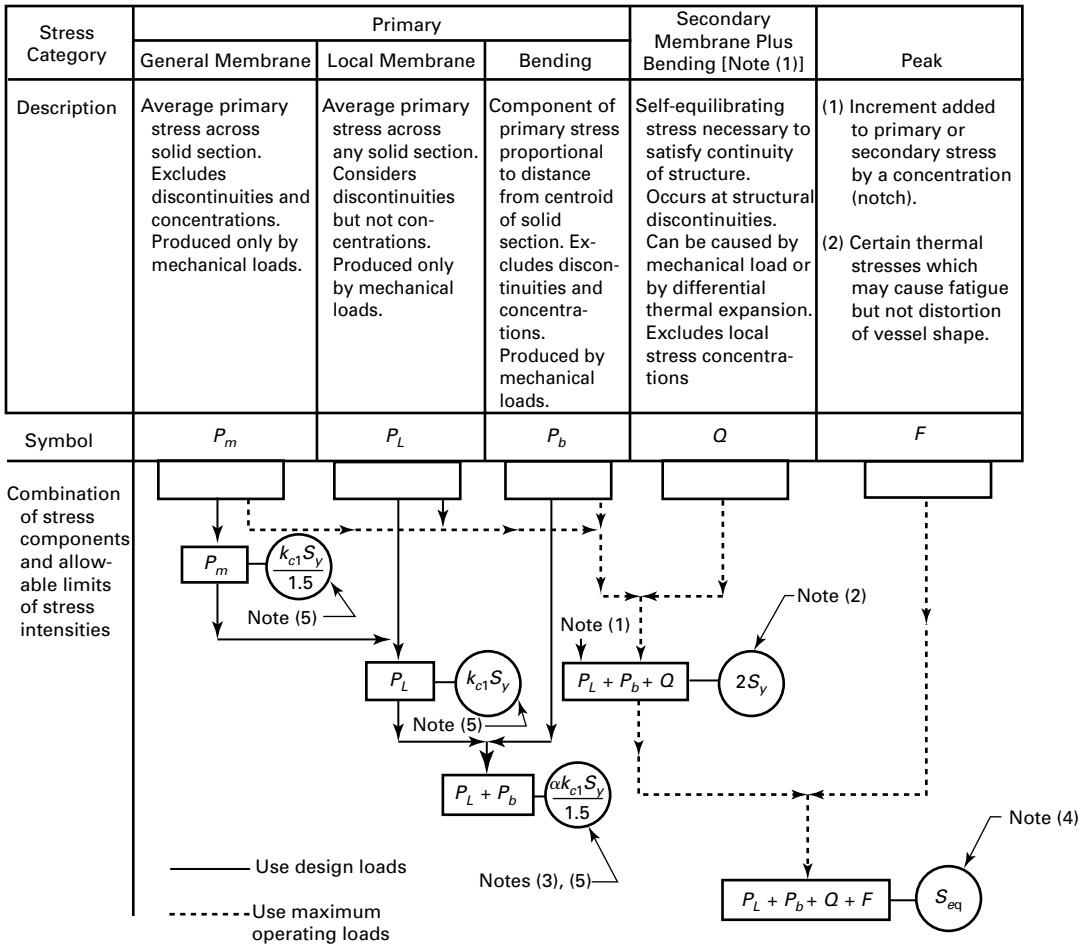
9-220 PRIMARY MEMBRANE AND BENDING STRESSES

(a) The general primary membrane equivalent stress, P_m, across the thickness of the section under consideration, due to any specified combination of design pressure and mechanical loading, shall not exceed the design equivalent stress value $k_{c1}S_y/1.5$.

(b) The local primary membrane equivalent stress, P_L, (see Figure 9-200.1) due to any specified combination of design pressure and mechanical loadings shall not exceed $k_{c1}S_y$. The distance over which this equivalent stress exceeds $0.73(k_{c1}S_y)$ shall not extend in the meridional direction more than $\sqrt{R_m t}$, where R_m is the radius at the midsurface of the shell or head at the location of the highest local primary membrane equivalent stress measured normal to the surface from the axis of revolution in the meridional plane, and t is the nominal thickness of the shell or head under consideration.

(c) The primary bending, P_b, plus local primary membrane equivalent stress, P_L, due to any specified combination of design pressure and mechanical loadings expected to occur simultaneously shall not exceed

Figure 9-200.1
Stress Categories and Limits of Equivalent Stress



GENERAL NOTES:

(a) The stress limits permitted in these 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 equivalent stress of 2 S_y has been placed at a level that ensures 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.

(b) Examples of stress classification are provided in Section VIII, Division 2, Table 5.6.

NOTES:

(1) The stresses in Category Q are those parts of the total stress that are produced by thermal gradients, structural discontinuities, etc., and do not include primary stresses, which may also exist at the same point. It should be noted, however, that a detailed stress analysis frequently gives the combination of primary and secondary stresses directly and, when appropriate, this calculated value represents the total of P_m (or P_L) + P_b + Q and not Q alone. Similarly, if the stress in Category F is produced by a stress concentration, the quantity F is the additional stress produced by the notch, over and above the nominal stress. For example, if a plate has a nominal equivalent stress S and has a notch with a stress concentration factor K, then $P_m = S$, $P_b = 0$, $Q = 0$, $F = P_m (K - 1)$, and the peak equivalent stress equals $P_m + P_m (K - 1) = KP_m$.

(2) This limitation applies to the range of equivalent stress. When the secondary stress is due to a temperature excursion at the point at which the stresses are being analyzed, the value of S_y shall be taken as the average of the S_y values tabulated in Section II, Part D for the highest and the lowest temperatures of the metal during the transient. When part or all of the secondary stress is due to mechanical load, the value of S_y shall be taken as the S_y value for the highest temperature of the metal during the transient.

(3) α is the shape factor [see 9-220(d)].

(4) This applies only if a fatigue analysis is performed in accordance with Article KD-3. See KD-140.

(5) K_{c1} is the design correction factor (see 9-210). k_{c1} is not applicable for bolts and wire (i.e.; k_{c1} = 1.0 for bolts and wire) (see KD-623 and KD-922).

$\alpha K_{C1} S_y/1.5$. (See Figure 9-200.1 when the design of components involves combinations of calculated stresses.)

(d) The shape factor, α, is defined as the ratio of the moment that produces a full plastic section (no strain hardening) to the bending moment that produces initial yielding at the extreme fibers of the section. For a rectangular section, α = 1.5.

9-230 PURE SHEAR STRESS

The average primary shear stress across a section loaded in pure shear (for example, keys, shear rings, pins) shall be limited to $0.4S_y$. For screw threads, see KD-623. The maximum primary shear under design conditions, exclusive of stress concentration at the periphery of a solid circular section in torsion, shall be limited to $0.57S_y$.

9-240 BEARING STRESS

(a) The average bearing stress for resistance to crushing under the maximum design load shall be limited to the yield strength S_y at temperature, except that when the distance to a free edge is greater than the distance over which the bearing load is applied, a stress of $1.5S_y$ at temperature is permitted.

(b) When bearing loads are applied on parts having free edges, such as at a protruding edge, the possibility of a shear failure shall be considered. In the case of primary stress only, the average shear stress shall be limited to $0.4S_y$. In the case of primary stress plus secondary stress, the average stress shall not exceed $0.5S_y$.

(c) When considering bearing stresses from pins in supporting members, the S_y at temperature value is applicable, except that a value of $1.5S_y$ may be used if the pin is at least three pin diameters from the edge.

9-250 SECONDARY STRESSES

The magnitude of the primary-plus-secondary stresses is limited to $2S_y$ in accordance with Figure 9-200.1.

9-260 SIMPLIFIED ELASTIC–PLASTIC ANALYSIS

The equivalent stress limit on the range of primary-plus-secondary equivalent stress may be exceeded provided that

(a) the range of primary plus secondary membrane plus bending equivalent stress, excluding thermal bending, shall be less than $2S_y$;

(b) the value of S_a is multiplied by the factor K_e (see KD-322);

(c) the material of the component has a ratio of the specified minimum yield strength to specified tensile strength of less than or equal to 0.80;

(d) the component meets the thermal stress ratcheting requirements of 9-270.

9-270 THERMAL STRESS RATCHETING ASSESSMENT

The equivalent stress limit on the secondary equivalent stress range for thermal loading to prevent ratcheting, when applied in conjunction with a steady state general or local primary membrane equivalent stress, is determined below. This procedure shall only be used with an assumed linear or parabolic distribution of a secondary equivalent stress range.

(a) Determine the ratio of the primary membrane equivalent stress to the specified minimum yield strength at the average temperature of the cycle.

$$X = \left(\frac{P_m}{S_y} \right) \tag{9-270.1}$$

(b) Compute the secondary equivalent stress range from the thermal loading, ΔQ, using elastic analysis methods.

(c) Determine the equivalent stress limit on the secondary equivalent stress range from thermal loading, S_Q.

(1) For a secondary equivalent stress range from thermal loading with a linear variation through the wall thickness:

$$S_Q = S_y \left(\frac{1}{X} \right) \text{ for } 0 < X < 0.5 \tag{9-270.2}$$

$$S_Q = 4.0 S_y (1 - X) \text{ for } 0.5 \le X \le 1.0 \tag{9-270.3}$$

(2) For a secondary equivalent stress range from thermal loading with a parabolic constantly increasing or decreasing variation through the wall thickness:

$$S_Q = S_y \left(\frac{1}{0.1224 + 0.9944X^2} \right) \text{ for } 0 < X < 0.615 \tag{9-270.4}$$

$$S_Q = 5.2 S_y (1 - X) \text{ for } 0.615 \le X \le 1.0 \tag{9-270.5}$$

(d) To demonstrate protection against ratcheting, the following criteria shall be satisfied:

$$\Delta Q \le S_Q \tag{9-270.6}$$

9-280 TRIAXIAL STRESSES

The algebraic sum of the three principal stresses, including the primary, secondary, and peak stresses, shall not exceed $2.5S_y$.

9-290 UPPER LIMIT FOR HYDROSTATIC TEST PRESSURE

For noncylindrical vessels, end closure, and other components, the upper limit for hydrostatic test pressure shall be verified (see KT-312.3).

9-300 PRINCIPAL STRESSES IN MONOBLOC VESSELS

For a vessel consisting of a hollow, circular cylinder of uniform wall thickness, the stresses in the cylinder wall remote from the ends of the cylinder or other discontinuities shall be calculated as follows if no residual stresses exist:

$$\sigma_t = \frac{P}{Y^2 - 1}\left(1 + Z^2\right) \tag{9-300.1}$$

$$\sigma_r = \frac{P}{Y^2 - 1}(1 - Z^2) \tag{9-300.2}$$

If the cylinder is a closed end, then:

$$\sigma_l = \frac{P}{Y^2 - 1} \tag{9-300.3}$$

where

D = diameter corresponding to any point in the wall
P = internal pressure
Y = diameter ratio D_O/D_I
Z = diameter ratio D_O/D

The maximum value of equivalent stress S calculated from eqs. (9-300.1), (9-300.2), and (9-300.3) is at the bore surface and is given by

$$S = P\frac{\sqrt{3}\,Y^2}{Y^2 - 1} \quad \text{(for closed-end)} \tag{9-300.4}$$

$$S = P\frac{\sqrt{1 + 3Y^4}}{Y^2 - 1} \quad \text{(for open-end)} \tag{9-300.5}$$

(25) ## 9-400 ANALYSIS OF THREADED FASTENERS AND COMPONENTS

Linear elastic analysis may be used under the following conditions:

(a) The number and cross-sectional area of bolts required to resist primary loads shall be determined. The yield strength values to be used are the values given in Section II, Part D for bolting materials.

(b) The average primary equivalent stress, S, in accordance with 9-200 shall be based on the thread root diameter and shall not exceed the following limit:

$$S = \frac{1}{1.8}S_y$$

(c) For bolts with a reduced shank, which have a diameter less than 0.9 times the thread root diameter, the above equation shall be replaced by

$$S = \frac{1}{1.5}S_y$$

provided the actual shank diameter is used.

(d) Primary-plus-secondary membrane equivalent stress in bolts shall not exceed $0.75S_y$. Primary-plus-secondary membrane plus bending equivalent stress in bolts shall not exceed S_y due to the combination of both the design loads and preloads. Stress intensification due to the threads shall not be considered in the above analysis.

(e) The limits in (f) and (g) need not be met for any bolt and nut pair conforming to bolt and nut standards listed in Table KG-141. The bolt and nut pair shall be made with materials approved for use in bolting components by this Division. Both members shall be made of the same material.

(f) The average shear stress in the threads, calculated by dividing the design load by the appropriate thread shear area, shall be limited to $0.25S_y$ at the design temperature. The relative strength of mating parts shall be considered

(g) The average bearing stress in the threads due to the maximum design load shall be limited to $0.75S_y$ at the design temperature. The relative strength of mating parts shall be considered.

(h) Relative radial displacement between mating threads shall be calculated considering the combination of applied loads and thermal effects. No credit shall be taken for thread friction. The results of this analysis shall demonstrate that the threads having relative radial displacement less than 10% of the minimum thread overlap meet the requirements of (f) and (g). No credit shall be taken for threads whose relative radial displacement exceed 10%.

(i)) Connections that have imposed loads on threads in tapped holes shall comply with the requirements of (j). The vessel or an integral weld buildup shall have a flat surface machined on the shell to receive the connection.

(j) Where tapped holes are provided, the threads shall be full and clean, and the engaged length shall not be less than the larger of d_s or

$$0.75d_s\left(\frac{S_y \text{ of stud material at design temperature}}{S_y \text{ of tapped material at design temperature}}\right)$$

in which d_s is the root diameter of the stud.

NONMANDATORY APPENDIX A
GUIDE FOR PREPARING MANUFACTURER'S DATA REPORTS

A-100 INTRODUCTION

(a) The instructions in this Appendix provide general guidance to the Manufacturer in preparing Data Reports as required in KS-300.

(b) Manufacturer's Data Reports required by this Division are for use with this Division only. They are not intended for use with special construction that requires and receives approval by jurisdictional authorities under the laws, rules, and regulations of the respective state, province, or municipality in which the vessel is to be installed.

(c) The instructions for completing the Data Reports are identified by parenthesized numbers corresponding to circled numbers on the sample forms in this Nonmandatory Appendix (see Forms K-1, K-2, K-3, CRPV-1A, CRPV-2A and Tables A-100.1 and A-100.2; and Section XIII, Forms K-4 and K-5, Tables C-2-3 and C-2-4).

(d) Where more space is needed than has been provided on the form for any item, insert the words "See Remarks" and then enter the data in the "Remarks" area or on Form K-3, Manufacturing Data Report Supplementary Sheet.

(e) It is not intended that these Data Reports replace in any way the required Manufacturer's Design Report (see KG-323) or the Manufacturer's construction records (see KG-325). It is intended that the Data Reports be used for identifying the vessel, retrieval of records, and certification of compliance with this Division, and with the User's Design Specification, by the Manufacturer and by the Inspector.

(f) Any quantity to which units apply shall be entered on the Manufacturer's Data Report with the chosen units.

(g) Manufacturer's Data Report Forms and other forms in this Appendix may be preprinted or computer generated. Forms shall be identical in size, arrangement, and content, as shown in this Appendix, except that additional lines may be added or Form K-3 may be used.

When using forms that result in multiple pages, each page shall be marked to be traceable to the first page of the form. For Forms K-1, K-2, CRPV-1A, and CRPV-2A, each page shall contain, at the top of each page, as a minimum, the Manufacturer's name, Manufacturer's Serial No., CRN (as applicable), and National Board Number (as applicable), or other identifying number, as shown on the first page of multiple page forms. These requirements do not apply to Form K-3 and Section XIII, Forms K-4 and K-5 since they are intended to be a single-page form attached to another form.

Additionally, on all forms, each sheet shall contain the page number of that page and the total number of pages that compose the completed form.

FORM K-1 MANUFACTURER'S DATA REPORT FOR HIGH PRESSURE VESSELS Page____ of____
As Required by the Provisions of the ASME Boiler and Pressure Vessel Code, Section VIII, Division 3

(25)

1. Manufactured and certified by ① (name and address of manufacturer)
2. Manufactured for ② (name and address of purchaser)
3. Location of installation ③ (name and address)
4. Type ④ (horizontal/vertical) ⑤ (Manufacturer's serial no.) ⑥ (CRN) ⑦ (National Board No.) (year built)
   Drawing no. ⑧ Prepared by ⑨
5. User's Design Specification on file at ⑩
   Certified by ⑩ Licensing or Registration Authority ⑪ Reg. no.
6. Manufacturer's Design Report on file at ⑩
   Certified by ⑩ Licensing or Registration Authority ⑪ Reg. no.
7. Material ⑫ Impact tested at
8. ASME Boiler and Pressure Vessel Code, Section VIII, Division 3 ⑬ (year) ⑭ (Code Case no.)
9. Service ⑮
10. Restrictions and warnings ⑯ ⑰
    ⑱ cycles at
11. Construction ⑲ ⑳ ㉑ ㉒ ㉓
    Prestress method ㉔
12. Size and configuration ㉕ (I.D.) ㉖ (length) ㉗ (thickness) (cylindrical, spherical, other)
13. Supports and attachments ㉘
14. Design pressure ㉙ at maximum coincident metal temperature ㉚
    Maximum metal temperature ㉚ at ㉚
    Minimum design metal temperature ㉛ at ㉛
15. Test pressure ㉜ ㉜ (pneum./hydro./combination) at ㉜
    Performed in the ㉜ (horizontal/vertical) position [fluid(s) used in test]
16. Closures ㉝ (describe)
17. Connections, or provisions, for overpressure relief ㉞

(07/17)

FORM K-1

Page ____ of ____

Manufactured by ① _____

Manufacturer's Serial No. ⑤ _____ CRN ⑥ _____ National Board No. ⑦ _____

18. Nozzles and connections

Purpose (Inlet, Outlet, Drain)	Quantity	Diameter or Size	Type	Material	Nominal Thickness	Reinforcement Material	How Attached	Location
㉞ ㉟ ㊱		㉟	㉟ ㊲	⑫	㉗			㊱

19. Manufacturer's Partial Data Reports, properly identified and signed by commissioned Inspectors, have been furnished for the following components

㊳ _____

20. Remarks ⑯ _____

㊴

CERTIFICATE OF SHOP COMPLIANCE

We certify that the statements in this report are correct and that all details of design, material, construction, and workmanship of this vessel conform to the ASME Boiler and Pressure Vessel Code, Section VIII, Division 3.

U3 Certificate of Authorization no. _____ expires _____ .

Date _____ Co. name ㊴ (Manufacturer) _____ Signed ㊴ (representative) _____

㊵

CERTIFICATE OF SHOP INSPECTION

I, the undersigned, holding a valid commission issued by the National Board of Boiler and Pressure Vessel Inspectors and employed by

_____

of _____ , have inspected the pressure vessel described in this Manufacturer's Data Report on _____ , and state that, to the best of my knowledge and belief, the Manufacturer has constructed this part in accordance with ASME Code, Section VIII, Division 3. By signing this certificate, neither the Inspector nor the Inspector's employer makes any warranty, expressed or implied, concerning the part described in this Manufacturer's Data Report. Furthermore, neither the Inspector nor the Inspector's employer shall be liable in any manner for any personal injury or property damage or a loss of any kind arising from or connected with this inspection.

Date _____ Signed ㊵ (Authorized Inspector) _____ Commissions ㊶ (National Board Authorized Inspector Commission number) _____

㊴

CERTIFICATE OF FIELD ASSEMBLY COMPLIANCE

We certify that the field assembly construction of all parts of this vessel conforms with the requirements of Section VIII, Division 3 of the ASME BOILER AND PRESSURE VESSEL CODE.

U3 Certificate of Authorization no. _____ expires _____ .

Date _____ Co. name ㊴ (Assembler that certified and constructed field assembly) _____ Signed ㊴ (representative) _____

㊷

CERTIFICATE OF FIELD ASSEMBLY INSPECTION

I, the undersigned, holding a valid commission issued by the National Board of Boiler and Pressure Vessel Inspectors and employed by

_____

of _____ , have compared the statements in this Manufacturer's Data Report with the described pressure vessel and state that parts referred to as data items _____ , not included in the certificate of shop inspection, have been inspected by me and that, to the best of my knowledge and belief, the Manufacturer has constructed and assembled this part in accordance with the ASME Code, Section VIII, Division 3. The described vessel was inspected and subjected to a hydrostatic test of ㊷ _____ . By signing this certificate, neither the Inspector nor the Inspector's employer makes any warranty, expressed or implied, concerning the part described in this Manufacturer's Data Report. Furthermore, neither the Inspector nor the Inspector's employer shall be liable in any manner for any personal injury or property damage or a loss of any kind arising from or connected with this inspection.

Date _____ Signed ㊷ (Authorized Inspector) _____ Commissions ㊶ (National Board Authorized Inspector Commission number) _____

(07/25)

Page ____ of ____

(25)

FORM K-2 MANUFACTURER'S PARTIAL DATA REPORT FOR HIGH PRESSURE VESSELS
A Part of a Pressure Vessel Fabricated by One Manufacturer for Another Manufacturer
As Required by the Provisions of the ASME Boiler and Pressure Vessel Code, Section VIII, Division 3

1. Manufactured and certified by (1) (name and address of manufacturer)

2. Manufactured for (2) (name and address of purchaser)

3. Location of installation (3) (name and address)

4. Type (4) (horizontal/vertical) (5) (Manufacturer's serial no.) (6) (CRN) (7) (National Board No.) (year built)

   Drawing no. (8) Prepared by (9)

5. User's Design Specification on file at (10)
   Certified by (10) Licensing or Registration Authority (11) Reg. no.

6. Manufacturer's Design Report on file at (10)
   Certified by (10) Licensing or Registration Authority (11) Reg. no.

7. Material Impact tested at

8. ASME Boiler and Pressure Vessel Code, Section VIII, Division 3 (13) (year) (14) (Code Case no.)

9. Constructed to (8) (drawing no.) (9) (prepared by) (description of part inspected)

10. Construction (19) (20) (21) (23)
    Prestress method (24)

11. Size and configuration (25) (I.D.) (26) (length) (cylindrical, spherical, other)

12. Supports and attachments (28)

13. Design pressure (29) at maximum coincident metal temperature (30)
    Maximum metal temperature (30) at (30)
    Minimum design metal temperature (31) at (31)

14. Test pressure (32) (32) (pneum./hydro./combination) at (32)

    Performed in the (32) (horizontal/vertical) position [fluid(s) used in test]

15. Identification of Part(s) (45)

Name of Part	Quantity	Line No.	Mfr's. Identifying Number	Mfr's. Drawing Number	CRN	National Board Number	Year Built
(46)		(47)	(48)	(8)	(6)	(7)	

16. Remarks: (16)

(07/17)

FORM K-2

Page ____ of ____

Manufactured by ① _____

Manufacturer's Serial No. ⑤ _____ CRN ⑥ _____ National Board No. ⑦ _____

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⑲ **CERTIFICATE OF SHOP COMPLIANCE**

We certify that the statements made in this report are correct and that all details of design, material, construction, and workmanship of this vessel conform to the ASME BOILER AND PRESSURE VESSEL CODE, Section VIII, Division 3.

Certificate of Authorization no. _____ expires _____ .

Date _____ Co. name ⑲ _____ (Manufacturer) Signed ⑲ _____ (representative)

⑳ **CERTIFICATE OF SHOP INSPECTION**

I, the undersigned, holding a valid commission issued by the National Board of Boiler and Pressure Vessel Inspectors and employed by _____ of _____ , have inspected the pressure vessel described in this Manufacturer's Partial Data Report on _____ , and state that, to the best of my knowledge and belief, the Manufacturer has constructed this part in accordance with ASME Code, Section VIII, Division 3. By signing this certificate neither the Inspector nor the Inspector's employer makes any warranty, expressed or implied, concerning the part described in this Manufacturer's Partial Data Report. Furthermore, neither the Inspector nor the Inspector's employer shall be liable in any manner for any personal injury or property damage or a loss of any kind arising from or connected with this inspection.

Date _____ Signed ⑳ _____ (Authorized Inspector) Commissions ㉑ _____ (National Board Authorized Inspector Commission number)

⑲ **CERTIFICATE OF FIELD ASSEMBLY COMPLIANCE**

We certify that the field assembly construction of all parts of this vessel conforms with the requirements of Section VIII, Division 3 of the ASME BOILER AND PRESSURE VESSEL CODE.

Certificate of Authorization no. _____ expires _____ .

Date _____ Co. name ⑲ _____ (Assembler that certified and constructed field assembly) Signed ⑲ _____ (representative)

㉒ **CERTIFICATE OF FIELD ASSEMBLY INSPECTION**

I, the undersigned, holding a valid commission issued by the National Board of Boiler and Pressure Vessel Inspectors and employed by _____ of _____ have compared the statements in this Manufacturer's Partial Data Report with the described pressure vessel and state that parts referred to as data items _____ , not included in the certificate of shop inspection, have been inspected by me and that to the best of my knowledge and belief, the Manufacturer has constructed and assembled this part in accordance with the ASME Code, Section VIII, Division 3. The described vessel was inspected and subjected to a hydrostatic test of ㉒ _____ . By signing this certificate neither the Inspector nor the Inspector's employer makes any warranty, expressed or implied, concerning the part described in this Manufacturer's Partial Data Report. Furthermore, neither the Inspector nor the Inspector's employer shall be liable in any manner for any personal injury or property damage or a loss of any kind arising from or connected with this inspection.

Date _____ Signed ㉒ _____ (Authorized Inspector) Commissions ㉑ _____ (National Board Authorized Inspector Commission number)

(07/25)

FORM K-3 MANUFACTURER'S DATA REPORT SUPPLEMENTARY SHEET
As Required by the Provisions of the ASME Boiler and Pressure Vessel Code, Section VIII, Division 3

1. Manufactured and certified by _____ (1) (43)
(name and address of Manufacturer)

2. Type _____ (4) (43) _____ (5) (43) _____ (6) (43) _____ (8) (43) _____ (7) (43) _____
(horizontal, vertical, tank, etc.) (Mfr.'s serial no.) (CRN) (drawing) (Nat'l. Bd. No.) (year built)

Data Report Item Number	Remarks
(43)	(44)

Table A-100.1
Instructions for the Preparation of Manufacturer's Data Reports

Applies to Form			Reference to Circled Nos. in the Forms	Instructions
K-1	K-2	K-3		
X	X	X	(1)	Name and street address of Manufacturer, as shown on Manufacturer's ASME Code Certificate of Authorization.
X	X	...	(2)	Name and address of purchaser.
X	X	...	(3)	Name of user and address where vessel is to be installed.
X	X	X	(4)	Type of vessel, such as horizontal or vertical, separator, heat exchanger, reactor, storage, etc.
X	X	X	(5)	An identifying Manufacturer's serial number marked on the vessel (or vessel part) (see KS-120).
X	X	X	(6)	Canadian registration number where applicable.
X	X	X	(7)	Where applicable, National Board Number from Manufacturer's Series of National Board Numbers. National Board Number shall not be used for owner-inspected vessels.
X	X	X	(8)	Indicate drawing numbers, including revision numbers, that cover general assembly and list materials. For Canadian registration, also include the number of the drawing approved by Provincial authorities.
X	X	...	(9)	Organization that prepared drawing.
X	X	...	(10)	To be completed by the Manufacturer to show the disposition of the User's Design Specification and the Manufacturer's Design Report, and to identify the registered Professional Engineers who certify them.
X	X	...	(11)	State(s) of the U.S.A., provinces of Canada, or Engineers Mobility Forum as applicable.
X	X	...	(12)	Show the complete ASME specification number and grade of the actual material used in the vessel part. Material is to be as designated in Section VIII, Division 3. Exceptions: A specification number for a material not identical to an ASME specification may be shown *only* if such material meets the criteria in the Foreword of this Division. When material is accepted through a Code Case, the applicable Case number shall be shown.
X	X	...	(13)	Issue date of Section VIII, Division 3 under which vessel or vessel part was manufactured.
X	X	...	(14)	All Code Case numbers when vessel is manufactured according to any Cases.
X	...	...	(15)	Describe contents or service of the vessel.
X	X	...	(16)	Additional comments, including any Code restrictions on the vessel or any unusual Code or jurisdictional requirements that have been met, such as those noted in (17), (18), (20), (21), and (32). Indicate corrosion or erosion allowance.
X	...	...	(17)	Show need for start-up or shutdown temperature and/or controlled rate of heating or cooling, maximum temperature of any part.
X	...	...	(18)	Show results of fatigue analysis, number of cycles, limitations, or restrictions.
X	X	...	(19)	Type of longitudinal joint in cylindrical section, or any joint in a sphere (e.g., Type No. 1 butt or seamless).
X	X	...	(20)	When heat treatment is performed by the Manufacturer, give temperature and time. Explain any special cooling procedure and other pertinent heating during fabrication.
X	X	...	(21)	Indicate examination applied. Methods, location, and results should be included under Remarks.
X	...	...	(22)	Type of welding used in girth joints in the cylindrical section [see (19)].
X	X	...	(23)	For jacketed vessels, explain type of jacket closures used and Certification Marking.
X	X	...	(24)	Prestress, method, verification, etc.
X	X	...	(25)	Indicate inside diameter.
X	X	...	(26)	The shell length shall be shown as the overall length between closure or transition section welds or joints for a shell of a single diameter. In other cases, define length as appropriately descriptive.
X	...	...	(27)	Thickness is the nominal thickness of the material used in the fabrication of the vessel. It includes corrosion allowance.
X	X	...	(28)	Indicate provisions for support of the vessel and any attachments for superimposed equipment.
X	X	...	(29)	Show design pressure for which vessel is constructed (see KG-311). Other internal or external pressures with coincident temperatures shall be listed where applicable.
X	X	...	(30)	Show maximum coincident metal temperatures permitted for vessel at the design pressures.
X	X	...	(31)	Show minimum design metal temperature at coincident pressure. List if more than one set.
X	X	...	(32)	Show hydrostatic or other tests made with specified test pressure at top of vessel in the test position that applies (pneumatic, hydrostatic, or combination test pressure). Indicate if vessel was tested in the vertical position.
X	...	...	(33)	Bolts used to secure removable head(s), closures, or seals of vessel.
X	...	...	(34)	Indicate nozzle or other opening which is designated for pressure relief (see Part KOP).
X	...	...	(35)	Show other nozzles and openings by size, type, and purpose. See (37).

Table A-100.1
Instructions for the Preparation of Manufacturer's Data Reports (Cont'd)

Applies to Form			Reference to Circled Nos. in the Forms	Instructions
K-1	K-2	K-3		
X	...	...	(36)	Show opening designated for inspection. Show location.
X	...	...	(37)	Data entries with descriptions acceptable to Inspector. Abbreviations, coded identification, or reference to Code figure and illustration number may be used to define any generic name. For ASME B16.5 flanges, the class should be identified. Flange facing and attachment to neck is not required. Some typical abbreviations: Flanged fabricated nozzle Cl. 300 flg Long weld neck flange Cl. 300 lwn Weld end fabricated nozzle w.e.
X	...	...	(38)	To be completed when one or more parts of the vessel are furnished by others and certified on Data Report Form K-2 as required by KS-301. The part manufacturer's name and serial number should be indicated.
X	X	...	(39)	Certificate of compliance block is to show the name of the Manufacturer as shown on Manufacturer's ASME Code Certificate of Authorization. This should be signed in accordance with organizational authority defined in the Quality Control System (see Mandatory Appendix 2).
X	X	X	(40)	To be completed by the Manufacturer and signed by the Authorized Inspector who performs the shop inspection or signs Form K-1 for the completed vessel. Attach any applicable K-2 forms.
X	X	X	(41)	The National Board Authorized Inspector Commission Number must be shown.
X	X	...	(42)	This certificate is for the Authorized Inspector to sign for any field construction or assembly work [see (41) for National Board Commission Number requirements]. Indicate the method used to pressure test the vessel.
...	...	X	(43)	Fill in information identical to that shown on the Data Report to which this is supplementary.
...	...	X	(44)	Fill in information for which there was insufficient space for a specific item on the Data Report Form as identified by the notation "See attached Form K-3" on the Data Report. Identify the information by the applicable Data Report Item Number.
...	X	...	(45)	Identification of individual parts documented by the Form K-2. See KS-130.3.
...	X	...	(46)	Show the name of the part.
...	X	...	(47)	Show the data line number of Form K-2 for the named part.
...	X	...	(48)	Show the Manufacturer's serial number or other identifying number stamped on the part.

GENERAL NOTE: Any quantity to which units apply shall be entered on the Manufacturer's Data Report with the chosen units.

(25)

Page ____ of ____

FORM CRPV-1A MANUFACTURER'S DATA REPORT FOR COMPOSITE REINFORCED PRESSURE VESSELS
As Required by the Provisions of the ASME Boiler and Pressure Vessel Code, Section VIII, Division 3

1. Manufactured and certified by ① (name and address of Manufacturer)
2. Manufactured for ② (name and address of purchaser)
3. Operating location ③ (where installed and where transported)
4. Type ④ (horizontal/vertical) ⑤ (Manufacturer's serial no.) ⑥ (CRN) ⑦ (National Board No.) (year built)
   Drawing no. ⑧ Prepared by ⑨
5. User's Design Specification on file at ⑩
   Certified by ⑩ P.E. state ⑪ Reg. no.
6. Manufacturer's Design Report on file at ⑩
   Certified by ⑩ P.E. state ⑪ Reg. no.

6a. Laminate Procedure Specification on file at ⑩
   Qualification Report No. ____ Dated ____ , ____ Latest requalification date ____ , ____
7. Material ⑫ Impact tested at ____
8. ASME BOILER AND PRESSURE VESSEL CODE, Section VIII, Division 3 ⑬ (year) ⑭ (Code Case no.)
9. Service ⑮
10. Restrictions and warnings ⑯ ⑰
    ⑱ cycles at ____ at ____
11. Construction ⑲ ⑳ ㉑ ㉒ ㉓
    Prestress method ㉔
12. Size and configuration ㉕ (I.D.) ㉖ (length) ㉗ (thickness) (cylindrical, spherical, other)
13. Supports and attachments ㉘
14. Design pressure ㉙ at maximum coincident metal temperature ㉚
    Service pressure ㉛ at vessel/contents temperature of 70°F (20°C)
    Maximum metal vessel temperature ㉚ at ㉚
    Minimum design metal vessel temperature ㉜ at ㉜
15. Test pressure ㉝ ㉝ (pneum./hydro./combination) at ㉝
    Performed in the ㉝ (horiz./vertical) position [fluid(s) used in test]
16. Closures ㉞ (describe)
17. Connections, or provisions, for overpressure relief ㉟

(7/17)

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Page____ of____

Manufactured by ① _____

Manufacturer's Serial No. ⑤ _____ CRN ⑥ _____ National Board No. ⑦ _____

18. Nozzles and connections

Purpose (Inlet, Outlet Drain)	Quantity	Diameter or Size	Type	Material	Nominal Thickness	Reinforcement Material	How Attached	Location
㉟ ㊱ ㊲		㊱	㊱ ㊳	⑫	㉗			㊲

19. Manufacturer's Partial Data Reports, properly identified and signed by commissioned Inspectors, have been furnished for the following components

㊴

20. Remarks ⑯ ㊸

CERTIFICATE OF SHOP COMPLIANCE

We certify that the statements in this report are correct and that all details of design, material, construction, and workmanship of this vessel conform to the ASME BOILER AND PRESSURE VESSEL CODE, Section VIII, Division 3.

U3 Certificate of Authorization no. _____ expires _____ , _____ . (Stamped "U3" only)

RP Certificate of Authorization no. _____ expires _____ , _____ . (Stamped "RP" only)

Date _____ Co. name ㊵ _____ (Manufacturer) Signed ㊵ _____ (representative)

CERTIFICATE OF SHOP INSPECTION

I, the undersigned, holding a valid commission issued by the National Board of Boiler and Pressure Vessel Inspectors and employed by _____ of _____ , have inspected the pressure vessel described in this Manufacturer's Data Report on _____ , _____, and state that, to the best of my knowledge and belief, the Manufacturer has constructed this part in accordance with the ASME BOILER AND PRESSURE VESSEL CODE, Section VIII, Division 3. By signing this certificate, neither the Inspector nor the Inspector's employer makes any warranty, expressed or implied, concerning the part described in this Manufacturer's Data Report. Furthermore, neither the Inspector nor the Inspector's employer shall be liable in any manner for any personal injury or property damage or a loss of any kind arising from or connected with this inspection.

Date _____ Signed ㊶ _____ (Authorized Inspector) Commissions ㊷ _____ (National Board Authorized Inspector Commission number)

(07/25)

Table A-100.2
Instructions for the Preparation of Manufacturer's Data Reports Form CRPV-1A

Reference to Circled Nos. in the Form	Instructions
(1)	Name and street address of Manufacturer, as shown on Manufacturer's ASME Code Certificate of Authorization.
(2)	Name and address of purchaser.
(3)	Name of user and address of the Owner of the vessel.
(4)	Type of vessel, such as horizontal or vertical, separator, heat exchanger, reactor, storage, etc.
(5)	An identifying Manufacturer's serial number marked on the vessel (or vessel part) (see KS-120).
(6)	Canadian registration number where applicable.
(7)	Where applicable, National Board Number from Manufacturer's Series of National Board Numbers. National Board Number shall not be used for owner-inspected vessels.
(8)	Indicate drawing numbers, including revision numbers, which cover general assembly and list materials. For Canadian registration, also include the number of the drawing approved by Provincial authorities.
(9)	Organization that prepared drawing.
(10)	To be completed by the Manufacturer to show the disposition of the User's Design Specification and the Manufacturer's Design Report, and to identify the registered Professional Engineers who certify them.
(11)	State of the U.S.A. or province of Canada, as applicable.
(12)	Show the complete ASME specification number and grade of the actual material used in the vessel part. Material is to be as designated in Section VIII, Division 3. Exceptions: A specification number for a material not identical to an ASME specification may be shown only if such material meets the criteria in the Foreword of Section VIII, Division 3. When material is accepted through a Code Case, the applicable Case number shall be shown.
(13)	Issue date of Section VIII, Division 3 under which vessel or vessel part was manufactured.
(14)	All Code Case numbers when vessel is manufactured according to any Cases.
(15)	Describe contents or service of the vessel.
(16)	Additional comments, including any Code restrictions on the vessel or any unusual Code or jurisdictional requirements that have been met, such as those noted in 17, 18, 20, 21, and 33. Indicate corrosion or erosion allowance.
(17)	Show need for start-up or shutdown temperature and/or controlled rate of heating or cooling, maximum temperature of any part.
(18)	Show results of fatigue analysis, number of cycles, limitations, or restrictions.
(19)	Type of longitudinal joint in cylindrical section, or any joint in a sphere (e.g., Type No. 1 butt or seamless).
(20)	When heat treatment is performed by the Manufacturer, give temperature and time. Explain any special cooling procedure and other pertinent heating during fabrication.
(21)	Indicate examination applied. Methods, location, and results should be included under Remarks.
(22)	Type of welding used in girth joints in the cylindrical section (see 19).
(23)	For jacketed vessels, explain type of jacket closures used and Code stamping.
(24)	Prestress, method, verification, etc.
(25)	Indicate inside diameter.
(26)	The shell length shall be shown as the overall length between closure or transition section welds or joints for a shell of a single diameter. In other cases, define length as appropriately descriptive.
(27)	Thickness is the nominal thickness of the material used in the fabrication of the vessel. It includes corrosion allowance.
(28)	Indicate provisions for support of the vessel and any attachments for superimposed equipment.
(29)	Show design pressure for which vessel is constructed (see KG-311). Other internal or external pressures with coincident temperatures shall be listed where applicable.
(30)	Show maximum coincident metal temperatures permitted for vessel at the design pressures.
(31)	Show service pressure/working pressure for which the vessel is constructed (see KG-515).
(32)	Show minimum design metal temperature at coincident pressure. List if more than one set.
(33)	Show hydrostatic or other tests made with specified test pressure at top of vessel in the test position that applies (pneumatic, hydrostatic, or combination test pressure). Indicate if vessel was tested in the vertical position.
(34)	Bolts used to secure removable head(s), closures, or seals of vessel.
(35)	Indicate nozzle or other opening that is designated for pressure relief (see Part KOP).
(36)	Show other nozzles and openings by size, type, and purpose. See 38.
(37)	Show opening designated for inspection. Show location.

Table A-100.2
Instructions for the Preparation of Manufacturer's Data Reports Form CRPV-1A (Cont'd)

Reference to Circled Nos. in the Form	Instructions
(38)	Data entries with descriptions acceptable to Inspector. Abbreviations, coded identification, or reference to Code figure and illustration number may be used to define any generic name. For ASME B16.5 flanges, the class should be identified. Flange facing and attachment to neck is not required. Some typical abbreviations: Flanged fabricated nozzle Cl. 300 flg Long weld neck flange Cl. 300 lwn Weld end fabricated nozzle w.e.
(39)	To be completed when one or more parts of the vessel are furnished by others and certified on Data Report Form K-2 as required by KS-301. The part manufacturer's name and serial number should be indicated.
(40)	Certificate of compliance block is to show the name of the Manufacturer as shown on Manufacturer's ASME Code Certificate of Authorization. This should be signed in accordance with organizational authority defined in the Quality Control System (see Mandatory Appendix 2).
(41)	To be completed by the Manufacturer and signed by the Authorized Inspector who performs the shop Inspection or signs Form CRPV-lA for the completed vessel. Attach any applicable K-2 forms.
(42)	The National Board Authorized Inspector Commission Number must be shown.
(43)	If additional thickness is provided as a protective or sacrificial layer beyond the thickness specified in 27, then that additional thickness shall be indicated here.

GENERAL NOTE: Any quantity to which units apply shall be entered on the Manufacturer's Data Report with the chosen units.

(25)

FORM CRPV-2A RECOMMENDED FORM FOR QUALIFYING THE LAMINATE DESIGN AND THE LAMINATE PROCEDURE SPECIFICATION USED IN MANUFACTURING COMPOSITE REINFORCED PRESSURE VESSELS
As required by the Provisions of the ASME Boiler and Pressure Vessel Code, Section VIII, Division 3

Page____ of____

Qualification Test Report No. _____

Laminate Procedure Specification No. _____

A change in any of the essential variables denoted by an asterisk below requires a new Laminate Procedure Specification

*Fiber _____
(Manufacturer and Designation)

*Sizing or Finish _____
(Manufacturer and Designation)

*Resin _____
(Type, Manufacturer, and Designation)

*Curing Agent _____
(Type, Manufacturer, and Designation)

Curing Agent/Resin Ratio _____

Viscosity of Resin System _____ (min.) to _____ (max.) @ _____

*Manner of Impregnation _____
(Prepreg., Wet Wind, Postpreg.)

*Percent Fiber by Weight in Composite _____
[See Note (1)]

*Variables of Winding Process [See Note (2)] _____

Helix Angle _____ (measured on cylinder between axis and band path)

Circumferential Band Density _____ end/unit length.

Circumferential Band Width _____

Tension: Per Strand (End), Roving, or Band (specify which) _____ per _____

Method of Control _____ Program _____

Layer Sequence _____
[See Note (2)]

*Primer _____
(Type, Manufacturer, and Designation)

Primer Application Method _____

*Primer Curing Schedule _____ for _____ hr _____ min

Exterior Treatment (Non-Structural, Describe) _____

	Fiber Type	Fiber Form	Manufacturer	Manufacturing No.
Material No. 1				
Material No. 2				

*Inner Liner _____
[Material, Grade, and Thickness. See Note (1)]

*Liner Size and Configuration _____ (O.D.) _____ (Length) _____ (Cylindrical, Spherical, Other)

Laminate Strength _____ Method of Measurement _____
(If other than ASTM D2290)

Interlaminar Shear Strength _____

Acoustic Emission Test Report Number _____

NOTES:
(1) Where a range of values or a tolerance applies, state the applicable range or tolerance.
(2) Use O to indicate full layer of circumferential windings (down and back), include number of passes.
Use o to indicate half layer of circumferential windings (single pass).

(07/23)

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*Laminate Curing Schedule _____ (temperature) for _____ hr _____ min
_____ (temperature) for _____ hr _____ min
_____ (temperature) for _____ hr _____ min
_____ (temperature) for _____ hr _____ min
_____ (temperature) for _____ hr _____ min

Manner of Measuring Temperature: Oven Air _____ Wrong Surface _____

Vessel Head _____ Other (Describe) _____

*Barcol Hardness _____
(Use a separate sheet to record individual readings and their location [See Note (1)])

Laminate Thickness _____
(Use a separate sheet to record individual readings and their location [See Note (1)])

*Volumetric Expansion _____

Gel Time _____ min Peak Exothermic Temperature _____

Minimum Temp. Cycle Test: _____ (no. of cycles) from _____ to _____ @ _____ maximum test temperature

Maximum Temp. Cycle Test: _____ (no. of cycles) from _____ to _____ @ _____ minimum test temperature

Burst Pressure _____ Qualification Pressure _____

Mode of Failure _____

Cathodic Disbondment Test Results _____

Qualification:

Qualification Vessel Designation Number _____

Design Report Number _____

Original Qualification Report Number _____

If Requalification, Requalification Report Number _____

ASME BOILER AND PRESSURE VESSEL CODE, Section VIII, Division 3 _____ (Year)

We certify that the statements in this Specification are correct:

Date _____ , _____ Signed _____

By _____

Certificate of Authorization Number (U3) _____ Expires _____

Certificate of Authorization Number (RP) _____ Expires _____

CERTIFICATION BY SHOP INSPECTOR
OF QUALIFICATION OF LAMINATE DESIGN AND LAMINATE PROCEDURE SPECIFICATION

Laminate Procedure Specification of _____ at _____

for _____ process of manufacturing vessel(s) described in

User's Design Specification Number _____ and

Manufacturer's Design Report Number _____

I, the undersigned, holding a valid commission issued by the National Board of Boiler and Pressure Vessel Inspectors and employed by _____ of _____

have inspected the pressure vessel and witnessed tests described in the Qualification Test Report of the Laminate Design and Procedure Specification and state that, to the best of my knowledge and belief, the Manufacturer has constructed this part in accordance with the ASME BOILER AND PRESSURE VESSEL CODE, Section VIII, Division 3, and the Laminate Design and Procedure Specification being qualified. By signing this certificate, neither the Inspector nor the Inspector's employer makes any warranty, expressed or implied, concerning the design or procedure covered by this Qualification Test Report. Furthermore, neither the Inspector nor the Inspector's employer shall be liable in any manner for any personal injury or property damage or a loss of any kind arising from or connected with this inspection.

Date _____ Signed _____ (Authorized Inspector) Commissions _____ (National Board Authorized Inspector Commission number)

(07/25)

NONMANDATORY APPENDIX B
SUGGESTED PRACTICE REGARDING EXTENDING LIFE BEYOND THE CYCLIC DESIGN LIFE

B-100 EXTENDING ALLOWED CYCLIC LIMITS WHILE IN OPERATION

(a) It is recognized that the fatigue and fracture analyses of Articles KD-3 and KD-4, respectively, calculate only the minimum cyclic life of a high pressure vessel.

(b) Article KD-3 is applicable only if the pressure vessel remains in as-new condition; however, the results of the analysis may not be valid if in-service deterioration occurs.

(c) Further, Article KD-4 requires assuming an initial material flaw size which may not exist when a pressure vessel is first manufactured.

(d) To accommodate the potentially restrictive limits described above and at the same time provide realistic guidance to users of high pressure vessels, Post-Construction Inspection Planning (PCC-3) includes such guidance governing periodic examinations for vessels in cyclic service. Such information, however, is outside the scope of this Division.

NONMANDATORY APPENDIX D
FRACTURE MECHANICS CALCULATIONS (25)

DELETED

NONMANDATORY APPENDIX E
CONSTRUCTION DETAILS

E-100 INTEGRAL HEADS (BLIND ENDS)

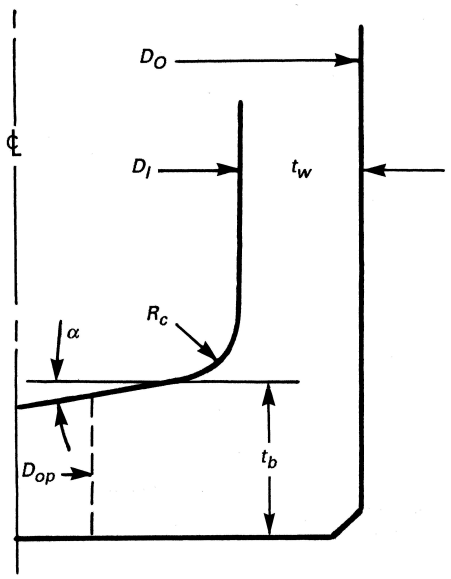
The thickness and proportions of blind ends of cylindrical vessels may conform to the recommendations given in this Appendix.

E-110 THICK WALL PROPORTIONS

(a) For initial sizing, if the D_O/D_I ratio of the vessel is 1.25 or more, the proportions of blind pressure vessel ends shall be kept within the following limits (see Figure E-110).

(1) The minimum inside corner radius R_c shall be 25% of the design thickness of the vessel wall.

Figure E-110
Thick Wall Blind End Proportions Not Requiring Detailed Analysis



Legend:
D_{op} = opening diameter = $0.15D_I$ max.
R_c = corner radius = $025t_w$ min.
t_b = bottom thickness = t_w min., $2t_w$ max.
t_w = design wall thickness
Y = D_O/D_I = 1.5 min.
α = 10 deg max.

(2) The thickness of the blind end at the tangent of the inside corner (t_b in Figure E-110) shall be no less than the design thickness of the vessel wall and no greater than twice the design thickness, t_w, of the vessel wall. For $Y = 1.5$ to 2.25 and $R_c = 0.25t_w$, the minimum blind end thickness shall be calculated by the following equation:

$$t_b = t_w\left(-1.0677Y^3 + 6.80Y^2 - 15.433Y + 13.45\right) \quad \text{(E.1)}$$

For $Y > 2.25$ and $R_c \geq 0.25t_w$, the minimum thickness, t_b, shall be calculated by the following equation:

$$t_b = t_w \quad \text{(E.2)}$$

(3) The maximum angle α from the tangent of the inside corner to the vessel centerline shall be 10 deg from the plane perpendicular to the vessel axes (see Figure E-110).

(4) The diameter D_{op} of any opening in the blind end shall not exceed 15% of the vessel inside diameter and shall be located on the vessel centerline.

(b) The corner radius principal stresses used to perform the fatigue evaluation in accordance with Article KD-3 shall be calculated by the following equations for $Y = 1.25$ to 4.0 and $R_c = 0.25t_w$:

$$\sigma_1 = P\left(0.6320 - 1.5160Y + 4.5731\frac{Y}{\ln Y} - 19.1428\frac{1}{\sqrt{Y}} + 31.0567\frac{\ln Y}{Y^2}\right) \quad \text{(E.3)}$$

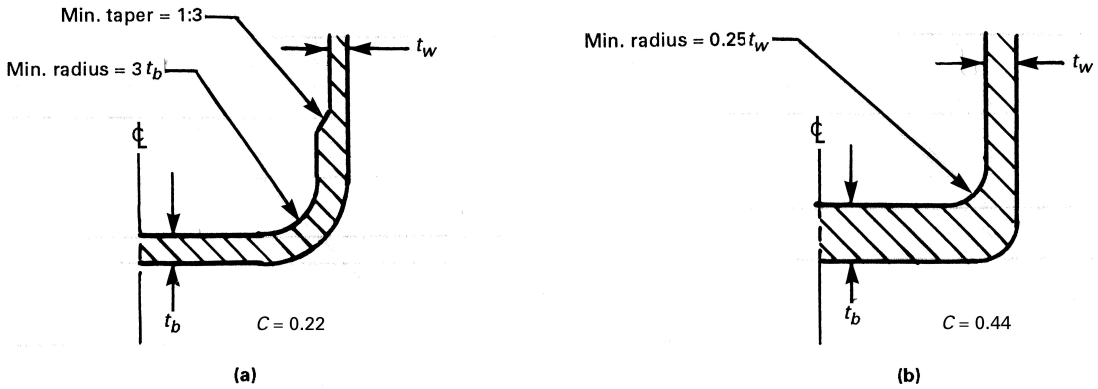
$$\sigma_2 = P\left(-0.5718 + 0.1141Y + 1.0208\frac{1}{\ln Y} + 1.6096\frac{\ln Y}{Y^2} - 1.3667\frac{1}{Y^2}\right) \quad \text{(E.4)}$$

$$\sigma_3 = -P \quad \text{(E.5)}$$

E-120 THIN WALL PROPORTIONS

(a) If the D_O/D_I ratio of the vessel is less than 1.25, the minimum thickness of blind ends (see Figure E-120) shall be calculated by the following equation without detailed stress analysis:

Figure E-120
Thin Wall Blind End Proportions Not Requiring Detailed Analysis



$$t_b = D_I\left(1.5CP / S_y\right)^{0.5} \quad \text{(E.6)}$$

(b) The minimum multiplier to be used with the C values below when performing fatigue and fracture mechanics evaluations using Articles KD-3 and KD-4, respectively, is 1.8. The stress intensity is:

$$S = 1.8C(D_I / t_b)^2 P \quad \text{(E.7)}$$

(c) The value of C to be used in eqs. (a)(E.6) and (b)(E.7) shall be based on the following:

(1) C = 0.22 if the inside corner radius is at least three times the minimum required end thickness.

(2) C = 0.44 if the inside corner radius is less than three times the minimum required end thickness. The inside corner radius shall be greater than or equal to 25% of the design thickness of the vessel wall t_w.

(d) There is no special requirement with regard to cylinder lengths in the case of dissimilar cylindrical thicknesses; however, the taper between such thicknesses shall be a minimum of 3:1.

E-200 THREADED END CLOSURES

Specific requirements for threads and threaded closures are given in Article KD-6. In the following, *one thread* is understood to mean one 360 deg turn of a single start thread with a full cross section. The number of threads should be less than 20 but at least 4. The helix angle of the thread should not exceed 2 deg. The internal thread should have a generous undercut. The axial length of the external threaded portion should be at least one thread pitch longer than the mating internal threaded portion to ensure full engagement of all internal threads.

The threads do not carry the axial load uniformly. The internal thread closest to the undercut carries generally the largest portion of the load. The following method may be used to determine the load distribution. The threads are numbered from the undercut.

For vessels where the outside diameter is not uniform along the whole length of the body, the methods given in this Appendix for calculating thread load distribution may be nonconservative due to the effects of the vessel outer diameter on the flexibility factors calculated in E-210 for such vessels. See KD-100(b).

E-210 NOMENCLATURE (SEE FIGURES E-210.1, E-210.2, AND E-210.3)

A_B = cross-sectional area of the vessel normal to the vessel axis through the internal threads
= $\frac{\pi}{4}\left(D_o^2 - D_p^2\right)$

A_C = cross-sectional area of the closure normal to the vessel axis through the external threads
= $\frac{\pi}{4}D_p^2$

C_M = combined flexibility factor of the body and closure
= $\left(\frac{1}{E_B A_B} + \frac{1}{E_C A_C}\right)P_T$

C_T = flexibility factor of the threads
= $\frac{1}{D_p}\left(\frac{1}{E_B} + \frac{1}{E_C}\right)$

D_o = outside diameter of the vessel
D_p = pitch diameter of the threads
E_B = modulus of elasticity of the body
E_C = modulus of elasticity of the closure
F_1 = load on the first thread
F_2 = load on the second thread
F_i = load on the ith thread

F_n = load on the last thread
F_T = total load on all threads
P_T = thread pitch
S = number of loaded segments in one pitch
S_i = segment load
S_M = combined flexibility factor of the body and the closure
= $\frac{C_M}{S}$
S_T = flexibility factor of the threads
= $C_T 2S$
n = total number of threads

E-220 THREAD LOAD DISTRIBUTION

E-221 CONTINUOUS THREADS

The thread load distribution may be obtained by:

$$F_i = F_{i+1} + \frac{C_M}{C_T}(F_{\text{sum}}) \tag{E.8}$$

where

$$F_{\text{sum}} = \sum_{j=i+1}^{n} F_j \tag{E.9}$$

(See Crum, A. S. D.; High Pressure Technology, ASME PVP-Vol. 148, pp. 43–53, June 1988.) Starting with the last thread F_n, calculate the load on the previous thread F_{n-1} and the load on F_{n-2}, and so on.

E-222 INTERRUPTED (BREECH) THREAD

A similar equation for segments to those for full threads is:

$$S_i = S_{i+1} + \frac{S_M}{S_T}(S_{\text{sum}}) \tag{E.10}$$

(a) Example for Continuous Thread. Assuming the load on the last thread is unity, given the values below where the mating parts are the same material, we obtain the values in Table E-222.1.

A_B = 398.197
A_C = 132.732
C_M = 0.01
C_T = 0.154
D_O = 26
D_p = 13
n = 10
P_T = 1

(b) Example for Interrupted Thread. For S = 4 (one-eighth turn to open), we obtain the values in Table E-222.2.

Figure E-210.1
Typical Threaded End Closure

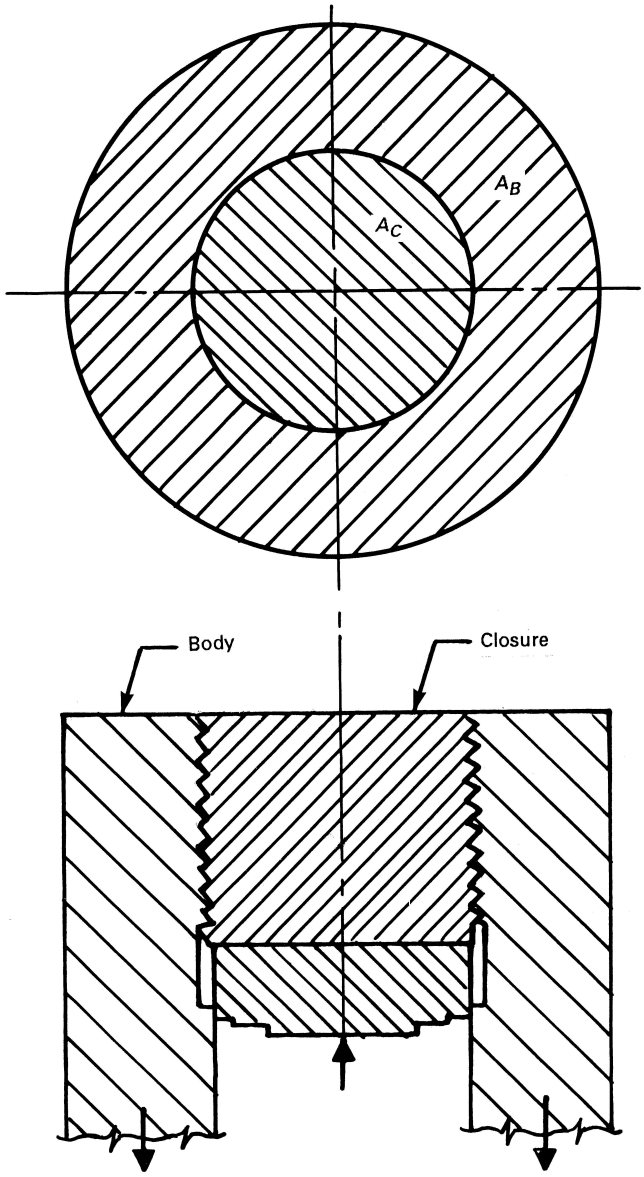


Figure E-210.2
Thread Loading Distribution

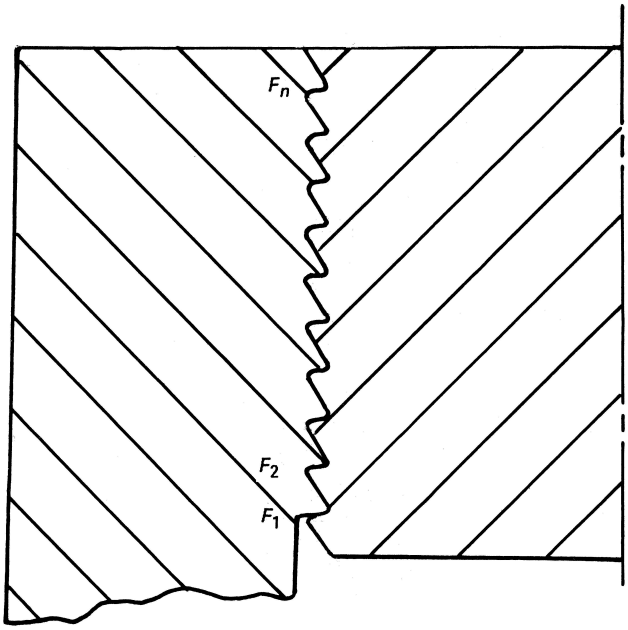


Figure E-210.3
Detail of First Thread

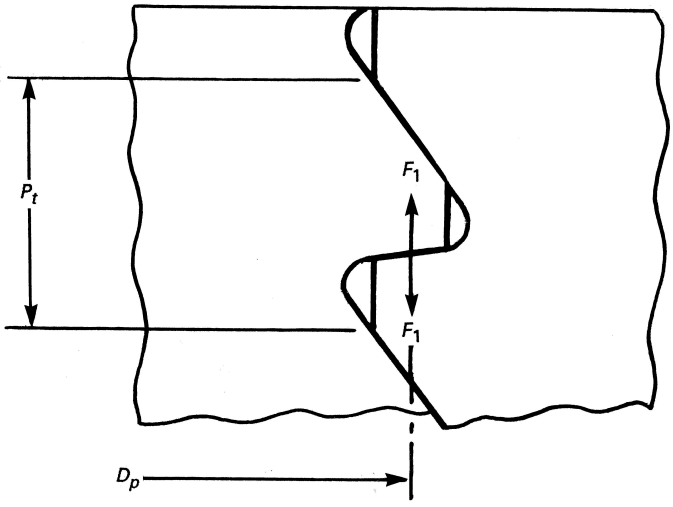


Table E-222.1
Continuous Thread Example

Thread	F_i [Note (1)]	F_{sum}	$C_M/C_T \times F_{sum}$	F_i, %
10	1.000	1.000	0.065	4.1
9	1.065	2.065	0.135	4.3
8	1.200	3.265	0.213	4.9
7	1.413	4.679	0.305	5.7
6	1.719	6.398	0.418	7.0
5	2.137	8.534	0.557	8.7
4	2.694	11.228	0.733	10.9
3	3.427	14.655	0.957	13.9
2	4.384	19.039	1.243	17.8
1	5.627	24.666	1.611	22.8

NOTE: (1) F_T = 24.666 (obtained by adding the ten F_i values).

Table E-222.2
Interrupted Thread Example

Thread No.	Segment No.	S_i	S_{sum}	$S_M/S_T \times S_{sum}$	S, %	Thread, %
10	40	1.000	1.000	0.002	1.52	6.12
10	39	1.002	2.002	0.004	1.53	...
10	38	1.006	3.008	0.006	1.53	...
10	37	1.012	4.020	0.008	1.54	...
9	36	1.020	5.041	0.010	1.56	6.33
9	35	1.031	6.072	0.012	1.57	...
9	34	1.043	7.115	0.015	1.59	...
9	33	1.058	8.172	0.017	1.61	...
8	32	1.074	9.247	0.019	1.64	6.74
8	31	1.093	10.340	0.021	1.67	...
8	30	1.114	11.454	0.023	1.70	...
8	29	1.138	12.592	0.026	1.74	...
7	28	1.163	13.755	0.028	1.77	7.36
7	27	1.191	14.947	0.030	1.82	...
7	26	1.222	16.169	0.033	1.86	...
7	25	1.255	17.424	0.036	1.91	...
6	24	1.290	18.714	0.038	1.97	8.24
6	23	1.329	20.043	0.041	2.03	...
6	22	1.370	21.412	0.044	2.09	...
6	21	1.413	22.826	0.047	2.15	...
5	20	1.460	24.285	0.050	2.23	9.38
5	19	1.509	25.795	0.053	2.30	...
5	18	1.562	27.357	0.056	2.38	...
5	17	1.618	28.975	0.059	2.47	...
4	16	1.677	30.652	0.063	2.56	10.82
4	15	1.739	32.391	0.066	2.65	...
4	14	1.806	34.197	0.070	2.75	...
4	13	1.875	36.072	0.074	2.86	...
3	12	1.949	38.021	0.078	2.97	12.62
3	11	2.027	40.047	0.082	3.09	...
3	10	2.108	42.156	0.086	3.21	...
3	9	2.194	44.350	0.090	3.35	...
2	8	2.285	46.635	0.095	3.48	14.83
2	7	2.380	49.015	0.100	3.63	...
2	6	2.480	51.495	0.105	3.78	...
2	5	2.585	54.080	0.110	3.94	...
1	4	2.695	56.775	0.116	4.11	17.54
1	3	2.811	59.586	0.122	4.29	...
1	2	2.933	62.519	0.128	4.47	...
1	1	3.060	65.579	0.134	4.67	...

NONMANDATORY APPENDIX G
DESIGN RULES FOR CLAMP CONNECTIONS

G-100 SCOPE

(a) The guidelines in this Appendix may be used for the design of clamp connections for pressure vessels and vessel parts. Unless the requirements in this Appendix are used to meet specific requirements of this Division, they may be used to supplement the applicable requirements of Article KD-2. They may also supplement the applicable requirements of Articles KD-3, KD-4, and KD-6 of this Division. These guidelines should not be used for the determinations of thickness of supported or unsupported tubesheets integral with a hub nor for the determination of thickness of covers. These rules provide only for hydrostatic end loads, assembly, and gasket seating. Consideration shall be given to loads other than pressure, such as piping loads that may act upon the clamp connection (see KG-311.8 and KD-110).

(b) The design of a clamp connection involves the selection of the gasket, bolting, hub, and clamp geometry. Bolting should be selected to satisfy the requirements of G-400. Connection dimensions should be such that the stresses in the clamp and the hub calculated in accordance with G-700 and G-800 do not exceed the allowable stresses specified in Table G-900. All calculations should be made on dimensions in the corroded condition. Calculations for assembly, gasket seating, and operating conditions are required.

(c) It is recommended that either a pressure energized and/or low seating load gasket be used. Figure G-300 shows typical pressure energized gaskets. This type of gasket is consistent with the relatively low preloading capability of this type of construction. Gasket factors m for other than pressure energized gaskets may be found in other Divisions of the Code. The designer should consider the deflection of the gasket contact faces under both assembly and operating loads when selecting or designing a gasket. Hub faces shall be designed such as to have metal-to-metal contact outside the gasket seal diameter. This may be provided by recessing the hub faces or by use of a metal spacer (see Figure G-100.1). The contact area shall be sufficient to prevent yielding of either the hub face or spacer under both operating and assembly loads.

(d) It is recognized that there are clamp designs which utilize no wedging action during assembly since clamping surfaces are parallel to the hub faces. Such designs are acceptable and should satisfy the bolting and corresponding clamp and hub requirements of a clamp connection designed for a total included clamping angle of 10 deg.

(e) The design methods used herein to calculate stresses, loads, and moments can also be used in designing clamp connections of shapes differing from those shown in Figures G-100.1, G-100.2, and G-100.3, and for clamps consisting of more than two circumferential segments. The design equations presented herein are based on simple straight beam theory and are conservative in that they do not account for curvature or hoop-restraint effects. Alternative techniques such as finite element analysis methods can be used to evaluate clamp designs.

(f) Clamps designed to the rules of this Appendix should be provided with two or more bolts per segment connection.

(g) The design of the hub faces and clamps should incorporate weep holes and vent passages adequately sized to vent pressure in the event of gasket leakage to prevent hub and clamp overstress.

G-200 MATERIALS

(a) Materials used in the construction of clamp connections shall comply with the requirements given in Part KM.

(b) Hubs and clamps should not be machined from plate.

(c) Bolts, studs, nuts, and washers should comply with Article KD-6 and Part KM. Minimum diameter should be $\frac{1}{2}$ in. (13 mm).

G-300 NOMENCLATURE

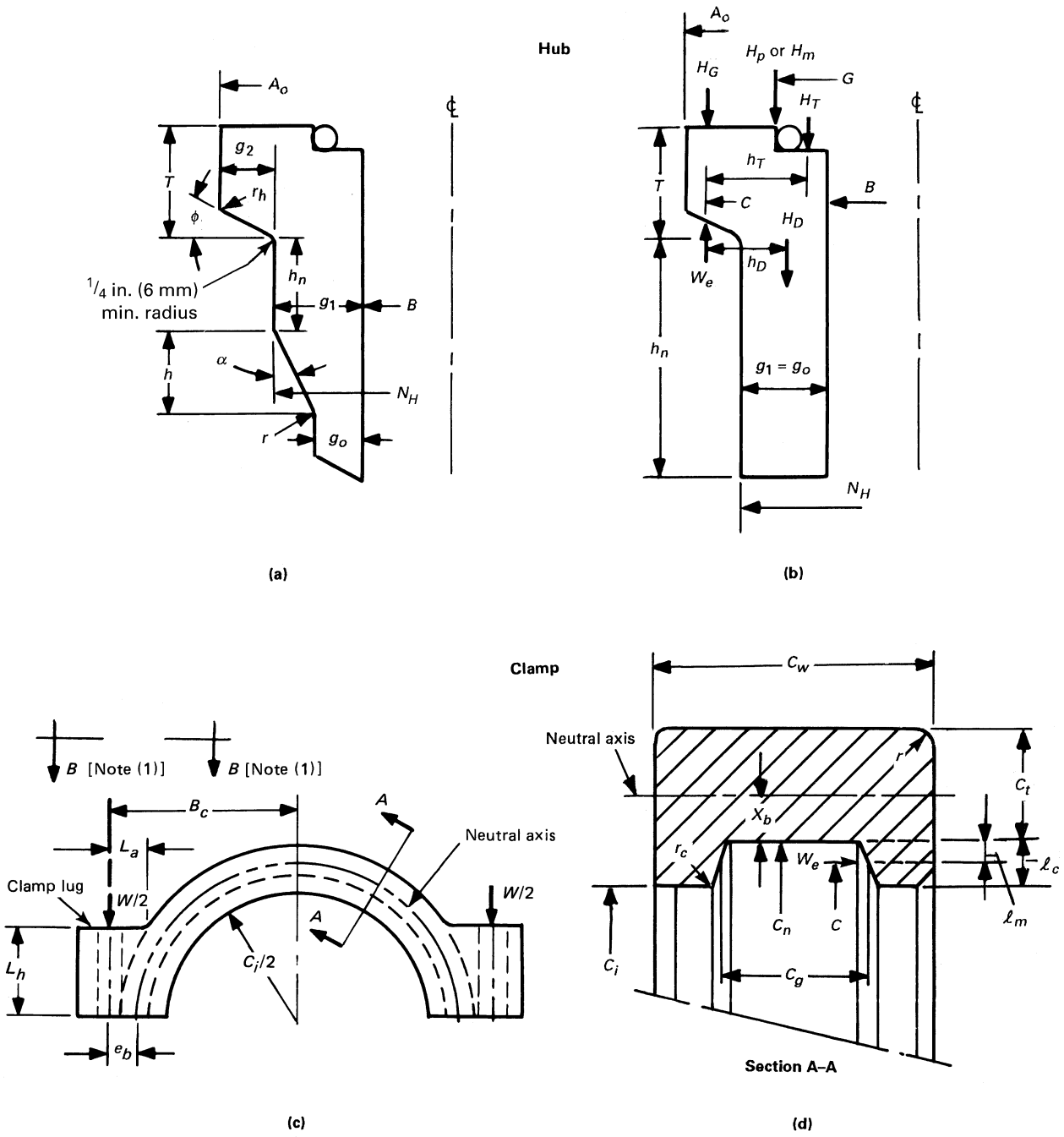
The nomenclature below is used in the equations for the design of clamp-type connections (see also Figures G-100.1, G-100.2, and G-100.3).

A_b = total cross-sectional area of the bolts per clamp lug using the minimum of the root diameter of the thread or least diameter of unthreaded portion, in.^{2} (mm^2)

A_c = total clamp cross-sectional area, in.^{2} (mm^2). This may be calculated as shown below or by any other consistent method based on the clamp geometry:

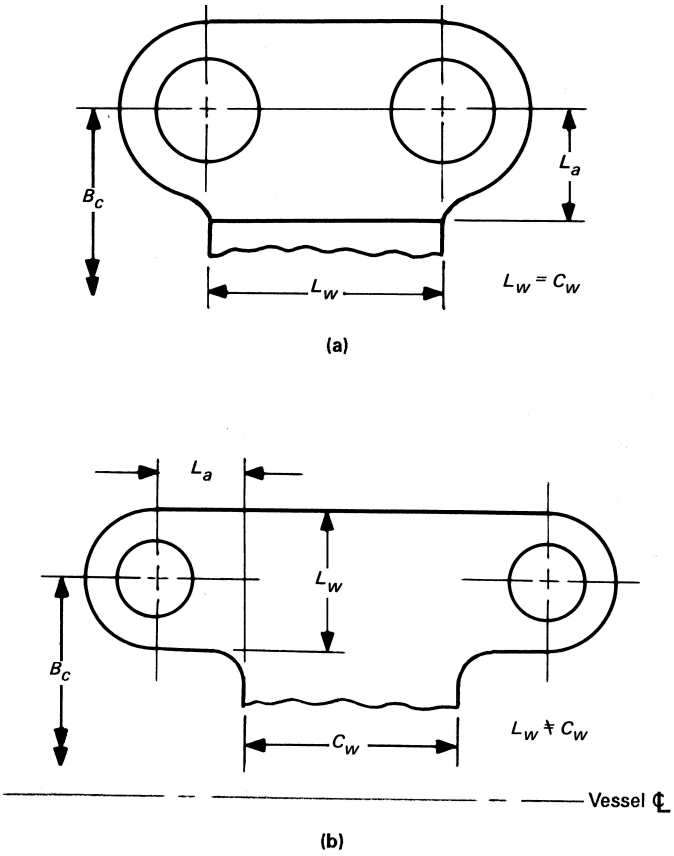
= $A_{c1} + A_{c2} + A_{c3}$

Figure G-100.1
Clamp Nomenclature



NOTE: (1) See Figure G-100.2 for view *B-B*.

Figure G-100.2
Typical Clamp Lug Configurations
[View *B-B* From Figure G-100.1, Sketch (c)]



A_{c1} = partial clamp area, in.^{2} (mm^2)
= $(C_w - 2C_t)C_t$

A_{c2} = partial clamp area, in.^{2} (mm^2)
= $2C_t^2 - \left(2 - \frac{\pi}{2}\right)r^2$

A_{c3} = partial clamp area, in.^{2} (mm^2)
= $(C_w - C_g)\ \ell_c$

A_m = total required cross-sectional area of bolts per clamp segment connection, taken as the greater of A_{m1} and A_{m2}, in.^{2} (mm^2)

A_{m1} = total cross-sectional area of bolts per clamp segment connection at root of thread or section of least diameter under stress, required for the operating conditions, in.^{2} (mm^2)
= $W_{m1}/2S_b$

A_{m2} = total cross-sectional area of bolts per clamp segment connection at root of thread or section of least diameter under stress, required for gasket seating, in.^{2} (mm^2)
= $W_{m2}/2S_a$

A_o = outside diameter of the hub, in. (mm)

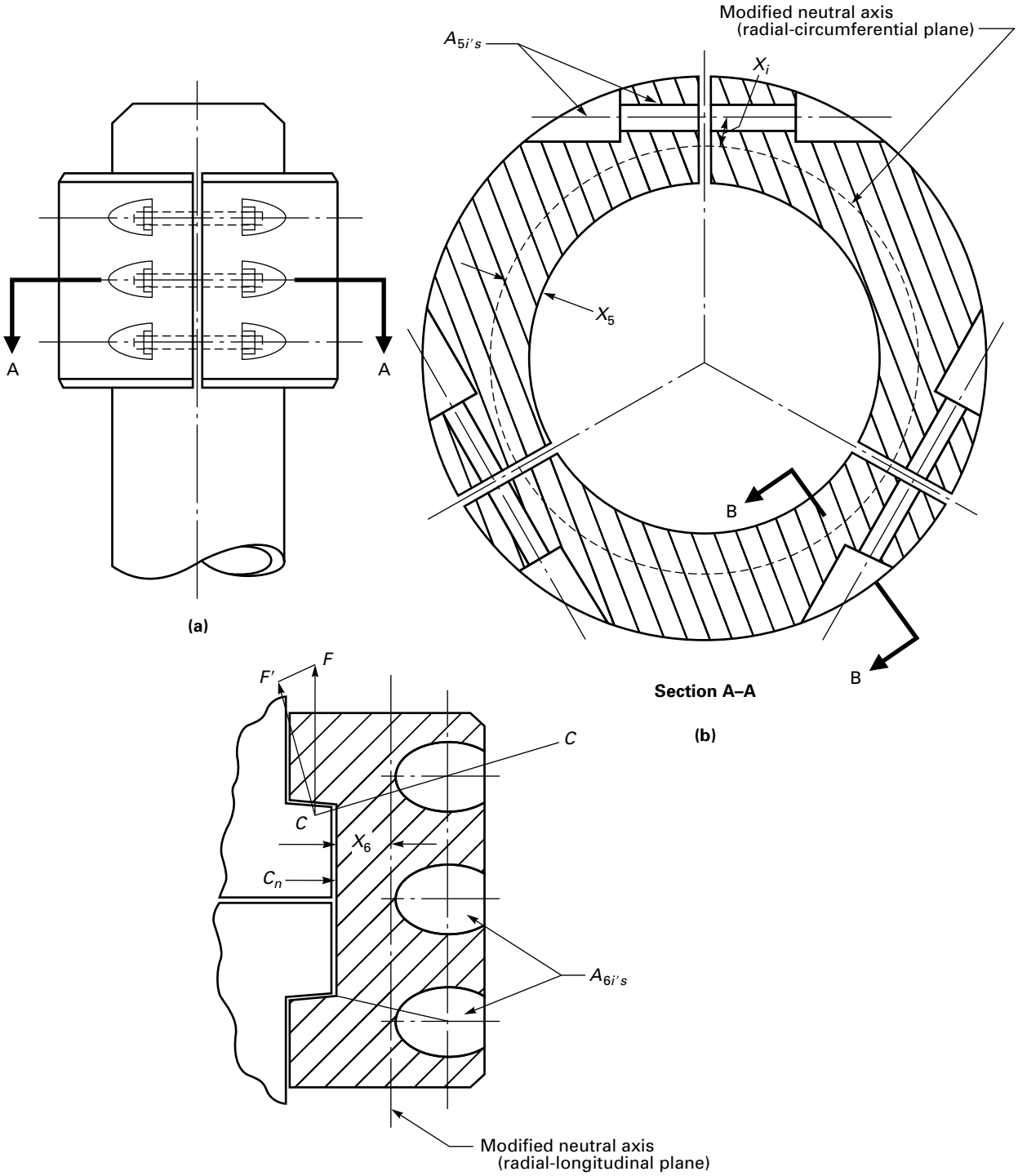
A_{or} = outside bearing diameter of the hub accounting for the corner radius r_h, in. (mm)
= $A_o - 2r_h$

A_3 = hub longitudinal shear area, taken as the lesser of A_{3a} and A_{3b}, in.^{2} (mm^2)

A_{3a} = hub longitudinal shear area based on a straight shear surface in the tangential–longitudinal plane, in.^{2} (mm^2)
= $\pi C_{ir} T_h$

A_{3b} = hub longitudinal shear area based on a 45 deg conical shear surface, in.^{2} (mm^2). This can be calculated by any consistent method and may be limited by chamfers on the hub and thickness of the hub shoulder. A typical formulation when these effects are not limiting is shown below:
= $\frac{\pi\sqrt{2}}{4}\left(A_o^2 - C_{ir}^2\right)$

Figure G-100.3
Typical Hub Design With the Bolts Contained Within the Body of the Clamp



A_5 = minimum clamp cross-sectional area in the radial–tangential plane, in.^{2} (mm^2)
= $\pi(C_n + C_t)\, C_t - A_{5b}$
(The A_5 area can be further modified if only two sets of bolts are used and the bolt hole cutout regions fall within a region adjacent to the clamp lip. Such a case is illustrated by Section A–A of Figure G-100.3, illustration (b). For this configuration, A_5 can be based on a section indicated by Section A–A of Figure G-100.3, illustration (b), provided that the force acting normal to the plane is also appropriately modified.)

A_{5b} = maximum clamp bolt hole cutout area (including spot faces and undercuts) around the full circumference in any radial–tangential plane when no external lugs are used and the bolts are contained within the main body of the clamp (see Figure G-100.3), in.^{2} (mm^2)
= $\sum A_{5i}$
(A_{5b} = 0 for external bolt lugs like those shown in Figure G-100.2)

A_{5i} = individual clamp bolt hole cutout areas in the radial–tangential plane, in.^{2} (mm^2) (see Figure G-100.3)

A_6 = minimum clamp cross-sectional area in the radial–longitudinal plane, in.^{2} (mm^2)
= $A_c - A_{6b}$

A_{6b} = maximum clamp bolt hole cutout area (including spot faces and undercuts) in any radial–longitudinal plane when the bolts are contained within the main body of the clamp, in.^{2} (mm^2). This corresponds to the bolt hole cutout areas indicated in Section B–B of Figure G-100.3, illustration (c).
= $\sum A_{6i}$
(A_{6b} = 0 for external bolt lugs like those shown in Figure G-100.2)

A_{6i} = individual clamp bolt hole cutout areas in the radial–longitudinal plane, in.^{2} (mm^2) (see Figure G-100.3)

A_7 = clamp lip longitudinal shear area, taken as the lesser of A_{7a} and A_{7b}, in.^{2} (mm^2)

A_{7a} = clamp lip longitudinal shear area based on a straight shear surface in the tangential–longitudinal plane, in.^{2} (mm^2)
= $\pi A_{or} T_c$

A_{7b} = clamp lip longitudinal shear area based on a 45 deg conical shear surface, in.^{2} (mm^2). This can be calculated by any consistent method and may be limited by chamfers on the lip and the lip thickness. A typical formulation when these effects are not limiting is shown below:
= $\frac{\pi\sqrt{2}}{4}\left(A_{or}^2 - C_i^2\right)$

B = inside diameter of hub, in. (mm)

B_c = radial distance from connection centerline to center of bolts, in. (mm) [see Figure G-100.1, illustration (c)]

C = diameter of effective clamp–hub reaction circle, in. (mm)
= $(A_{or} + C_{ir})/2$

C_g = effective clamp gap determined at diameter C, in. (mm)

C_i = inside bearing diameter of clamp, in. (mm)

C_{ir} = inside bearing diameter of the clamp accounting for the corner radius r_c, in. (mm)
= $C_i + 2r_c$

C_n = inside diameter of the neck of the clamp, in. (mm)

C_t = effective clamp thickness (C_t shall be equal to or greater than r), in. (mm)

C_w = clamp width, in. (mm)

C_6 = tangential bending stress moment arm, in. (mm)
= $C_t - X_6$
(if $e_b < 0$, $C_6 = X_6$)

G = diameter at location of gasket load reaction, in. (mm). As noted in Figure G-100.1, G is defined as the diameter to the outside of the seal surface. For other than pressure energized seals, other Divisions of this Code may be consulted for appropriate gasket effective diameter. See additional illustration of G for self-energizing seals in Figure G-300.

H = total end force required for operating or assembly conditions, as applicable, kip (N)

H_D = hydrostatic end force on bore area, kip (N)
= $\pi B^2 P/4$

H_e = total hydrostatic end force, kip (N)
= $\pi G^2 P/4$

H_G = difference between total effective axial clamping preload and the sum of total hydrostatic end force and total joint-contact surface compression, kip (N)
= $[\pi W/(2\tan(\phi + \mu)] - (H + H_p)$

H_m = total axial gasket seating requirements for makeup, kip (N) (the axial seating load for self-energizing gaskets, if significant)

H_p = total joint-contact surface compression load, kip (N)
= $2b \times \pi G m P$ (for self-energized gaskets, use H_p = 0 or actual retaining load if significant)

H_T = difference between total hydrostatic end force and hydrostatic end force on bore area, kip (N)
= $H - H_D$

I_c = moment of inertia of clamp relative to neutral axis of the radial–longitudinal cross section, ignoring any bolt holes through the main body of the clamp, in.^{4} (mm^4). This can be calculated by any consistent method, such as that shown below based on the clamp geometry.
= $\frac{1}{3}\left[(A_{c1} + A_{c2})\, C_t^2 + A_{c3}\ell_c^2\right] - A_c X_b^2$

I_h = moment of inertia of hub shoulder relative to its neutral axis, in.^{4} (mm^4)
$= \frac{g_1 T^3}{3} + \frac{g_2 h_2^3}{3} - \left(g_2 h_2 + g_1 T\right)\overline{h}^2$

I_5 = minimum clamp moment of inertia in any radial–tangential plane, in.^{4} (mm^4)
$= \left[\pi(C_n + C_t)\, C_t^3/3\right] - I_{5b} - A_5 X_5^2$

I_{5b} = maximum reduction of the clamp moment of inertia due to bolt hole cutout areas around the full circumference in any radial–tangential plane, in.^{4} (mm^4)
$= \sum(A_{5i})(X_i)^2 + \sum$ (local moments of inertia of each area about its own centroid)[17] (I_{5b} = 0 when external bolt lugs are used like those shown in Figure G-100.2)

I_6 = minimum clamp moment of inertia in any tangential–longitudinal plane, in.^{4} (mm^4)
$= I_c - I_{6b} - A_6 X_6^2 + A_c X_b^2$

I_{6b} = maximum reduction of the clamp moment of inertia due to bolt hole cutout areas in any tangential–longitudinal plane, in.^{4} (mm^4)
$= \sum(A_{6i})(X_i)^2 + \sum$ (local moments of inertia of each area about its own centroid)[17] (I_{6b} = 0 when external bolt lugs are used like those shown in Figure G-100.2)

L_a = distance from centerline of the clamp bolt to the point where the clamp lug joins the clamp body, in. (mm) [see Figure G-100.1, illustration (c)]

L_h = clamp lug height, in. (mm) [see Figure G-100.1, illustration (c)]

L_w = clamp lug width, in. (mm) (see Figure G-100.2)

M_D = moment due to H_D, in.-kip (N·mm)
$= H_D h_D$

M_F = offset moment, in.-kip (N·mm)
$= H_D(g_1 - g_0)/2$

M_G = moment due to H_G, in.-kip (N·mm)
$= H_G h_G$

M_H = reaction moment at hub neck, in.-kip (N·mm)
$= \dfrac{M_0}{\left[1 + \frac{1.818}{\sqrt{Bg_1}} \times \left(T - \overline{h} + \frac{3.305\, I_h}{g_1^2 (B/2 + \overline{g})}\right)\right]}$

M_o = total rotational moment on hub, in.-kip (N·mm) (see G-600)

M_p = pressure moment, in.-kip (N·mm)
$= \pi \times PBT(T/2 - \overline{h})$

M_R = radial clamp equilibrating moment, in.-kip (N·mm)
$= (\pi W/2)\ \{\overline{h} - T + [(C - N_H)\tan\phi]/2\}$

M_T = moment due to H_T, in.-kip (N·mm)
$= H_T h_T$

M_5 = clamp longitudinal stress bending moment, in.-kip (N·mm)
$= H(\ell_m + X_5) + (\pi W/2)(C_g/2)$

M_6 = clamp tangential stress bending moment, in.-kip (N·mm)
$= |e_b|\ W/2$

N_H = outside diameter of hub neck, in. (mm)

P = internal design pressure, ksi (MPa)

Q = reaction shear force at hub neck, kip (N)
$= \frac{1.818 M_H}{\sqrt{Bg_1}}$

S_a = allowable bolt stress at room temperature (see KD-620), ksi (MPa)

S_b = allowable bolt stress at design temperature (see KD-620), ksi (MPa)

S_{YAC} = yield stress for clamp material at (assembly condition) room temperature, ksi (MPa)

S_{YAH} = yield stress for hub material at (assembly condition) room temperature, ksi (MPa)

S_{YOC} = yield stress for clamp material at (operating condition) design temperature, ksi (MPa)

S_{YOH} = yield stress for hub material at (operating condition) design temperature, ksi (MPa)

S_1 = hub longitudinal stress on outside at hub neck, ksi (MPa)

S_2 = maximum Lamé hoop stress at bore of hub, ksi (MPa)

S_3 = maximum hub shear stress at shoulder, ksi (MPa)

S_4 = maximum radial hub shear stress in neck, ksi (MPa)

S_5 = clamp longitudinal stress at clamp body inner diameter, ksi (MPa)

S_6 = clamp tangential stress at clamp body outer diameter, ksi (MPa)

S_7 = maximum shear stress in clamp lips, ksi (MPa)

S_8 = clamp lip bending stress, ksi (MPa)

S_9 = clamp lug bending stress, ksi (MPa)

S_{10} = maximum clamp lug shear stress, ksi (MPa)

S_{11} = effective bearing stress between clamp and hub, ksi (MPa)

T = thickness of hub shoulder in accordance with Figure G-100.1, in. (mm)

T_c = clamp lip thickness below the outside edge of the hub, in. (mm)
$= \frac{1}{2}\left[C_w - C_g + (A_{or} - C)\tan\phi\right]$

T_h = hub shoulder thickness below the inside edge of the clamp, in. (mm)
$= T - \left(\frac{C_{ir} - A_0}{2} + g_2\right)\tan\phi$

W = total design bolt load required for operating or assembly condition, as applicable, kip (N)

W_c = total effective axial clamping preload on one clamp lip and hub shoulder (gasket seating or assembly), kip (N)
$= \pi W/[2\ \tan(\phi + \mu)]$

W_{m1} = minimum required total bolt load for the operating conditions, kip (N) [see G-400(b)(1)]

W_{m2} = minimum required total bolt load for gasket seating, kip (N) [see G-400(b)(2)]

X_b = basic clamp dimension to neutral axis in the longitudinal–radial plane ignoring any bolt holes through the body of the clamp, in. (mm). This may be calculated as shown below or by any consistent method.

$$= \frac{(A_{c1} + A_{c2})C_t - A_{c3}\ell_c}{2A_c}$$

X_i = average radial distance, in. (mm), from each bolt cutout area in the applicable plane to the inner edge of the neck of the clamp [i.e., to the edge whose diameter is C_n as shown in Figure G-100.3, illustrations (b) and (c)]

X_5 = modified clamp dimension to the neutral axis in the radial–tangential plane, accounting for bolt holes in the main clamp cross section [see Figure G-100.3, illustration (b)], in. (mm)

$$= \frac{\pi(C_n + C_t)\left(C_t^2 / 2\right) - \sum A_{5i}X_i}{A_5}$$

($X_5 = C_t/2$ for external bolt lugs like those shown in Figure G-100.2)

X_6 = modified clamp dimension to the neutral axis in the longitudinal–radial plane, accounting for bolt holes in the main clamp cross section [see Figure G-100.3, illustration (c)], in. (mm)

$$= \frac{X_b A_c - \sum A_{6i}X_i}{A_6}$$

[$X_6 = X_b$ (see Figure G-100.1) for external bolt lugs like those shown in Figure G-100.2]

Z = clamp–hub taper angle, deg (for gasket seating and preload, $Z = \phi + \mu$; for operating, $Z = \phi - \mu$) [see G-400(b)(3)]

b = effective gasket or joint-contact-surface seating width, in. (mm)

e_b = radial distance from center of the bolts to the centroid of the clamp cross section, in. (mm)

$= B_c - (C_i/2) - \ell_c - X_6$

f = hub stress correction factor from Figure G-300.1 (this is the ratio of the stress in the small end of the hub to the stress in the large end). For values below limit of the figure, use $f = 1.0$.

$\overline{g}$ = radial distance from the hub inside diameter B to the hub shoulder ring centroid, in. (mm)

$$= \frac{Tg_1^2 + h_2 g_2\left(2g_1 + g_2\right)}{2\left(Tg_1 + h_2 g_2\right)}$$

g_0 = thickness of hub neck at small end, in. (mm)

g_1 = thickness of hub neck at intersection with hub shoulder, in. (mm)

g_2 = height of hub shoulder, in. (mm) (g_2 shall not be larger than T)

h = hub taper length, in. (mm)

$\overline{h}$ = longitudinal distance from the hub face to the hub shoulder ring centroid, in. (mm)

$$= \frac{T^2 g_1 + h_2^2 g_2}{2\left(Tg_1 + h_2 g_2\right)}$$

h_D = radial distance from effective clamp–hub reaction circle to the circle on which H_D acts, in. (mm)

$= [C - (B + g_1)]/2$

h_G = radial distance from effective clamp–hub reaction circle to the circle on which H_G acts, in. (mm) (for full-face contact geometries, $h_G = 0$)

h_n = hub neck length, in. (mm) (minimum length of h_n is $0.5g_1$ or 1/4 in. (6 mm), whichever is larger)

h_T = radial distance from effective clamp–hub reaction circle to the circle on which H_T acts, in. (mm)

$= [C - (B + G)/2]/2$

h_0 = $\sqrt{Bg_0}$, in. (mm)

h_2 = average thickness of hub shoulder, in. (mm)

$= T - (g_2 \tan\phi)/2$

ℓ_c = effective clamp lip length, in. (mm)

ℓ_m = effective clamp lip moment arm, in. (mm)

$$= \ell_c - \frac{(C - C_i)}{2}$$

m = gasket factor; $m = 0$ for pressure energized gaskets. For nonpressurized gaskets, other Divisions of this Code may be consulted.

r = clamp or hub cross section corner radius, in. (mm)

= 1/4 in. (6 mm) min., C_t max.

r_c = clamp inside corner radius on the surface that mates with the hub (see Figure G-100.1), in. (mm)

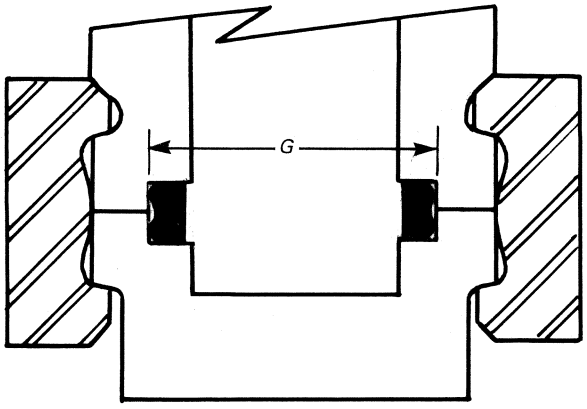
r_h = hub outside corner radius on the surface that mates with the clamp (see Figure G-100.1), in. (mm)

μ = friction angle, deg

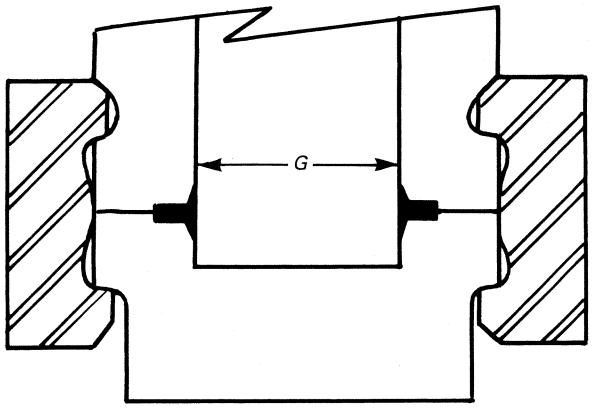
ϕ = clamp shoulder angle, deg

= 35 deg maximum

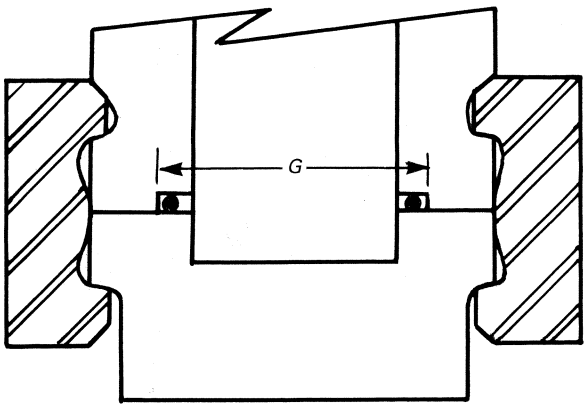
Figure G-300
Typical Self-Energizing Gaskets Used in This Division, Showing Diameter at Location of Gasket Load Reaction *G*



(a) Wave Ring Type Seal



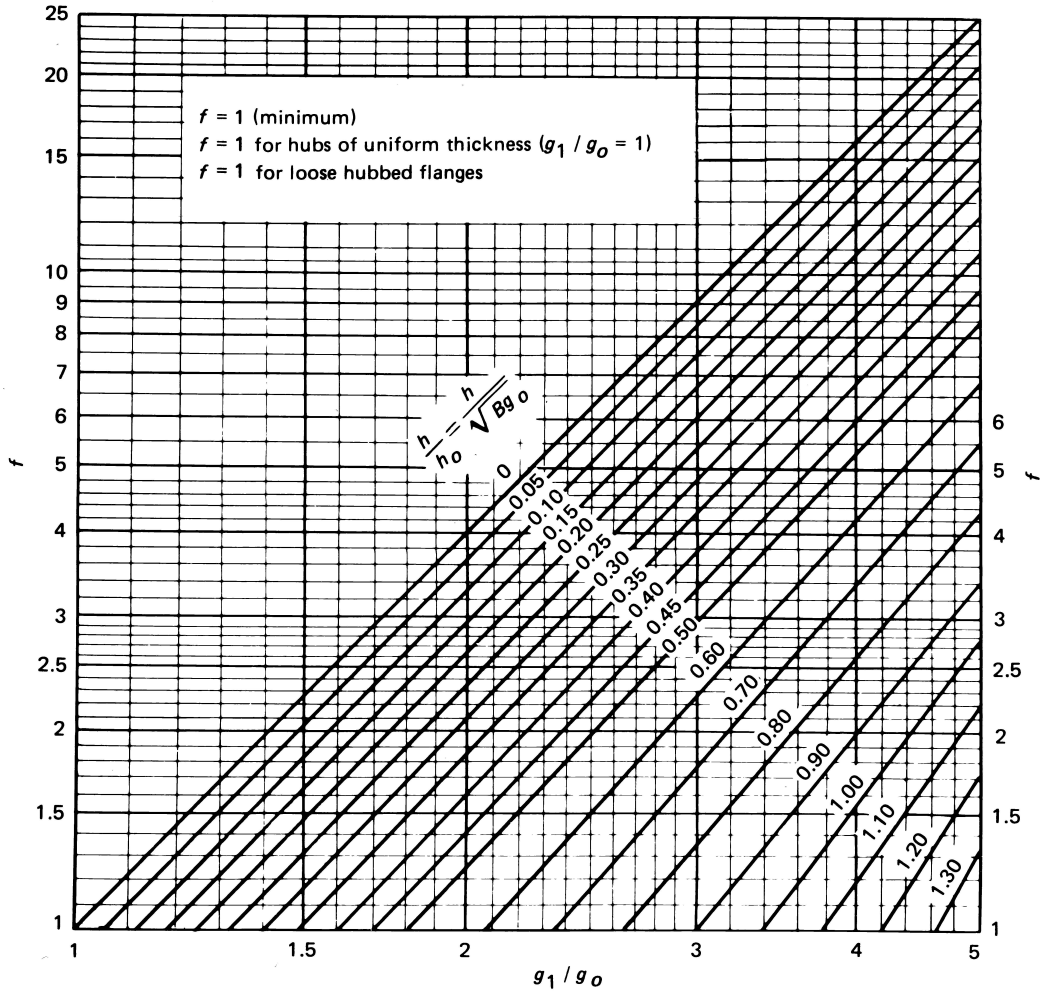
(b) Metallic Lip Type Seal



(c) "O" Ring Type Seal

GENERAL NOTE: $m = 0$

Figure G-300.1
Values of *f*
(Hub Stress Correction Factor)



G-400 BOLT LOADS

(a) General. During assembly of the clamp connection, the design bolt load W is resolved into an effective clamp preload W_c, which is a function of the clamp–hub taper angle ϕ and the friction angle μ. An appropriate friction angle should be established by the Manufacturer, based on test results for both assembly and operating conditions.

(b) Calculations. In the design of bolting for a clamp connection, complete calculations should be made for two separate and independent sets of conditions, which are defined as follows:

(1) The required bolt load for the operating conditions W_{m1} should be sufficient to resist the hydrostatic end force H_e exerted by the design pressure acting on the area bounded by the diameter of gasket reaction plus a gasket compressive load H_p which experience has shown to be sufficient to assure a tight joint. The minimum operating bolt load W_{m1} should be determined in accordance with eq. (1):

$$W_{m1} = \frac{2}{\pi}\left(H_e + H_p\right)\tan(\phi - \mu) \quad (1)$$

(2) Before a tight joint can be obtained, it is necessary to seat the gasket or joint-contact surface properly by applying a minimum initial load (under atmospheric temperature conditions without the presence of internal pressure), which is a function of the gasket material and the effective gasket area to be seated. The minimum initial bolt load required for gasket seating W_{m2} should be determined in accordance with eq. (2):

$$W_{m2} = \frac{2}{\pi}H_m\tan(\phi + \mu) \quad (2)$$

(3) In eq. (1)(1), credit for friction is allowed based on clamp connection geometry and experience, but the bolt load should not be less than that determined using a $\phi - \mu$ value of 5 deg. Friction is also considered in determining bolt loads by eq. (2)(2), but the μ factor used should not be less than 5 deg.

(c) Required Bolt Area. The total cross-sectional area of bolting A_m required should be the greater of the values for operating conditions A_{m1} and gasket seating conditions A_{m2}. Bolt bending in the assembly should be considered.

(d) Clamp Connection Design Bolt Load W. The bolt load used in the design of the clamp connection should be the value obtained from eqs. (3) and (4).

Operating conditions:

$$W = W_{m1} \tag{3}$$

Assembly conditions:

$$W = (A_m + A_b)S_a \tag{4}$$

Alternatively, if controlled bolting (e.g., torque controlled or bolt tensioning) techniques are to be used to assemble the clamp, the assembly design bolt load shall be taken as eq. (5):

$$W = 2A_mS_a \tag{5}$$

In addition, the Manufacturer shall provide the User with a copy of the bolting instructions that are to be used. It is recommended that the Manufacturer refer to ASME PCC-1, *Guidelines for Pressure Boundary Bolted Flange Joint Assembly*. It is cautioned that bolt loads in excess of those calculated by using eq. (5) may overstress the clamp.

G-500 LONGITUDINAL LOADS

The longitudinal clamp load H used in the design of the clamp connection should be the value obtained from eqs. (6) and (7).

Operating conditions:

$$H = H_e + H_p \tag{6}$$

Assembly conditions:

$$H = \frac{\pi W}{2\tan(\phi + \mu)} \tag{7}$$

[W is calculated in accordance with eq. G-400(d)(4).]

G-600 HUB MOMENTS

The moments used in determining hub stresses are the products of loads and moment arms illustrated in Figure G-100.1 and defined in G-300. In addition, reaction moments due to hub eccentricities and bearing pressure are considered.

For the operating condition, the design moment M_o is the sum of six individual moments: M_D, M_G, M_T, M_F, M_P, and M_R. The bolt load W used is that from eq. G-400(d)(3).

For assembly, the design moment M_o is based on the design bolt load of eq. G-400(d)(4):

$$M_o = \frac{\pi W(C - G)}{4\tan(\phi + \mu)}$$

G-700 CALCULATION OF HUB STRESSES

The stresses in the hub should be determined for both the operating and the assembly condition.

(a) The reaction moment M_H and the reaction shear Q are defined in G-300 and should be calculated at the hub neck for rotational moment M_o.

(b) Hub stresses should be calculated from the following equations:

(1) Hub longitudinal stress

$$S_1 = f\left(\frac{PB^2}{4g_1\left(B + g_1\right)} + \frac{6M_H}{\pi g_1^2\left(B + g_1\right)}\right)$$

(2) Hub Lamé hoop stress

$$S_2 = P\left(\frac{N_H^2 + B^2}{N_H^2 - B^2}\right)$$

(3) Hub longitudinal shear stress

$$S_3 = \frac{1.5H}{A_3}$$

(4) Hub radial shear stress

$$S_4 = \frac{1.5Q}{\pi g_1\left(B + g_1\right)}$$

G-800 CALCULATION OF CLAMP STRESSES

The stresses in the clamp should be determined for both the operating and the assembly conditions. Clamp stresses should be calculated from the following equations:

(a) Clamp longitudinal stress at clamp body inner diameter

$$S_5 = \frac{H}{A_5} + \frac{M_5(C_t - X_5)}{I_5}$$

(b) Clamp tangential stress at clamp body surface

$$S_6 = \frac{W}{2A_6} + \frac{M_6C_6}{I_6}$$

(c) Clamp lip shear stress

$$S_7 = \frac{1.5H}{A_7}$$

(d) Clamp lip bending stress

$$S_8 = \frac{6H\ell_m}{\pi C\left[\left(C_w - C_g\right)/2\right]^2}$$

(e) Clamp lug bending stress

$$S_9 = 3W\frac{L_a}{L_w L_h^2}$$

(f) Clamp lug shear stress

$$S_{10} = \frac{0.75\,W}{L_w L_h}$$

In addition, a bearing stress calculation should be made at the clamp-to-hub contact:

$$S_{11} = \frac{H}{\pi C(A_{or} - C_{ir})/2}$$

G-900 ALLOWABLE DESIGN STRESSES FOR CLAMP CONNECTIONS

Table G-900 gives the allowable stresses that are to be used with the equations of G-700 and G-800.

Table G-900
Allowable Design Stress for Clamp Connections

Stress Category	Allowable Stress
S_1	S_{YOH} or S_{YAH}
S_2	$S_{YOH}/1.5$
S_3	$0.6S_{YOH}$ or $0.6S_{YAH}$
S_4	$0.6S_{YOH}$ or $0.6S_{YAH}$
S_5	S_{YOC} or S_{YAC}
S_6	S_{YOC} or S_{YAC}
S_7	$0.6S_{YOC}$ or $0.6S_{YAC}$
S_8	$S_{YOC}/1.5$ or $S_{YAC}/1.5$
S_9	$S_{YOC}/1.5$ or $S_{YAC}/1.5$
S_{10}	$0.6S_{YOC}$ or $0.6S_{YAC}$
S_{11}	[Note (1)]

NOTE: (1) The lower of the yield stresses for the hub material (S_{YOH}, S_{YAH}) and clamp material (S_{YOC}, S_{YAC}).

NONMANDATORY APPENDIX H
OPENINGS AND THEIR REINFORCEMENT

H-100 SCOPE

The guidelines contained in the Appendix provide for a satisfactory design in the vicinity of openings in the pressure shell, under pressure loading only, on the basis of opening shape, area replacement, and its distribution. The requirements of Articles KD-2, KD-3, and KD-4 must also be satisfied. These guidelines do not include design requirements for piping loads that may be imposed on the nozzle and/or shell portion and that may be added to the pressure loadings.

These guidelines apply only to openings with integral reinforcement.

H-101 DIMENSIONS AND SHAPE OF OPENINGS

Openings may be circular, or elliptical, as results from the intersection of circular cylinders and circular vessels, provided

(a) the ratio of the diameter along the major axis to the diameter along the minor axis of the finished opening is 1.5 or less.

(b) the ratio $d/D_I \le 0.50$, where d is the largest inside diameter of the opening and D_I is the inside diameter of the vessel.

(c) the arc distance measured between the centerlines of adjacent nozzles along the inside surface of the vessel is not less than three times the sum of their inside radii for openings in a head, or along the longitudinal axis of a vessel is not less than two times the sum of their inside radii for openings along the circumference of a cylindrical vessel. When two nozzles in a cylindrical vessel are neither in a longitudinal line nor in a circumferential arc, their centerline distance along the inside surface of the vessel should be such that $\sqrt{(\ell_c/2)^2 + (\ell_\ell/3)^2}$ is not less than the sum of their inside radii, where ℓ_c is the component of the centerline distance in the circumferential direction and ℓ_ℓ is the component of the centerline distance in the longitudinal direction.

(d) reinforcement is provided around the edge of the opening in amount and distribution such that the area requirements for reinforcement are satisfied for all planes through the center of the opening and normal to the vessel surface as stipulated in H-120.

Some high pressure connections are shown in Figure H-101.

H-110 CIRCULAR OPENINGS NOT REQUIRING REINFORCEMENT

Circular openings need not be provided with reinforcement if all of the following requirements are satisfied:

(a) A single opening has a diameter not exceeding D_I $(0.077Y - 0.0725)$, or if there are two or more openings within any circle of diameter $0.887D_I\sqrt{Y^2 - 1}$, then the sum of the diameters of such unreinforced openings should not exceed D_I $(0.09624Y - 0.0906)$.

(b) No two unreinforced openings should have their centers closer to each other, measured on the inside of the vessel wall, than 1.5 times the sum of their diameters.

(c) No unreinforced opening should have its center closer than $0.887D_I\sqrt{Y^2 - 1}$ to the edge of a locally stressed area in the shell, where D_I is the inside diameter and Y is the cylinder diameter ratio at the location of the opening(s); locally stressed area means any area in the shell where the primary local membrane stress exceeds $0.73S_y$, but excluding those areas where such primary local membrane stress is due to an unreinforced opening.

H-120 REINFORCEMENT FOR OPENINGS IN SHELLS AND FORMED HEADS

(a) Design for Internal Pressure. The total cross-sectional area of reinforcement A required in any given plane for a vessel under internal pressure should be not less than

$$A = dt_rF \tag{1}$$

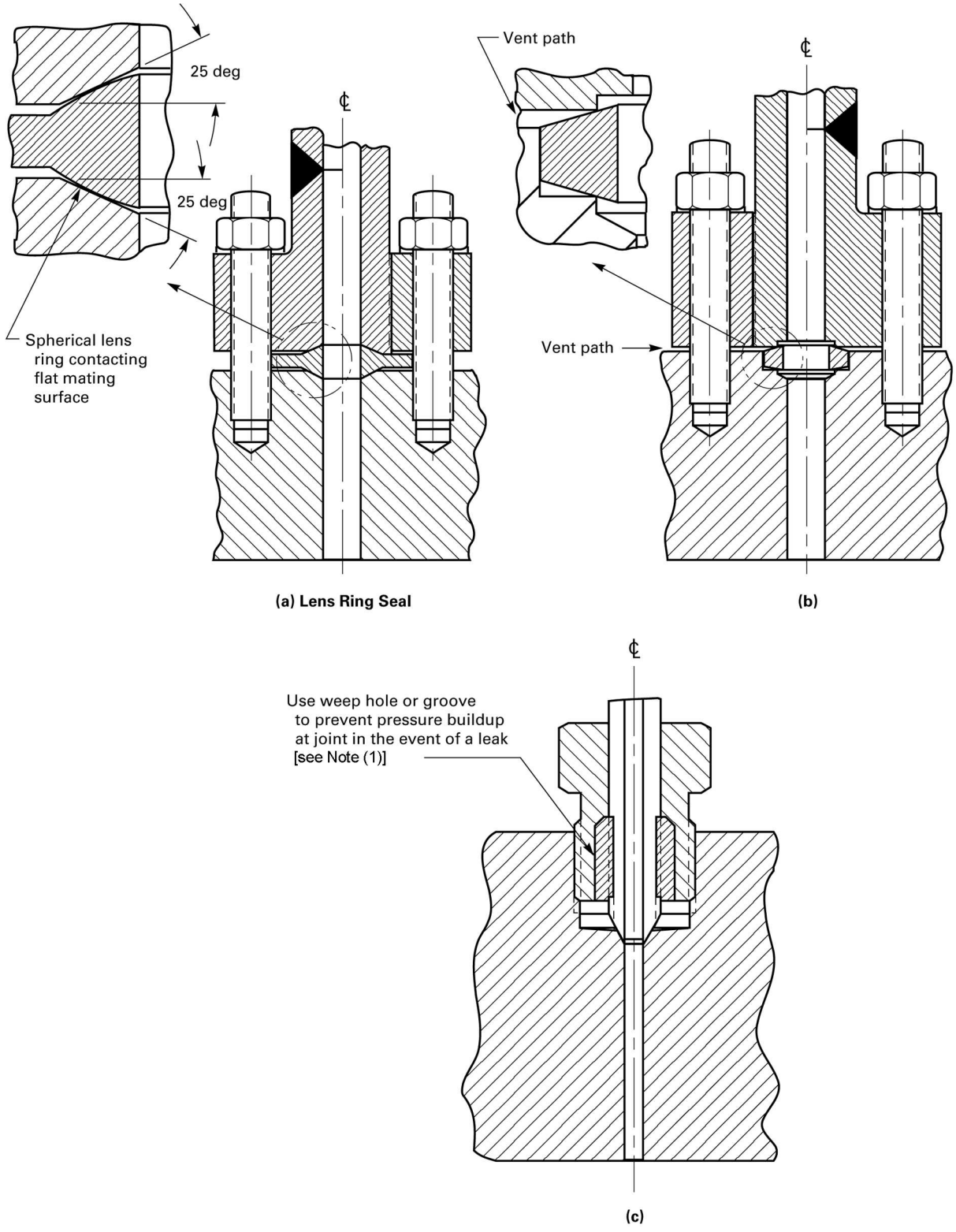
where

d = diameter in the given plane of the finished opening, in. (mm)

t_r = minimum thickness which meets the requirements of 9-210 in the absence of the opening, in. (mm)

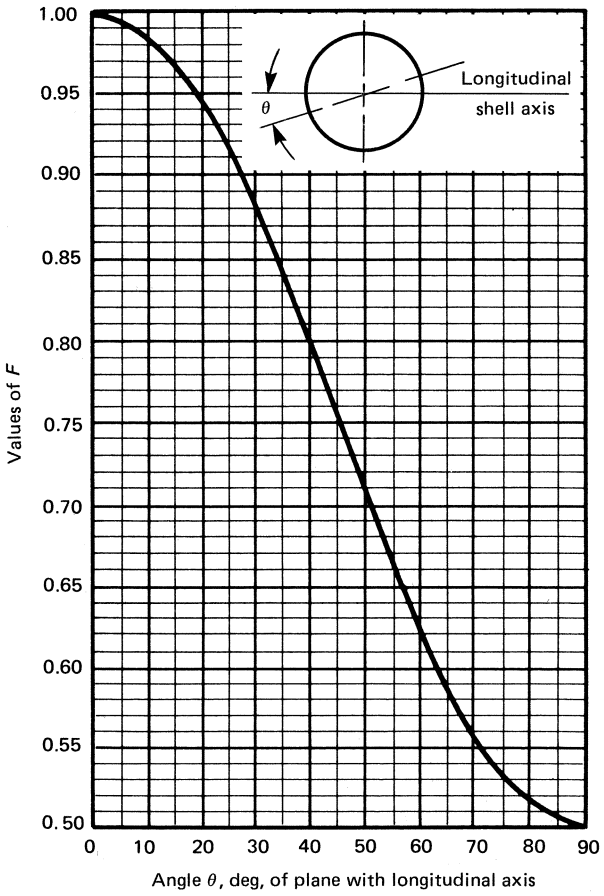
F = 1.00 when the plane under consideration is in the spherical portion of a head or when the given plane contains the longitudinal axis of a cylindrical shell. For other planes through a shell, use the value of F determined from Figure H-120.1.

Figure H-101
Straight Drill Connections for Thick-Walled Cylinders



NOTE: (1) See KD-661(a).

Figure H-120.1
Chart for Determining Value of *F*



(b) Design for External Pressure. The reinforcement requirements for openings in vessels subject to external pressure need be only 50% of that required in the preceding eq. (a)(1).

H-130 REINFORCEMENT FOR OPENINGS IN FLAT HEADS

Flat heads that have an opening with a diameter that does not exceed one-half of the head diameter should have a total cross-sectional area of reinforcement not less than that given by the equation

$$A = 0.5dt_r$$

where

d = diameter of the finished opening, in. (mm)
t_r = minimum thickness which meets the requirements of KD-640 in the absence of the opening, in. (mm)

H-140 LIMITS OF REINFORCEMENT

The boundaries of the cross-sectional area in any plane normal to the vessel wall and passing through the center of the opening within which metal should be located in order to have value as reinforcement are designated as the limits of reinforcement for that plane and are as described in H-141 and H-142.

H-141 BOUNDARY ALONG VESSEL WALL

Two requirements on the limits of reinforcement measured along the midsurface of the nominal wall thickness should be met as follows:

(a) 100% of the required reinforcement should be within a distance on each side of the axis of the opening equal to the greater of the following:

(1) the diameter of the finished opening in the corroded condition

(2) the radius of the finished opening in the corroded condition plus the thickness of the vessel wall plus the thickness of the nozzle wall

(b) Two-thirds of the required reinforcement should be within a distance on each side of the axis of the opening equal to the greater of the following:

(1) $r + 0.5\sqrt{R_m t}$, where R_m is the mean radius of shell or head, t is the nominal vessel wall thickness, and r is the radius of the finished opening in the corroded condition

(2) the radius of the finished opening in the corroded condition plus the thickness of the vessel wall plus the thickness of the nozzle wall

H-142 BOUNDARY NORMAL TO VESSEL WALL

The limits of reinforcement, measured normal to the vessel wall, should conform to the contour of the surface at a distance from each surface equal to the following limits:

(a) For Figure H-142, illustrations (a) and (b), the limit is the larger of $0.5\sqrt{r_m t_n} + K$ and $1.73x + 2.5t_p + K$, but this limit should not exceed either $2.5t$ or $L + 2.5t_p$, where

K = $0.73r_2$ when a transition radius r_2 is used and the smaller of the two legs when a fillet weld transition is used, in. (mm)
L = length along nozzle with thickness of t_n plus transition length, in. (mm)
r = inside radius of nozzle, in. (mm)
r_m = mean radius of nozzle, in. (mm)
= $r + 0.5t_n$
r_2 = transition radius between nozzle and vessel wall, in. (mm)
t = nominal vessel thickness, in. (mm)
t_n = nominal nozzle thickness, in. (mm)

t_p = nominal thickness of connecting pipe, in. (mm)
x = slope offset distance, in. (mm)
= $t_n - t_p$

(b) For Figure H-142, illustration (c):

(1) When 45 deg ≥ θ ≥ 30 deg, the limit is the larger of $0.5\sqrt{r_m t_n'}$ and $L' + 2.5t_p \le t$.

(2) When θ < 30 deg, the limit is the larger of $0.5\sqrt{r_m t_n'}$ and $1.73x + 2.5t_p \le 2.5t$, where

L' = length of tapered section along nozzle, in. (mm)
r = inside radius of nozzle, in. (mm)
r_m = $r + 0.5t_n'$
t_n' = $t_p + 0.667x$
θ = angle between vertical and slope (45 deg or less), deg

Other terms are given in (a).

(c) For Figure H-142, illustration (d), the limit is the larger of $0.5\sqrt{r_m t_n} + t_e$ and $2.5t_n + t_e \le 2.5t$. In no case can the thickness t_e used to establish the limit exceed $1.5t$ or $1.73W$, where

t_e = thickness of added reinforcing element, in. (mm)
W = width of added reinforcing element, in. (mm)

Other terms are given in (a).

H-150 METAL AVAILABLE FOR REINFORCEMENT

Metal may be counted as contributing to the area of reinforcement called for in H-120 and H-130 provided it lies within the area of reinforcement specified in H-140, and should be limited to material which meets the following requirements:

(a) metal forming a part of the vessel wall which is in excess of that required by the static design requirements of Article KD-2, and is exclusive of corrosion allowance

(b) similar metal in the nozzle wall, provided the nozzle is integral with the vessel wall or is joined to it by a full-penetration weld

(c) all reinforcement metal should be fully continuous with the shell, nozzle, or combination thereof

(d) the metal to be included as reinforcement under (b) and (c) should meet the following limit:

$$|(\alpha_r - \alpha_v)\Delta T| \le 0.0008$$

where

α_r = mean coefficient of the thermal expansion of reinforcing metal at design temperature, in./in. °F (mm/mm °C)
α_v = mean coefficient of thermal expansion of vessel metal at design temperature, in./in. °F (mm/mm °C)
ΔT = operating temperature range from 70°F (21°C) to the operating temperature, or the difference from the lowest operating temperature to the highest operating temperature, if greater

For designs exceeding this limit, no credit should be taken for reinforcing potentially available in the nozzle neck within the limits of reinforcement.

NOTE: It is likely that designs exceeding the limit in (d) will not meet the desired results of the required fatigue analysis.

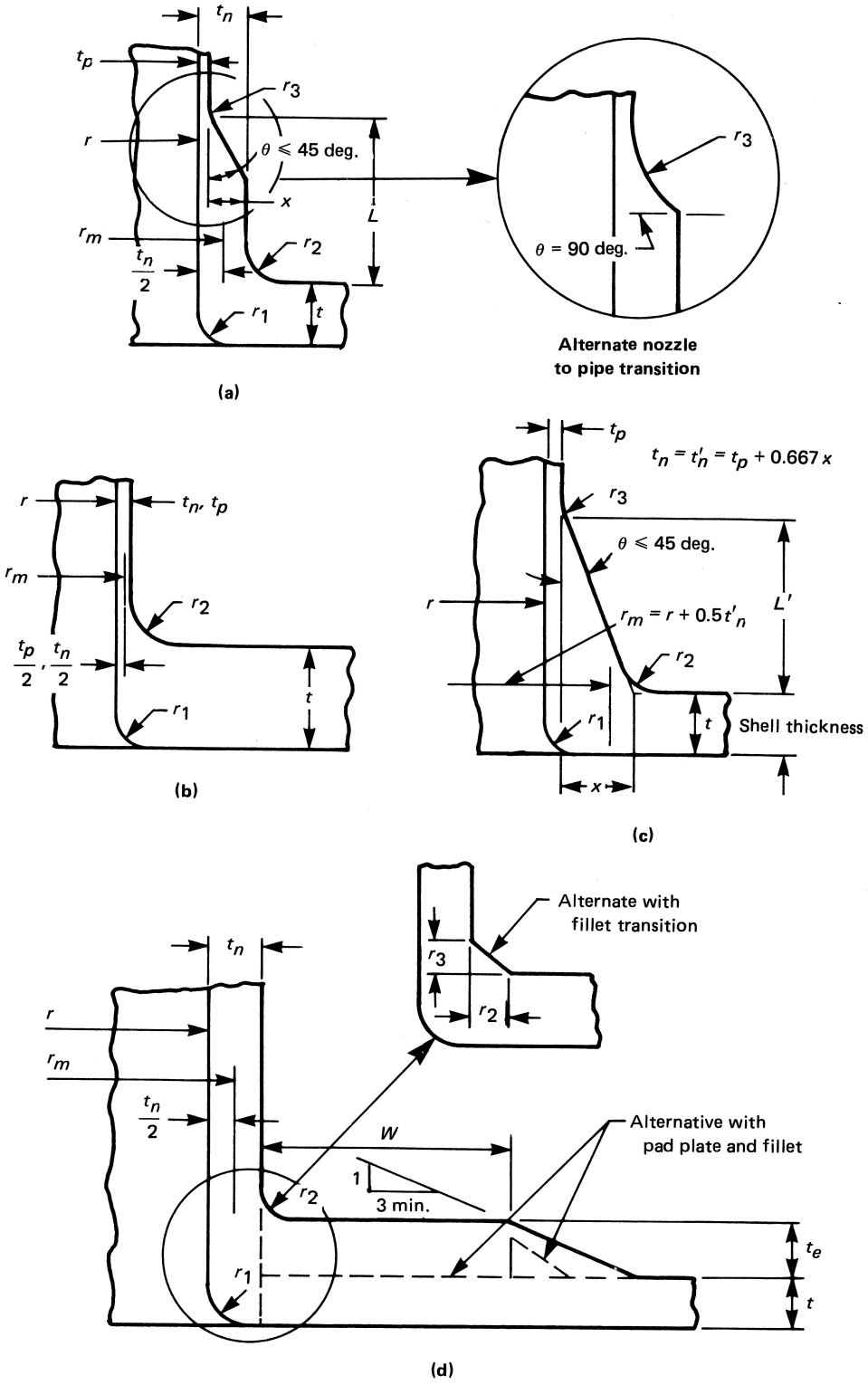
(e) metal available for reinforcement should not be considered as applying to more than one opening.

H-151 STRENGTH OF REINFORCEMENT MATERIAL

In no case should the yield strength of the nozzle material be less than 80% of the yield strength of the vessel wall at the design temperature.

If material with a lower yield strength is used, the area provided by such material should be increased in proportion to the inverse ratio of the yield strength of the nozzle and the vessel wall material. No reduction in the reinforcement requirement may be made if the nozzle material or weld metal has a yield strength higher than that of the material of the vessel wall. The strength of the material at the point under consideration should be used in fatigue analyses.

Figure H-142
Nozzle Nomenclature and Dimensions
(Depicts Configuration Only. See Article KD-11 for Details of Construction.)



NONMANDATORY APPENDIX I
GUIDANCE FOR THE USE OF U.S. CUSTOMARY AND SI UNITS IN THE ASME BOILER AND PRESSURE VESSEL CODE

I-100 USE OF UNITS IN EQUATIONS

The equations in this Division are suitable for use with either the U.S. Customary or the SI units provided in Table KG-150, or with the units provided in the nomenclatures associated with the equations. It is the responsibility of the individual and organization performing the calculations to ensure that appropriate units are used. Either U.S. Customary or SI units may be used as a consistent set. When necessary to convert from one system of units to another, the units shall be converted to at least three significant figures for use in calculations and other aspects of construction.

I-200 GUIDELINES USED TO DEVELOP SI EQUIVALENTS

The following guidelines were used to develop SI equivalents:

(a) SI units are placed in parentheses after the U.S. Customary units in the text.

(b) In general, separate SI tables are provided if interpolation is expected. The table designation (e.g., table number) is the same for both the U.S. Customary and SI tables, with the addition of suffix "M" to the designator for the SI table, if a separate table is provided. In the text, references to a table use only the primary table number (i.e., without the "M"). For some small tables, where interpolation is not required, SI units are placed in parentheses after the U.S. Customary unit.

(c) Separate SI versions of graphical information (charts) are provided, except that if both axes are dimensionless, a single figure (chart) is used.

(d) In most cases, conversions of units in the text were done using hard SI conversion practices, with some soft conversions on a case-by-case basis, as appropriate. This was implemented by rounding the SI values to the number of significant figures of implied precision in the existing U.S. Customary units. For example, 3,000 psi has an implied precision of one significant figure. Therefore, the conversion to SI units would typically be to 20 000 kPa. This is a difference of about 3% from the "exact" or soft conversion of 20 684.27 kPa. However, the precision of the conversion was determined by the Committee on a case-by-case basis. More significant digits were included in the SI equivalent if there was any question. The values of allowable stress in Section II, Part D generally include three significant figures.

(e) Minimum thickness and radius values that are expressed in fractions of an inch were generally converted according to the following table:

Fraction, in.	Proposed SI Conversion, mm	Difference, %
1/32	0.8	−0.8
3/64	1.2	−0.8
1/16	1.5	5.5
3/32	2.5	−5.0
1/8	3	5.5
5/32	4	−0.8
3/16	5	−5.0
7/32	5.5	1.0
1/4	6	5.5
5/16	8	−0.8
3/8	10	−5.0
7/16	11	1.0
1/2	13	−2.4
9/16	14	2.0
5/8	16	−0.8
11/16	17	2.6
3/4	19	0.3
7/8	22	1.0
1	25	1.6

(f) For nominal sizes that are in even increments of inches, even multiples of 25 mm were generally used. Intermediate values were interpolated rather than converting and rounding to the nearest mm. See examples in the following table. [Note that this table does not apply to nominal pipe sizes (NPS), which are covered below.]

Size, in.	Size, mm
1	25
1 1/8	29
1 1/4	32
1 1/2	38
2	50
2 1/4	57

Table continued

Size, in.	Size, mm
2½	64
3	75
3½	89
4	100
4½	114
5	125
6	150
8	200
12	300
18	450
20	500
24	600
36	900
40	1 000
54	1 350
60	1 500
72	1 800

Size or Length, ft	Size or Length, m
3	1
5	1.5
200	60

(g) For nominal pipe sizes, the following relationships were used:

U.S. Customary Practice	SI Practice	U.S. Customary Practice	SI Practice
NPS ⅛	DN 6	NPS 20	DN 500
NPS ¼	DN 8	NPS 22	DN 550
NPS ⅜	DN 10	NPS 24	DN 600
NPS ½	DN 15	NPS 26	DN 650
NPS ¾	DN 20	NPS 28	DN 700
NPS 1	DN 25	NPS 30	DN 750
NPS 1¼	DN 32	NPS 32	DN 800
NPS 1½	DN 40	NPS 34	DN 850
NPS 2	DN 50	NPS 36	DN 900
NPS 2½	DN 65	NPS 38	DN 950
NPS 3	DN 80	NPS 40	DN 1000
NPS 3½	DN 90	NPS 42	DN 1050
NPS 4	DN 100	NPS 44	DN 1100
NPS 5	DN 125	NPS 46	DN 1150
NPS 6	DN 150	NPS 48	DN 1200
NPS 8	DN 200	NPS 50	DN 1250
NPS 10	DN 250	NPS 52	DN 1300
NPS 12	DN 300	NPS 54	DN 1350
NPS 14	DN 350	NPS 56	DN 1400
NPS 16	DN 400	NPS 58	DN 1450
NPS 18	DN 450	NPS 60	DN 1500

(h) Areas in square inches ($in.^2$) were converted to square millimeters (mm^2), and areas in square feet (ft^2) were converted to square meters (m^2). See examples in the following table:

Area (U.S. Customary)	Area (SI)
1 $in.^2$	650 mm^2
6 $in.^2$	4 000 mm^2
10 $in.^2$	6 500 mm^2
5 ft^2	0.5 m^2

(i) Volumes in cubic inches ($in.^3$) were converted to cubic millimeters (mm^3), and volumes in cubic feet (ft^3) were converted to cubic meters (m^3). See examples in the following table:

Volume (U.S. Customary)	Volume (SI)
1 $in.^3$	16 000 mm^3
6 $in.^3$	100 000 mm^3
10 $in.^3$	160 000 mm^3
5 ft^3	0.14 m^3

(j) Although the pressure should always be in MPa for calculations, there are cases where other units are used in the text. For example, kPa is used for small pressures. Also, rounding was to one significant figure (two at the most) in most cases. See examples in the following table. (Note that 14.7 psi converts to 101 kPa, while 15 psi converts to 100 kPa. While this may seem at first glance to be an anomaly, it is consistent with the rounding philosophy.)

Pressure (U.S. Customary)	Pressure (SI)
0.5 psi	3 kPa
2 psi	15 kPa
3 psi	20 kPa
10 psi	70 kPa
14.7 psi	101 kPa
15 psi	100 kPa
30 psi	200 kPa
50 psi	350 kPa
100 psi	700 kPa
150 psi	1 MPa
200 psi	1.5 MPa
250 psi	1.7 MPa
300 psi	2 MPa
350 psi	2.5 MPa
400 psi	3 MPa
500 psi	3.5 MPa
600 psi	4 MPa
1,200 psi	8 MPa
1,500 psi	10 MPa

(k) Material properties that are expressed in psi or ksi (e.g., allowable stress, yield and tensile strength, elastic modulus) were generally converted to MPa to three significant figures. See example in the following table:

Strength (U.S. Customary)	Strength (SI)
95,000 psi	655 MPa

(l) In most cases, temperatures (e.g., for PWHT) were rounded to the nearest 5°C. Depending on the implied precision of the temperature, some were rounded to the nearest 1°C or 10°C or even 25°C. Temperatures colder than 0°F (negative values) were generally rounded to the nearest 1°C. The examples in the table below were created by rounding to the nearest 5°C, with one exception:

Temperature, °F	Temperature, °C
70	20
100	38
120	50
150	65
200	95
250	120
300	150
350	175
400	205
450	230
500	260
550	290
600	315
650	345
700	370
750	400
800	425
850	455
900	480
925	495
950	510
1,000	540
1,050	565
1,100	595
1,150	620
1,200	650
1,250	675
1,800	980

Table continued

Temperature, °F	Temperature, °C
1,900	1 040
2,000	1 095
2,050	1 120

I-300 SOFT CONVERSION FACTORS (25)

The following table of "soft" conversion factors is provided for convenience. Multiply the U.S. Customary value by the factor given to obtain the SI value. Similarly, divide the SI value by the factor given to obtain the U.S. Customary value. In most cases it is appropriate to round the answer to three significant figures.

U.S. Customary	SI	Factor	Notes
in.	mm	25.4	...
ft	m	0.3048	...
$in.^2$	mm^2	645.16	...
ft^2	m^2	0.09290304	...
$in.^3$	mm^3	16,387.064	...
ft^3	m^3	0.02831685	...
U.S. gal.	m^3	0.003785412	...
U.S. gal.	liters	3.785412	...
psi	MPa (N/mm^2)	0.0068948	Used exclusively in equations
psi	kPa	6.894757	Used only in text and for nameplate
psi	bar	0.06894757	...
ft-lbf	J	1.355818	...
°F	°C	$^5/_9 \times (°F - 32)$	Not for temperature difference
°F	°C	$^5/_9$	For temperature differences only
°R	K	$^5/_9$	Absolute temperature
lbm	kg	0.4535924	...
lbf	N	4.448222	...
in.-lbf	N·mm	112.98484	Use exclusively in equations
ft-lbf	N·m	1.3558181	Use only in text
$ksi\sqrt{in.}$	$MPa\sqrt{m}$	1.0988434	...
Btu/hr	W	0.2930711	Use for boiler rating and heat transfer
lb/ft^3	kg/m^3	16.018463	...

NONMANDATORY APPENDIX J
STRESS CONCENTRATION FACTORS FOR CROSS-BORES IN CLOSED-END CYLINDERS AND SQUARE BLOCKS

J-100 SCOPE

The guidelines in this Appendix provide a method for calculating the linear elastic stresses at the intersection of cross-bored holes at the bore of a pressure vessel remote from discontinuities. Note that the internal pressure is acting inside the entire cross-bore.

The use of these factors are appropriate only when the openings are perpendicular to the axis of the main bore in either the block or the cylinder, when their axes intersect and the opening is remote from the ends of the cylinder, block, or other discontinuities. The factors are appropriate for sharp-edged holes or holes that have a smooth blend radius less than one-fourth the diameter of the cross-bore.

Nonmandatory Appendix H shall be used in conjunction with this Appendix to ensure adequate reinforcement of openings.

J-110 METHODOLOGY

The tangential stress and stress intensity found at an opening in cylinders and square-cross-section blocks (see Figure J-110-1) should be found by multiplying the stresses found with 9-300, eq. (9-300.1) or 9-300, eq. (9-300.2) by the stress concentration factor, K_T (see Figure J-110-1).

D_O = outer diameter of vessel or width across square section of block
D_I = inner diameter of vessel or block
D_H = diameter of cross-bore opening
K_T = tangential stress concentration factor (see Figures J-110-2 and J-110-3; and Tables J-110-2 and J-110-3)

Figure J-110-1
Geometries of Square Blocks and Cylinders With Cross-Bores

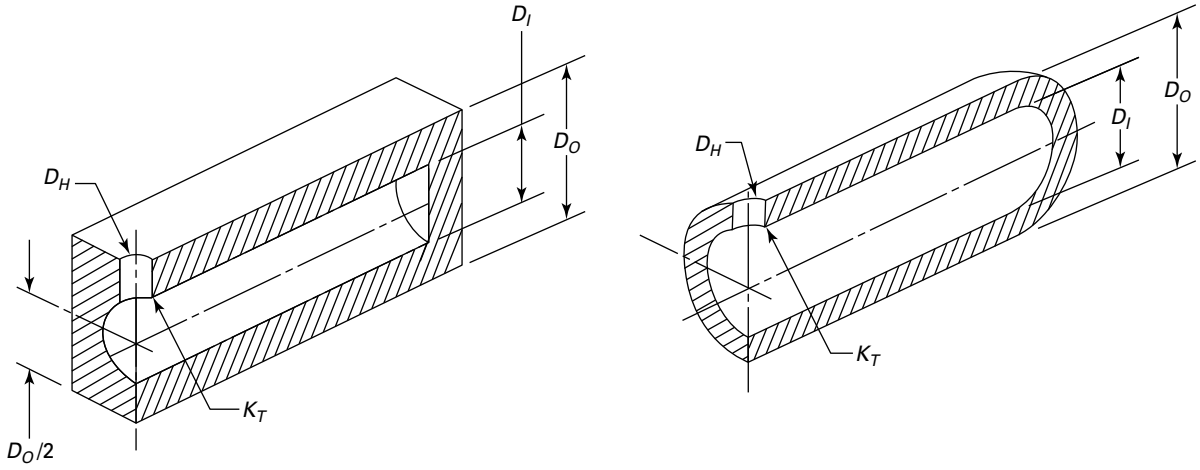


Figure J-110-2
Tangential Stress Concentration Factors for Openings in Cylinders

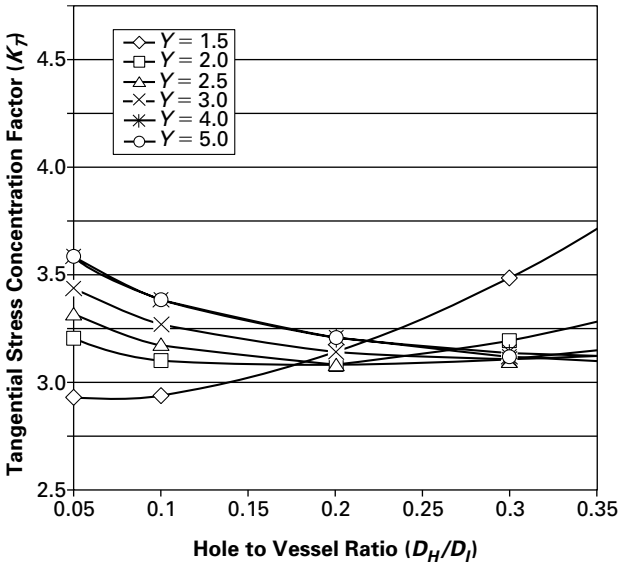


Figure J-110-3
Tangential Stress Concentration Factors for Openings in Square Cross-Section Blocks

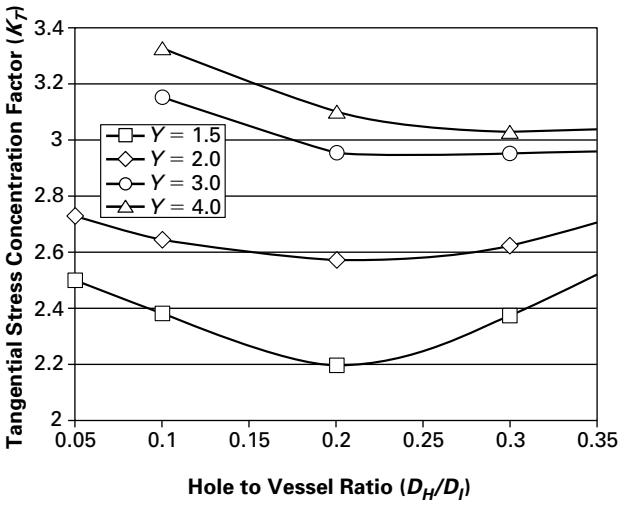


Table J-110-2
Tangential Stress Concentration Factors for Openings in Cylinders (Tabulated Values From Figure J-110-2)

	D_H/D_I				
K_T, Y	0.05	0.10	0.20	0.30	0.35
1.5	2.93	2.94	3.15	3.49	3.74
2.0	3.21	3.11	3.09	3.20	3.295
2.5	3.33	3.18	3.10	3.12	3.165
3.0	3.44	3.28	3.15	3.12	3.135
4.0	3.58	3.39	3.22	3.14	3.125
5.0	3.59	3.39	3.21	3.12	3.1

GENERAL NOTES:
(a) Values in tables may be interpolated.
(b) Equation for the stress concentration factors:
Figure J-110-2 – Tangential Stress Concentration Factor in Cylinders

$$K_T = A + B\ln\left(\frac{D_H}{D_I}\right) + C\frac{1}{\ln\left(D_H / D_I\right)}$$

where

$$A = 0.279 + 28.6\left(\frac{1}{Y}\right) - 119\left(\frac{1}{Y}\right)^2 + 195\left(\frac{1}{Y}\right)^3 - 116\left(\frac{1}{Y}\right)^4$$

$$B = -0.310$$

$$C = -1.63 + 18.7\left(\frac{1}{Y}\right) - 79.7\left(\frac{1}{Y}\right)^2 + 129\left(\frac{1}{Y}\right)^3 - 81.4\left(\frac{1}{Y}\right)^4$$

Table J-110-3
Tangential Stress Concentration Factors for Openings in Square Cross-Section Blocks (Tabulated Values From Figure J-110-3)

	D_H/D_I				
K_T, Y	0.05	0.10	0.20	0.30	0.35
1.5	2.50	2.38	2.20	2.38	2.53
2.0	2.73	2.64	2.57	2.62	2.71
3.0	...	3.15	2.96	2.95	2.96
4.0	...	3.33	3.10	3.03	3.04

GENERAL NOTES:
(a) Values in tables may be interpolated.
(b) Equation for the stress concentration factors:
Figure J-110-3 – Tangential Stress Concentration Factor in Square Cross-Section Blocks

$$K_T = A + B\ln\left(\frac{D_H}{D_I}\right) + C\frac{1}{\ln\left(D_H / D_I\right)}$$

where

$$A = 2.83 - 12.1\left(\frac{1}{Y}\right)^2 + 13.7\left(\frac{1}{e^Y}\right)$$

$$B = -0.202 - 5.74\left(\frac{1}{Y}\right)^2 + 10.1\left(\frac{1}{e^Y}\right)$$

$$C = -0.0103 - 6.90\left(\frac{1}{Y}\right)^2 + 7.04\left(\frac{1}{e^Y}\right)$$

NONMANDATORY APPENDIX K
FATIGUE AND FRACTURE ASSESSMENT OF IMPULSIVELY LOADED VESSELS

K-100 SCOPE

This Appendix describes a means of carrying out a fatigue and fracture analysis of impulsively loaded vessels as required by KD-240(g).

K-110 NOMENCLATURE

a = crack depth, in. (m)
$2c$ = crack length, in. (m)
C = Paris Law constant, (ksi-in.$^{1/2}$)^m [(MPa-m$^{1/2}$)^m]
K_I = stress intensity factor, ksi-in.$^{1/2}$ (MPa-m$^{1/2}$)
$\dot{K}$ = stress intensity factor rate, ksi-in.$^{1/2}$/s (MPa-m$^{1/2}$/s)
K_{Ic} = transition fracture toughness,[18] ksi-in.$^{1/2}$ (MPa-m$^{1/2}$)
K_{Jc} = upper shelf fracture toughness, [18] ksi-in.$^{1/2}$ (MPa-m$^{1/2}$)
Lr = reference stress load ratio, nondimensional
m = index in Paris crack law, nondimensional
MDMT = minimum design metal temperature, °F (°C)
S_u = ultimate strength, ksi (MPa)
S_y = yield strength, ksi (MPa)
t = wall thickness, in. (m)
T_o = reference temperature for Master Curve, °F (°C) (obtained according to ASTM E1921)
ΔT_M = extent that MDMT is above upper shelf temperature, °F (°C)
ΔT_{SR} = temperature shift due to strain rate, °F (°C)
δ = damping decay constant, nondimensional
σ = stress, ksi (MPa)
$\dot{\sigma}$ = stress rate of change, ksi/sec (MPa/s)
σ_b = bending stress, ksi (MPa)
σ_m = membrane stress, ksi (MPa)

K-200 ANALYSIS

(a) This analysis determines a pair of impulsive membrane and bending stresses that can be used conservatively to assess fracture at the section. Determine the in-plane principal components of the stress-time histories at the surface points of the section of interest and determine the absolute greatest of the components to obtain a new surface stress time history, retaining the components original sign. For example, if at one surface and at one time the components are 10 and −15, as |−15|> |10| use −15 in the new surface time history. Assume the stresses across any section are linear and obtain the resulting membrane and bending histories from the new surface values at all times. Determine the largest tensile value of the membrane stress history σ_m and the largest tensile value of the new surface stress histories on the inner and outer surfaces, σ_t, and take the absolute value of $\sigma_t - \sigma_m$ as a conservative value of maximum bending stress σ_b for fracture analysis. This approach may be very conservative at local surface stress concentrations.

(b) Select a given crack size of depth a, based upon the detection limits of the nondestructive examinations methods used, with an aspect ratio as given in KD-411 for the geometry at the section, in a section thickness of t, and apply a stress distribution given by

$$\sigma = (\sigma_m + \sigma_b) + (- 2\sigma_b)(a/t) \quad (1)$$

(c) Use API-579-1/ASME FFS-1 to determine the stress intensity factor, K_I. For semi-elliptic surface cracks, obtain two values, one at the surface and one at maximum depth. The largest of these values should be selected.

(d) Evaluate any steady pressure stress also applied to the section, which may have membrance and bending components, and use API-579-1/ASME FFS-1 to determine the stress intensity factor and the references stress load ratio Lr^P for these stresses.

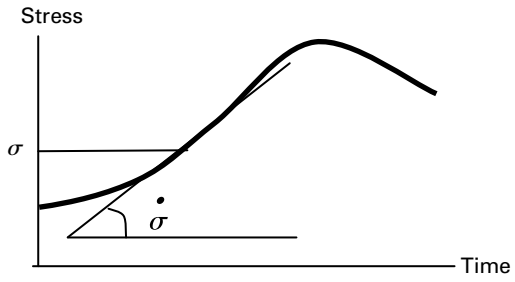
(e) Determine the the upper shelf fracture toughness, K_{Jc}.

(f) For ferritic steels, determine the stress intensity factor rate of change, $\dot{K}$, and the Master Curve Reference Temperature, T_o for the material. $\dot{K}$ can be determined from the stress rate of change with time, $\dot{\sigma}$, when the stress and stress intensity factor are known, from eq. (2). See Figure K-200-1.

$$\dot{K} = K\,\dot{\sigma}/\sigma \quad (2)$$

The fracture toughness transition shift due to high strain rate can be obtained from eqs. (3) through (6).

Figure K-200-1
Stress History



$$\Delta T_{SR} = \frac{(T_o + 460)\ln(1.1\,\dot{K})}{\Gamma - \ln(1.1\,\dot{K})} \text{ (°F, ksi-in.}^{1/2}\text{ s}^{-1}\text{ units)} \quad (3)$$

where

$$\Gamma = 9.8 \exp\left[\left(\frac{T_o + 460}{342}\right)^{1.66} + \left(\frac{S_y}{105}\right)^{1.09}\right] \text{ (°F, ksi units)} \quad (4)$$

or

$$\Delta T_{SR} = \frac{(T_o + 273)\ln(\dot{K})}{\Gamma - \ln(\dot{K})} \text{ (°C, MPa-m}^{1/2}\text{s}^{-1}\text{ units)} \quad (5)$$

where

$$\Gamma = 9.9 \exp\left[\left(\frac{T_o + 273}{190}\right)^{1.66} + \left(\frac{S_y}{722}\right)^{1.09}\right] \quad (6)$$

(°C, MPa units)

(g) For ferritic steels, determine the extent to which the material is on the upper shelf at low strain rates. See Figure K-200-2.

$$\Delta T_M = \text{MDMT} - \frac{\ln\left(\frac{K_{Jc} - 22.9}{33.3}\right)}{0.01055} - T_o \text{ (°F, ksi-in.}^{1/2}\text{ units)} \quad (7)$$

$$\Delta T_M = \text{MDMT} - \frac{\ln\left(\frac{K_{Jc} - 25.2}{36.6}\right)}{0.019} - T_o \text{ (°C, MPa-m}^{1/2}\text{units)} \quad (8)$$

where MDMT is the minimum design metal temperature.

The fracture toughness $K_{Ic} = K_{Jc}$ if $\Delta T_M > \Delta T_{SR}$ otherwise

$$K_{Ic} = 22.9 + 33.3 \exp\left[0.0106\,(\text{MDMT} - T_o - \Delta T_{SR})\right] \text{ (°F, ksi-in.}^{1/2}\text{ units)} \quad (9)$$

$$K_{Ic} = 25.2 + 36.6 \exp\left[0.019\,(\text{MDMT} - T_o - \Delta T_{SR})\right] \text{ (°C, MPa-m}^{1/2}\text{ units)} \quad (10)$$

(h) For austenitic steels, $K_{Ic} = K_{Jc}$

(i) Use the procedures in API-579-1/ASME FFS-1, Part 9 with partial safety factors set at unity, treating the dynamic stress as secondary and the steady quasi-static pressure stress as primary to obtain a point on the Failure Assessment Diagram (FAD), and adjust the crack size, and repeat K-110(c) to (g) until the point lies on the FAD line, when a is the critical size.

(j) Fatigue crack size a_{i+1} after all cycles of one impulsive load is obtained from

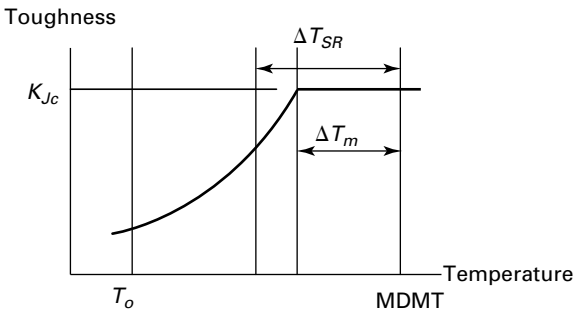
$$a_{i+1} = a_i\left[1 + \left(1 - \frac{m}{2}\right)\frac{C(1.2\,K_I)^m}{m\,\delta\,a_i}\right]^{\frac{2}{2-m}} \quad (11)$$

where a_i is the starting crack size, C and m are the Paris Law constants given in Table KD-430 (Table KD-430M), is the decay constant taken as 4% unless experimental data indicates otherwise, and K_I is the stress intensity factor for the crack size a_i and the stress given in (b). This equation assumes that the cycles have a range of $\pm K_I$ and incorporates the f (R_K) values in D-500. The equation is used starting with the crack size at the limit of detection and repeated until the crack reaches the number of design cycles defined as the lesser of

(1) the number of cycles corresponding to one-half the number of cycles required to propagate a flaw from the limit of detection to the critical crack length, or

(2) the number of cycles to propagate a crack from the limit of detection to either one-quarter of the critical depth or one-quarter of the wall thickness, whichever occurs earlier

Figure K-200-2
Toughness Temperature Curve



NONMANDATORY APPENDIX L
LINEARIZATION OF STRESS RESULTS FOR STRESS CLASSIFICATION

Refer to ASME Section VIII, Division 2, Annex 5-A.

ENDNOTES

1 It is acknowledged that a single Professional Engineer may not have the expertise to certify all aspects of the User's Design Specification or the Manufacturer's Design Report. Accordingly, more than one Professional Engineer may certify parts of the User's Design Specification or the Manufacturer's Design Report. Each Professional Engineer shall clearly indicate on the applicable report the area of responsibility assumed for certification of that report. In addition, one of the Professional Engineers shall certify that all elements required by this Division are included in the report.

2 The Designer is cautioned that fine threads may cause assembly problems and possible loss of engagement because of thermal expansion and dilation due to loading.

3 The prior deposition of weld metal to provide a boss for the butt weld is permissible provided it is examined for soundness by suitable nondestructive examination. The Manufacturer shall also give consideration to heat treatment of the buildup.

4 One test specimen may represent a group of forgings, provided they are of the same design, are from the same heat of material, and are forged in the same manner.

5 Because of the different coefficients of thermal expansion of dissimilar metals, caution should be exercised in design and construction under provisions of these paragraphs in order to avoid difficulties in service under extreme temperature conditions or with unusual restraint of parts such as may occur at points of stress concentration.

6 Postweld heat treatment temperatures may be in the carbide precipitation range for unstabilized austenitic chromium–nickel steel, as well as within the range where a sigma phase may form. Improper treatment could result in material of inferior physical properties and inferior corrosion resistance and could result in the ultimate failure of the vessel.

7 Additional postweld heat treatment requirements may result from the requirements of Article KT-2.

8 Other hardness testing methods may be used and converted to Brinell numbers by means of the table in ASTM E140.

9 Layer wash is defined as the indications resulting from slight weld penetration at the layer interfaces.

10 A *temper bead welding technique* is when additional weld beads are deposited after completion of the main weld for tempering purposes. These additional beads are deposited only on previous beads without making contact with the base metal, resulting in an over-flush condition. The additional beads are then removed by grinding or other mechanical means.

11 The direction of ultrasonic examinations referenced is the direction of sound propagation.

12 *Communicating chambers* are defined as appurtenances to the vessel which intersect the shell or heads of a vessel and form an integral part of the pressure-containing enclosure, e.g., sumps.

13 *Side plates* of a flat-sided vessel are defined as any of the flat plates forming an integral part of the pressure-containing enclosure.

14 To decrease the pressure energy of the fluid during hydrostatic test, filler bars may be inserted into vessels. Safety precautions should be scaled according to the test location, fluid properties, and the pressure energy contained in the vessel under test.

15 The complexity of the work includes factors such as design simplicity versus complexity, the types of materials and welding procedures used, the thickness of materials, the types of nondestructive examinations applied, and whether heat treatments are applied.

16 The size and complexity of the organization includes factors such as the number of employees, the experience level of employees, the number of Code items produced, and whether the factors defining the complexity of the work cover a wide or narrow range.

17 In calculating I_{5b} and I_{6b} the local moment of inertia contribution can often be ignored.

18 This usage of nomenclature only applies to this Appendix; these terms have other definitions elsewhere.

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