v = Poisson's ratio
v_1 = Poisson's ratio for inner layer
v_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_tt = 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 temperature 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:

$$ P_I = \frac{\delta}{D_I} $$

where

$$ A = \frac{1}{E_1} \left( \frac{D_2^4}{D_2^2 - D_1^2} - \frac{1}{E_0} \left( \frac{D_2^2 + D_0^2}{D_2^2 - D_0^2} + \gamma_0 \right) \right) $$

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 ≤ D ≤ D_O, are then calculated from eqs. (1) and (2):

$$ \sigma_{rr} = -\frac{P_I}{\delta} \left( 1 + \frac{D_1^2}{D^2} \right) $$

(1)

$$ \sigma_{rr} = -\frac{P_I}{\delta} \left( 1 - \frac{D_1^2}{D^2} \right) $$

(2)

and in the outer layer, D_I ≤ D ≤ D_O, from eqs. (3) and (4):

$$ \sigma_{rr} = \frac{P_O}{\delta} \left( 1 + \frac{D_0^2}{D^2} \right) $$

(3)

$$ \sigma_{rr} = \frac{P_O}{\delta} \left( 1 - \frac{D_0^2}{D^2} \right) $$

(4)

where

$$ \gamma_I = D_{II} / D_I $$

$$ \gamma_0 = D_{II} / D_O $$
Figure KD-830.4
Some Acceptable Flanges for Layered Shells

Legend:
$t_2 = \text{thickness of layered shell}$

3:1 taper min.

3:1 taper min.

3:1 taper min.
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Figure KD-830.5
Some Acceptable Welded Joints of Layered-to-Layered and Layered-to-Solid Sections

(a) Backing strip [Note (1)]
(b) Tack weld [Note (1)]
(c) Buttered weld

(d) Insert
Dummy layer

(e) Backing strip [Note (1)]
Tack weld [Note (1)]

(f) Butt Girth Welds

NOTE:
(1) Shall be removed after welding.

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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-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 gauges are used, a minimum of four gauges 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 or B weld joints that attach a layered section to a solid section shall be Type No. 1 butt joints. See Figure KD-830.6 for some acceptable configurations.

(g) Category B weld joints that attach a layered section to a layered section shall either be Type No. 1 butt joints or be in an offset pattern such that the centers of the adjacent weld joints are separated by a minimum of five times the layer thickness to be joined.

The offset pattern circumferential welds as shown in Figure KD-830.5 (d), (e) and (f) and circumferential weld using an insert as shown in Figure KD-830.5 (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 five times the layer thickness to be joined.

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 ¼ in. (6 mm) diameter or larger. Holes may be drilled radially through the multiple layers or may be staggered in individual layer plates. All vent holes shall not be obstructed. If a monitoring system is used, it shall be designed to prevent buildup 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.

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.

KF-825.2 Category A Weld Joints in Layers.

(a) Category A joints in layers ¾ in. (6 mm) through ½ in. (8 mm) in thickness welded to the previous surface shall be examined for 100% of their length in accordance with Article KE-3 by the magnetic particle or liquid penetrant method only.

(b) Category A joints in layers over ¾ 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.
Figure KF-823(a)
Solid-to-Layered and Layered-to-Layered Test Plates

Clamp layered stack for hold down during welding. Number and location of clamps is at discretion of fabricator.

These items are required at layered portions of test plates only—typical

After specimen location is laid out, the outer edges of layered stack shall be welded together in this location in order to prevent layers from separating.

(a) Plan-View of Solid-to-Layered and Layered-to-Layered Test Plates

Removable backing strip (optional)

(b) Layered-to-Solid Test Plate

Removable backing strip (optional)

(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.
(b) It is recognized that layer wash 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 standards in KE-332 Radiographic Acceptance Standard.
penetrant 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.**

(a) All weld metal buildup in solid wall sections in layered transitions shall be examined over the full surface of the deposit by either a magnetic particle method or by a liquid penetrant 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.** The random magnetic particle examinations or liquid penetrant examinations required by KF-825.3(a), and the ultrasonic examinations required by KF-825.3(b), shall be performed as follows:

(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 his own 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
Figure KF-625.4
Indications of Layer Wash

Judged in accordance with KE-332

Typical indication of layer wash

(shall not exceed acceptance criteria standards in KE-332.)

Layered section

Solid wall section
Delete

Figure KF-825.4(b)
Angled Radiographic Technique for Detecting Layer Wash

- X-Ray film
- Fusion line
- Possible superimposed condition (indication)
- Source
- Approximate location of radiation source for angle shot

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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

(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 nonrelevan. 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 count 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 \( h \) given by eq. (1) or \( \frac{1}{16} \) in. (5 mm), whichever is less:

\[
h = 0.55 \left( 2.5 - \frac{P}{0.675 R_g} \right) \frac{0.675 R_g}{E} \tag{1}
\]

where

\( E \) = modulus of elasticity, ksi (MPa)
\( h \) = gap between any two layers, in. (mm)
\( P \) = design pressure, ksi (MPa)
\( R_g \) = outside radius of layer above which the gap is located, in. (mm)
\( S_y \) = yield stress at design temperature, ksi (MPa)

(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. (2):

\[
F = 0.109 \frac{bh}{R_g^2} \tag{2}
\]

where

\( b \) = length of gap, in. (mm)
\( F \) = gap value (dimensionless)
\( h \) = gap between any two layers, in. (mm)

---

**Figure KF-826**

Gap Area Between Layers

Legend:

- \( h \) = radial gap, in. (mm)
- \( b \) = arc length of relevant radial gap, in. (mm)
- \( R_g \) = radius of vessel at gap, in. (mm)
- \( t \) = layer thickness, in. (mm)
- \( A_g \) = area of gap (approx.) = \( \frac{1}{2} h b \), in.² (mm²)

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\( R_g \) = outside radius of layer above which the gap is located, in. (mm)

(3) The total sum of the values of \( F \) calculated above shall not exceed the value \( F_f \) calculated by eq. (3):

\[
F_f = \frac{1 - \nu^2}{E} \left( 1.675 \sigma_y - \frac{2PG}{R_0 - R_f} \right)
\]

where

- \( E \) = modulus of elasticity, ksi (MPa)
- \( P \) = design pressure, ksi (MPa)
- \( R_i \) = inside radius of vessel, in. (mm)
- \( R_o \) = outside radius of vessel, in. (mm)
- \( \sigma_y \) = yield stress at design temperature, ksi (MPa)
- \( \nu \) = Poisson’s ratio

(4) The gap area, \( A_{gap} \), 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.

(6) 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 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 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.

(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-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.