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# PV Newsletter

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## *Low Temperature Operation*

The major concern for low temperature pressure vessels is brittle-fracture phenomenon which can be a cause for vessel failure. Many metals lose their ductility and toughness; they become susceptible to brittle fracture as the metal temperature decreases. At normal or high temperatures, a warning is normally given by plastic deformation (bulging, stretching or leaking) as signs of potential vessel failure. However, under low temperature conditions, no such warnings of plastic deformation are given. Unfortunately, an abrupt fracture can cause a catastrophic event.

Only materials that have been impact tested to ensure metal toughness at or above a specified metal temperature should be used. However, certain paragraphs in ASME Section VIII, Div. 1 applying to low temperature vessels indicate when impact testing may not be required for a pressure vessel component (impact test exemptions). In general, four main factors, in combination, can cause brittle fracture of steel vessels. These factors are represented in the form of “brittle facture square” as shown in Figure 1 below. The factors that contribute to the brittle fracture of carbon or low alloy steel pressure vessels are briefly discussed here.

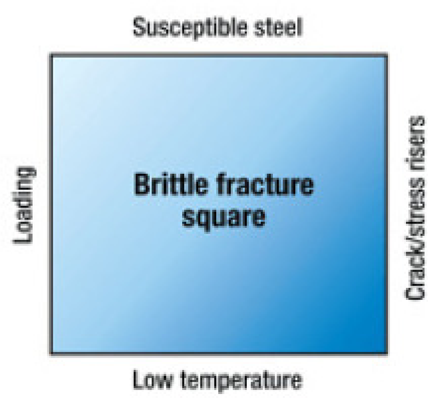



**Figure 1: Brittle Fracture Square**

**Low temperature**

A metal depending on its toughness property has a transition temperature range within which it is in a semi-brittle condition (ductile to brittle transition). Within this range, a notch or crack may cause brittle fracture (notch brittleness). Above the transition range (warmer), brittle fracture will not happen even if a notch exists. Below the transition range (colder), brittle fracture can happen even though no notches or cracks may exist. Although the transition from ductile to brittle fracture actually occurs over a temperature range, a point within this range is selected as the “transition temperature” to delineate the boundaries of ductile and brittle zones. One of the ways to determine this temperature is by performing many impact tests on the construction material.

**Loading**

The type and level of mechanical/thermal loading will affect the vessel’s susceptibility to brittle fracture. Dynamic loading associated with cyclic mechanical/thermal or impact loading, as opposed to quasi-static loading, is a brittle-fracture contributing factor. Furthermore, shock-chilling effects, defined as rapid decreases in equipment temperatures, can be a cause for brittle fracture. Based on the stress levels applied (in a quasi-static loading), component material, effective thickness and minimum metal temperature, ASME Section VIII, Divisions 1 and 2 present criteria for vessel-component material-impact test requirements and/or exemptions.

**Susceptible steel**

Susceptibility of steels depends on several parameters such as poor toughness, material flaws (cracks and notches), corrosion vulnerability, large thickness, etc.:

- **Steel composition:** Steels with lower carbon content are proven to have higher toughness at lower temperatures. Also, phosphorous present in steels decreases the transition temperature of steel and improves weldability. In general, steel-transition temperature is a function of carbon content percent plus 20 times the percentage of phosphorous. Furthermore, adding nickel to steel can increase steel toughness and decrease its transition temperature. Stainless steel 304 with 8% nickel can resist impact loads at –320°F. Furthermore, sufficiently low carbon equivalents contribute to the weldability of the material (reducing hardness and cold-cracking susceptibility) and, thus making metal crack-free girth welds. Selecting the appropriate welding material also is a determining factor to ensure a crack-free weld.
- **Steel structure:** A correlation was developed between steel structure (microstructure and grain size) and fracture-toughness by numerous fracture toughness tests at different low temperatures. Based on this correlation, steels with coarse-grained microstructures have lower toughness at low temperatures as compared to steels with the fine-grained microstructure. During a 1999 incidence with a high-density polyethylene (HDPE) reactor, a brittle fracture occurred at a temperature of –12°C in a 24-in. flange of ASTM A105 material that had a coarse-grain microstructure (ASTM grain size number 5 to 6 ferrite-pearlite microstructure).
- **Hydrogen cracks** (hydrogen-induced cracks or so-called flakes): When hydrogen atoms diffuse into the metal during material manufacturing operations such as forming, forging and welding or when hydrogen is introduced to the metal through a galvanic or hydrogen sulfide ($H_2S$) corrosion process, the metal is prone to hydrogen cracks.

  There are various techniques to prevent hydrogen cracks, including appropriate heat treatments or slow cooling after forging, in which the hydrogen within the metal diffuses out. In the case of welding, usually pre-heating and post-heating are applied to diffuse out the hydrogen and to prevent any cracks and brittleness.
- **Environmental stress fracture:** Steels exposed to corrosive fluids such as wet $H_2S$, moist air or sea water are prone to premature fracture under tensile stresses, considerably below their "fracture toughness" threshold. Suitable steel materials should be used when exposure to corrosive fluids is possible.

**Crack/stress risers.**

Steel vessels with thicker walls have a greater probability potential for brittle fracture due to the larger thermal gradient across the wall thickness. Thicker metal walls can result in differential expansion of material across the wall thickness and could possibly lead to a crack occurrence and eventually brittle fracture.

**Stress raisers** such as sharp or abrupt transitions or changes of sections, corners or notches (as may be found in weld defects) as a result of design or fabrication processes are all stress risers, which can cause stress intensification. The weak points are prone to brittle fracture when other susceptible conditions exist.

## *ASME Section VIII, Div. 1 and Low Teperature Operation*

ASME VIII-1 lays down guidelines for impact test exemptions for pressure vessel components in low temperature applications, and also provides procedures for Charpy V-notch impact tests for those components where impact tests are required (UG 84). The starting point for determining the exemption from impact testing is usually paragraph UG 20(f) followed by applicable paragraphs in Subsection C for different materials. The paragraphs in Subsection C that are pertinent to low temperature operations are listed below:

- Part UCS *Carbon and Low Alloy Steels*: Paragraphs UCS 65 and 66. UCS 67 that covers the rules for impact testing of welds and heat-affected zones is not discussed here.
- Part UNF *Non-ferrous Materials*: Paragraph UNF 65
- Part UHA *High Alloy Steels*: Paragraph UHA 51

This article will discuss in detail the requirements in paragraphs UG 20(f) and UCS 65 and 66 for exemptions to impact testing, and will also touch upon the requirements of paragraphs UNF 65 and UHA 51.

**Paragraph UG 20(f)**

Impact testing is not required for pressure vessel materials that satisfy all of the following:

- The materials are limited to P-No. 1, Gr. No. 1 or 2, and thicknesses do not exceed
    - 13 mm (1/2 in.) for materials listed in curve A of Figure UCS 66 (see Figure 2 in the article)
    - 25 mm (1 in.) for materials listes in curves B, C or D of Figure UCS 66
- The completed vessel shall be hydrostatically tested
- Design temperature is no warmer than 345°C (650°F) nor colder than -29°C (-20°F). Occasional operating temperatures colder than -29°C (-20°F) are acceptable when due to lower seasonal atmospheric temperature.
- Thermal or mechanical shock loadings are not a controlling design requirement

***What are P-Numbers?***

*To reduce the number of welding and brazing procedure qualifications required, base metals have been assigned P-Numbers by ASME Boiler and Pressure Vessel Code. Ferrous metals which have specified impact test requirements have been assigned Group Numbers within the P-Numbers.These assignments have been based on comparable base metal characteristics, such as composition, weldability, brazeability and mechanical properties.*

*Indiscriminate substitution of materials in a set of P-Numbers or Group Numbers may lead to problems or potential failures. Engineering assessment is necessary prior to a change in materials.*

*Carbon Manganese steels are assigned P-Number 1. Within this P-Number, there are four Groups: Group 1 is for materials with tensile strength up to 65 ksi, Group 2 for tensile strength up to 70 ksi, Group 3 for tensile strength up to 80 ksi, and Group 4 for tensile strength beyond 80 ksi.*

*Austenite Stainless steels have been assigned P-Number 8. Within this P-Number, there are four Groups: Group 1 is for grades 304, 316 and 347; Group 2 is for grades 309 and 310; Group 3 is for high manganese grades, and Group 4 is for 254 SMO type steels.*

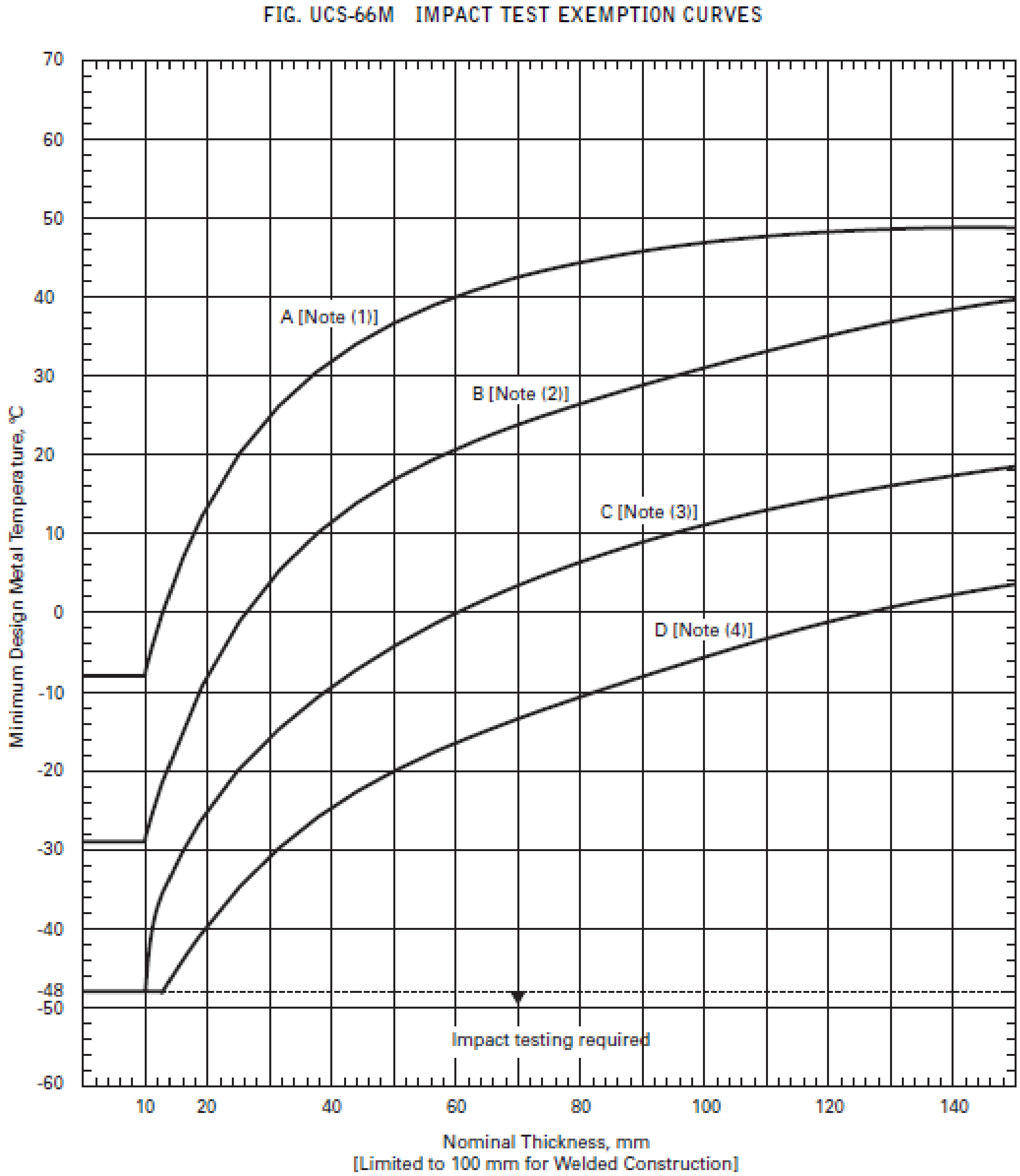



**Figure 2: Impact Test Exemption Curves**

NOTES:
(1) Curve A applies to:
  (a) all carbon and all low alloy steel plates, structural shapes, and bars not listed in Curves B, C, and D below;
  (b) SA-216 Grades WCB and WCC if normalized and tempered or water-quenched and tempered; SA-217 Grade WC6 if normalized and tempered or water-quenched and tempered.
(2) Curve B applies to:
  (a) SA-216 Grade WCA if normalized and tempered or water-quenched and tempered
    SA-216 Grades WCB and WCC for thicknesses not exceeding 2 in. (50 mm), if produced to fine grain practice and water-quenched and tempered
    SA-217 Grade WC9 if normalized and tempered
    SA-285 Grades A and B
    SA-414 Grade A
    SA-515 Grade 60
    SA-516 Grades 65 and 70 if not normalized
    SA-612 if not normalized
    SA-662 Grade B if not normalized
    SA/EN 10028-2 Grades P295GH and P355GH as-rolled;
  (b) except for cast steels, all materials of Curve A if produced to fine grain practice and normalized which are not listed in Curves C and D below;
  (c) all pipe, fittings, forgings and tubing not listed for Curves C and D below;
  (d) parts permitted under UG-11 shall be included in Curve B even when fabricated from plate that otherwise would be assigned to a different curve.
(3) Curve C applies to:
  (a) SA-182 Grades F21 and F22 if normalized and tempered
    SA-302 Grades C and D
    SA-336 F21 and F22 if normalized and tempered, or liquid quenched and tempered
    SA-387 Grades 21 and 22 if normalized and tempered, or liquid quenched and tempered
    SA-516 Grades 55 and 60 if not normalized
    SA-533 Grades B and C
    SA-662 Grade A;
  (b) all materials listed in 2(a) and 2(c) for Curve B if produced to fine grain practice and normalized, normalized and tempered, or liquid quenched and tempered as permitted in the material specification, and not listed for Curve D below.
(4) Curve D applies to:
  SA-203
  SA-508 Grade 1
  SA-516 if normalized or quenched and tempered
  SA-524 Classes 1 and 2
  SA-537 Classes 1, 2, and 3
  SA-612 if normalized
  SA-662 if normalized
  SA-738 Grade A
  SA-738 Grade A with Cb and V deliberately added in accordance with the provisions of the material specification, not colder than −20°F (−29°C)
  SA-738 Grade B not colder than −20°F (−29°C)
  SA/AS 1548 Grades 7-430, 7-460, and 7-490 if normalized
  SA/EN 10028-2 Grades P295GH and P355GH if normalized
  SA/EN 10028-3 Grade P275NH

**Figure 2: Impact Test Exemption Curves (Contd.)**

## Carbon and Low Alloy Steels

Unless exempted by the rules of UG 20(f), Fig. UCS 66 [see Figure 2 above in this article] shall be used to establish impact test exemptions for steels listed in Part UCS. When Fig. UCS 66 is used, impact testing is required for a combination of minimum design metal temperature (MDMT) and thickness which is below the curve assigned to the subject material. If a MDMT and thickness combination is on or above the curve, impact testing is not required.

Components such as shells, heads, nozzles, manways, reinforcing pads, flanges, tubesheets, flat cover plates, backing strips which remain in place, and attachments which are essential to the structural integrity of the vessel when welded to pressure retaining components, shall be treated as separate components. Each component shall be evaluated for impact test requirements based on its individual material classification, thickness and the MDMT.

The following thickness limitations apply when using Fig. UCS 66:

1) The governing thickness, $t_g$, of a welded part is as follows:
   a. For butt joints except those in flat heads and tube sheets, the nominal thickness of the thickest welded joint.
   b. For corner, fillet, or lap welded joints, the thinner of the two parts joined.
   c. For flat heads or tubesheets, the larger of (b) above and the flat component thickness divided by 4.

d. For the welded assemblies comprised of more than two components (nozzle-to-shell joint with reinforcement pad), the governing thickness and the permissible MDMT of each of the individual welded joints of the assembly shall be determined, and the warmest of the MDMTs shall be used as the permissible MDMT of the welded assembly.

If the governing thickness at any welded joint exceeds 100 mm (4 in.) and the MDMT is colder than 50$^o$C (120$^o$F), impact tested material shall be used.

2) The governing thickness of a casting shall be its largest nominal thickness.

3) The governing thickness of flat nonwelded parts, such as bolted flanges, tubesheets, and flat heads is the flat component thickness divided by 4.

4) The governing thickness of a nonwelded dished head is the greater of flat flange thickess divided by 4 or the minimum thickness of the dished portion.

5) If the governing thickness of the nonwelded part exceeds 150 mm (6 in.) and the MDMT is colder than 50$^o$C (120$^o$F), impact tested material shall be used.

*Coincident Ratio*

When the coicident ratio defined in Fig. UCS 66.1 is less than 1, Fig. UCS 66.1 provides a basis for the use of components made of Part UCS materials to have a colder MDMT without impact testing. When the MDMT is colder than -48$^o$C (-55$^o$F) and no colder than -105$^o$C (-155$^o$F), and the coicident ratio as defined in Fig. UCS 66.1 is less than equal to 0.35, impact testing is not required. For all other cases where the MDMT is less than -105$^o$C (-55$^o$F), impact testing is required for all materials.

*Flanges*

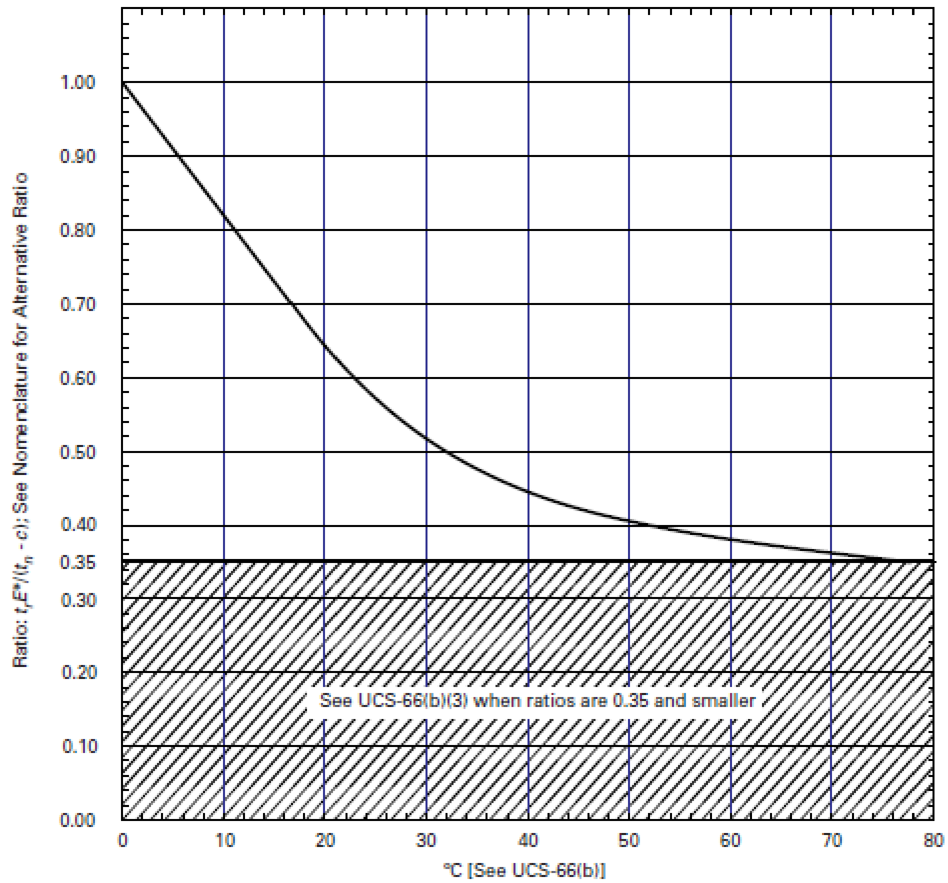
No impact testing is required for the following flanges when used at MDMT no colder than -20$^o$F:

- ASME B16.5 flanges of ferritic steel
- ASME B16.47 flanges of ferritic steel
- Split loose flanges of SA-216 Gr WCB when the outside dimensions and the bolting dimensions are either ASME B16.5 Class 150 or Class 300, and the flange thicknesses are not greater than that of either ASME B16.5 Class 150 or Class 300 respectively
- Long weld neck flanges defined as forged nozzlesthat meet the dimensional requirements of a flanged fitting given in ASME B16.5 but having a straight hub/ neck. The neck inside diameter shall not be less than the nominal size of the flange and the outside diameter of the neck and any nozzle reinforcement shall not exceed diameter of the hub as specified in ASME B16.5.

*Materials 2.5 mm (0.10 in.) Thickness and Thinner*

No impact testing is required for UCS materials 2.5 mm (0.10 in.) thickness and thinner, but such exempted UCS materials shall not be used at design metal temperature colder than -48$^o$C (-55$^o$F). For vessels or components made from DN 100 (NPS 4) or smaller tubes or pipe of P-No. 1 materials, the following exemptions from impact testing are also permitted as a function of the material specified minimum yield strength (SMYS) for metal temperatures of -105$^o$C (-155$^o$F) and warmer:

| SMYS, MPa (ksi) | Thickness, mm (in.) |
|---|---|
| 140 to 240 (20 to 35) | 6.0 (0.237) |
| 250 to 310 (36 to 45) | 3.2 (0.125) |
| 320 (46) and higher | 2.5 (0.10) |




$c$ = corrosion allowance, mm
$E^*$ = as defined in General Note (c) of Fig. UCS-66.2
$t_n$ = nominal thickness of the component under consideration before corrosion allowance is deducted, mm
$t_r$ = required thickness of the component under consideration in the corroded condition for all applicable loadings [General Note (b) of Fig. UCS-66.2], based on the applicable joint efficiency $E$ [General Note (c) of Fig. UCS-66.2], mm
*Alternative Ratio* = $S^*E^*$ divided by the product of the maximum allowable stress value from Table UCS-23 times $E$, where $S^*$ is the applied general primary membrane tensile stress and $E$ and $E^*$ are as defined in General Note (c) of Fig. UCS-66.2

**Figure 3: Reduction in MDMT without Impact Testing**

*Backing Strips*

No impact testing is required for metal backing strips that remain in place made of materials assigned to curve A of Fig. UCS 66 in thicknesses not exceeding 6 mm (¼ in.) when MDMT is -29°C (-20°F) or warmer.

*Other Requirements*

The material manufacturer's identification marking required by the material specification shall not be stamped on plate material less than ¼ in. in thickness unless the following requirements are met:

- The material shall be limited to P-No. 1 Gr 1 or 2
- The minimum nominal plate thickness shall be 5 mm (3/16 in.), or the minimum pipe wall thickness shall be 3.91 mm (0.154 in.)
- The MDMT shall be no colder than -29°C (-20°F)

Unless specifically exempted in Fig. UCS 66, material having specified minimum yield strength greater than 450 MPa (65 ksi) must be impact tested.

**Non-Ferrous Materials (UNF 65)**

Non-ferrous materials do not undergo a marked drop in impact resistance at sub-zero temperature. Therefore no additional requirements are specified for:

- Wrought aluminum alloys when they are used at temperatures down to -269°C (-425°F)
- Copper and copper alloys, nickel and nickel alloys, and cast aluminum alloys when they are used at temperatures down to -198°C (-325°F)
- Titanium and zirconium and their alloys used at temperatures down to -59°C (-75°F)

**High Alloy Steels (UHA 51)**

The rules for impact testing of high alloy steels are given in paragraph UHA 51. Impact testing is not required for the following combinations of base metals and heat-affected zones (if welded) and MDMTs:

- For austenitic chromium-nickel stainless steels as follows:
  - Types 304, 304L, 316, 316L, 321 and 347 at MDMTs of -196°C (-320°F) and warmer
  - Other types having a carbon content not exceeding 0.10% at MDMTs of -196°C (-320°F) and warmer
  - Other types having a carbon content exceeding 0.10% at MDMTs of -48°C (-55°F) and warmer
  - For castings at MDMTs of -29°C (-20°F) and warmer
- For austenitic chromium-manganese-nickel stainless steels (200 series) as follows:
  - Having a carbon content not exceeding 0.10% at MDMTs of -196°C (-320°F) and warmer
  - Having a carbon content exceeding 0.10% at MDMTs of -48°C (-55°F) and warmer
  - For castings at MDMTs of -29°C (-20°F) and warmer
- For following steels in al product forms at MDMTs of -29°C (-20°F) and warmer:
  - Austenitic ferritic duplex steels with a nominal material thickness of 10 mm (3/8 in.) and thinner
  - Ferritic chromium stainless steels with a nominal material thickness of 3 mm (1/8 in.) and thinner
  - Martensitic chromium stainless steels with a nominal material thickness of 6 mm (¼ in.) and thinner
- Impact testing of high alloy steels is not required for vessels when the coincident ratio of design stress in tension to allowable tensile stress is less than 0.35

## *Sources:*


1. Khazrai, F., Haghighi, H. B. and H. Kordabadi, *Avoid Brittle Fracture in Pressure Vessels*, Hydrocarbon Processing, March 2011
2. ASME Boiler & Pressure Vessel Code, Section VIII, Division 1: Edition 2010


***** END OF THE ARTICLE *****

## *About CoDesign Engineering*

*CoDesign Engineering* is involved in projects that promote sustainable development and improvement in system efficiencies with specific focus on energy and waste management. Its operations can be broadly classified into following business groups:

- Pressure Vessels and Heat Exchangers
- Combined Cycle Power Plants
- Solar Photovoltaic Power Plants

We provides training, consultancy, and operation and maintenance services as described below:

**Training**

- Pressure vessel & heat exchanger design (ASME Section VIII, Div. 1)
- Power and process piping design (ASME B31.1 & B31.3)
- Combined cycle power plant system design
- Solar PV power plant design

**Consultancy**

- Supply and installation of static equipment in power plants and refineries
- Project Management Consultancy for construction of combined cycle power plants
- PMC as well as EPC services for solar PV power plants

*We have designed a 3-day training course for ASME BPVC Section VIII, Div. 1 that can be offered at most cities in India. In-house training can also be provided at any location in India or in US upon request. The training is designed as a workshop where the delegates are encouraged to do all calculations using only pencil, paper and calculators. Please contact Ramesh Tiwari at rtiwari123@gmail.com for 2012 training calendar, rates and the contents of the course.*

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