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TECHNICAL BASIS AND APPLICATION OF NEW RULES ON FRACTURE CONTROL OF HIGH PRESSURE HYDROGEN VESSEL IN ASME SECTION VIII, DIVISION 3 CODE

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ABSTRACT

As a part of an ongoing activity to develop ASME Code rules for the hydrogen infrastructure, the ASME Boiler and Pressure Vessel Code Committee approved new fracture control rules for Section VIII, Division 3 vessels in 2006. These rules have been incorporated into new Article KD-10 in Division 3. The new rules require determining fatigue crack growth rate and fracture resistance properties of materials in high pressure hydrogen gas. Test methods have been specified to measure these fracture properties, which are required to be used in establishing the vessel fatigue life. An example has been given to demonstrate the application of these new rules.

1.0 INTRODUCTION

As a part of an ongoing activity to develop ASME Code rules for the hydrogen infrastructure, the ASME Boiler and Pressure Vessel Code Committee formed a “Project Team on Hydrogen Vessels” in 2004. The charter of this project team is to develop Code rules for all metal and composite pressure vessels to be used in transport and stationary application for 15,000 psi (103 MPa) hydrogen gas at ambient temperature. A series of rules are under development for these vessels.

The first set of rules were developed and approved for fatigue and fracture analysis of Section VIII, Division 3 [1] vessels in 2006. These rules have been incorporated into new Article KD-10 in Division 3. The new rules require determining the fatigue crack growth rate and fracture resistance properties of the materials to be used in the construction of pressure vessels in high pressure hydrogen gas. Test methods have been specified to measure these properties, which are required to be used in establishing the vessel fatigue life. This paper presents the technical basis for the KD-10 rules. An example also has been given to demonstrate the application of these new rules.

2.0 NOMENCLATURE

K_{IC} = plane-strain fracture toughness, ksi-in.^{½} (MPa-m^{½}).
K_{IH} = threshold stress intensity factor for hydrogen-assisted cracking, ksi-in.^{½} (MPa-m^{½}).
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.

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.
UTS = Ultimate tensile strength, ksi (MPa)
YS = Yield strength, ksi (MPa)
a = principal planar dimension of a crack, crack depth, in. (mm).
l = major axis of the crack, crack length, in. (mm).
t = section thickness, in. (mm).

3.0 SCOPE OF KD-10

Paragraph KD-1000 specifies the scope of the new KD-10 rules. The requirements of this Article are mandatory for the following vessels and materials in hydrogen service.

3.1 Nonwelded Vessels

(a) Nonwelded vessels with hydrogen partial pressure exceeding 6000 psi (41 MPa).

(b) Nonwelded vessels constructed of materials with actual UTS exceeding 137 ksi (945 MPa) and hydrogen partial pressure exceeding 750 psi (5.2 MPa).

The 6000 psi pressure limit was set based on successful experience (for example US DOT 3AA specification gas cylinders). The lower hydrogen partial pressure limit of 750 psi (5.2 MPa) was imposed for materials with an ultimate tensile strength exceeding 137 ksi (945 MPa) due to the known tendency of materials to be increasingly susceptible to cracking in hydrogen gas as the strength is increased.

3.2 Vessels of Welded Construction

(a) Vessels of welded construction with hydrogen partial pressure exceeding 2,500 psi (17 MPa).

(b) Vessels of welded construction in hydrogen service using materials with actual maximum ultimate tensile strength exceeding 90 ksi (620 MPa) and hydrogen partial pressure exceeding 750 psi (5.2 MPa).

The above limits on pressure and material strength were set based on successful industry experience in hydrogen service.

3.3 Materials

The rules of this Article are applicable to the materials listed in Tables KCS-1 (for example SA-516, SA-517, SA-372, SA-723 etc.) and KHA-1 (for example SA-336, Gr. F316) of Section VIII, Division 3, and to aluminum alloys 6061-T6 and 6061-T651 only.

3.4 Limitations on the Applicability of KD-10

Paragraph KD-1001 specifies the following limitations on the applicability of KD-10.

(a) The design pressure shall not exceed 15,000 psi (103 MPa).

(b) The maximum design temperature is limited by the following:

(1) For carbon and low alloy steels in Table KCS-1 that are included in Fig. 1 of API RP 941[2], the maximum design temperature shall be on or below the applicable curve in Fig. 1 of API RP 941 for operating limits in hydrogen service.

The applicable curve in Fig. 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 (103 MPa).

(2) For austenitic stainless steels, the maximum design temperature is limited to that specified in Table KHA-1.

(3) For aluminum alloys 6061-T6 and 6061-T651, the maximum design temperature is limited to 225ºF (107ºC).

(4) For all other materials, the maximum design temperature shall not exceed 400ºF (205ºC).

The intent of the temperature limitations on carbon and low alloy steel is to preclude hydrogen attack. The limitations on Table KHA-1 materials are based on the tensile strength properties at elevated temperature and the expected maximum permissible design temperature in Table KDA-1. The limitations on 6061 aluminum are based on those in Code Case 2563.

4.0 MATERIAL QUALIFICATION REQUIREMENTS

Article KD-10 requires fracture mechanics tests to obtain the following fracture mechanics properties for the analysis and to qualify materials for vessels to be used in high pressure gaseous hydrogen transport and storage service:

- Plane-strain fracture toughness, K_{IC}
- Threshold stress intensity factor for hydrogen-assisted cracking, K_{IH}
- Fatigue-crack-growth rate, da/dn

The qualification tests for the fracture mechanics properties to be used in the analysis are given in KD-1021, KD-1022, and KD-1023 of Section VIII, Division 3. The required testing and the test procedures are described in paragraphs 4.1 – 4.5 of this paper.

4.1 Qualification Tests for K_{IC} Values to be Used in the Design (KD-1021)

(a) The plane-strain fracture toughness values, K_{IC}, shall be obtained in air at minimum design temperature from the thickest section from each heat of the material used in the vessel construction. 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 from 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 specimens shall be tested in accordance with ASTM E 399 [3] or E 1820 [4] at the minimum design metal temperature (MDMT). The lowest measured value of K_{IC} shall be used in the analysis.

(b) As an alternative to the requirements in (a) above, the plane-strain fracture toughness K_{IC} may also be obtained from other tests by the use of the fracture toughness correlations given in Appendix D-600(a) of Section VIII, Division 3. The lowest value obtained from the tests in the base metal, weld metal, and the heat affected zone of welds shall be used for the fracture mechanics evaluation.

(c) As an alternative to the requirements in (a) above, for 6061-T6 and 6061-T651 aluminum alloys the sharp notch tension test may be used to validate the lower bound plane-strain fracture toughness, in which case the resulting sharp-notch net section strength at fracture/tensile yield strength ratio (NYR) shall not be less than 0.90 and a lower bound fracture toughness value of K_{IC} = 23 ksi-in.^{½} (25 MPa-m.^{½}) shall be used for fracture mechanics evaluation. The sharp notch tension test specimen shall conform to ASTM E 338 [5], Fig. 3 for sheet type specimens and to ASTM E 602[6], Fig. 1 for round specimens.

4.2 Qualification Tests for K_{IH} Values to be Used in the Analysis (KD-1022)

(a) The purpose of this test is to qualify the construction material by testing three heats. The threshold stress intensity values, 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 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.

(b) The values obtained in (a) above may be used for other vessels manufactured from the same material specification/ grade or similar specification/grade having the same nominal chemical composition and same heat treatment condition, providing its tensile and yield strengths do not exceed the values of the material used in the qualification tests by more than 5 percent. The welded joints shall meet the requirements of the WPS used for qualifying the construction material.

4.3 Test Method for K_{IH} Determination (KD-1040)

(a) Testing shall be conducted using applicable rules of ASTM E 1681 [7] 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_{IAPP}, where K_{IAPP} is the initial applied elastic stress-intensity factor, ksi-in.^{½} (MPa-m^{½}), 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. The test chamber shall be pressurized with hydrogen gas to a pressure equal to or greater than the design pressure of the vessel. 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), the material is characterized as suitable for construction of pressure vessels with respect to the hydrogen assisted cracking (HAC) resistance requirement. The value of K_{IAPP} is designated as K_{IH}.

(d) If the subcritical crack growth exhibited by the test specimen is greater than or equal to 0.01” (0.25 mm), the procedure specified in ASTM E 1681 Paragraph 9.2.1 and 9.2.2 shall be used in establishing the K_{IH} value.

4.4 Qualification Tests for da/dn Values to be Used in the Analysis (KD-1023)

(a) 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 $\mathbf{da/dn = c\,(\Delta K)^m}$ shall be obtained using the test method described in KD-1050. Testing shall be conducted in accordance with all applicable rules of ASTM E 647[8] at room temperature in gaseous hydrogen at a pressure not less than the design pressure of the vessel.

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 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.

(b) The data obtained in (a) may be used for other vessels manufactured from the same material specification and grade or similar specification/grade having the same nominal chemical composition and heat treatment condition, providing its tensile and yield strengths do not exceed the values of the material used in the qualification tests by more than 5 percent. The welded joints shall meet the requirements of the WPS used for qualifying the construction material.

5.0 FRACTURE MECHANICS BASED DESIGN ANALYSIS

The rules in KD-10 require that the fatigue analysis for high pressure hydrogen pressure vessels be performed using the fracture mechanics method. Division 3 provides the methodology for determining the design fatigue life using a fracture mechanics approach in Article KD-4. Additional requirements for the fracture analysis for vessels in hydrogen service are provided in KD-1010. These additional requirements are discussed below. The reason to supplement the current Division 3 rules for high pressure hydrogen vessels is based on well documented effects of reduced fatigue and fracture properties resulting from hydrogen embrittlement. It is essential that materials have good ductility and excellent toughness because of the higher stresses permitted in Division 3. The additional requirements ensure an acceptable margin for design in hydrogen service.

The basic fracture mechanics analysis in Division 3 uses a linear-elastic approach. Structures made from materials with sufficient toughness may not be susceptible to brittle fracture, but they can fail by plastic collapse if they are overloaded. The potential failure mechanism of most structures lies between the extremes of brittle fracture and limit load failure. KD-10 requires that the critical crack size be calculated considering the possibility of both fracture and plastic collapse using the failure assessment diagram (FAD). Specifically the Level 2 assessment approach in Part 9 of API RP-579 [9] is required. The FAD concept addresses both fast fracture and plastic collapse and describes the interaction between fracture and collapse. API 579 also provides a comprehensive library of stress intensity and limit-load solutions. Figure 1 shows the FAD curve for the Level 2 assessment of API 579. The stress intensity and reference stress solutions provided in API RP-579 shall be used, except that the effect of pressure on the crack tip shall be included in the stress intensity solutions.

KD-1030 places additional restrictions on the critical crack size. The rules require that the critical crack depth at design pressure be the smaller of that obtained by using either K_{IC} or K_{IH}. K_{IC} and K_{IH} are determined using paragraphs KD-1021 and KD-1022 respectively. The specific requirements for determining the fracture properties in high pressure hydrogen are provided above. The minimum critical crack size shall also not be smaller than 0.25 t deep and 1.5 t long.

A fracture based fatigue analysis assumes that a flaw exists at the high stress location. Because of the high stress gradients seen in thick wall pressure vessels, surface flaws generally control the fatigue analysis. The size of the surface flaw that must be assumed in the fatigue analysis is determined by the resolution of the nondestructive examination (NDE) method used. Paragraph KE-232 provides acceptance criteria for both dye penetrant and magnetic particle examination techniques. The surface flaw acceptance criteria provided in KE-232 are a reasonable starting point for design, but if longer fatigue life is needed smaller initial flaws will be required. It must always be demonstrated that the NDE method to be used will reliably detect a flaw of the size specified.

A crack growth rate in the hydrogen environment is required to determine the fatigue life of the vessel. The crack growth rate factors in Tables KD-430 and KD-430M shall be replaced with factors determined in accordance with the rules in paragraph KD-1023.

Vessel failure will occur when the initial flaw propagates through wall or reaches the critical crack size. Criteria for the allowable final crack size are provided in paragraph KD-412 of Section VIII, Division 3. Two design margins are considered when calculating the number of allowable design cycles:

(1) The number of cycles to propagate a crack from the assumed initial size to the critical crack depth divided by 2.

(2) The number of cycles to propagate a crack from the assumed initial size to 25% of the critical crack depth.

The fatigue design life is the lesser of the two criteria. The fatigue criteria are illustrated in Figure 2. In the illustration of the fracture based failure criteria shown below, criterion 1 governs the fatigue design life. Either criterion can control the fatigue life depending on the stress field around the crack.

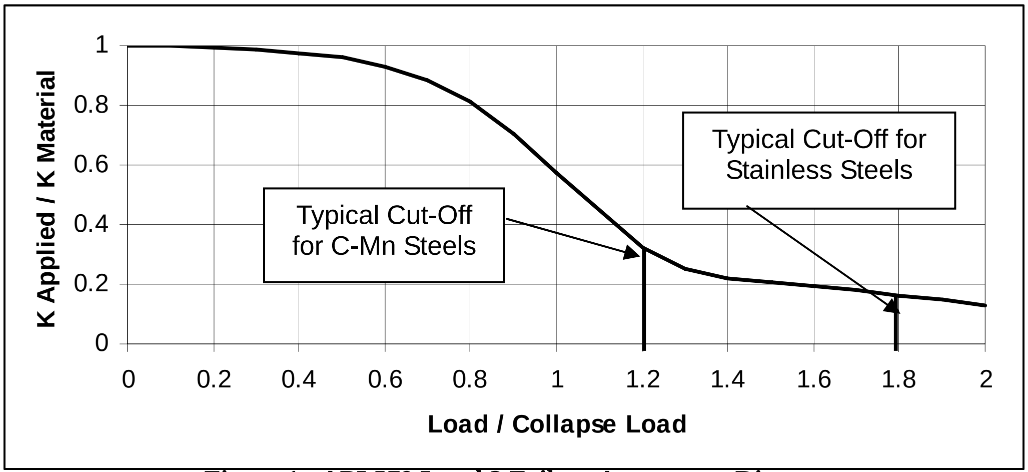

Figure 1: API 579 Level 2 Failure Assessment Diagram

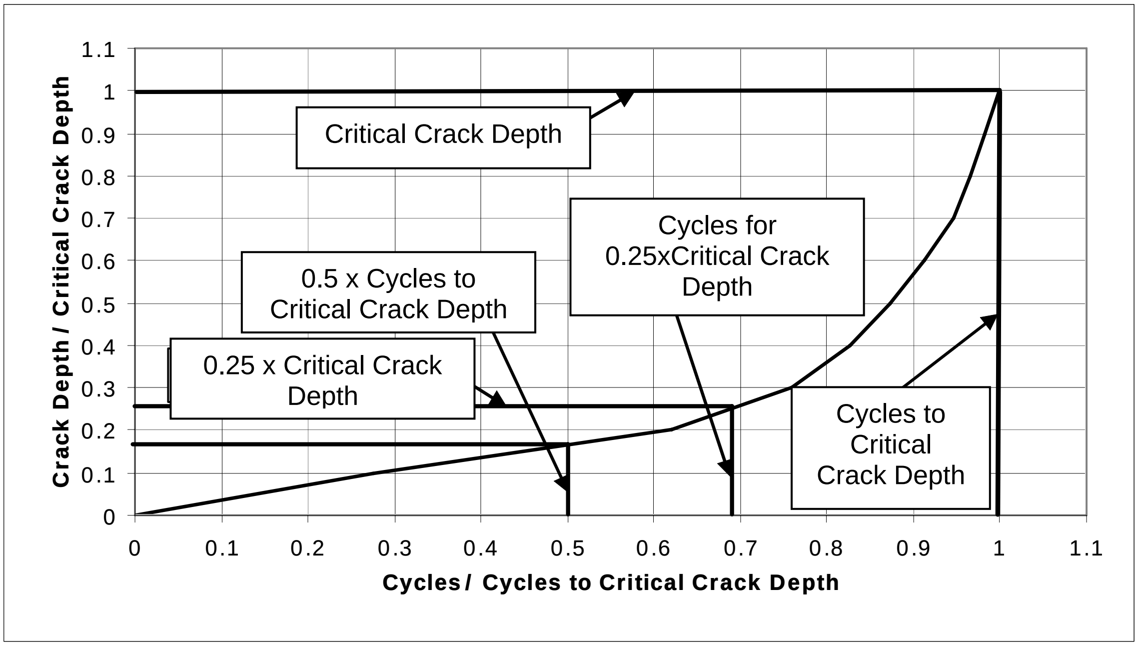

Figure 2: ASME Section VIII Division 3 Fracture Mechanics Based Design Criteria

6.0 DESIGN EXAMPLE

This example has been developed only to illustrate one possible analysis method. It is not intended to represent an actual pressure vessel for high pressure hydrogen service. For example, it is likely that many of the vessels in this service will use non-welded construction. A center girth weld was included in this example only to illustrate the more detailed calculation method that would be required.

A series of pressure vessels are to be designed (using ASME Code rules) for use in ISO shipping frames aboard an ocean going ship for the purpose of transporting hydrogen at a pressure of 15,000 psi (103 MPa). The vessel design parameters are listed in Table 1.

Table 1: Vessel Design Parameters

Design Pressure	15,000 psi (103 MPa)
Design Temperature	100^{o}F (38^{o}C)
Liner material	SA-372, Grade E, Class 70
Liner Yield Strength	70 ksi (483 MPa)
Liner Tensile Strength	120 ksi (827 MPa)
Composite Tensile Strength	140 ksi (965 MPa)
Inside Diameter	16 in (406 mm)
Liner wall thickness	1.631 in (41.4 mm)
Composite wall thickness	1.631 in (41.4 mm)
Vessel Length	40 ft (12.2 m)
Liner Elastic Modulus	29,500 ksi (203,395 MPa)
Composite Elastic Modulus	7,000 ksi (48,263 MPa)

An iterative calculation was used to determine the plastic collapse pressure of the vessel. For the purpose of this example, the liner was considered to have ideal elastic, perfectly plastic properties. Since the composite material does not exhibit a yield point, the stress at the inside surface of the composite was limited to its tensile strength. This gave a plastic collapse pressure of 36,729 psi (253 MPa), which exceeds the required margin of 2.0. Note that in an actual design analysis, the strain hardening characteristics of the liner would be considered, since the margin of 2.0 is relative to the burst pressure. This would permit a reduction in the wall thickness of the liner, the composite or both.

The longitudinal stress in the liner is approximately equal to the hoop stress, because the composite provides about ½ of the strength in the hoop direction, but is assumed to provide no strength in the longitudinal direction. Since the vessel is oriented horizontally in service, and is supported on the ends, the combination of pressure and ship motion loads causes relatively high stresses in the center of the vessel. There is a girth weld at this location that could have up to 0.079 inches (2 mm) misalignment, which intensifies the stress at this location. Therefore, this location was selected as the "fatigue sensitive location" for this example. In an actual design analysis, several other locations would be examined as well.

In an actual design analysis, a series of finite element analyses would be conducted to obtain through thickness stress distributions at all "fatigue sensitive" locations considering all applied loads for input to the required fracture mechanics analysis. For this example, finite element results from another vessel with a misaligned center girth weld were scaled to provide a credible through thickness distribution. The through thickness stress distributions for the Outbound (full) Inbound (empty) and Pressure Only portions of a single round trip voyage are shown in Figures 3 through 5. The sharp peak near the bore surface is due to the misalignment. The outside surface has been ground smooth.

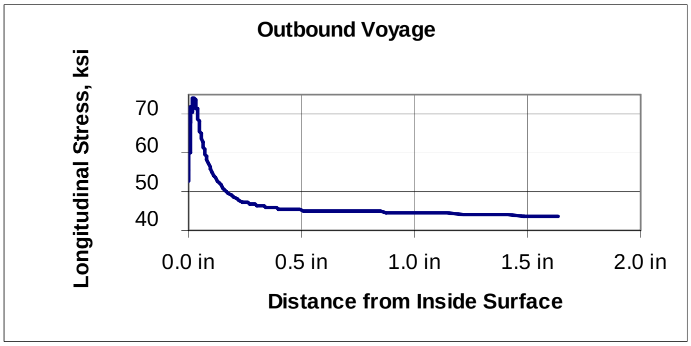

Figure 3: Thru Thickness Stress Distribution for Outbound Voyage

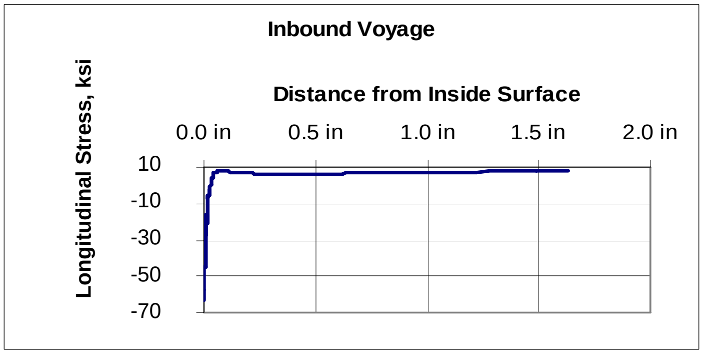

Figure 4: Thru Thickness Stress Distribution for Inbound Voyage

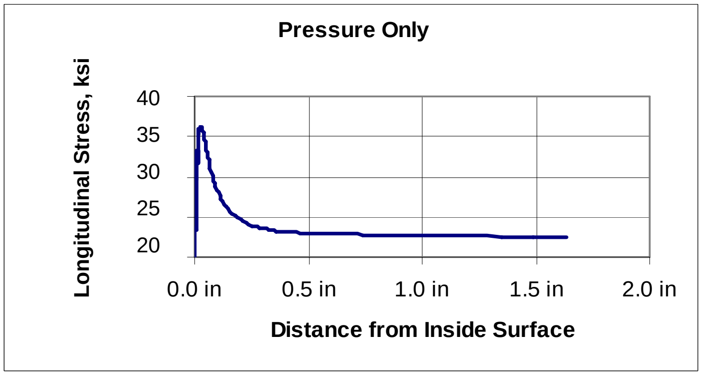

Figure 5: Thru Thickness Stress Distribution for Pressure

New Article KD-10 of Division 3 requires that crack growth rate data and the threshold for subcritical crack growth be obtained by measurements on three heats of steel, and the lowest measured threshold and highest crack growth rate be used for the fracture mechanics analysis. For the purpose of this example, data were taken from the work of McIntyre and Pumphrey [10]. These data were obtained on a different material, at a lower hydrogen partial pressure than the material and conditions for the example vessel, so the results are for illustration only. Therefore, the data were modified by applying a factor of 3 to the measured values to obtain a lower bound from the average data provided. The resulting crack growth parameters are shown in Table 2.

Table 2 Crack Growth Parameters

Δk Range (ksi $\sqrt{\text{in.}}$)	**Base Metal**		**Weld/HAZ**	
	C	**m**	**C**	**m**
0 to <9	1.08E-09	3.00	1.08E-09	3.00
9 to <10	6.75E-11	4.30	6.75E-11	4.30
10 to <16	2.10E-08	1.80	2.10E-08	1.80
16 to <21	1.01E-18	10.40	1.37E-26	17.00
≥21	2.40E-09	3.20	3.33E-07	2.25

The stress distributions and crack growth rate parameters were used in a fracture mechanics analysis using the stress intensity and reference stress solutions in API-579[9] with the weight function method. The results are shown in Tables 3a and 3b for the weld and base metal respectively. For the purpose of this example a “Lifetime” was assumed to be 2000 round trip voyages (100 voyages per year times a 20 year life). Using the fracture mechanics acceptance criteria from Section VIII, Division 3 as shown in the Tables, the design life does not meet the target, particularly for the weld. This is due primarily to the use of a factor of three on the crack growth data. In addition, the stress distribution was conservative.

7.0 DISCUSSION

The rules specified in KD-10 invoke fracture mechanics based design. The fracture and fatigue properties of the construction materials are required to be measured in an H_2 environment using ASTM test methods. Sufficient test control guidelines have been specified to obtain reliable fracture and fatigue properties. The fatigue design life calculations are carried out using the API 579 [9] procedure. Design margins have been specified on critical crack size and fatigue life to assure fracture safe performance in service.

Table 3a: Results of Fracture Mechanics Analysis for the Weld

Initial crack depth, a_0, (in.)	K_{IH} (ksi $\sqrt{in.}$)	1/4 of Critical Crack Depth (in.)	Lifetimes to 1/4 of Critical Crack Depth	1/2 x Lifetimes to Critical Crack Depth	Design Number of Trips
0.0625	60.0	0.1112	0.075	0.142	149
0.0625	75.0	0.1749	0.142	0.174	284
0.0625	90.0	0.2408	0.191	0.194	382
0.0625	130.0	0.4078	0.274	0.211	421

Table 3b: Results of Fracture Mechanics Analysis for Adjacent Base Metal

Initial crack depth, a_0, (in.)	K_{IH} (ksi $\sqrt{in.}$)	1/4 of Critical Crack Depth (in.)	Lifetimes to 1/4 of Critical Crack Depth	1/2 x Lifetimes to Critical Crack Depth	Design Number of Trips
0.0625	60.0	0.1144	0.580	0.810	1,160
0.0625	75.0	0.1805	0.990	0.911	1,822
0.0625	90.0	0.2416	1.216	0.958	1,915
0.0625	130.0	0.4078	1.572	0.995	1,989

8.0 CONCLUSIONS

The new KD-10 rules have been developed using fracture mechanics procedures to address the well known effects of hydrogen embrittlement on materials.

The vessels constructed using KD-10 rules will provide fracture safe service in up to 15,000 psi (103 MPa) hydrogen gas pressure.

9.0 ACKNOWLEDGMENT

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10.0 REFERENCES

[1] ASME Section VIII, Division 3 Code, 2004 Edition, “Alternative rules for construction of high pressure vessels”, ASME, New York, NY, 10016

[2] API RP 941, 2004 Edition, “Steels for hydrogen service at elevated temperatures and pressures in petroleum refineries and petrochemical plants” American Petroleum Institute, Washington D.C, 20005

[3] ASTM E399, “Standard test method for linear – elastic plane – strain fracture toughness KIC of metallic materials”, ASTM, West Conshohocken, PA, 19428

[4] ASTM E 1820, “Standard test method for measurement of fracture toughness”, ASTM, West Conshohocken, PA, 19428

[5] ASTM E 338,”Standard test method of sharp – notch tension testing of high- strength sheet materials”, ASTM, West Conshohocken, PA, 19428

[6] ASTM E 602 “Standard test method for sharp- notch tension testing with cylindrical specimens”, ASTM, West Conshohocken, PA, 19428

[7] ASTM E 1681, “Standard test method for determining threshold stress intensity factor for environment – assisted cracking of metallic materials”,ASTM,West Conshohocken, PA, 19428

[8] ASTM E 647, “Standard Test Method for measurement of fatigue crack growth rates”, ASTM, West Conshohocken, PA, 19428

[9] API RP- 579, “First Edition 2000 “Recommended Practice for Fitness–for–Service”, American Petroleum Institute, Washington D.C., 20005

[10] Private Communication.