Fitness-For-Service Example Problem Manual

API 579-2/ASME FFS-2 2009

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Fitness-For-Service Example Problem Manual

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API 579-2/ASME FFS-2 2009 Fitness-For-Service Example Problem Manual

FOREWORD

The publication of the standard API 579-1/ASME FFS-1 *Fitness-For-Service*, in July 2007 provides a compendium of consensus methods for reliable assessment of the structural integrity of industrial equipment containing identified flaws or damage. API 579-1/ASME FFS-1 was written to be used in conjunction with industry's existing codes for pressure vessels, piping and aboveground storage tanks (e.g. API 510, API 570, API 653, and NB-23). The standardized Fitness-For-Service assessment procedures presented in API 579-1/ASME FFS-1 provide technically sound consensus approaches that ensure the safety of plant personnel and the public while aging equipment continues to operate, and can be used to optimize maintenance and operation practices, maintain availability and enhance the long-term economic performance of plant equipment.

This publication is provided to illustrate the calculations used in the assessment procedures in API 579-1/ASME FFS-1 published in July, 2007.

This publication is written as a standard. Its words *shall* and *must* indicate explicit requirements that are essential for an assessment procedure to be correct. The word *should* indicates recommendations that are good practice but not essential. The word *may* indicates recommendations that are optional.

The API/ASME Joint Fitness-For-Service Committee intends to continuously improve this publication as changes are made to API 579-1/ASME FFS-1. All users are encouraged to inform the committee if they discover areas in which these procedures should be corrected, revised or expanded. Suggestions should be submitted to the Secretary, API/ASME Fitness-For-Service Joint Committee, The American Society of Mechanical Engineers, Three Park Avenue, New York, NY 10016, or SecretaryFFS@asme.org.

Items approved as errata to this edition are published on the ASME Web site under Committee Pages at http://cstools.asme.org. Under Committee Pages, expand Board on Pressure Technology Codes & Standards and select ASME/API Joint Committee on Fitness-For-Service. The errata are posted under Publication Information.

This publication is under the jurisdiction of the ASME Board on Pressure Technology Codes and Standards and the API Committee on Refinery Equipment and is the direct responsibility of the API/ASME Fitness-For-Service Joint Committee. The American National Standards Institute approved API 579-2/ASME FFS-2 2009 Fitness-For-Service Example Problem Manual on August 11, 2009.

Although every effort has been made to assure the accuracy and reliability of the information that is presented in this standard, API and ASME make no representation, warranty, or guarantee in connection with this publication and expressly disclaim any liability or responsibility for loss or damage resulting from its use or for the violation of any regulation with which this publication may conflict.

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PART 1

INTRODUCTION

PART CONTENTS

1.1 Introduction

Fitness-For-Service (FFS) assessments in API 579-1/ASME FFS-1 *Fitness-For-Service* are engineering evaluations that are performed to demonstrate the structural integrity of an in-service component that may contain a flaw or damage or that may be operating under specific conditions that could produce a failure. API 579-1/ASME FFS-1 provides guidance for conducting FFS assessments using methodologies specifically prepared for pressurized equipment. The guidelines provided in this standard may be used to make run-repair-replace decisions to help determine if pressurized equipment containing flaws that have been identified by inspection can continue to operate safely for some period of time. These FFS assessments of API 579-1/ASME FFS-1 are currently recognized and referenced by the API Codes and Standards (510, 570, & 653), and by NB-23 as suitable means for evaluating the structural integrity of pressure vessels, piping systems and storage tanks where inspection has revealed degradation and flaws in the equipment or where operating conditions suggest that a risk of failure may be present.

1.2 Scope

Example problems illustrating the use and calculations required for Fitness-For-Service Assessments described in API 579-1/ASME FFS-1 are provided in this document. Example problems are provided for all calculation procedures in both SI and US Customary units.

1.3 Organization and Use

An introduction to the example problems in this document is described in Part 2 of this Standard. The remaining Parts of this document contain the example problems. The Parts in this document coincide with the Parts in API 579-1/ASME FFS-1. For example, example problems illustrating calculations for local thin areas are provided in Part 5 of this document. This coincides with the assessment procedures for local thin areas contained in Part 5 of API 579-1/ASME FFS-1.

1.4 References

API 579-1/ASME FFS-1 *Fitness For Service.*

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PART 2

FITNESS-FOR-SERVICE ENGINEERING ASSESSMENT PROCEDURE

PART CONTENTS

2.1 General

The Fitness-For-Service assessment procedures in API 579-1/ASME FFS-1 are organized by flaw type or damage mechanism. A list of flaw types and damage mechanisms and the corresponding Part that provides the FFS assessment methodology is shown in API 579-1/ASME FFS-1, Table 2.1. In some cases it is required to use the assessment procedures from multiple Parts based on the damage mechanism being evaluated.

2.2 Example Problem Solutions

2.2.1 Overview

Example problems are provided for each Part and for each assessment level, see API 579-1/ASME FFS-1, Part 2. In addition, example problems have also been provided to illustrate the interaction among Parts as required by the assessment procedures in API 579-1/ASME FFS-1. A summary of the example problems is contained in Tables E2-1 - E2.11.

2.2.2 Calculation Precision

The calculation precision used in the example problems is intended for demonstration proposes only; an intended precision is not implied. In general, the calculation precision should be equivalent to that obtained by computer implementation, rounding of calculations should only be done on the final results.

2.3 Tables and Figures

Table E2-1 - Part 3 Examples on Assessment for Brittle Fracture

Example	Assessment Level	Units	Type of Equipment	Geometry	Type or Description of Analysis
1	1	US	Pressure Vessel	---	MAT calculation with PWHT
2	1	US	Pressure Vessel	---	MAT calculation without PWHT
3	1	US	Pressure Vessel	---	MAT calculation without PWHT
4	1	US	Pressure Vessel	---	MAT calculation with PWHT
5	2	US	Pressure Vessel	---	MAT reduction vs P/P_{rating} (Pressure Temperature Rating Basis)
6	2	SI	Pressure Vessel	Cylinder	MAT reduction vs S*E*/SE (Stress Basis)
7	1 and 2	US	Pressure Vessel	Sphere	MAT reduction vs S*E*/SE (Stress Basis)
8	2	US	Pressure Vessel	Sphere	MAT reduction vs S*E*/SE (Stress Basis)
9	2	US	Pressure Vessel	Sphere	MAT reduction vs operating pressure / hydrotest pressure
10	3	US	Demethanizer tower	---	Assessment based on fracture mechanics principles of Part 9

Table E2-2 - Part 4 Examples on Assessment of General Metal Loss

Example	Assessment Level	Units	Type of Equipment	Geometry	Location of Metal Loss	Loading(s)	Average Thickness based on
1	1 and 2	SI	Heat exchanger	Cylinder	Away from msd	Internal pressure Full vacuum	Point thickness reading
2	1 and 2	US	Pressure Vessel	Cylinder	Away from msd	Internal pressure	Critical thickness profiles
3	1 and 2	SI	Pressure Vessel	Elliptical head	Away from msd	Internal pressure	Critical thickness profiles
4	2	US	Pressure Vessel	Nozzle	At msd	Internal pressure	Given in the data

Table E2-3 - Part 5 Examples on Assessment of Local Metal Loss

Example	Assessment Level	Units	Type of Equipment	Geometry	Location of Metal Loss	Loading(s)	Type of Metal Loss
1	1	US	Pressure Vessel	Cylinder	Away from msd	Internal pressure	LTA
2	1 and 2	US	Pressure Vessel	Cylinder	Away from msd	Internal pressure	2 Grooves
3	2	US	Pressure Vessel	Cylinder	Away from msd	Internal pressure Supplemental loads	LTA
4	2	US	Pressure Vessel	Cylinder	Away from msd	Internal pressure	LTA
5	1	SI	Pressure Vessel	Cylinder	Away from msd	Internal pressure	LTA
6	2	US	Pressure Vessel	Nozzle	At msd	Internal pressure	Uniform LTA
7	1	US	Storage Tank	Cylinder	Away from msd	Fill Height	LTA
8	1	US	Piping	Elbow	Away from msd	Internal pressure	Uniform LTA
9	2	US	Pressure Vessel	Cylinder	Away from msd	Vacuum	LTA

Table E2-4 - Part 6 Examples on Assessment of Pitting Corrosion

Example	Assessment Level	Units	Type of Equipment	Geometry	Loading(s)	Type of Pitting	Comment
1	1	US	Pressure Vessel	Cylinder	Internal pressure	Widespread pitting	---
2	1	SI	Piping	Cylinder	Internal pressure	Widespread pitting	---
3	2	US	Horizontal Pressure Vessel	Cylinder	Internal pressure Supplemental loads	Widely scattered pitting	---
4	2	US	Pressure Vessel	Cylinder	Internal pressure	Localized pitting	LTA per Part 5 Level 1
5	2	US	Pressure Vessel	Cylinder	Internal pressure	Pitting in LTA	LTA per Part 5 Level 1
6	2	US	Pressure Vessel	Cylinder	Internal pressure	Widespread pitting Inside and outside	---

Table E2-5 - Part 7 Examples on Assessment of Blisters and HIC and SOHIC Damage

HIC Damages

Example	HIC Area	Level	Location in Thickness	Comment	Service Condition
1	1	1 and 2	Surface breaking	Level 2 per Part 5 Level 1	Equipment will remain in hydrogen charging service
	2a	1	Surface breaking	Combined	
	2b		Sub surface		
	3	1	Surface breaking	---	
	4	1 and 2	Sub surface	Level 2 per Part 5 Level 1	
3	1	1	Sub surface	---	Equipment will not remain in hydrogen charging service
	2	1 and 2	Sub surface	Level 2 per Part 5 Level 1	

Blisters

Example	Blister	Level	Bulge Direction	Cracking at Periphery	Crown Cracking or Venting	Comment
2	A	1 and 2	Outside	No	Crack	Level 2 per Part 5 Level 1
	B	1	Outside	No	Vent	---
	C	1	Inside	No	Vent	---
	D	1 and 2	Inside	No	Crack	Level 2 per Part 5 Level 1
	E	1	Inside	No	Vent	---
	F	1	Inside	No	No	---
	G	1 and 2	Outside	Yes (Inward)	Crack	Level 2 per Part 5 Level 1
	H	1 and 2	Outside	No	Vent	Level 2 per Part 5 Level 1

Note: Common characteristics:
- Type of Equipment: Pressure Vessel
- Geometry: Cylinder
- Units: US
- Loading: Internal pressure

Table E2-6 - Part 8 Examples on Assessment of Weld Misalignment and Shell Distortions

Example	Assessment Level	Units	Type of Equipment	Geometry	Loading(s)	Type of Damage	Comment
1	1 and 2	US	Piping	Cylinder	Internal pressure	Weld misalignment	Peaking
2	2	US	Piping	Cylinder	Fluctuating internal pressure	Weld misalignment Peaking	Fatigue assessment by: - elastic stress analysis and equivalent stress - elastic stress analysis and structural stress
3	1and 2	US	Pressure Vessel	Cylinder	Internal pressure	Out-of-roundness	Assessment based on D_{max}-D_{min}
4	2	US	Pressure Vessel	Cylinder	Internal pressure	Weld misalignment	Center line offset and peaking
5	1 and 2	US	Pressure Vessel	Cylinder	Internal pressure	Out-of-roundness	Assessment based on radius expressed as a Fourier series
6	1 and 3	US	Pressure Vessel	Shell - Heads - Stiffening rings	Internal pressure Vacuum conditions	General shell distortion	Level 3 based on Finite Element Analysis: - limit load analysis (elastic perfectly plastic material behavior) - check of local strain (elastic-plastic with strain hardening material behavior) - elastic buckling analysis (check of stability of deformed shell) - check of fatigue requirements

Table E2-7 - Part 9 Examples on Assessment of Crack-Like Flaws

Example	Assessment Level	Units	Type of Equipment	Geometry	Loading(s)	Type of Crack	Comment
1	1	US	Pressure Vessel	Cylinder	Internal pressure	- Longitudinal - Semi-elliptical	Shallow crack in parallel to weld seam
2	1	SI	Pressure Vessel	Sphere	Internal pressure	- Circumferential - Semi-elliptical	Deep crack perpendicular to weld seam
3	1and 2	US	Pressure Vessel	Cylinder	Internal pressure	- Semi-elliptical - Oriented at 30° from principal direction	Flaw length to be used in assessment
4	1 and 2	US	Pressure Vessel	Cylinder	Internal pressure	- Semi-elliptical - Oriented along bevel angle	Flaw depth to be used in assessment
5	1 and 2	US	Pressure Vessel	Cylinder	Internal pressure	- Longitudinal - Semi-elliptical	- Residual stresses due to welding based on surface distribution - Uniform distribution along thickness
6	1 and 2	SI	Piping	Cylinder	Internal pressure Global bending moment	- Circumferential - 360degree crack	- Residual stresses due to welding based on through-thickness distribution - Fourth order polynomial along thickness
7	2	SI	Piping	Cylinder	Internal pressure Global bending moment	- Circumferential - Semi-elliptical	- Residual stresses identical to those of example 9.6 - Coefficients of polynomial calculated by weight function method
8	3	US	Pressure Vessel	Cylinder	Internal pressure	- Longitudinal - Semi-elliptical	- Residual stresses identical to those of example 9.5 - Subcritical fatigue crack growth - Remaining life assessment
9	3	US	---	---	---	---	Failure Assessment Diagram based on actual material properties
10	3	SI	Pressure Vessel	Nozzle	Internal pressure	Quarter-elliptical	Assessment based on elastic-plastic Finite Element Analysis

Table E2-8 - Part 10 Examples on Assessment of Components Operating in the Creep Range

Example	Assessment Level	Units	Type of Equipment	Geometry	Loading(s)	Comment
1	1	US	Pressure Vessel	Cylinder Elliptical head	Internal pressure	- Temperature excursion in the creep range - Check that damage is below the acceptable one
2	1	US	Heater	Tubes	Internal pressure	- Heater operating in the creep range - Excursion at higher temperature than design one - Calculation of overall damage in the complete expected life
3	2	US	Heater	Tubes	Internal pressure	- Same as example 10.2 with the addition of - Calculation of remaining life using Larson Miller parameters
4	3	US	Pressure Vessel	Cylinder	Internal pressure	- Vessel operating in the creep range - Longitudinal semi-elliptical surface crack - Creep crack growth - Calculation of remaining life using MPC Omega project data

Table E2-9 - Part 11 Examples on Assessment of Fire Damage

Example	Assessment Level	Units	Type of Equipment	Geometry	Loading(s)	Comment
1	1	US				HEZ from observation after fire
2	1	US	Horizontal Pressure Vessel	Cylinder	Internal pressure Supplemental loads	HEZ from observation after fire
	2					Allowable stress from hardness results
3	1	US (+SI)	Depropanizer tower	---	Internal pressure	HEZ from observation after fire
	2					Allowable stress from hardness results
	3					- Stress analysis for shell distortion - Testing and metallographic evaluation of material samples

Table E2-10 - Part 12 Examples on Assessment of Dents, Gouges and Dent-Gouge Combinations

Example	Assessment Level	Units	Type of Equipment	Geometry	Type of Damage	Loading(s)	Comment
1	1	SI	Piping	Cylinder	Dent	Internal pressure	---
2	2	SI	Piping	Cylinder	Dent	Fluctuating internal pressure	Fatigue analysis
3	1	SI	Piping	Cylinder	Gouge	Internal pressure	---
4	1	SI	Piping	Cylinder	Dent-Gouge	Internal pressure	---
5	2	SI	Piping	Cylinder	Dent-Gouge	Internal pressure	---

Table E2-11 - Part 13 Examples on Assessment of Laminations

Example	Assessment Level	Units	Type of Equipment	Geometry	Loading(s)	Comment
1	1	US	Pressure Vessel	Cylinder	Internal pressure	- 2 laminations away from msd - Not in hydrogen charging service
2	2	US	Pressure Vessel	Cylinder	Internal pressure	

PART 3

ASSESSMENT OF EXISTING EQUIPMENT FOR BRITTLE FRACTURE

EXAMPLE PROBLEMS

3.1 Example Problem 1

A pressure vessel, 1 in thick, fabricated from SA-285 Grade C in caustic service was originally subject to $PWHT$ at the time of construction. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1. Determine the Level 1 MAT for the shell section.

Based on Curve A in Figure 3.4, a MAT of 69°F was established for the vessel shell section without any allowance for $PWHT$. The material is a P1 Group 1 steel; therefore, applying the allowance for $PWHT$ reduces the MAT by 30°F and establishes a new MAT of 39°F.

3.2 Example Problem 2

The cylindrical shell of a horizontal vessel 0.5 in thick is fabricated from SA-53 Grade B seamless pipe. There is no toughness data on the material. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1. Determine the Level 1 MAT.

Since all pipe, fittings, forgings, and tubing not listed for Curves C and D are included in the Curve B material group, this curve of Figure 3.4 may be used. In this case, the MAT for the cylindrical shell is found to be -7°F.

3.3 Example Problem 3

A horizontal drum 1.5 in thick is fabricated from SA-516 Grade 70 steel that was supplied in the normalized condition. There is no toughness data on the steel. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1. Determine the Level *1* MAT for the shell section.

Since SA-516 Grade 70 is manufactured to a fine grain practice and was supplied in this case in the normalized condition, Curve D of Figure 3.4 may be used. In this case, the MAT for the shell section is found to be -14°F.

3.4 Example Problem 4

A stripper column was constructed following the rules of the ASME B&PV Code, Section VIII, Division 1. This vessel has the following material properties and dimensions.

<u>Vessel Data</u>

- Material = $SA-516\ Grade\ 65\ Year\ 1968$
- Design Conditions = $250\ \text{psi} @ 300\ °\text{F}$
- Allowable Stress = $16{,}250\ \text{psi}$
- Inside Diameter = $90\ \text{in}$
- Operating Pressure = $240\ \text{psi}$
- Wall Thickness = $1.00\ \text{in}$
- Critical Exposure Temperature = $20\ °\text{F}$
- The vessel was $PWHT$
- Impact test data is not available.

Perform a Level 1 Assessment for the shell section per paragraph 3.4.2.1

Since SA-516 Grade 65 used in the construction of the stripper is in the non normalized condition, Curve B of Figure 3.4 may be used. In this case, the MAT for the shell section is found to be 31°F. The vessel was $PWHT$ and an ASME P1 Group 1 material was used. Therefore, the MAT determined before can be reduced further using Equation 3.1. The reduced MAT of this section is equal to 1°F, which is lower than the $CET\ 20°F$.

The Level 1 Assessment Criteria are Satisfied for the shell section.

3.5 Example Problem 5

A reactor vessel fabricated from SA-204 Grade B 1993 (C-½ Mo) has the following material properties and dimensions. The reactor was constructed to the ASME B&PV Code, Section VIII, Division 1. Develop a table of MAT for the shell section as a function of pressure based on paragraph 3.4.3.1 and the allowances given in Figure 3.7 and Table 3.4.

Vessel Data

- Material = $SA-204\ Grade\ B\ Year\ 1993$
- Design Conditions = $390\ \text{psi} @ 300\ °\text{F}$
- Allowable Stress = $17{,}500\ \text{psi}$
- Inside Diameter = $234\ \text{in}$
- Operating Pressure = $240\ \text{psi}$
- Wall Thickness = $2.72\ \text{in}$
- Startup Pressure = $157\ \text{psi}$
- Weld Joint Efficiency = 1.0
- Corrosion Allowance = $1/16\ \text{in}$
- MAT at Design Pressure = $108\ °\text{F}$ see Curve A of Figure 3.4
- Impact test data is not available.

Using this relationship, a table of MAT can be established for the shell section as a function of pressure based on paragraph 3.4.3.1 and the allowances given in Figure 3.7 and Table 3.4.

Table E3.5-1

$P\ (psi)$	P/P_{rating}	$T_R\ (°F)$	$MAT\ (°F)$
390	1.00	0	108
351	0.90	10	98
312	0.80	20	88
288	0.74	26	82
273	0.70	30	78
240	0.62	40	70
195	0.50	58	50
157	0.40	——	-155

The operating pressures and corresponding values of the shell section MAT in this table must be compared to the actual vessel operating conditions to confirm that the metal temperature (CET) cannot be below the MAT at the corresponding operating pressure.

3.6 Example Problem 6

A CO_2 storage tank with a 2032.0 millimeters ID shell section with a nominal thickness of 17.5 millimeters, was constructed in 1982 according to the ASME Code Section VIII, Division 1. The material of construction was SA-612, which is a carbon steel. It was designed for a non corrosion service (corrosion allowance equals zero), with a joint efficiency 100% (full X-ray inspection), and without post-weld heat treatment. This storage vessel has the following characteristics.

Tank Data

- Material = $SA-612\ Year\ 1982$
- Design Conditions = $2.3744\ MPa@93\ {}^{\circ}C$
- Allowable Stress = $139.6\ MPa$
- Inside Diameter = $2032.0\ mm$
- Operating Pressure = $2.3744\ MPa@16\ {}^{\circ}C$
- Wall Thickness = $17.5\ mm$
- Weld Joint Efficiency = 1.0
- Corrosion Allowance = $None$
- MAT at Design Pressure = -12 °C see Curve B of Figure 3.4M
- Impact test data is not available.

Develop a table of MAT for the shell section as a function of pressure based on paragraph 3.4.3.1 and the allowances given in Figure 3.7M and Table 3.4.

Calculate the membrane stress for a cylindrical pressure vessel as a function of pressure (see Annex A):

$$R_c = \left(\frac{D}{2}\right) + FCA + LOSS = \left(\frac{2032.0}{2}\right) + 0.0 + 0.0 = 1016\ mm$$

$$t_c = t - FCA - LOSS = 17.5 - 0.0 - 0.0 = 17.5\ mm$$

$$S^*E^* = P\left[\left(\frac{R_c}{t_c}\right) + 0.6\right] \times E^* = P\left[\left(\frac{1016}{17.5}\right) + 0.6\right] \times 1.0 = 58.657 \times P$$

Using this relationship, a table of MAT can be established as a function of pressure based on paragraph 3.4.3.1 and the allowances given in Figure 3.7 and Table 3.4.

Table E3.6-1

$P\ (MPa)$	$S^*E^*\ (MPa)$	$R_{ts} = \frac{S^*E^*}{SE}$	$T_R\ (^{o}C)$	$MAT\ (^{o}C)$
2.3744	139.28	1.00	0	-12
2.1370	123.35	0.90	6	-18
1.8995	111.42	0.80	11	-23
1.6621	97.49	0.70	17	-29
1.4246	83.56	0.60	22	-34
1.1872	69.64	0.50	32	-44
0.9498	55.71	0.40	——	-104
0.7123	41.78	0.30	——	-104
0.4749	27.86	0.20	——	-104

The operating pressures and corresponding values of the MAT in this table must be compared to the actual vessel operating conditions to confirm that the metal temperature (CET) cannot be below the MAT at the corresponding operating pressure.

3.7 Example Problem 7

A spherical platformer reactor was constructed in 1958 according to the ASME Code, Section VIII, Division 1. The material of construction is C-½Mo, specification SA-204 Grade A. The vessel has the following information available:

<u>Vessel Data</u>

- Material = $SA-204\ Grade\ A\ Year\ 1958$
- Design Conditions = $650\text{ psig}@300\,^{\circ}F$
- Allowable Stress = $16{,}250\text{ psi}$
- Inside Diameter = $144\ in$
- Operating Pressure = 390 psig
- Nominal Thickness = $1.6875\ in$
- Actual Wall Thickness = $1.7165\ in$
- Weld Joint Efficiency = 0.95
- Corrosion Allowance = $0.1563\ in$
- Impact test data is not available.
- The vessel was $PWHT$
- Critical Exposure Temperature = $60\,^{\circ}F$

Perform a Level 1 Assessment for the shell section per paragraph 3.4.2.1

SA-204 Grade A is one of the low alloy steel plates not listed in Curves B, C, and D. Therefore Curve A of, Figure 3.4 shall be used to determine the MAT. In this case, the MAT found is equal to 93°F. The reactor was $PWHT$; however, an ASME P3 Group 1 material was used. Therefore, the MAT determined before cannot be reduced further using Equation 3.7. The MAT is equal to 93°F, which is higher than the CET of 60°F.

The Level 1 Assessment Criteria are Not Satisfied.

Perform a Level 2 Assessment per paragraph 3.4.3.1 and develop a table of MAT as a function of pressure based on the allowances given in Figure 3.7 and Table 3.4.

Calculate the membrane stress for a spherical pressure vessel as a function of pressure (see Annex A):

$$\mathrm{R_c} = \left(\frac{D}{2}\right) + FCA + LOSS = \left(\frac{144}{2}\right) + 0.1563 + 0.0 = 72.1563\ in$$

$$\mathrm{t_c} = t - FCA - LOSS = 1.7165 - 0.1563 - 0.0 = 1.5602\ in$$

$$\mathrm{S^*E^*} = \frac{P}{2}\left[\left(\frac{\mathrm{R_c}}{\mathrm{t_c}}\right) + 0.2\right] \times \mathrm{E^*} = \frac{P}{2}\left[\left(\frac{72.1563}{1.5602}\right) + 0.2\right] \times 0.95 = 22.065 \times P$$

Using this relationship, a table of MAT can be established as a function of pressure based on paragraph 3.4.3.1, the procedure in Table 3.4 and the allowances given by the appropriate curve in Figure 3.7.

Table E3.7-1

$P\ (psi)$	S*E* (psi)	$R_{ts} = \dfrac{S^*E^*}{SE}$	$T_R\ (^{\circ}F)$	$MAT\ (^{\circ}\text{F})$
650	14,342	0.93	7	86
584	12,886	0.83	17	76
520	11,474	0.74	26	67
455	10,040	0.65	35	58
390	8,605	0.56	44	49
325	7,171	0.46	72	21
263	5,803	0.38	——	-155
260	5,737	0.37	——	-155
195	4,303	0.28	——	-155

The operating pressures and corresponding values of the MAT in this table must be compared to the actual vessel operating conditions to confirm that the metal temperature CET cannot be below the MAT at the corresponding operating pressure. In this particular case the reactor is operating at 390 psig, and the CET is equal to 60°F. According to this table at 390 psig the reduced MAT is equal to 49°F, which is lower than the CET. Therefore,

The Level 2 Assessment Criteria are Satisfied for the operating conditions.

3.8 Example Problem 8

A sphere fabricated from SA-414 Grade G has the following material properties and dimensions. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1. Develop a table of MAT for the shell section as a function of pressure based on paragraph 3.4.3.1 and the allowances given in Figure 3.7 and Table 3.4.

Vessel Data

- Material = $SA-414\ Grade\ G\ Year\ 2005$
- Design Conditions = $175.0\ psig\ @\ 300\ ^{\circ}F$
- Allowable Stress = $21,400\ psi$
- Inside Diameter = $585.6\ in$
- Wall Thickness = $1.26\ in$
- Weld Joint Efficiency = 1.0
- Corrosion Allowance = $0.0625\ in$
- MAT at Design Pressure = $80\ ^{\circ}\text{F}$ see Curve A of Figure 3.4
- Impact test data is not available.

Calculate the membrane stress for a spherical pressure vessel as a function of pressure (see Annex A):

$$\mathrm{R_c} = \frac{D}{2} + FCA + LOSS = \frac{585.6}{2} + 0.0625 + 0.000 = 292.8625\ in$$

$$\mathrm{t_c} = t - FCA - LOSS = 1.2600 - 0.0625 - 0.0 = 1.1975\ in$$

$$S*E* = \frac{P}{2}\left[\left(\frac{R_c}{t_c}\right) + 0.2\right] \times E* = \frac{P}{2}\left[\left(\frac{292.8625}{1.1975}\right) + 0.2\right] \times 1.0 = 122.4 \times P$$

Using this relationship, a table of MAT can be established as a function of pressure based on paragraph 3.4.3.1, the procedure in Table 3.4 and the allowances given by the appropriate curve in Figure 3.7.

Table E3.8-1

$P\ (psi)$	S*E* (psi)	$R_{ts} = \frac{S^* E^*}{SE}$	$T_R\ (^oF)$	$MAT\ (^o\text{F})$
174.86	21,400	1.00	0	80
157.35	19,620	0.90	10	70
139.87	17,120	0.80	20	60
122.39	14,980	0.70	30	50
104.90	12,840	0.60	40	40
87.42	10,700	0.50	58	22
69.93	8,560	0.40	104	-24
61.19	7,496	0.35	—	-155
52.45	6,420	0.3	—	-155

The operating pressures and corresponding values of the MAT in this table must be compared to the actual sphere operating conditions to confirm that the metal temperature CET cannot be below the MAT at the corresponding operating pressure.

3.9 Example Problem 9

A spherical pressure vessel has the following properties and has experienced the following hydrotest conditions. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1. Using paragraph 3.4.3.2 and Figure 3.8, prepare a table showing the relationship between operating pressure and MAT for the shell section.

<u>Vessel Data</u>

- Hydrotest pressure = $300\ psig\ or\ 150\%\ of\ design\ pressure$
- Design pressure = $200\ psig$
- Metal temperature during hydrotest = $50\ °F$

The maximum measured metal temperature during hydrotest was 50°F. To be conservative, 10°F is added to this and the analysis is based on a hydrotest metal temperature of 60°F.

Table E3.9-1

Operating Pressure (psig)	$\frac{\text{Operating Pressure}}{\text{Hydrotest Pressure}}$	**Temperature Reduction** (°F)	$MAT\ (°F)$
200	0.67	35	25
180	0.6	43	17
150	0.5	55	5
120	0.4	70	-10
90	0.3	90	-30
75	0.25	——	-155

The operating pressures and corresponding values of the MAT in this table must be compared to the actual sphere operating conditions to confirm that the metal temperature CET cannot be below the MAT at the corresponding operating pressure.

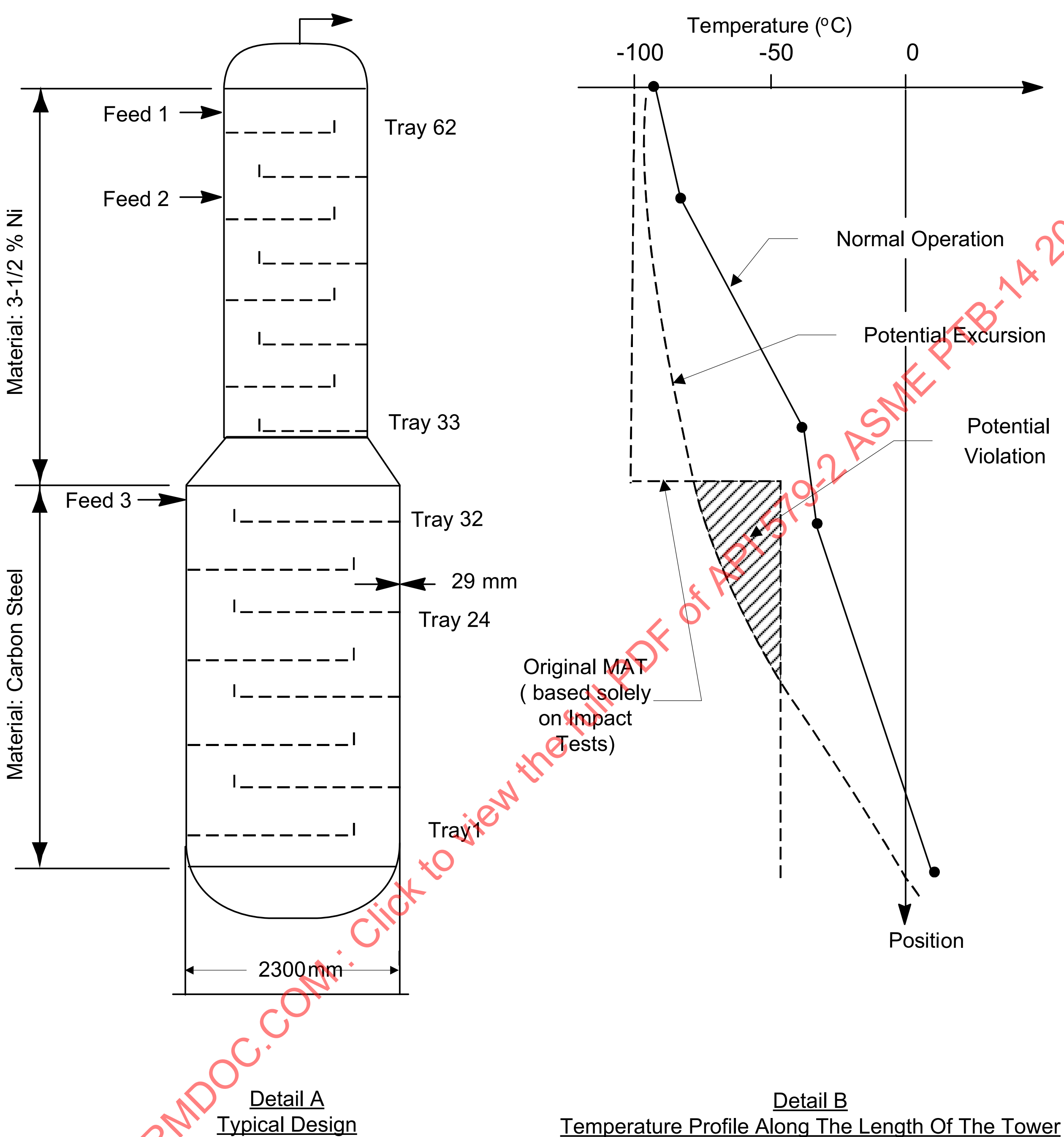
3.10 Example Problem 10

A demethanizer tower in the cold end of a ethylene plant typically operates colder in the top portion of the tower and warmer at the bottom of the tower. The bottom of the tower is kept warm with a side stream circulated through a reboiler. The top portion of the tower is constructed from a 3½% Ni steel which has been impact tested for toughness at -101°C. The lower portion of the tower is constructed from a fully killed, fine grained and normalized carbon steel which is impact tested for toughness at -46°C. A potential for brittle fracture exists if the reboiler does not operate because cold liquid will flow down the tower into the carbon steel section resulting in operating temperatures significantly lower than -46°C. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1. Perform a brittle fracture assessment of ethylene plant demethanizer tower considering all aspects of operation. The upset condition of the reboiler not operating properly should be included in the assessment.

A brittle fracture assessment consistent with paragraph 3.4.4 (Level 3 assessment) can be performed on the demethanizer tower. The approach is illustrated with reference to the demethanizer tower as illustrated in Figure E3.10-1.

The assessment to be utilized is based on the fracture mechanics principles presented in Part 9. In the assessment, the limiting flaw size in the tower will be established, and a sensitivity study will be performed to determine how the limiting flaw size changes as the temperature in the tower drops during an excursion. Based on the results of the assessment, a graph of limiting flaw size versus temperature will be constructed. This graph is referred to as a Fracture Tolerance Signature (FTS). The FTS provides an indication of the safety margin in terms of limiting flaw size. In addition, the FTS can be used to select a lower thermal excursion limit by establishing a flaw size that can be detected with sufficient confidence using an available NDE technique. The FTS can then be used to develop a modified MAT diagram, onto which the excursion limits can be superimposed.

An assumption in the assessment is that the tower has been correctly fabricated to code standards at the time of construction. It is also a required that the vessel material specifications and inspection history are known and documented. These are essential to enable reasonable assumptions to be made about the material toughness properties, stress levels, and likelihood of fabrication or service induced flaws.



Material: SA-516 Grade 70 (KCS)
Minimum Yield Stength at operating conditions 262 MPa
Pressure: 3.72 MPa-g
Toughness: 33/32J @ -46°C
PWHT: Yes
Weld Joint Efficiency: 1.0

Figure E3.10-1
Schematic Of Demethanizer

Assessment Approach

The fracture analysis part of the assessment is based on the methodology presented in Part 9. In order to perform this analysis a flaw size must be assumed, and the applied stress and material toughness must be known. The fracture assessment is limited to the lower carbon steel section of the tower since this is the only section to experience an MAT violation (see Figure E3.10-1).

Assumed Flaw Size

A conservative yet representative hypothetical surface breaking elliptical crack with an aspect ratio of 6:1 (2c:a) is assumed to be located on the inside surface of the vessel. The crack is also assumed to be parallel to a longitudinal weld seam. Other representative flaws elsewhere in the vessel could also be considered. However, as will be seen latter, the relative nature of the results as expressed by the FTS are not significantly affected by such variations, though the minimum excursion temperature will be.

Applied Stress

In order to utilize the assessment procedures of Part 9, the applied stress at the location of the flaw must be computed and categorized. Based on the operation sequence of the tower, four load sources are used to describe the applied stress; the hoop stress from internal pressure, the residual stress in welds, local stress effects from nozzles and attachments, and thermal transient stresses during the upset. In addition, consideration should be given to occasional loads such as wind or earthquake loads. These loads are ignored in this example.

Hoop Stress From Internal Pressure – The pressure stress is calculated using the code design equations. This stress is categorized as a primary membrane stress (see Annexes A and B1).

Residual Stress In Welds – The residual stress can be estimated based on whether post weld heat treatment (PWHT) has been performed (see Annex E). Because the tower was subject to PWHT at the time of construction, the residual stress is taken as 20% of the weld metal room temperature yield strength plus 69 MPa. This stress is classified as a secondary membrane stress.

Local Stress Effects From Nozzles And Attachments – In this screening study, a detailed analysis of the local stresses at the nozzles and attachments were not performed. To account for a level of stress concentration at these locations a stress concentration factor is used. In this example a stress concentration factor 1.3 will be applied to all primary membrane and bending stresses.

Transient Thermal Stresses – These stresses may be evaluated by using closed form solutions or a finite element analysis. In this example, a temperature excursion model consisting of a "cold front" of liquid is assumed to move down the tower. The liquid temperature in the cold front is defined by the process upset condition. The vessel wall is subsequently cooled from its pre-excursion steady-state temperature to the cold liquid temperature. Convective heat transfer from the cold fluid to the vessel shell is assumed to be instantaneous, and heat loss to the atmosphere is neglected. The stress versus time history at a point on the vessel wall computed using a finite element analysis is shown in Figure E3.10-2.

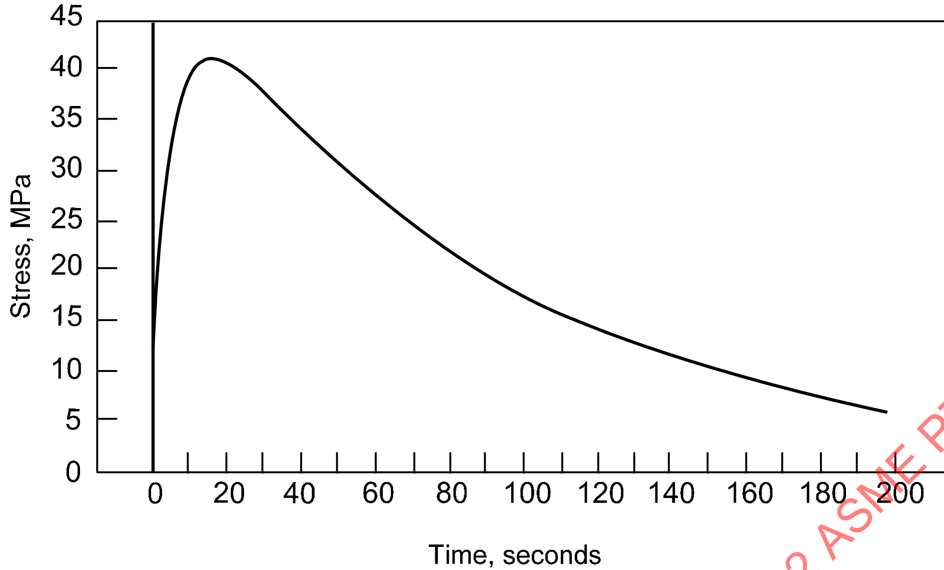


Figure E3.10-2
Transient Thermal Stress Computed From A Finite Element Stress Analysis

The results from the finite element analysis confirm that the magnitude of the maximum transient stress can be readily evaluated from the following equation:

$$\sigma = \frac{E\alpha\,\Delta T}{\left(1.5+\frac{3.25}{\beta}-0.5\exp\left(\frac{-16}{\beta}\right)\right)(1-\nu)}$$

where,

$$\beta = \frac{hL}{k}$$

with,

E	=	Modulus of Elasticity, MPa,
h	=	Convection Coefficient, W/m^2-^{o}C,
k	=	Thermal Conductivity of the shell material, W/m-^{o}C,
L	=	Shell Wall Thickness, m.
ΔT	=	Temperature difference; the difference between the steady state wall temperature before the excursion and the temperature of the fluid causing the excursion, ^{o}C,
α	=	Thermal expansion coefficient, 1/^{o}C,
ν	=	Poisson's ratio
σ	=	Thermal stress, MPa.

Based on the results of the finite element analysis, the maximum stress is a through thickness bending stress with tension on the inside surface. The resultant transient stress is considered to be a primary stress and for further conservatism in this example, it is categorized into equal membrane and bending components. In this example, a thermal stress of 20 MPa is computed based on a liquid temperature of -72°C and a shell temperature of -35°C.

A summary of the applied stresses is shown in Table E3.10-1.

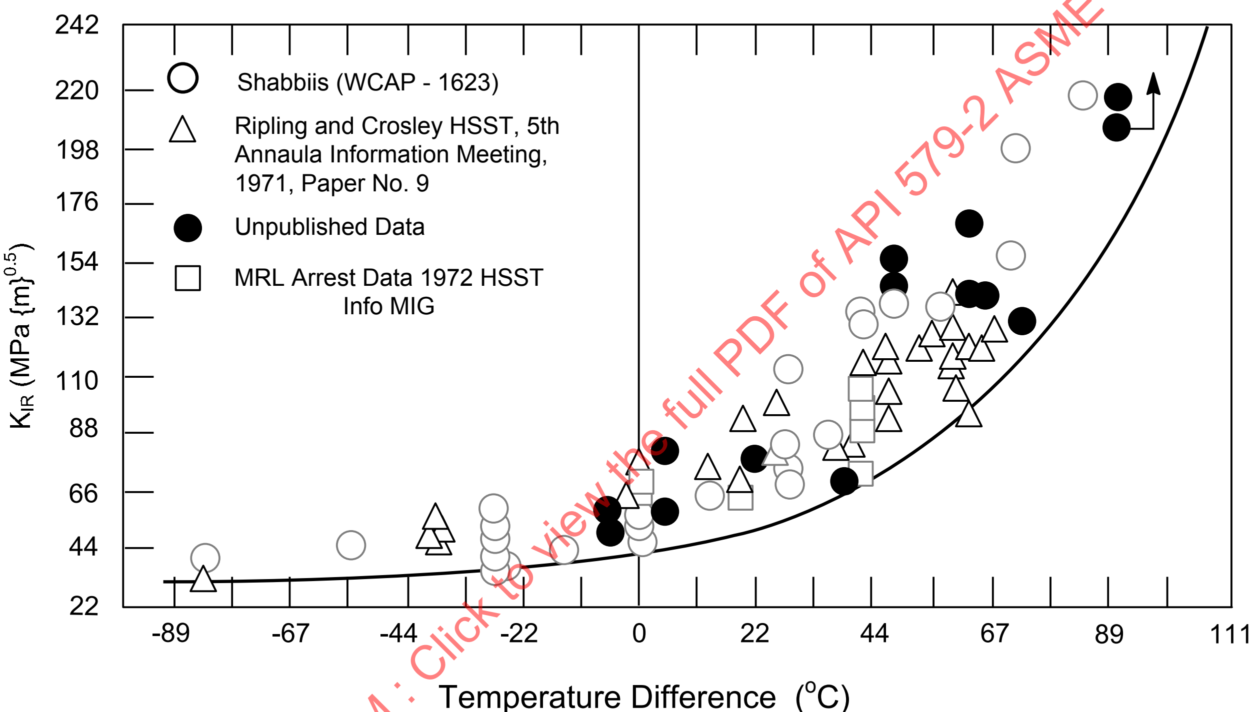
Table E3.10-1
Summary Of Applied Stresses

Magnitude And Classification Of Applied Stresses		
Source Of Stress	Magnitude Of Stress	Classification Of Stress
Hoop Stress From Internal Pressure	$153\ MPa$	$P_m = 153\ MPa$
Residual Stress In Welds	$67\ MPa$	$Q_m = 67\ MPa$
Local Stress Effects From Nozzles And Attachments	A stress concentration factor of 1.3 is used in the analysis.	A stress concentration factor of 1.3 is used in the analysis.
Transient Thermal Stresses	$20\ MPa$	$P_m = \frac{20\ MPa}{2} = 10\ MPa$ $P_b = \frac{20\ MPa}{2} = 10\ MPa$

Applied Stress Results For Use In Fracture Assessment	
Stress Category	Final Stress Result
Primary Membrane Stress	$P_m = (153MPa + 10MPa) \times 1.3 = 212MPa$
Primary Bending Stress	$P_b = (10MPa) \times 1.3 = 13MPa$
Secondary Membrane Stress	$Q_m = 67MPa$

Material Fracture Toughness

Actual fracture toughness data is not normally available for process equipment; therefore, it is necessary to adopt a lower bound approach to describe the variation of toughness with temperature. The most widely used lower bound is the K_{IR} curve from Figure F.3 in Annex F. This curve is shown in Figure E3.10-3. To use this curve it is necessary to estimate a reference temperature to position the temperature axis on an absolute scale. The reference temperature is typically taken as the Nil Ductility Temperature (NDT). In this example, the temperature at which a 40 Joules Charpy V-Notch energy is obtained from a longitudinal specimen is selected as the NDT. It should be noted that Annex F recommends the less conservative value of 20 J. The use of this value would shift the FTS curve shown in Figure E3.10-4 upward. When an impact temperature corresponding to 40 J is not available, actual values are extrapolated to give an effective 40 J test temperature using the relationship: 1.5 J/°C. For this assessment the lowest average Charpy value was used for determining the NDT as opposed to the lowest minimum. The use of actual values is illustrated in Figure E3.10-3.



Notes:

1. Actual Charpy V-Notch data: 33/32 Joules at -46 °C
2. Equivalent temperature at 40 Joules from: -46 °C + (40 J – 33 J)/1.5 J/ °C = -41 °C; therefore, NDT in this figure, indexes to -41 °C.

Figure E3.10-3
Toughness Evaluation Using The K_{IR} Curve

Material Properties

Actual material properties obtained from equipment records should be used for yield strength and Charpy impact energy. Other properties can be determined using Annex F. A correction can be adopted to increase the value of yield strength at low temperature. While this was used in the example its effect is primarily a higher plastic collapse limit, which is not a typical limiting factor for low temperature brittle fracture.

Fracture Tolerance Signature (FTS)

The applied stress, material properties, and fracture toughness parameter defined above are used to create a plot of limiting flaw size versus temperature as illustrated in Figure E3.10-4. The critical flaw depth is in the through thickness direction and is expressed as a percentage of the wall thickness with a 6:1 aspect ratio maintained. The absolute factor of safety in the critical flaw size is undetermined, but is a function of the assumptions made with respect to lower bound toughness, stress, stress multiplier, and the NDT indexing temperature.

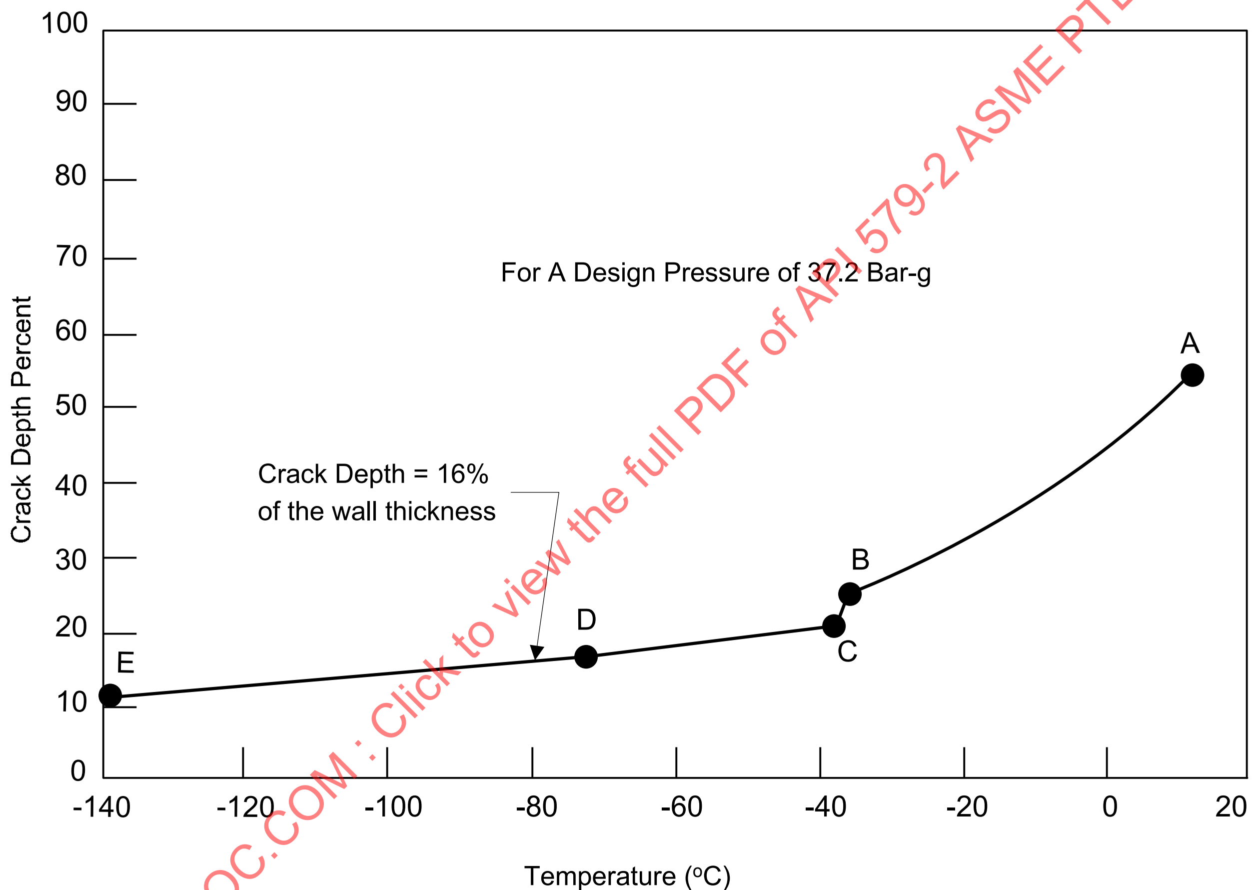


Figure E3.10-4
Fracture Tolerance Signature

The influence of the transient operation on the limiting flaw size is shown in Figure E3.10-4. Line segment A-B represents steady operation and defines the limiting flaw for gradual cool down to -36°C where the limiting flaw is 25% of the wall thickness. The exposure to cold liquid at -72°C, begins at B and results in an almost instantaneous drop in limiting flaw size to 21% of the wall thickness at C. This occurs as a result of the applied thermal stress. The initial effect of the thermal transient decreases as the shell cools, which results in a decrease of the temperature difference between the shell and the cold liquid. During this period the material toughness is reduced, but the thermal stress is also reduced, with the net result that the limiting flaw size is reduced to 17% of the wall thickness at Point D. At this point the metal temperature reaches equilibrium with the cold liquid, and from point D to E a return to steady state cool-down continues. The limiting flaw size is 12% of the wall thickness at Point E where the minimum temperature reached.

The shape of the FTS curve in Figure E3.10-4 follows that of the K_{IR} curve, and is modified only by the transient thermal effect. More or less conservative assumptions on stress and flaw size will lower or raise the curve vertically, respectively. Assuming a lower NDT will move the curve horizontally to the left. For example, using the less conservation K_{IC} curve in place of the K_{IR} curve in evaluating the toughness would shift the curve in Figure E3.10-4 upward resulting in a higher permitted crack depth. For this reason the curve provides useful insight into brittle fracture resistance during an excursion.

The flatness of the curve between points C and E makes limiting temperature predictions highly sensitive to the minimum flaw size. This in turn is greatly influenced by type and extent of inspection and factors such as probability of detection (POD) of flaws. While work still needs to be done to clarify POD issues, application of detailed NDE to a vessel should enable a minimum flaw size to be assumed with sufficient confidence to enable the FTS to be used to specify a minimum excursion temperature. Based on the POD curve shown in Figure E3.10-5, a flaw depth of 4.5 mm should be detectable using a magnetic particle examination technique (MT) with a confidence level greater than 90%. For the 6:1 aspect ratio assumed in developing the $FTS,$ this equates to a crack of length 27 mm.

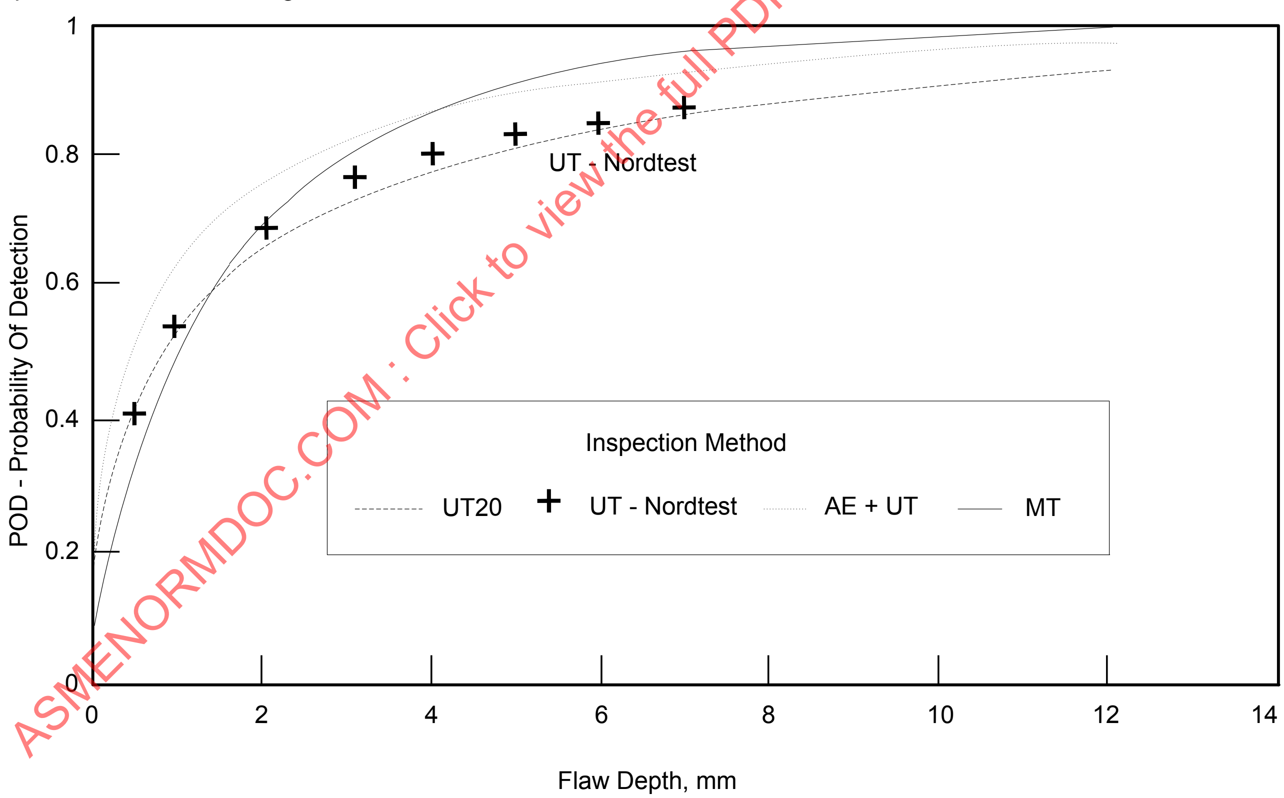


Figure E3.10-5
Comparison Of Inspection Methods - Probability Of Detection Curves

Summary Of Results

The evaluation of a potential thermal excursion for the demethanizer tower illustrated in Figure E3.10-1 is summarized in Figure E3.10-6. The stresses and other factors assumed in conducting the evaluation are shown in Table E3.10-1. An important aspect of the required data is a realistic estimate of the critical exposure temperature (*CET*). This is the actual metal temperature, or more likely the metal temperature predicted by process simulation programs during an excursion. The excursion temperature in the example illustrates that an *MAT* violation will not occur in the 3.5% Ni section above tray 33. Hence the evaluation need only consider the lower carbon steel section.

The excursion temperature plotted in Figure E3.10-6 defines two cases to be considered.

- Case 1 – The lowest temperature in the carbon steel section is at tray 32 with a pre-excursion temperature of -35°C and an excursion delta of -37°C to -72°C.
- Case 2 – The largest delta of -49°C occurs from a steady state temperature of -12°C at tray 24 to give an excursion temperature of -61°C.

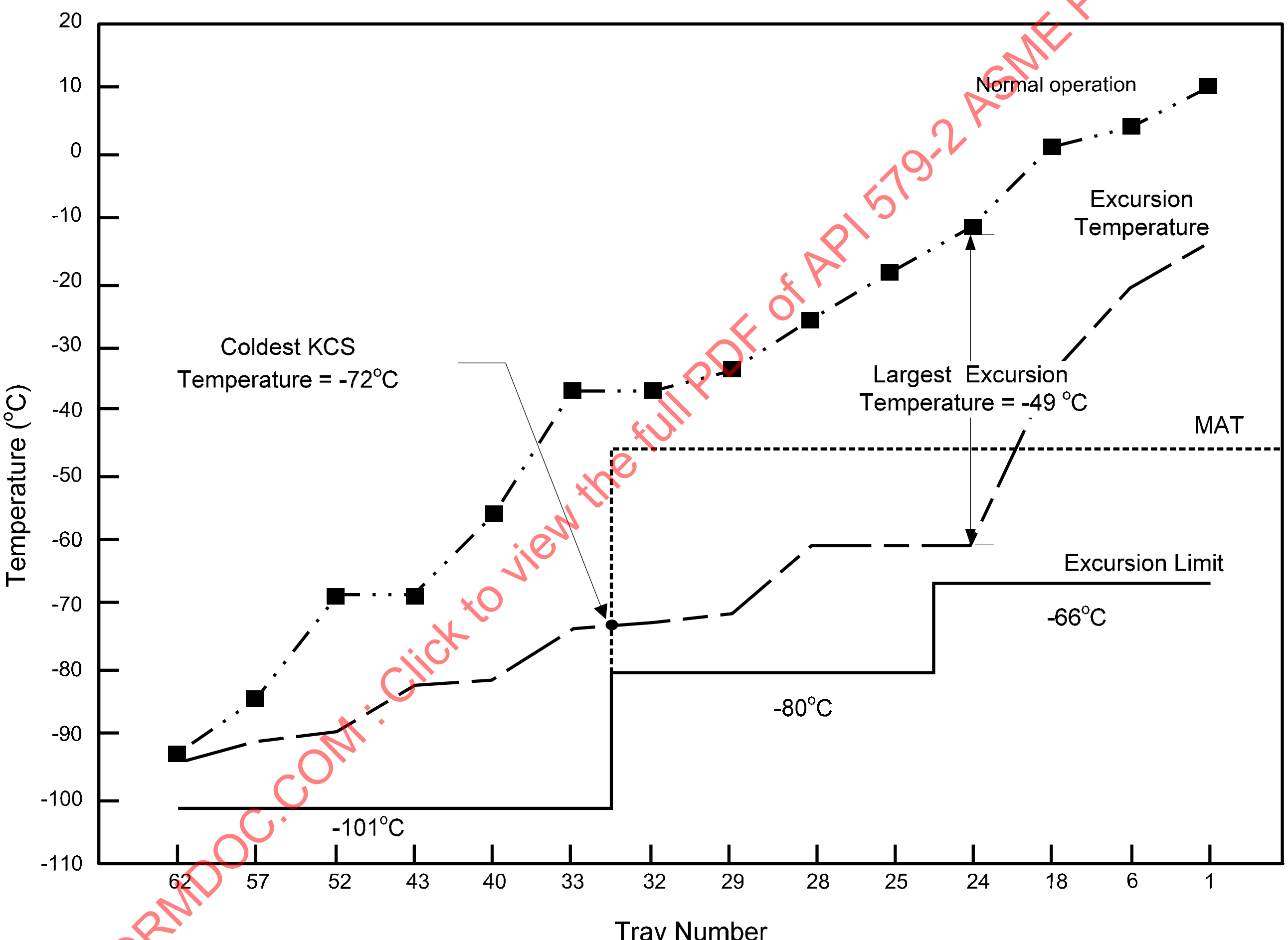


Figure E3.10-6
Demethanizer MAT Versus Location

To illustrate the influence of inspection on the results, it is assumed that the tower has been 100% visually inspected internally. In addition, it is assumed that all internal weld seams are inspected by wet fluorescent magnetic particle methods, and angle probe ultrasonic, from the bimetallic weld to a circumferential weld between trays 24 and 25. It is further assumed that any flaw indications would be removed by light grinding. As part of such an assessment it would also be reasonable to conduct a hydrostatic test at 150% of design pressure. These assumptions allow the carbon steel section to be evaluated by two approaches:

- The visually inspected region can be assessed using basic *MAT* principles in accordance with the "code compliant approach", or
- The MT/UT inspected region can be assessed using the more sophisticated FTS approach.

The *MAT* approach for two constant flaw sizes is shown in Figure E3.10-7. One is 22% of the wall thickness, and was selected to pass through original design conditions. For clarity, the effect of the transient stress is ignored in Figure E3.10-7. The 22% curve illustrates that the excursion temperature at tray 24 of -61°C is within the acceptable MAT zone and, provided that additional transient stresses can be accommodated within the excursion margin, the *MAT* can be set at -66°C based on operating rather than design pressure. This check is made by evaluating the critical flaw size during the excursion, using an FTS for tray 24, and ensuring it is always above 22%. The check is made using tray 24 temperature and excursion conditions, with operating pressure applied rather than design. The check confirms that in this case -66°C is an acceptable excursion limit below tray 24.

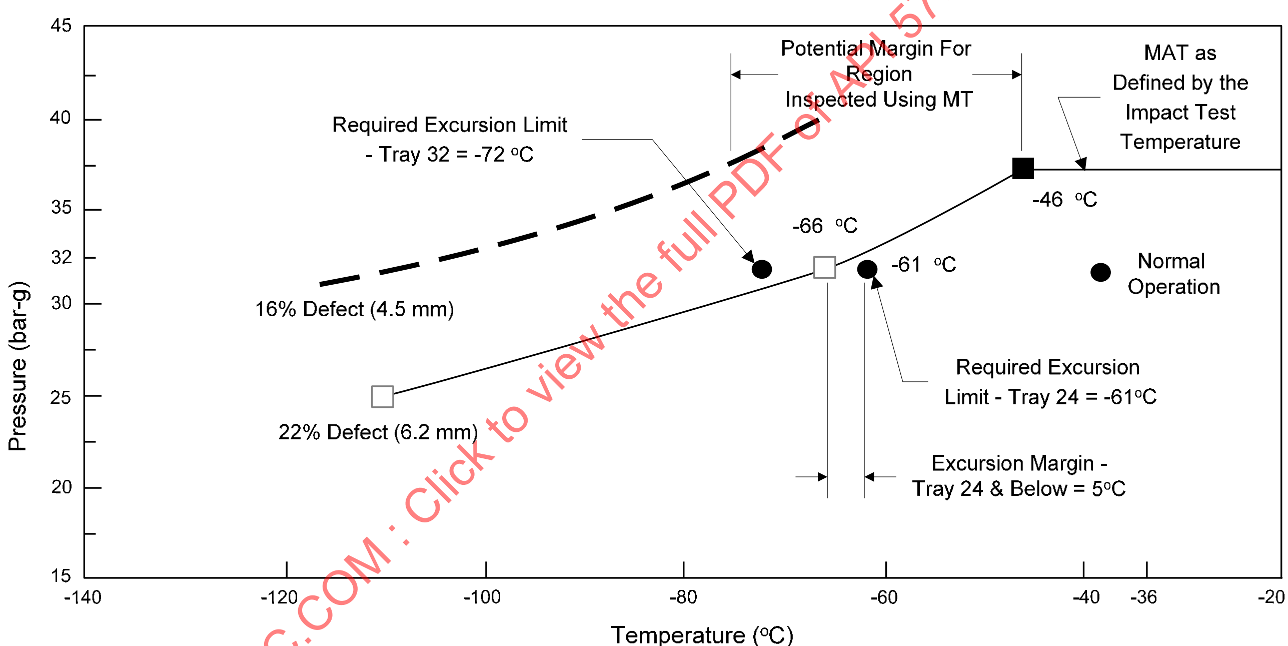


Figure E3.10-7
Pressure Temperature Relationship for Constant Defect Size - Killed Carbon Steel Section

The second feature apparent from the 22% curve is that a violation still exists at tray 32. Tray 32 is however, located in the section of the tower that was subject to MT/UT inspection. Thus it can be assessed on the basis of a smaller flaw size.

The 16% of the wall thickness curve in Figure E3.10-7 represents this criterion as proposed earlier. It is clear that the -72°C excursion is accommodated, even at design pressure.

The FTS curve in Figure E3.10-4, indicates that a 4.5 mm limiting flaw is critical below -80°C when analyzed at full design pressure. In practice the contingency is unlikely to violate design conditions, hence there is an inherent conservatism over the more realistic operating case. An FTS for the operating case results in -111°C as the limiting temperature.

To be of value to operating personnel, and to compare it with the excursion temperature, it is useful to express the result in the form of an excursion limit for the tower, as shown in Figure E3.10-6. This allows a direct comparison of normal operation, excursion temperature, MAT and excursion limits. The distinction between the MAT and the excursion limits is to differentiate between the "code compliant" and non code compliant aspects of the assessment. The purpose of the analysis is to establish reasonable excursion limits and to quantify the risk associated with excursions below the MAT. It is not meant to encourage normal operation at temperatures lower than the MAT.

Recommendations and Conclusions

For this particular type of Level 3 assessment only, the equipment to be evaluated should satisfy the following criteria:

- Meets the design and fabrication requirements of a recognized code of construction,
- Demonstrates, by measured values, minimum toughness of weld, HAZ and plate materials, and
- An appropriate NDE technique is used to preclude the existence of flaws with sufficient confidence based on a risk assessment.

When a Level 3 assessment is made, its acceptability should be subjected to suitable criteria such as the following:

1) Where no additional detailed inspection for a surface breaking flaw is performed by an appropriate NDE technique, the excursion limits should be no lower than the *MAT* as developed by using the assessment procedures in this part.
2) Where MT examination or equivalent is carried out around nozzles and attachments, the MAT may be based on a ¼-t or 6.4 mm deep flaw, whichever is the smaller, with a 6:1 aspect ratio.
3) Where an appropriate NDE technique is used to preclude the existence of flaws with sufficient confidence, the excursion limit can be based on a Fracture Tolerance Signature FTS approach.
4) The assessment is only valid if the service conditions in the vessel are essentially unchanged or less severe than those experienced in the past.
5) Poor operation in terms of control techniques leading to frequent cycling or process upsets should be discouraged by limiting the number of excursions allowed during the life of the vessel.
6) Hydrostatic testing at a temperature where the material toughness is above the lower shelf is recommended.

This is an example of a Level 3 Assessment. It is not intended to be a "prototype" for all Level 3 assessments, since there are many different approaches which can be used successfully at this level.

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PART 4

ASSESSMENT OF GENERAL METAL LOSS

EXAMPLE PROBLEMS

4.1 Example Problem 1

Internal corrosion on the cylindrical shell of a heat exchanger has been found during an inspection. Details regarding the heat exchanger and inspection data are given below. The heat exchanger was constructed to the ASME B&PV Code, Section VIII, Division 1, Edition 1989. Determine if the heat exchanger is suitable for continued operation.

<u>Vessel Data</u>

- Material = $SA-516\ Grade\ 60\ Year\ 1989$
- Design Conditions = $3.85\ MPa\ @380°C\ and\ \ full\ vacuum\ @380°C$
- Inside Diameter = $484\,mm$
- Nominal Thickness = $16\,mm$
- Future Corrosion Allowance = $2\,mm$
- Weld Joint Efficiency = 1.0
- Tubesheet to tubesheet distance = $1524\,mm$

Inspection Data

Based on a visual inspection, the corrosion loss is characterized as general, and point thickness readings will be used in the assessment (see paragraph 4.3.3.1 and 4.3.3.2). Point thickness readings were taken in accordance with paragraph 4.3.3.2.

Table E4.1-1

Location	Thickness Reading t, mm
1	13
2	12
3	11
4	13
5	10
6	12
7	11
8	12
9	13
10	13
11	11
12	12
13	12
14	13
15	13

Perform a Level 1 assessment for internal pressure per paragraph - 4.4.2

a) STEP 1 – Use the point thickness readings shown above; and determine the minimum measured thickness, t_{mm}, the average measured thickness, t_{am}, and the Coefficient of Variation, COV. A template for computing the COV is provided in Table 4.3 and is used in Table E4.1-2.

Table E4.1-2

Location	Thickness Reading $t_{rd,i}, i = 1 \ to \ N$	$t_{rd,i} - t_{am}$	$(t_{rd,i} - t_{am})^2$
1	13	0.9333	0.8711
2	12	-0.0667	0.0044
3	11	-1.0667	1.1378
4	13	0.9333	0.8711
5	10	-2.0667	4.2711
6	12	-0.0667	0.0044
7	11	-1.0667	1.1378
8	12	-0.0667	0.0044
9	13	0.9333	0.8711
10	13	0.9333	0.8711
11	11	-1.0667	1.1378
12	12	-0.0667	0.0044
13	12	-0.0667	0.0044
14	13	0.9333	0.8711
15	13	0.9333	0.8711
	$t_{am} = \frac{1}{N}\sum_{i=1}^{N} t_{rd,i} = 12.0667$		$S = \sum_{i=1}^{N}(t_{rd,i} - t_{am})^2 = 12.9333$
$COV = \frac{1}{t_{am}}\left[\frac{S}{N-1}\right]^{0.5} = 0.080$			

b) STEP 2 – The COV equals 8.0%, which is less than 10%; therefore, the average thickness to be used in the calculation is the average thickness of the thickness distribution, or

$$t_{am} = 12.0667 \ mm$$

$$LOSS = t_{nom} - t_{am} = 16 - 12.0667 = 3.9333 \ mm$$

c) STEP 3 – Calculate the minimum required thickness (see Annex A).

$$t_{min}^{c} = \frac{PR}{(SE - 0.6P)} = \frac{3.85(242 + 2 + 3.9333)}{96.196(1.0) - 0.6(3.85)} = 10.1670 \ mm$$

$$t_{min}^{L} = \frac{PR}{(2SE + 0.4P)} = \frac{3.85(242 + 2 + 3.9333)}{2(96.196)(1.0) + 0.4(3.85)} = 4.9221 \ mm$$

$$t_{min} = \max\left[t_{min}^{c}, t_{min}^{L}\right] = \max[10.1670, 4.9221] = 10.1670 \ mm$$

d) STEP 4 – Determine if the component is acceptable for continued operation.

Perform a Level 1 assessment using Table 4.4.

$$(t_{am} - FCA = 10.0667 \ mm) \geq (t_{min} = 10.1670 \ mm) \rightarrow False$$

Alternatively, the maximum allowable working pressure $MAWP$ based on the average thickness (t_{am}) can be compared to the design pressure with the design pressure as the criterion.

$$t = t_{am} - FCA = 10.0667\ mm$$

$$MAWP = \frac{SEt}{R + FCA + LOSS + 0.6t} = \frac{(96.196)(1)(10.0667)}{(242 + 2 + 3.9333) + (0.6)(10.0667)} = 3.813\ MPa$$

$$3.813\ MPa \geq 3.85\ MPa \rightarrow False$$

The Level 1 assessment criteria are not satisfied.

Perform a Level 2 assessment for internal pressure using Table 4.4.

$$(t_{am} - FCA = 10.0667\ mm) \geq (RSF_a \cdot t_{\min} = (0.9)(10.1287) = 9.1158\ mm) \rightarrow True$$

Alternatively, the maximum allowable working pressure ($MAWP$) based on the average thickness (t_{am}) can be compared to the design pressure with the design pressure as the criterion.

$$t = \frac{(t_{am} - FCA)}{RSF_a} = \frac{10.0667}{0.9} = 11.1852\ mm$$

$$MAWP = \frac{SEt}{R + FCA + LOSS + 0.6t} = \frac{(96.196)(1)(11.1852)}{(242 + 2 + 3.9333) + (0.6)(11.1852)} = 4.225\ MPa$$

$$4.225\ MPa \geq 3.85\ MPa \rightarrow True$$

Check the minimum measured thickness criterion.

$$(t_{mm} - FCA = 8\ mm) \geq \max[0.5t_{\min} = 5.065, t_{\lim}]$$

$$t_{\lim} = \max[0.2t_{nom} = (0.2)(16) = 3.200, 2.500] = 3.200\ mm$$

$$8\ mm \geq (\max[5.065, 3.200] = 5.065\ mm) \rightarrow True$$

The minimum measured thickness criterion is satisfied.

The Level 2 assessment criteria for internal pressure are satisfied.

Perform Level 1 assessment for full vacuum condition.

For this example, the unsupported length of the vessel is given as 1524.00 mm. The thickness used for the calculation is 10.0667 mm computed in STEP 4, above. The calculations below follow the steps shown in Annex A.4.4.

$$E_y = 172(10)^3 \ MPa$$

$$S_y = 157 \ MPa$$

$$R_o = R + t = 242 + 16 = 258 \ mm$$

$$D_o = 2R_o = 516 \ mm$$

$$M_x = \frac{L}{\sqrt{R_o t}} = \frac{1524}{\sqrt{(258)(10.0667)}} = 29.9041$$

$$2\left(\frac{D_o}{t}\right)^{0.94} = 2\left(\frac{516}{10.0667}\right)^{0.94} = 80.9481$$

$$C_h = 1.12 M_x^{-1.058} \quad \rightarrow for\ 13 < M_x < 2\left(\frac{D_o}{t}\right)^{0.94}$$

$$= (1.12)\left(29.904^{-1.058}\right) = 0.0308$$

$$F_{he} = \frac{1.6 C_h E_y t}{D_o} = \frac{(1.6)(0.0308)\left(172 \times 10^3\right)(10.0667)}{516} = 165.3623 \ MPa$$

$$F_{ic} = 0.7 S_y \left(\frac{F_{he}}{S_y}\right)^{0.4} \quad \rightarrow for\ 0.552 < \frac{F_{he}}{S_y} = 1.0533 < 2.439$$

$$= (0.7)(157)\left(\frac{165.3623}{157}\right)^{0.4} = 112.2051 \ MPa$$

$$FS = 2.407 - 0.741\left(\frac{F_{ic}}{S_y}\right) \quad \rightarrow for\ 0.55 S_y < F_{ic} < S_y$$

$$= 2.407 - 0.741\left(\frac{112.2051}{157}\right) = 1.8774$$

$$F_{ha} = \frac{F_{ic}}{FS} = \frac{112.2051}{1.8774} = 59.7662 \ MPa$$

$$P_a = 2F_{ha}\left(\frac{t}{D_o}\right) = (2)(59.7662)\left(\frac{10.0667}{516}\right) = 2.332 \ MPa$$

$$2.332 MPa > 0.101 \ MPa$$

The assessment criterion for full vacuum condition is satisfied.

4.2 Example Problem 2

Internal corrosion at a longitudinal weld seam in a pressure vessel has been found during an inspection. Details regarding the pressure vessel and inspection data are given below. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1, Edition 1998 with the 1999 Addenda. Evaluate if the vessel shell is fit-for-service.

Vessel Data

- Material = $SA-516\,Grade\,70\;Year\;1999$
- Design Conditions = $300\;psig\,@\,350\;°F$
- Inside Diameter = $48\;in$
- Nominal Thickness = $0.75\;in$
- Uniform metal loss = $0.0\;in$
- Future Corrosion Allowance = $0.1\;in$
- Weld Joint Efficiency = 0.85

Inspection Data

The grid used for the inspection and the thickness readings are shown below. The grid spacing set by the Inspector in the circumferential and longitudinal directions is 1.5 in based on the corrosion profile.

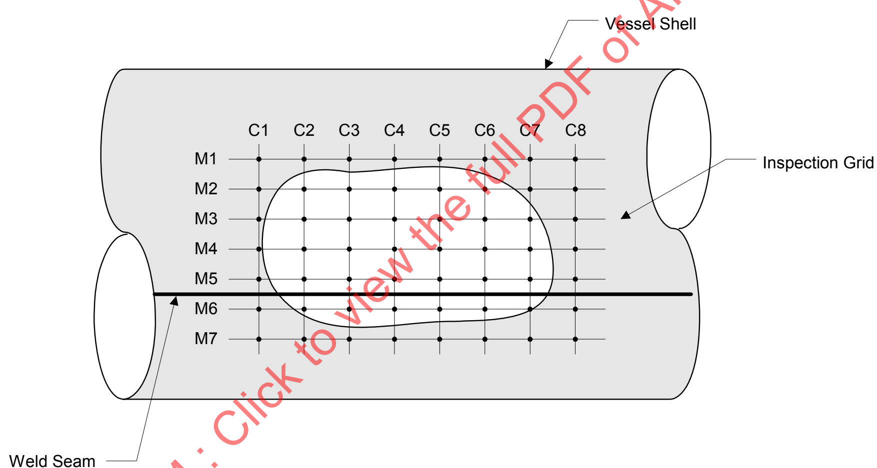

Figure E4.2-1 – Inspection Grid

Table E4.2-1 – Inspection Data (in)

Longitudinal Inspection Planes	Circumferential Inspection Planes								Circumferential CTP
	C1	C2	C3	C4	C5	C6	C7	C8	
M1	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
M2	0.75	0.48	0.52	0.57	0.56	0.58	0.60	0.75	0.48
M3	0.75	0.57	0.59	0.55	0.59	0.60	0.66	0.75	0.55
M4	0.75	0.61	0.47	0.58	0.36	0.58	0.64	0.75	0.36
M5	0.75	0.62	0.59	0.58	0.57	0.48	0.62	0.75	0.48
M6	0.75	0.57	0.59	0.61	0.57	0.56	0.49	0.75	0.49
M7	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Longitudinal CTP	0.75	0.48	0.47	0.55	0.36	0.48	0.49	0.75	

Perform a Level 1 assessment for internal pressure per paragraph 4.4.2

a) STEP 1 – Calculate the minimum required thickness.

$$t^C_{\min} = \frac{PR}{(SE - 0.6P)} = \frac{300(24+0.10)}{20000(0.850) - 0.600(300)} = 0.430\ in$$

$$t^L_{\min} = \frac{PR}{(2SE + 0.4P)} = \frac{300(24+0.10)}{2(20000)(0.850) + 0.400(300)} = 0.212\ in$$

$$t_{\min} = \max\left[t^c_{\min}, t^L_{\min}\right] = \max\left[0.430, 0.212\right] = 0.430\ in$$

b) STEP 2 – Thickness profiles are provided, the data for thickness readings is in the above table.

$$t_{mm} = 0.360\ in$$

c) STEP 3 – Determine wall thickness to be used in the assessment.

$$t_c = t_{rd} - FCA = 0.750 - 0.100 = 0.650\ in$$

d) STEP 4 – Compute the remaining thickness ratio, R_t

$$R_t = \frac{0.360 - 0.100}{0.650} = 0.400$$

e) STEP 5 – Compute the length for thickness averaging from Table 4.5 with $R_t = 0.4$ and $RSF_a = 0.9$, $Q = 0.46$ is read from the table or by the equation:

$$Q = 1.123\left[\left(\frac{1-0.40}{1-\left(\frac{0.400}{0.900}\right)}\right)^2 - 1\right]^{0.5} = 0.4581$$

$$D = 48 + 2(LOSS + FCA) = 48 + 2(0.0 + 0.10) = 48.20\ in$$

$$L = Q\sqrt{Dt_c} = 0.4581\sqrt{(48.20)(0.650)} = 2.564\ in$$

f) STEP 6 – Establish the Critical Thickness Profiles (CTP's) from the thickness profile data (see paragraph 4.3.3.3). Determine the average measured thickness t^s_{am} based on the longitudinal CTP and the average measured thickness t^c_{am} based on the circumferential CTP.

Longitudinal CTP

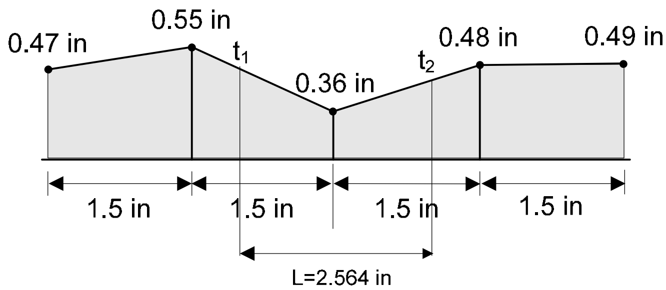

Figure E4.2-2 – Longitudinal Critical Thickness Profile

$$t_1 = 0.360 + (0.550 - 0.360)\left(\frac{1.282}{1.500}\right) = 0.522\ in$$

$$t_2 = 0.360 + (0.480 - 0.360)\left(\frac{1.282}{1.500}\right) = 0.463\ in$$

The area method is used to determine the average thickness.

$$A_1 = \frac{0.522 + 0.360}{2}(1.282) = 0.565\ in^2$$

$$A_2 = \frac{0.360 + 0.463}{2}(1.282) = 0.528\ in^2$$

$$A_1 + A_2 = 1.093\ in^2$$

$$t^s_{am} = \frac{1.093}{2.564} = 0.426\ in$$

Circumferential CTP

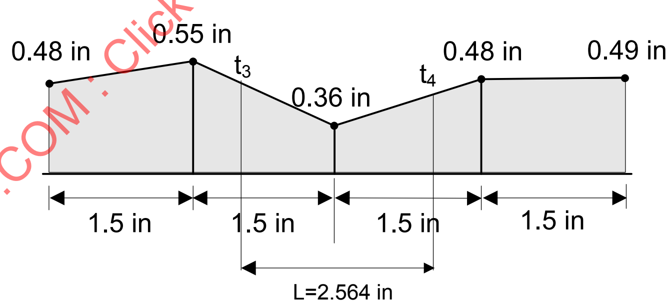

Figure E4.2-3 – Circumferential Critical Thickness Profile

$$t_3 = 0.360 + (0.550 - 0.360)\left(\frac{1.282}{1.500}\right) = 0.522\ in$$

$$t_4 = 0.360 + (0.480 - 0.360)\left(\frac{1.282}{1.500}\right) = 0.463\ in$$

$$A_3 = \frac{0.522 + 0.360}{2}(1.282) = 0.565\ in^2$$

$$A_4 = \frac{0.360 + 0.463}{2}(1.282) = 0.528\ in^2$$

$$A_3 + A_4 = 1.093\ in^2$$

$$t_{am}^c = \frac{1.093}{2.564} = 0.426\ in$$

g) STEP 7 – Determine the acceptability for continued operation using Level 1 criteria in Table 4.4. The averaged measured thickness acceptance is used in this example.

Use averaged measured thickness.

$$t_{am}^s - FCA = 0.426 - 0.10 = 0.326\ in$$

$$t_{\min}^c = 0.430\ in\ from\ step\ 1$$

$$t_{am}^s - FCA > t_{\min}^c \quad \rightarrow False$$

$$t_{am}^c - FCA = 0.426 - 0.10 = 0.326\ in$$

$$t_{\min}^L = 0.212\ in\ from\ step\ 1$$

$$t_{am}^c - FCA > t_{\min}^L \quad \rightarrow True$$

The Level 1 assessment criteria are not satisfied due to the average measured thickness in the longitudinal CTP.

Check the minimum thickness criteria in Table 4.4

$$t_{\lim} = \max\left[(0.20)(0.75), 0.10\right] = 0.150\ in$$

$$t_{mm} - FCA = 0.360 - 0.10 = 0.260\ in$$

$$\max\left[(0.50)(0.430), 0.150\right] = 0.215\ in$$

$$t_{mm} - FCA \geq \max[0.5 t_{\min}, t_{\lim}]$$

$$0.260\ in > 0.215\ in \quad \rightarrow True$$

The minimum thickness criteria are satisfied.

The Level 1 assessment criteria are not satisfied.

Perform a Level 2 Assessment using Table 4.4.

$$(t_{am}^s - FCA = 0.326\ in) \geq (RSF_a \cdot t_{\min} = (0.9)(0.430) = 0.387\ in) \rightarrow False$$

The Level 2 Assessment criteria are not satisfied.

4.3 Example Problem 3

A localized region of internal corrosion on a 2:1 elliptical head has been found during an inspection. The corroded region is within the spherical portion of the elliptical head within 0.8D centered on the head centerline. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1, Edition 1989. Determine if the vessel head is suitable for continued operation.

Vessel Data

- Material = $SA-516\,Grade\,70\;Year\;1989$
- Design Conditions = $1.850\;MPa\;@340\;°C$
- Head Inside Diameter = $2032\;mm$
- Nominal Thickness = $19\;mm$
- Uniform Metal Loss = $0\;mm$
- Future Corrosion Allowance = $3\;mm$
- Weld Joint Efficiency = $1.0\;\;Seamless\;Head$

Inspection Data

The grid used for the inspection and the thickness readings are shown below. The grid spacing is 100 mm.

Table E4.3-1 – Inspection Data (mm)

Meridional Inspection Planes	Circumferential Inspection Planes								Circumferential CTP
	C1	C2	C3	C4	C5	C6	C7	C8	
M1	20	20	19	20	20	19	20	20	19
M2	20	20	20	19	19	19	20	20	19
M3	19	19	19	19	19	19	19	20	19
M4	20	19	19	17	17	18	19	19	17
M5	19	19	19	17	14	15	19	19	14
M6	19	19	20	17	15	16	19	19	15
M7	20	20	19	19	20	19	19	19	19
M8	20	20	19	19	19	19	20	19	19
Meridional CTP	19	19	19	17	14	15	19	19	

Perform a Level 1 assessment per paragraph 4.4.2

a) STEP 1 – Calculate the minimum required thickness using an equivalent radius based on the parameter K_c for the spherical portion of an elliptical head and the spherical shell design equation, (see Annex A).

$$R_{ell} = 2$$

$$K_c = 0.25346 + 0.13995 R_{ell} + 0.12238\left(R_{ell}\right)^2 - 0.015297\left(R_{ell}\right)^3$$

$$K_c = 0.25346 + 0.13995(2) + 0.12238(2)^2 - 0.015297(2)^3 = 0.9005$$

$$t_{\min} = \frac{PDK_c}{2SE - 0.2P} = \frac{(1.850)(2038)(0.9005)}{2(120.658)(1.0) - 0.2(1.850)} = 14.09\;mm$$

b) STEP 2 – Thickness profiles are provided, the data for thickness readings is in the above table. Determine the minimum measured thickness, t_{mm}.

$$t_{mm} = 14\;mm$$

c) STEP 3 – Determine the wall thickness to be used in the assessment using Equation. 4.2 or Equation. 4.3

$$t_c = t_{nom} - LOSS - FCA$$
$$t_c = 19.0 - 0 - 3.0 = 16.0\ mm$$

d) STEP 4 – Compute the remaining thickness ratio, R_t

$$R_t = \frac{t_{mm} - FCA}{t_c} = \frac{14.0 - 3.0}{16.0} = 0.688$$

e) STEP 5 – Determine the length for thickness averaging, L.

From Table 4.5 with $R_t = 0.688$ and $RSF_a = 0.9$, and $Q \approx 1.0$, or by equation:

$$Q = 1.123\left[\left(\frac{1.0 - 0.688}{1.0 - \frac{0.688}{0.90}}\right)^2 - 1.0\right]^{0.5} = 0.975$$
$$R_c = K_c D = (0.9005)(2038) = 1835.219\ mm$$
$$D = 2R_c = 2(1835.219) = 3670.44\ mm$$
$$L = Q\sqrt{Dt_c} = 0.975\sqrt{3670.44(16.0)} = 235.95\ mm$$

f) STEP 6 – Thickness profiles were taken; therefore, determine the longitudinal and circumferential CTP – The thickness readings for the critical inspection planes are shown in the above table.

Meridional CTP

Since in this example the meridional CTP is identical to circumferential CTP, only the assessment of circumferential CTP is performed below. The assessment results of circumferential CTP can be applied for merindional CTP.

Circumferential CTP

Table E4.3-2 – Determine Circumferential CTP

Circumferential Distance (mm)	Thickness Reading (mm)	Thickness – FCA (mm)
0	19	16
100	19	16
200	19	16
300	17	14
400	14	11
500	15	12
600	19	16
700	19	16

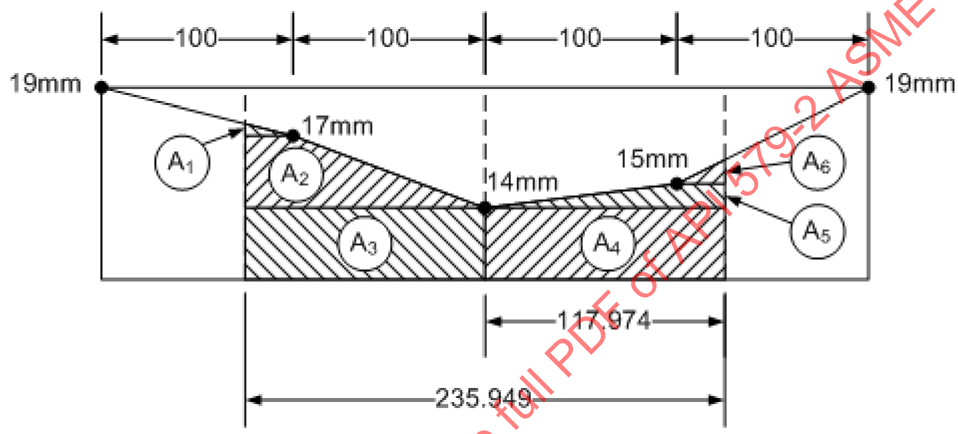

Figure E4.3-1 – Critical Thickness Profile

The average thickness can be determined using the area method.

$$A_1 = \frac{1}{2}\left(\frac{2(17.974)}{100}\right)(17.974) = 3.231\ mm^2$$

$$A_2 = \frac{1}{2}(3)(100) + 3(17.974) = 203.922\ mm^2$$

$$A_3 = A_4 = (117.974)(14) = 1651.636\ mm^2$$

$$A_5 = \frac{1}{2}(1)(100) + 1(17.974) = 67.974\ mm^2$$

$$A_6 = \frac{1}{2}\left(\frac{4(17.974)}{100}\right)(17.974) = 6.461\ mm^2$$

$$A_{TOT} = A_1 + A_2 + A_3 + A_4 + A_5 + A_6$$
$$= 3.231 + 203.922 + 1651.636 + 1651.636 + 67.974 + 6.461 = 3584.860\ \ mm^2$$

$$t^c_{am} = t^s_{am} = \frac{A_{TOT}}{L} = \frac{3584.860}{235.949} = 15.193\ mm$$

g) STEP 7 – Determine the acceptability for continued operation using Level 1 criteria in Table 4.4.

$$t_{am}^{c} - FCA = 15.193 - 3 = 12.193\ mm$$
$$12.193\ mm \geq (t_{\min} = 14.090\ mm) \rightarrow False$$

The Level 1 assessment criteria are not satisfied.
Perform a Level 2 assessment using Table 4.4.

$$(t_{am} - FCA = 12.193\ mm) \geq (RSF_a \cdot t_{\min} = 0.9(14.090) = 12.681\ mm) \rightarrow False$$

Check the minimum measured thickness criterion.

$$t_{mm} - FCA = 14 - 3 = 11\ mm \geq \left(\max\left[0.5t_{\min}, 3\ mm\right] = 7.045\ mm\right) \rightarrow True$$

The minimum measured thickness criterion is satisfied
The Level 2 assessment criteria are not satisfied.

4.4 Example Problem 4

A region of internal corrosion on a 12 inch Class 300 long weld neck nozzle has been found during the inspection of a pressure vessel. The corroded region includes the nozzle bore and a portion of the vessel cylindrical shell (see inspection data). The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1, Edition 1999. Determine if the vessel nozzle is suitable for continued operation.

Vessel Data

- Shell Material = $SA-516\,Grade\,70\;Year\;1999$
- Design Conditions = $185\;psig\,@\,400\;°F$
- Shell Inside Diameter = $60\;in$
- Shell Thickness = $0.60\;in$
- Shell Weld Joint Efficiency = 1.0
- Shell FCA = $0.125\;in$
- Nozzle Inside Diameter = $12.0\;in$
- Nozzle Thickness = $1.375\;in$
- Nozzle Material = $SA-105\;Year\;1999$
- Nozzle Weld Joint Efficiency = 1.0
- Nozzle FCA = $0.125\;in$
- Reinforcing Pad Material = $SA-516\,Grade\,70\;Year\;1999$

Inspection Data

A sketch of the nozzle and metal loss are shown below.

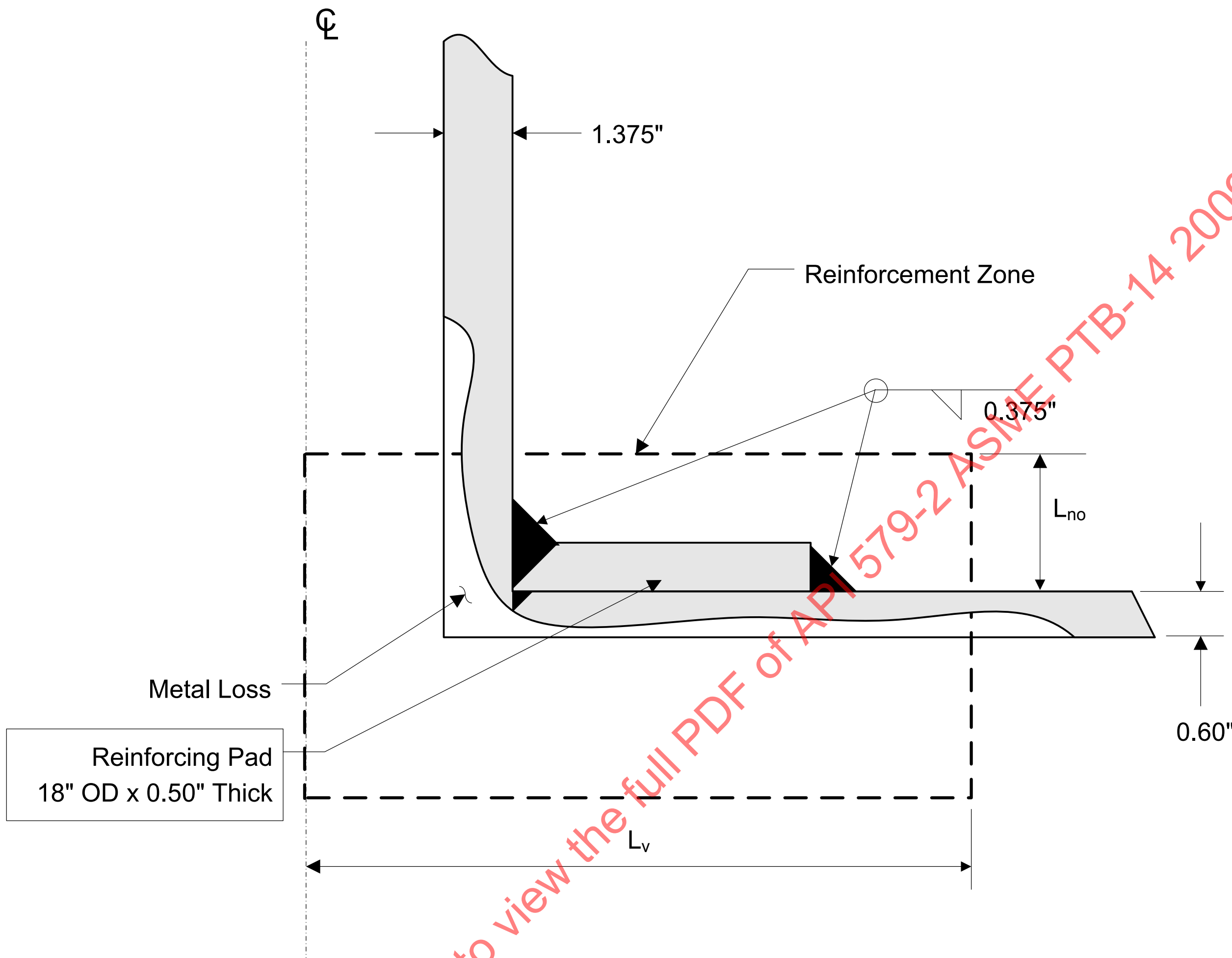

Figure E4.4-1 – Nozzle Metal Loss

From the inspection data:

- The average shell thickness in the nozzle reinforcement zone is 0.50 in.
- The average nozzle thickness in the nozzle reinforcement zone is 0.90 in.
- The corrosion is uniform for each inspection plane.
- The thickness for the shell and nozzle to be used in the assessment were determined by averaging thicknesses within the nozzle reinforcement zone (see paragraph 4.4.3.3.c.1 and Figure 4.9).

Perform a Level 2 assessment because the corrosion is at a major structural discontinuity

From the inspection data:

$$t_{am}^{nozzle} = 0.90 \ in$$

$$t_{am}^{shell} = 0.50 \ in$$

Required thickness of the shell:

$$t_r = \frac{PR}{SE - 0.6P} = \frac{(185)(30 + 0.125 + 0.60 - 0.50)}{(20000)(1.0) - (0.6)(185)} = 0.2811 \ in$$

Required thickness of the nozzle:

$$t_{rn} = \frac{PR}{SE - 0.6P} = \frac{(185)(6 + 0.125 + 1.375 - 0.9)}{(20000)(1) - (0.6)(185)} = 0.0614\ in$$

Check the nozzle reinforcement (see Annex A):
Required Area:

$$d_c = 12.0 + 2(1.375 - 0.90 + 0.125) = 13.2\ in$$
$$F = 1$$
$$f_{r1} = 1 \Rightarrow B = 0.0$$
$$A = (13.2)(0.281)(1) + 0 = 3.709\ in$$

Available area:

$$f_{r2} = 1$$
$$E_1 = 1.0$$
$$f_{r3} = 1$$
$$f_{r4} = 1$$
$$c_s = 0.6 - 0.5 + 0.125 = 0.225\ in$$
$$c_n = 1.375 - 0.9 + 0.125 = 0.60\ in$$
$$w_n = 0.375\ in$$
$$w_p = 0.375\ in$$
$$D_p = 18\ in$$
$$t_e = 0.50\ in$$
$$h = 0.0 \Rightarrow A_3 = 0.0,\ w_h = 0.0\ and\ A_{43} = 0.0$$

$$A_1 = \max\begin{bmatrix} \{d_c(E_1(t - c_s) - Ft_r) - B\} \\ \{2(t + t_n - c_s - c_n)(E_1(t - c_s) - Ft_r) - B\} \end{bmatrix}$$

$$A_1 = \max\begin{bmatrix} \{13.2(1(0.60 - 0.225) - 1(0.2811)) - 0\} = 1.239\ in^2 \\ \{2((0.60 + 1.375 - 0.225 - 0.60)(1(0.6 - 0.225) - 1(0.2811)) - 0\} = 0.2160\ in^2 \end{bmatrix} = 1.239\ in^2$$

$$A_2 = \min\begin{bmatrix} \{5(t_n - c_n - t_{rn})f_{r2}(t - c_s)\} \\ \{2(t_n - c_n - t_{rn})(2.5(t_n - c_n) + t_e)f_{r2}\} \end{bmatrix}$$

$$A_2 = \min\begin{bmatrix} \{5(1.375 - 0.60 - 0.0614)(1)(0.6 - 0.225)\} = 1.338\ in^2 \\ \{2(1.375 - 0.60 - 0.0614)(2.5(1.375 - 0.60) + 0.5)1\} = 3.479\ in^2 \end{bmatrix} = 1.338 in^2$$

$$A_{41} = w_n^2 f_{r2} = (0.375^2)(1) = 0.141\ in^2$$

$$A_{42} = w_p^2 f_{r4} = (0.375^2)(1) = 0.141\ in^2$$

$$A_5 = [D_p - d_c - 2(t_n - c_n)]t_e f_{r4} = [18 - 13.2 - 2(1.375 - 0.6)](0.5)(1) = 1.625\ in^2$$

Reinforcement check:

$$A_1 + A_2 + A_{41} + A_{42} + A_5 = 1.239 + 1.338 + 0.141 + 0.141 + 1.625 = 4.484\ in^2$$

$$4.484\ in^2 \geq (A = 3.709\ in^2) \rightarrow True$$

Analysis Results:

The area reinforcement calculation per the original construction code is satisfied using the average thicknesses for the shell and nozzle in the nozzle reinforcement zone.

The Level 2 assessment criterion is satisfied.

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PART 5

ASSESSMENT OF LOCAL THIN AREAS

EXAMPLE PROBLEMS

5.1 Example Problem 1

A region of localized corrosion has been found on the inside surface of a pressure vessel during a scheduled turnaround. The vessel and inspection data are provided below. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1, 1989 Edition. Determine if the vessel is acceptable for continued operation using a Level 1 Assessment.

<u>Vessel Data</u>

- Material = $SA-516\,Grade\,70\ Year\ 1989$
- Design Conditions = $300\ psig\ @\ 650°F$
- Inside Diameter = $96\ in$
- Fabricated Thickness = $1.25\ in$
- Uniform Metal Loss (Internal) = $0.10\,in$
- FCA = $0.125\,in$
- Longitudinal Weld Joint Efficiency = 1.0
- Circumferential Weld Joint Efficiency = 1.0
- Supplemental Loads = $0\ negligible$

Inspection Data

The thickness data and the grid used for the inspection are shown below. The distance from the region of local metal loss to the nearest structural discontinuity is 60 in. Another region of local metal loss with a smaller amount of metal loss is located 16 in from the region shown below.

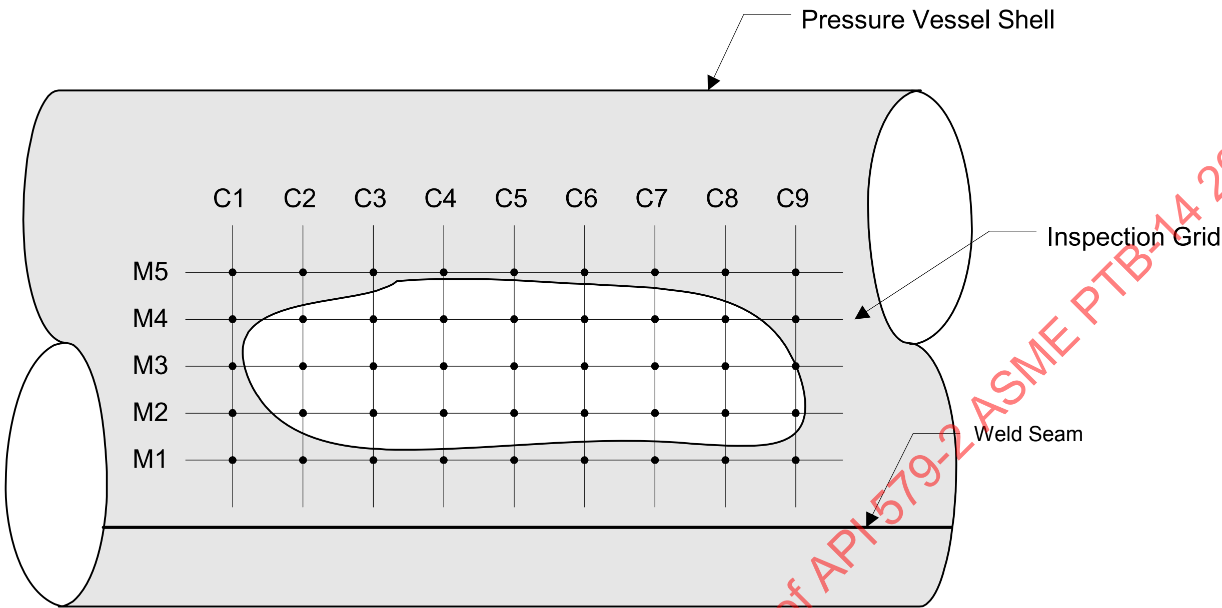


Figure E5.1-1

Table E5.1-1

Inspection Data (in)										
Longitudinal Inspection Planes	Circumferential Inspection Planes									Circumferential CTP
	C1	C2	C3	C4	C5	C6	C7	C8	C9	
M1	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
M2	1.15	0.87	0.75	0.70	0.76	0.80	0.85	0.94	1.15	0.70
M3	1.15	0.81	0.82	0.84	0.62	0.47	0.65	0.90	1.15	0.47
M4	1.15	0.85	0.88	0.81	0.84	0.83	0.90	0.91	1.15	0.81
M5	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
Longitudinal CTP	1.15	0.81	0.75	0.70	0.62	0.47	0.65	0.90	1.15	

Notes:
1. Spacing of thickness readings in longitudinal direction is ½ in.
2. Spacing of thickness readings in circumferential direction is 1.0 in.
3. The localized corrosion is located away from all weld seams.

Perform a Level 1 Assessment per paragraph 5.4.2.2

a) STEP 1 – Determine the CTP (Critical Thickness Profiles) (see paragraph 5.3.3.2) – the thickness readings for the critical inspection planes are indicated in Figure E5.1-1 and Table E5.1-1 above.

b) STEP 2 – Determine the wall thickness to be used in the assessment using equation (5.3).

$$t_{nom} = 1.25\ in$$

$$LOSS = 0.1\ in$$

$$FCA = 0.125\ in$$

$$t_{rd} = t_{nom} - LOSS = 1.25 - 0.1 = 1.15\ in$$

$$t_c = t_{nom} - LOSS - FCA = 1.25 - 0.1 - 0.125 = 1.025\ in$$

c) STEP 3 – Determine the minimum measured thickness, t_{mm} , and the dimension, s, for the longitudinal CTP. The LTA being evaluated satisfies the spacing criteria in Part 4, paragraph 4.3.3.3.f.3; therefore, the dimensions of the LTA do not need to be adjusted (see Figure E5.1-2).

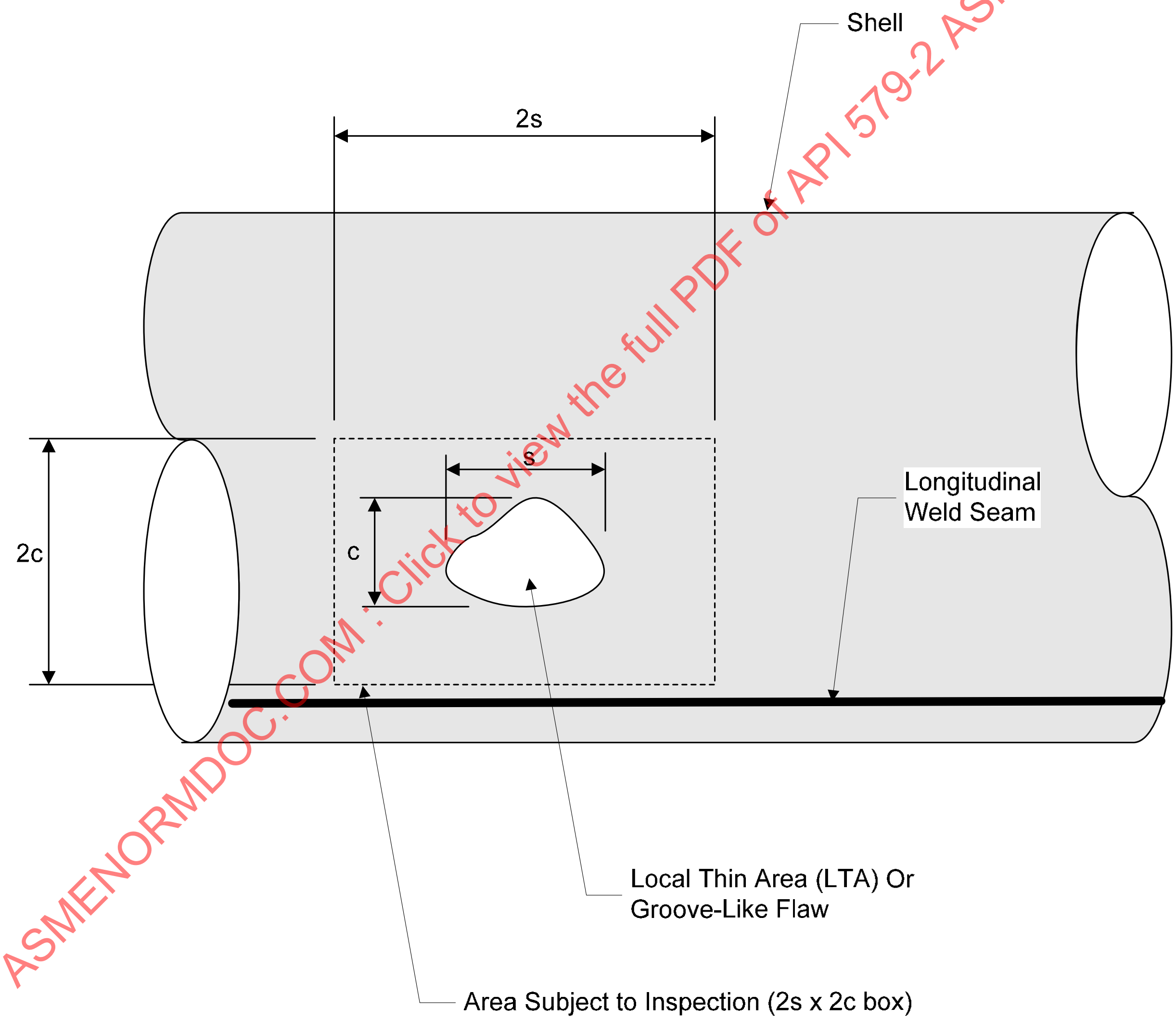


Figure E5.1-2

From inspection data table, the minimum measured thickness is

$$t_{mm} = 0.47\ in$$

From longitudinal CTP, the longitudinal extent of the metal loss is the length between the two end points where the metal loss profile crosses $t_{rd} = 1.15\ in$. Linear interpolation is used to determine the length.

$$s = 8 \times 0.5 = 4\ in$$

d) STEP 4 – Determine the remaining thickness ratio and the longitudinal flaw length parameter. λ using equations (5.5) and (5.6).

$$R_t = \frac{t_{mm} - FCA}{t_c} = \frac{0.47 - 0.125}{1.025} = 0.3366$$

$$D = 96 + 2\times(LOSS + FCA) = 96 + 2\times(0.1 + 0.125) = 96.45\ in$$

$$\lambda = \frac{1.285s}{\sqrt{Dt_c}} = \frac{1.285(4.0)}{\sqrt{96.45(1.025)}} = 0.5170$$

e) STEP 5 – Check the limiting flaw size criteria using equations (5.7), (5.8), and (5.9).

$$(R_t = 0.3366) \geq 0.20 \qquad True$$

$$(t_{mm} - FCA = 0.47 - 0.125 = 0.345\ in) \geq 0.10\ in \qquad True$$

$$(L_{msd} = 60\ in) \geq \left(1.8\sqrt{Dt_c} = 1.8\sqrt{96.45(1.025)} = 17.8972\ in\right) \qquad True$$

f) STEP 6 – Check the criterion for a groove-like flaw. This step is not applicable because the region of localized metal loss is categorized as an LTA.

g) STEP 7 – Determine the $MAWP$ for the component using equations (A.10), (A.16), and (A.22).

Note that $E = 1.0$ since the LTA is remote from weld seams (see paragraph A.2.5.b) of Annex A.

$$R = \frac{D}{2} = \frac{96.45}{2} = 48.225\ in$$

$$MAWP^C = \frac{SEt_c}{R + 0.6t_c} = \frac{(17500)(1.0)(1.025)}{(48.225) + 0.6(1.025)} = 367.2707\ psi$$

$$MAWP^L = \frac{2SE(t_c - t_{sl})}{R - 0.4(t_c - t_{sl})} = \frac{(2)(17500)(1.0)(1.025 - 0.0)}{(48.225) - 0.4(1.025 - 0.0)} = 750.2876\ psi$$

$$MAWP = \min[367.2702,\ 750.2876] = 367.2702\ psi$$

h) STEP 8 – Evaluate the longitudinal extent of the flaw.

From Figure 5.6 with $\left\{\begin{array}{l} \lambda = 0.5170 \\ R_t = 0.3366 \end{array}\right\}$, the longitudinal extent of the flaw is acceptable. Using Table 5.2 and equation (5.11):

$$M_t = 1.0595$$

$$\left(RSF = \frac{R_t}{1 - \frac{1}{M_t}(1 - R_t)} = \frac{0.3366}{1 - \frac{1}{1.0595}(1 - 0.3366)} = 0.9004 \right) \geq (RSF_a = 0.9)$$

The longitudinal extent of the flaw is acceptable.

i) STEP 9 – Evaluate circumferential extent of the flaw.

1) STEP 9.1 – From the circumferential CTP, determine λ_C using equation (5.12)

$$c = 4 \times 1 = 4.0 \ in$$

$$\lambda_C = \frac{1.285c}{\sqrt{Dt_c}} = \frac{1.285(4.0)}{\sqrt{(96.45)(1.025)}} = 0.517$$

2) STEP 9.2 – Check the following conditions (equations (5.13) to (5.17)).

$$(\lambda_c = 0.517) \le 9 \qquad True$$

$$\left(\frac{D}{t_c} = \frac{96.45}{1.025} = 94.0976\right) \ge 20 \qquad True$$

$$0.7 \le (RSF = 0.9004) \le 1.0 \qquad True$$

$$0.7 \le (E_L = 1) \le 1.0 \qquad True$$

$$0.7 \le (E_C = 1) \le 1.0 \qquad True$$

3) STEP 9.3 – Calculate tensile strength factor using equation (5.18),

$$TSF = \frac{E_C}{2 \times RSF}\left(1 + \frac{\sqrt{4 - 3E_L^2}}{E_L}\right) = \frac{1}{2 \times 0.9004}\left(1 + \frac{\sqrt{4 - 3 \times 1^2}}{1}\right) = 1.1106$$

From Figure 5.8 with $\left\{\begin{matrix} \lambda_C = 0.517 \\ R_t = 0.3366 \end{matrix}\right\}$, the circumferential extent of the flaw is acceptable. From Table 5.4,

$$R_{t\_\min} = 0.2$$

$$(R_t = 0.3366) > (R_{t\_\min} = 0.2)$$

The circumferential extent of the flaw is acceptable.

The Level 1 Assessment Criteria are satisfied.

$$(MAWP = 367.27 \ \ psi) > (P_{Design} = 300 \ \ psi)$$

The equipment is acceptable for continued operation.

5.2 Example Problem 2

A pressure vessel shell has two groove-like flaws with the following dimensions. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1, 1989 Edition. Determine if the vessel is acceptable for continued operation.

Vessel Data

- Material = $SA-516\,Grade\,70\ Year\ 1989$
- Design Conditions = $300\ psig\ @\ 250\ ^\circ F$
- Inside Diameter = $90\ in$
- Measured Uniform Thickness = $1.125\ in$
- Uniform Metal Loss = $0.0\ in$
- FCA = $0.125\ in$
- Longitudinal Weld Joint Efficiency = 1.0
- Circumferential Weld Joint Efficiency = 1.0
- Supplemental Loads = $0\ negligible$

Inspection Data

- Groove 1 & 2 Orientation = $longitudinal$
- Groove 1 & 2 Width = $1.5\ in$
- Groove 1 Depth = $0.45\ in$
- Groove 2 Depth = $0.65\ in$
- Groove 1 & 2 Length = $8.0\ in$
- Groove 1 Radius = $0.60\ in$
- Groove 2 Radius = $0.10\ in$

The groove-like flaws are located 20 in apart from each other. Each of the groove-like flaws is located a minimum distance of 36 in away from the nearest structural discontinuity or weld. Based on process conditions and a visual examination, it was determined that both of the grooves were caused by fluid erosion; therefore, both of the groove-like flaws are characterized as a groove per paragraph 5.2.1.b.1).

Perform a Level 1 Assessment per paragraph 5.4.2.2 – Groove 1

a) STEP 1 – Determine the Critical Thickness Profiles(s) (see paragraph 5.3.3.2).

b) STEP 2 – Determine the wall thickness to be used in the assessment using equation (5.4).

$$t_{rd} = t_{nom} - LOSS = 1.125 - 0.0 = 1.125\ in$$

$$t_c = t_{rd} - FCA = 1.125 - 0.125 = 1.0\ in$$

c) STEP 3 – Determine the minimum measured thickness, t_{mm}, and the dimension, s, for the longitudinal CTP.

The groove-like flaw being evaluated satisfies the spacing criteria in Part 4, paragraph 4.3.3.3.f.3; therefore, the dimensions of the groove-like flaw do not need to be adjusted (see Figure E5.2-1).

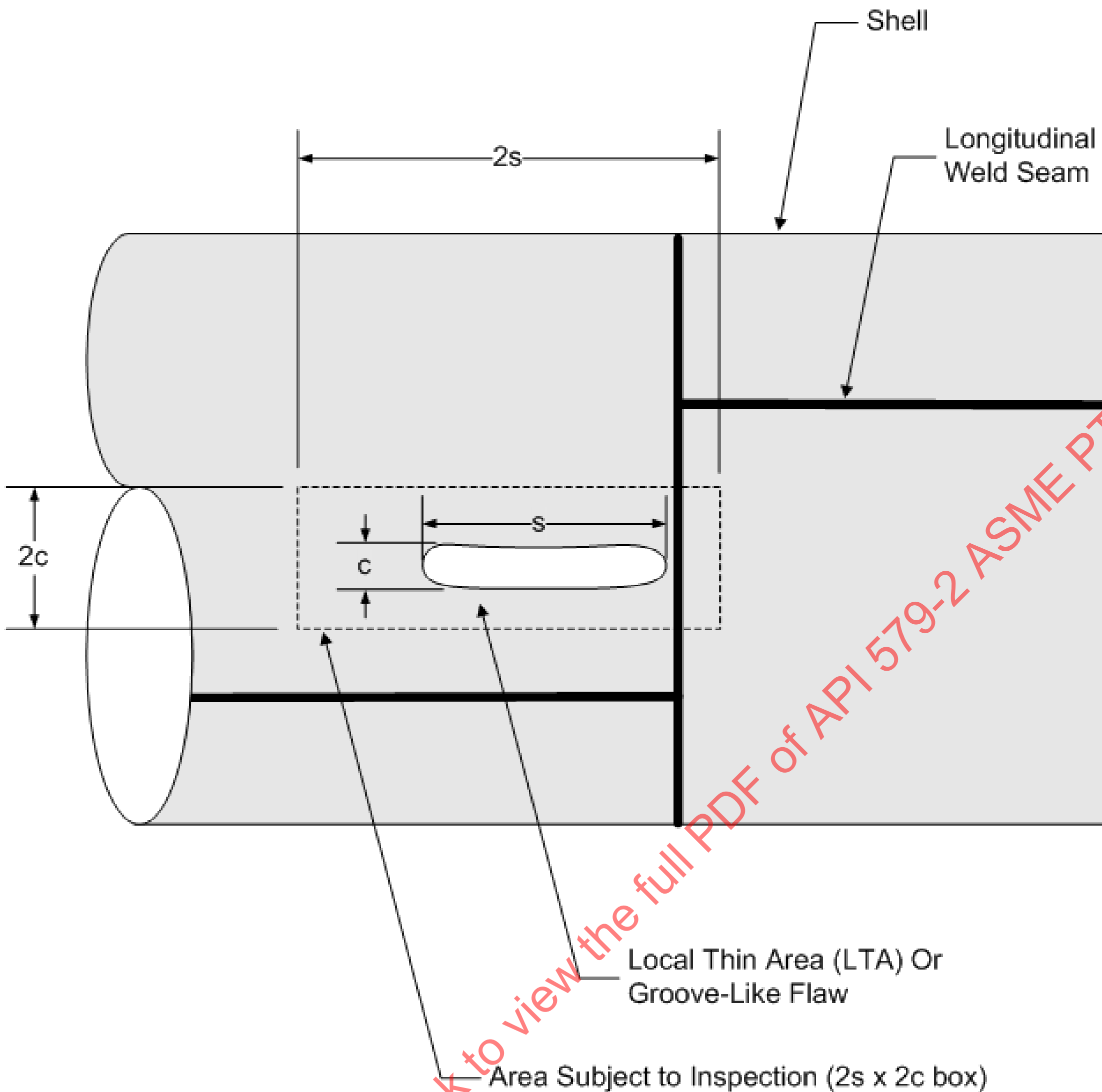


Figure E5.2-1

$$t_{mm} = 1.125 - 0.45 = 0.675\ in$$
$$s = g_l = 8\ in$$
$$\beta = 0.0^o$$

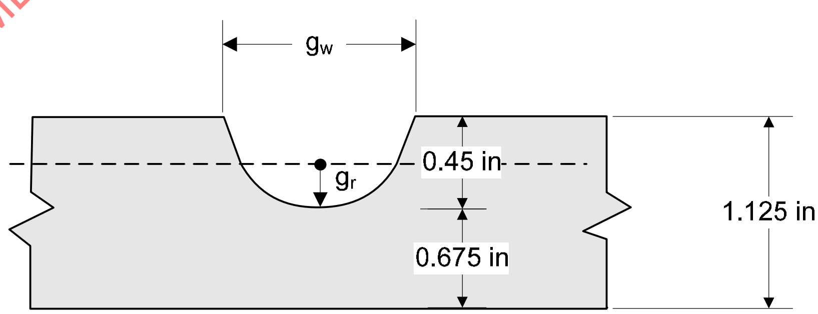


Figure E5.2-2

d) STEP 4 – Determine the remaining thickness ratio and the longitudinal flaw length parameter. λ using equations (5.5) and (5.6).

$$R_t = \frac{t_{mm} - FCA}{t_c} = \frac{0.675 - 0.125}{1.0} = 0.55$$

$$D = 90 + 2 \times FCA = 90 + 2 \times 0.125 = 90.25\ in$$

$$\lambda = \frac{1.285s}{\sqrt{Dt_c}} = \frac{1.285(8.0)}{\sqrt{90.25(1.0)}} = 1.0821$$

e) STEP 5 – Check the limiting flaw size criteria for a Level 1 Assessment using equations (5.7), (5.8), and (5.9).

$$(R_t = 0.55) \geq 0.20 \qquad True$$

$$(t_{mm} - FCA = 0.675 - 0.125 = 0.55\ in) \geq 0.10\ in \qquad True$$

$$(L_{msd} = 36\ in) \geq \left(1.8\sqrt{Dt_c} = 1.8\sqrt{90.25(1.0)} = 17.1\ in\right) \qquad True$$

f) STEP 6 – Check the criterion for a groove-like flaw using equation (5.10).

$$(g_r = 0.6\ in) \geq \left[(1 - R_t)t_c = (1 - 0.55)(1) = 0.45\ in\right] \qquad True$$

The groove satisfies the equation. Proceed to STEP 7.

g) STEP 7 – Determine the $MAWP$ for the component using equations (A.10), (A.16), and (A.22). Note that $E = 1.0$ since the LTA is remote from weld seams (see paragraph A.2.5.b of Annex A).

$$R = \frac{D}{2} = \frac{90.25}{2} = 45.125\ in$$

$$MAWP^C = \frac{SEt_c}{R + 0.6t_c} = \frac{(17500)(1.0)(1.0)}{(45.125) + 0.6(1.0)} = 382.7228\ psi$$

$$MAWP^L = \frac{2SE(t_c - t_{sl})}{R - 0.4(t_c - t_{sl})} = \frac{(2)(17500)(1.0)(1.0 - 0.0)}{(45.125) - 0.4(1.0 - 0.0)} = 782.5601\ psi$$

$$MAWP = \min[382.7228,\ 782.5601] = 382.7228\ psi$$

h) STEP 8 – Evaluate the longitudinal extent of the flaw.

From Figure 5.6 with $\left\{\begin{array}{l} \lambda = 1.0821 \\ R_t = 0.55 \end{array}\right\}$, the longitudinal extent of the flaw is unacceptable at the current $MAWP$ determined in STEP 7. Using Table 5.2 and equations (5.11) and (2.2) to determine the reduced maximum allowable working pressure $MAWP_r$:

$$M_t = 1.2287$$

$$\left(RSF = \frac{R_t}{1 - \frac{1}{M_t}(1 - R_t)} = \frac{0.55}{1 - \frac{1}{1.2287}(1 - 0.55)} = 0.8679 \right) < \left(RSF_a = 0.9 \right)$$

$$MAWP_r = MAWP \frac{RSF}{RSF_a} = (382.7228)\left(\frac{0.8679}{0.9}\right) = 369.072 \ psi$$

$$\left(MAWP_r = 369.072 \ psi \right) > \left(P_{Design} = 300 \ psi \right)$$

The longitudinal extent of the flaw is acceptable.

i) STEP 9 – Evaluate circumferential extent of the flaw.

1) STEP 9.1 – From the circumferential CTP, determine λ_C using equation (5.12).

$$c = g_w = 1.5 \ in$$

$$\lambda_C = \frac{1.285(1.5)}{\sqrt{(90.25)(1.0)}} = 0.2029$$

2) STEP 9.2 – Check the following conditions (equations (5.13) to (5.17)).

$$(\lambda_c = 0.2029) \le 9 \qquad True$$

$$\left(\frac{D}{t_c} = \frac{90.25}{1} = 90.25 \right) \ge 20 \qquad True$$

$$0.7 \le (RSF = 0.8679) \le 1.0 \qquad True$$

$$0.7 \le (E_L = 1) \le 1.0 \qquad True$$

$$0.7 \le (E_C = 1) \le 1.0 \qquad True$$

3) STEP 9.3 – Calculate tensile strength factor using equation (5.18),

$$TSF = \frac{E_C}{2 \times RSF}\left(1 + \frac{\sqrt{4 - 3E_L^2}}{E_L}\right) = \frac{1}{2 \times 0.8679}\left(1 + \frac{\sqrt{4 - 3 \times 1^2}}{1}\right) = 1.1523$$

From Figure 5.7 with $\left\{ \begin{matrix} \lambda_C = 0.2029 \\ R_t = 0.55 \end{matrix} \right\}$, the circumferential extent of the flaw is acceptable. From Table 5.4,

$$R_{t\_min} = 0.2$$

$$(R_t = 0.55) > (R_{t\_min} = 0.2)$$

The circumferential extent of the flaw is acceptable.

The Level 1 Assessment Criteria are Satisfied with a $MAWP_r$ of 369.072 psi (greater than 300 psi design pressure).

Perform a Level 1 Assessment per paragraph 5.4.2.2 – Groove 2

a) STEP 1 – Determine the Critical Thickness Profiles(s) (see paragraph 5.3.3.2).

b) STEP 2 – Determine the wall thickness to be used in the assessment using equation (5.4).

$$t_{rd} = t_{nom} - LOSS = 1.125 - 0.0 = 1.125\ in$$

$$t_c = t_{rd} - FCA = 1.125 - 0.125 = 1.0\ in$$

c) STEP 3 – Determine the minimum measured thickness, t_{mm}, and the dimension, s, for the longitudinal CTP.

The groove-like flaw being evaluated satisfies the spacing criteria in Part 4, paragraph 4.3.3.3.f.3; therefore, the dimensions of the groove-like flaw do not need to be adjusted (see Figure E5.2-1).

$$t_{mm} = 1.125 - 0.65 = 0.475\ in$$

$$s = g_l = 8\ in$$

$$\beta = 0.0^o$$

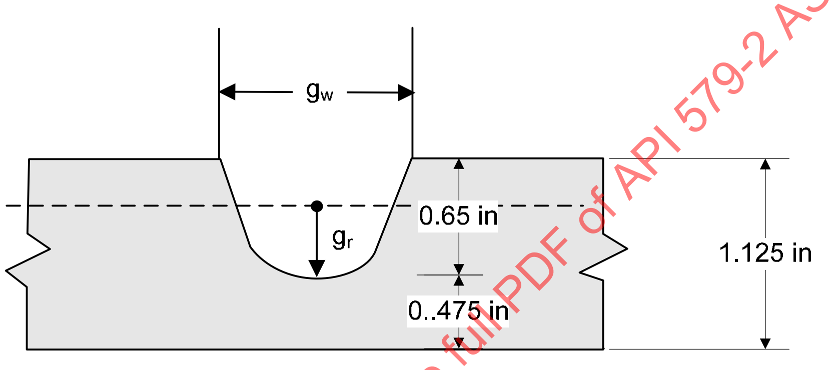


Figure E5.2-3

d) STEP 4 – Determine the remaining thickness ratio and the longitudinal flaw length parameter. λ using equations (5.5) and (5.6).

$$R_t = \frac{t_{mm} - FCA}{t_c} = \frac{0.475 - 0.125}{1.0} = 0.35$$

$$D = 90 + 2 \times FCA = 90 + 2 \times 0.125 = 90.25\ in$$

$$\lambda = \frac{1.285 s}{\sqrt{D t_c}} = \frac{1.285(8.0)}{\sqrt{90.25(1.0)}} = 1.0821$$

e) STEP 5 – Check the limiting flaw size criteria for a Level 1 Assessment using equations (5.7), (5.8), and (5.9).

$$(R_t = 0.35) \geq 0.20 \qquad True$$

$$(t_{mm} - FCA = 0.475 - 0.125 = 0.35\ in.) \geq 0.10\ in \qquad True$$

$$(L_{msd} = 36\ in) \geq \left(1.8\sqrt{D t_c} = 1.8\sqrt{90.25(1.0)} = 17.1\ in\right) \qquad True$$

f) STEP 6 – Check the criterion for a groove-like flaw.

$$(g_r = 0.1\ in) < \left[(1 - R_t) t_c = (1 - 0.35)(1) = 0.65\ in\right] \qquad False$$

The groove is not acceptable per Level 1.

Groove 2 is not acceptable per Part 5 Level 1 Assessment Criteria.

Perform a Level 2 Assessment per paragraph 5.4.3.2 – Groove 2

The Level 2 screening criteria for groove-like flaws are the same as the criteria in Level 1 procedure; therefore, this groove does not satisfy the Level 2 Assessment criteria.

Groove 2 is not acceptable per Part 5 Level 2 Assessment Criteria.

The vessel is unacceptable for continued operation. Alternatively, Groove 2 can be evaluated as a crack-like flaw using the procedures in Part 9.

5.3 Example Problem 3

Inspection of a process vessel indicates a region of local corrosion on the inside surface in the lower shell section. In addition to internal pressure, the vessel is also subjected to axial forces and bending moments. The vessel data is shown below. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1, 1989 Edition. Evaluate the region of localized metal loss for pressure plus supplemental loads and determine acceptability for continued operation without repairs.

<u>Vessel Data</u>

- Material = $SA-516\,Grade\,70\;Year\,1989$
- Design Conditions = $220\;psig\,@\,350\;°F$
- Nominal Thickness = $0.50\;in$
- Inside Diameter = $42\;in$
- Uniform Metal Loss = $0.0\;in$
- *FCA* = $0.06\;in$
- Longitudinal Weld Joint Efficiency = 1.0
- Circumferential Weld Joint Efficiency = 1.0
- Weight Case Loads (see Figure 5.11 for definition of applied loads)
- Applied Axial Force = $500.0\;lbs$
- M_x Applied Bending Moment = $1.79(10)^6\;in-lb$
- M_y Applied Bending Moment = $0.0\;in-lb$
- Applied Shear Force = $137600.0\;lbs$
- Applied Torsional Moment = $1.63(10)^5\;in-lb$
- Thermal Case Loads (see Figure 5.11 for definition of applied loads)
- Applied Axial Force = $2550.0\;lbs$
- M_x Applied Bending Moment = $3.81(10)^6\;in-lb$
- M_y Applied Bending Moment = $0.0\;in-lb$
- Applied Shear Force = $38400.0\;lbs$
- Applied Torsional Moment = $2.59(10)^5\;in-lb$

Note: The weight case and thermal case loads are typically obtained from a stress analysis. The applied forces and moments were computed at the location of maximum metal loss.

Inspection Data

The thickness data and the grid used for the inspection are shown below. This is the only region of localized metal loss found on the vessel during the inspection. The distance from the region of local metal loss to the nearest structural discontinuity is 28 in.

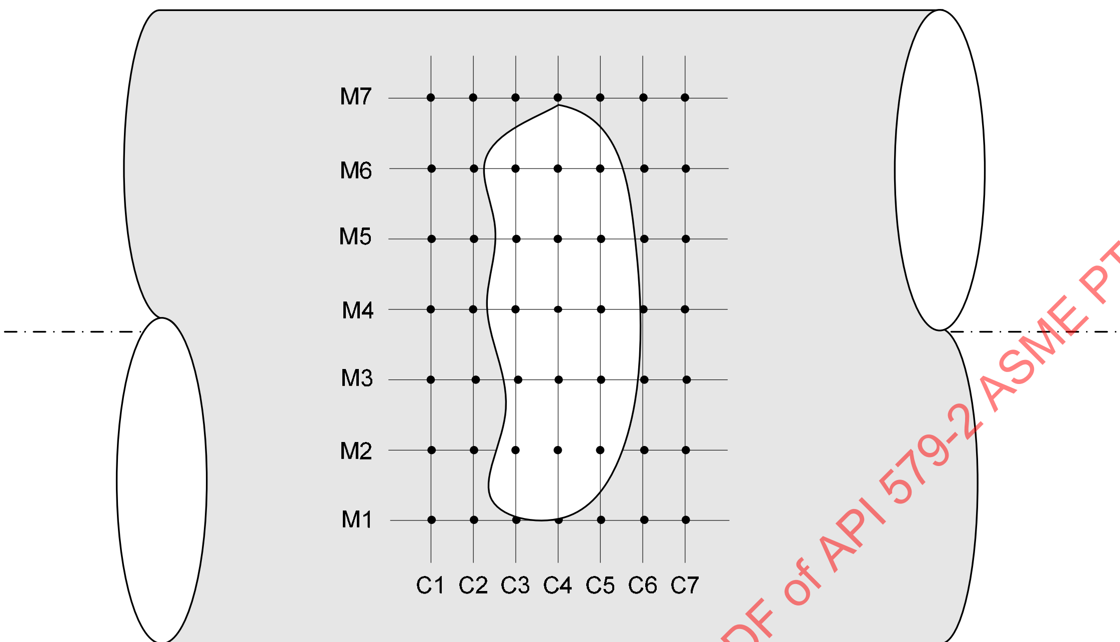


Figure E5.3-1

Table E5.3-1

Inspection Data (in)								
Longitudinal Inspection Planes	Circumferential Inspection Planes							Circumferential CTP
	C1	C2	C3	C4	C5	C6	C7	
M1	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
M2	0.50	0.47	0.44	0.47	0.46	0.48	0.50	0.44
M3	0.50	0.35	0.33	0.39	0.44	0.46	0.50	0.33
M4	0.50	0.41	0.39	0.28	0.26	0.37	0.50	0.26
M5	0.50	0.47	0.42	0.40	0.37	0.35	0.50	0.35
M6	0.50	0.48	0.46	0.42	0.42	0.46	0.50	0.42
M7	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Longitudinal CTP	0.50	0.35	0.33	0.28	0.26	0.35	0.50	

Notes:
1. Spacing of thickness readings in longitudinal direction is 1.0 in.
2. Spacing of thickness readings in circumferential direction is 3.0 in.

Perform a Level 2 Assessment per paragraph 5.4.3.2 because of the presence of external loads.

a) STEP 1 – Determine the Critical Thickness Profiles (see paragraph 5.3.3.2) (same as STEP 1 for the Level 1 Assessment) - the thickness readings for the critical inspection planes are indicated in Figure E5.3-1 and Table E5.3-1 above.

b) STEP 2 – Determine the wall thickness to be used in the assessment using equation (5.3).

$$t_{rd} = t_{nom} - LOSS = 0.5 - 0.0 = 0.5\ in$$
$$t_c = t_{nom} - LOSS - FCA = 0.5 - 0.0 - 0.06 = 0.44\ in$$

c) STEP 3 – Determine the minimum measured thickness, t_{mm}, and the dimension, s, for the longitudinal CTP. There is only one LTA in the vessel; therefore, the spacing criteria in Part 4, paragraph 4.3.3.3.f.3 do not need to be checked .

$$t_{mm} = 0.26\ in$$
$$s = 6 \times 1 = 6\ in$$

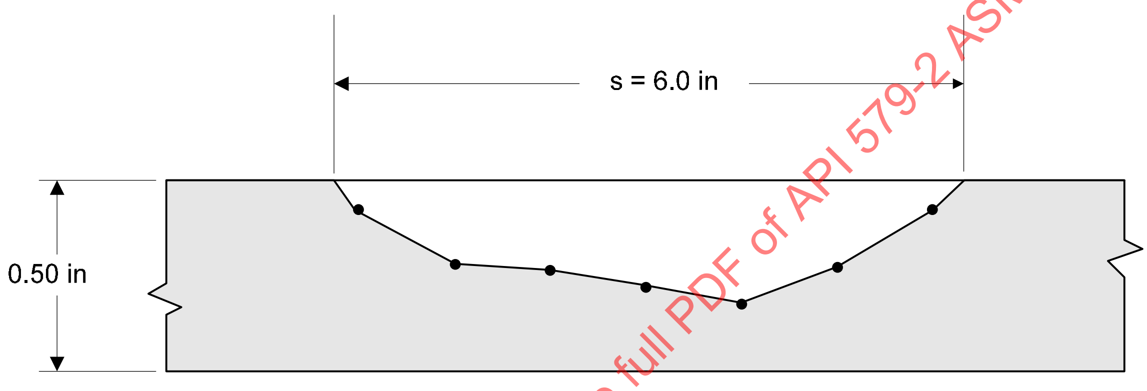


Figure E5.3-2 Longitudinal CTP

d) STEP 4 – Determine the remaining thickness ratio and the longitudinal flaw length parameter. λ using equations (5.5) and (5.6).

$$R_t = \frac{t_{mm} - FCA}{t_c} = \frac{0.26 - 0.06}{0.44} = 0.4545$$
$$D = 42 + 2 \times FCA = 42 + 2 \times 0.06 = 42.12\ in$$
$$\lambda = \frac{1.285s}{\sqrt{Dt_c}} = \frac{1.285(6.0)}{\sqrt{42.12(0.44)}} = 1.791$$

e) STEP 5 – Check the limiting flaw size criteria for a Level 1 Assessment using equations (5.7), (5.8), and (5.9).

$$(R_t = 0.4545) \geq 0.20 \qquad True$$
$$(t_{mm} - FCA = 0.26 - 0.06 = 0.20\ in) \geq 0.10\ in \qquad True$$
$$(L_{msd} = 28\ in) \geq \left(1.8\sqrt{Dt_c} = 1.8\sqrt{42.12(0.44)} = 7.749\ in\right) \qquad True$$

f) STEP 6 – Check the criterion for a groove-like flaw. This step is not applicable because the region of localized metal loss is categorized as an LTA.

g) STEP 7 – Determine the $MAWP$ for the component using equations (A.10), (A.16), and (A.22).

$$R_m = \frac{\left(\frac{D}{2} - FCA + t_{nom}\right) + \frac{D}{2}}{2} = \frac{\left(\frac{42.12}{2} - 0.06 + 0.5\right) + \frac{42.12}{2}}{2} = \frac{21.5 + 21.06}{2} = 21.28\ in$$

$$t_{sl} = \frac{F}{2SE\pi R_m} + \frac{M}{SE\pi R_m^2} = \frac{500}{2(17500)(1.0)\pi(21.28)} + \frac{1.79(10)^6}{(17500)(1.0)\pi(21.28)^2} = 0.0721\ in$$

$$R = \frac{D}{2} = \frac{42.12}{2} = 21.06\ in$$

$$MAWP^C = \frac{SEt_c}{R + 0.6t_c} = \frac{(17500)(1.0)(0.44)}{(21.06) + 0.6(0.44)} = 361.0955\ psi$$

$$MAWP^L = \frac{2SE(t_c - t_{sl})}{R - 0.4(t_c - t_{sl})} = \frac{(2)(17500)(1.0)(0.44 - 0.0721)}{(21.06) - 0.4(0.44 - 0.0721)} = 615.7011\ psi$$

$$MAWP = \min[361.0955,\ 615.7011] = 361.0955\ psi$$

h) STEP 8 – Determine the Remaining Strength Factor for the longitudinal CTP. The remaining strength factor is based on the Level 1 Assessment procedure. This will provide conservative estimates of the RSF. In general, the RSF should be computed using the Level 2 assessment procedure. Using Table 5.2 and equation (5.11):

$$M_t = 1.5221$$

$$\left(RSF = \frac{R_t}{1 - \frac{1}{M_t}(1 - R_t)} = \frac{0.4545}{1 - \frac{1}{1.5221}(1 - 0.4545)} = 0.7084 \right) < (RSF_a = 0.9)$$

i) STEP 9 – Evaluate the longitudinal extent of the flaw.

Since $RSF < RSF_a$, the reduced $MAWP$ can be calculated as

$$MAWP_r = MAWP \frac{RSF}{RSF_a} = (361.0955)\left(\frac{0.7084}{0.9}\right) = 284.2209\ psi$$

$$(MAWP_r = 284.221\ psi) > (P_{Design} = 220\ psi)$$

The longitudinal extent of the flaw is acceptable. Therefore, a remaining strength factor based on Level 2 Assessment is not necessary.

j) STEP 10 – Evaluate the circumferential extent of the flaw – Because of the presence of external loads, the extent of the flaw in the circumferential direction must be evaluated using the procedure in paragraph 5.4.3.4.

1) STEP 10.1 – Determine the Critical Thickness Profile (CTP) in the circumferential direction. This is done in STEP 1.

2) STEP 10.2 – For the circumferential inspection plane being evaluated, approximate the circumferential extent of metal loss on the plane under evaluation as a rectangular shape (Figure 5.11). Calculate D_f using equation (5.23) and θ using equation (5.25).

$$D_o = D + (2t_{nom} - FCA) = 42.12 + (2)(0.5 - 0.06) = 43\ in$$
$$D_f = D_o - 2(t_{mm} - FCA) = 43 - 2(0.26 - 0.06) = 42.6\ in$$
$$c = 6 \times 3 = 18.0\ in$$
$$\theta = \frac{c}{D_f} = \frac{18.0}{42.6} = 0.4225\ radians$$

3) STEP 10.3 – Determine the remaining strength factor, RSF, the reduced maximum allowable working pressure, and supplemental loads on the circumferential plane.

$$RSF = 0.7084$$
$$MAWP_r = 284\ psi$$
$$Weight\ Case\ Supplemental\ Loads$$
$$F = 500.0\ lbs$$
$$M_x = 1.79 \times (10)^6\ in - lbs$$
$$M_y = 0.0\ in - lbs$$
$$V = 137600\ lbs$$
$$M_T = 1.63 \times (10)^5\ in - lbs$$
$$Thermal\ Case\ Supplemental\ Loads$$
$$F = 2550.0\ lbs$$
$$M_x = 3.81 \times (10)^6\ in - lbs$$
$$M_y = 0.0\ in - lbs$$
$$V = 38400\ lbs$$
$$M_T = 2.59 \times (10)^5\ in - lbs$$

4) STEP 10.4 – Compute the components of the resultant longitudinal bending moment (i.e., excluding torsion) in the plane of the defect relative to the region of metal loss. In this case, the moments stated in the problem were aligned with the flaw. In general, the moments will not be aligned with the flaw, and the moments results obtained from a stress analysis will need to be resolved to the axis of the flaw as shown in Figure 5.11.

$$Weight\ Case$$
$$M_x = 1.79 \times (10)^6\ in - lbs$$
$$M_y = 0.0\ in - lbs$$
$$Thermal\ Case$$
$$M_x = 3.81 \times (10)^6\ in - lbs$$
$$M_y = 0.0\ in - lbs$$

5) STEP 10.5 – Compute the circumferential stress resulting from pressure for both weight and weight plus thermal load cases at points A and B in the cross section (Figure 5.12) using equation (5.26).

$$\sigma_{cm} = \frac{MAWP_r}{RSF}\left(\frac{D}{D_o - D} + 0.6\right) = \frac{(284.2209)}{0.7084}\left[\frac{42.12}{43.0 - 42.12} + 0.6\right] = 19444.4444\ psi$$

6) STEP 10.6 – Compute section properties (use equations in Table 5.3) and the longitudinal membrane stress and shear stress for the weight and weight plus thermal load cases at points A and B in the cross section.

i) STEP 10.6.1 – The circumferential plane of the metal loss can be approximated by a rectangular area. Compute section properties of a cylinder without an LTA.

$$A_a = \frac{\pi}{4}D^2 = \frac{\pi}{4}(42.12)^2 = 1393.3705\ in^2$$

$$A_m = \frac{\pi}{4}\left(D_o^2 - D^2\right) = \frac{\pi}{4}\left[(43.0)^2 - (42.12)^2\right] = 58.8307\ in^2$$

$$I_X = \frac{\pi}{64}\left(D_o^4 - D^4\right) = \frac{\pi}{64}\left[(43.0)^4 - (42.12)^4\right] = 13321.8284\ in^4$$

$$I_Y = I_X = 13321.8284\ in^4$$

ii) STEP 10.6.2 – Compute section properties for cylinder with LTA on inside surface.

$$A_f = \frac{\theta}{4}\left(D_f^2 - D^2\right) = \frac{0.4225}{4}\left[(42.6)^2 - (42.12)^2\right] = 4.2957\ \text{in}^2$$

$$A_w = A_a + A_f = 1393.3705 + 4.2957 = 1397.6661\ \text{in}^2$$

$$\bar{y} = \frac{1}{12}\frac{\sin[\theta]\left(D_f^3 - D^3\right)}{A_m - A_f} = \frac{1}{12}\sin[0.4225]\frac{\left[(42.6)^3 - (42.12)^3\right]}{(58.8307 - 4.2957)} = 1.6191\ in$$

$$x_A = 0.0\ in$$

$$y_A = \bar{y} + \frac{D_o}{2} = 1.6191 + \frac{43.0}{2} = 23.1191\ in$$

$$x_B = \frac{D_o}{2}\sin[\theta] = \frac{43.0}{2}\sin[0.4225] = 8.8166\ in$$

$$y_B = \bar{y} + \frac{D_o}{2}\cos[\theta] = 1.6191 + \frac{43.0}{2}\cos[0.4225] = 21.2283\ in$$

$$b = \frac{1}{12}\frac{\sin[\theta]\left(D_f^3 - D^3\right)}{A_a + A_f} = \frac{1}{12}\sin[0.4225]\frac{\left[(42.6)^3 - (42.12)^3\right]}{1393.3705 + 4.2957} = 0.0632\ in$$

$$R = \frac{D_f}{2} = \frac{42.6}{2} = 21.3\ in$$

$$d = \frac{\left(D_f - D\right)}{2} = \frac{42.6\text{-}42.12}{2} = 0.24\ in$$

$$A_{tf} = \frac{c\left(D_o + D_f\right)}{8} = \frac{18.0(43.0 + 42.6)}{8} = 192.6\ in^2$$

with,

$$\bar{y}_{LX}=\frac{2R\sin[\theta]}{3\theta}\left(1-\frac{d}{R}+\frac{1}{2-d/R}\right)$$

$$=\frac{2(21.3)\sin[0.4225]}{3(0.4225)}\left[1-\frac{0.24}{21.3}+\frac{1}{2-\frac{0.24}{21.3}}\right]=20.5556\ in$$

$$I_{LX}=R^3d\left[\begin{array}{l}\left(1-\frac{3d}{2R}+\frac{d^2}{R^2}-\frac{d^3}{4R^3}\right)\left(\theta+\sin[\theta]\cos[\theta]-\frac{2\sin^2[\theta]}{\theta}\right)+\\ \frac{d^2\sin^2[\theta]}{3R^2\theta(2-d/R)}\left(1-\frac{d}{R}+\frac{d^2}{6R^2}\right)\end{array}\right]$$

$$=(21.3)^3(0.24)\left\{\begin{array}{l}\left[1-\frac{3(0.24)}{2(21.3)}+\frac{(0.24)^2}{(21.3)^2}-\frac{(0.24)^3}{4(21.3)^3}\right]\cdot\\ \left[\begin{array}{l}(0.4225).+\sin[0.4225]\cos[0.4225]\\ -\frac{2\sin^2[0.4225]}{(0.4225)}\end{array}\right]\\ +\frac{(0.24)^2\sin^2[0.4225]}{3(21.3)^2(0.4225)\left(2-\frac{0.24}{21.3}\right)}\left(1-\frac{0.24}{21.3}+\frac{(0.24)^2}{6(21.3)^2}\right)\end{array}\right\}$$

$$=1.35\ in^4$$

$$I_{\bar{X}}=I_X+A_m\bar{y}^2-I_{LX}-A_f\left(\bar{y}_{LX}+\bar{y}\right)^2$$

$$=13321.828+(58.8307)(1.6191)^2-1.35-(4.2957)(20.5556+1.6191)^2$$

$$=11362.4528\ \text{in}^4$$

$$I_{LY}=R^3d\left[\left(1-\frac{3d}{2R}+\frac{d^2}{R^2}-\frac{d^3}{4R^3}\right)\left(\theta-\sin[\theta]\cos[\theta]\right)\right]$$

$$=(21.3)^3(0.24)\left\{\begin{array}{l}\left[1-\frac{3(0.24)}{2(21.3)}+\frac{(0.24)^2}{(21.3)^2}-\frac{(0.24)^3}{4(21.3)^3}\right]\cdot\\ \left[(0.4225)-\sin[0.4225]\cos[0.4225]\right]\end{array}\right\}$$

$$=110.6573\ in^4$$

$$I_{\bar{Y}}=I_Y-I_{LY}=13321.8284-110.6573=13211.1711\ \text{in}^4$$

with,

$$A_t = \frac{\left[0.5\pi\left(D + D_o\right) - c\right]\left(D + D_o\right)}{8}$$

$$= \frac{\left[0.5\pi\left(42.12 + 43.0\right) - 18.0\right]\left[42.12 + 43.0\right]}{8} = 1231.1138\ in^2$$

iii) STEP 10.6.3 – Compute the longitudinal membrane stress and shear stress for the weight and weight plus thermal load cases at points A and B in the cross section using equations (5.27) to (5.32).

For the Weight Case, points A and B

$$\lambda_C = \frac{1.285c}{\sqrt{Dt_c}} = \frac{(1.285)(18.0)}{\sqrt{(42.12)(0.44)}} = 5.3729$$

$$M_t^C = \frac{1.0 + 0.1401(\lambda_C)^2 + 0.002046(\lambda_C)^4}{1.0 + 0.09556(\lambda_C)^2 + 0.0005024(\lambda_C)^4} = \frac{1.0 + 0.1401(5.3729)^2 + 0.002046(5.3729)^4}{1.0 + 0.09556(5.3729)^2 + 0.0005024(5.3729)^4}$$

$$= 1.6157$$

$$M_s^C = \frac{1 - \left(\frac{1}{M_t^C}\right)\left(\frac{d}{t_c}\right)}{1 - \left(\frac{d}{t_c}\right)} = \frac{1 - \left(\frac{1}{1.6157}\right)\left(\frac{0.24}{0.44}\right)}{1 - \left(\frac{0.24}{0.44}\right)} = 1.4573$$

$$\sigma_{lm}^{A}=\frac{M_s^C}{E_c}\left\{\begin{array}{l}\dfrac{A_w}{A_m-A_f}\left(MAWP_r\right)+\dfrac{F_T}{A_m-A_f}+\\ \dfrac{y_A}{I_{\bar{X}}}\left[F_T\bar{y}+\left(\bar{y}+b\right)\left(MAWP_r\right)A_w+M_x\right]+\dfrac{x_A}{I_{\bar{Y}}}M_y\end{array}\right\}$$

$$=\frac{1.4573}{1.0}\left\{\begin{array}{l}\dfrac{1397.6661}{58.8307-4.2957}\left(284.2209\right)+\dfrac{500}{58.8307-4.2957}+\\ \dfrac{23.1191}{11362.4528}\left[\begin{array}{l}\left(500\right)\left(1.6191\right)+\left(1.6191+0.0632\right)\left(284.2209\right)\left(1397.6661\right)\\+1.79\times\left(10\right)^6\end{array}\right]\\ +\dfrac{\left(0\right)}{13211.1711}\left(0\right)\end{array}\right\}$$

$$=17920.3858\ psi$$

$$\sigma_{lm}^{B}=\frac{M_s^C}{E_c}\left\{\begin{array}{l}\dfrac{A_w}{A_m-A_f}\left(MAWP_r\right)+\dfrac{F_T}{A_m-A_f}+\\ \dfrac{y_B}{I_{\bar{X}}}\left[F_T\bar{y}+\left(\bar{y}+b\right)\left(MAWP_r\right)A_w+M_x\right]+\dfrac{x_B}{I_{\bar{Y}}}M_y\end{array}\right\}$$

$$=\frac{1.4573}{1.0}\left\{\begin{array}{l}\dfrac{1397.6661}{58.8307-4.2957}\left(284.2209\right)+\dfrac{500}{58.8307-4.2957}+\\ \dfrac{21.2283}{11362.4528}\left[\begin{array}{l}\left(500\right)\left(1.6191\right)+\left(1.6191+0.0632\right)\left(284.2209\right)\left(1397.6661\right)\\+1.79\times\left(10\right)^6\end{array}\right]\\ +\dfrac{\left(8.8166\right)}{13211.1711\ in^4}\left(0\right)\end{array}\right\}$$

$$=17324.012\ psi$$

$$\tau=\frac{M_T}{2\left(A_t+A_{tf}\right)\left(t_{mm}-FCA\right)}+\frac{V}{A_m-A_f}$$

$$=\frac{1.63\times\left(10\right)^5}{2\left(1231.1138+192.6\right)\left(0.26-0.06\right)}+\frac{137600}{\left(58.8307-4.2957\right)}$$

$$=2809.3708\ psi$$

For the Weight plus Thermal Case, points A and B

$$\sigma_{lm}^{A}=\frac{M_s^C}{E_c}\left\{\begin{array}{l}\dfrac{A_w}{A_m-A_f}\left(MAWP_r\right)+\dfrac{F_T}{A_m-A_f}+\\ \dfrac{y_A}{I_{\bar{X}}}\left[F_T\bar{y}+\left(\bar{y}+b\right)\left(MAWP_r\right)A_w+M_x\right]+\dfrac{x_A}{I_{\bar{Y}}}M_y\end{array}\right\}$$

$$=\frac{1.4573}{1.0}\left\{\begin{array}{l}\dfrac{1397.6661}{58.8307-4.2957}\left(284.2209\right)+\dfrac{\left(500+2550\right)}{58.8307-4.2957}+\\ \dfrac{23.1191}{11362.4528}\left[\begin{array}{l}\left(500+2550\right)\left(1.6191\right)\\ +\left(1.6191+0.0632\right)\left(284.2209\right)\left(1397.6661\right)\\ +\left(1.79\times\left(10\right)^6+3.81\times\left(10\right)^6\right)\end{array}\right]\\ +\dfrac{\left(0\right)}{13211.1711}\left(0\right)\end{array}\right\}$$

$$=29298.0874\ psi$$

$$\sigma_{lm}^{B}=\frac{M_s^C}{E_c}\left\{\begin{array}{l}\dfrac{A_w}{A_m-A_f}\left(MAWP_r\right)+\dfrac{F_T}{A_m-A_f}+\\ \dfrac{y_B}{I_{\bar{X}}}\left[F_T\bar{y}+\left(\bar{y}+b\right)\left(MAWP_r\right)A_w+M_x\right]+\dfrac{x_B}{I_{\bar{Y}}}M_y\end{array}\right\}$$

$$=\frac{1.4573}{1.0}\left\{\begin{array}{l}\dfrac{1397.6661}{58.8307-4.2957}\left(284.2209\right)+\dfrac{\left(500+2550\right)}{58.8307-4.2957}+\\ \dfrac{21.2283}{11362.4528}\left[\begin{array}{l}\left(500+2550\right)\left(1.6191\right)\\ +\left(1.6191+0.0632\right)\left(284.2209\right)\left(1397.6661\right)\\ +\left(1.79\times\left(10\right)^6+3.81\times\left(10\right)^6\right)\end{array}\right]\\ +\dfrac{\left(8.8166\right)}{13211.1711}\left(0\right)\end{array}\right\}$$

$$=27776.7232\ psi$$

$$\tau=\frac{M_T}{2\left(A_t+A_{tf}\right)\left(t_{mm}-FCA\right)}+\frac{V}{A_m-A_f}$$

$$=\frac{1.63\times\left(10\right)^5+2.59\times\left(10\right)^5}{2\left(1231.1138+192.6\right)\left(0.26-0.06\right)}+\frac{137600+38400}{\left(58.8307-4.2957\right)}$$

$$=3968.3015\ psi$$

7) STEP 10.7 – Compute the equivalent membrane stress for both the weight and weight plus thermal load cases at points A and B in the cross section using equations (5.33) and (5.34).

Weight Case

$$\sigma_e^A = \sqrt{(\sigma_{cm})^2 - (\sigma_{cm})(\sigma_{lm}^A) + (\sigma_{lm}^A)^2 + 3\tau^2}$$
$$= \sqrt{(19444.4444)^2 - (19444.4444)(17920.3858) + (17920.3858)^2 + 3(2809.3708)^2}$$
$$= 19350.7725 \; psi$$

$$\sigma_e^B = \sqrt{(\sigma_{cm})^2 - (\sigma_{cm})(\sigma_{lm}^B) + (\sigma_{lm}^B)^2 + 3\tau^2}$$
$$= \sqrt{(19444.4444)^2 - (19444.4444)(17324.012) + (17324.012)^2 + 3(2809.3708)^2}$$
$$= 19105.7509 \; psi$$

Weight plus Thermal Case

$$\sigma_e^A = \sqrt{(\sigma_{cm})^2 - (\sigma_{cm})(\sigma_{lm}^A) + (\sigma_{lm}^A)^2 + 3\tau^2}$$
$$= \sqrt{(19444.4444)^2 - (19444.4444)(29298.0874) + (29298.0874)^2 + 3(3968.3015)^2}$$
$$= 26721.1819 \; psi$$

$$\sigma_e^B = \sqrt{(\sigma_{cm})^2 - (\sigma_{cm})(\sigma_{lm}^B) + (\sigma_{lm}^B)^2 + 3\tau^2}$$
$$= \sqrt{(19444.4444)^2 - (19444.4444)(27776.7232) + (27776.7232)^2 + 3(3968.3015)^2}$$
$$= 25627.5647 \; psi$$

8) STEP 10.8 – Evaluate the results using equation (5.35).

Weight Case

$$\left\{\max\left[\sigma_e^A, \sigma_e^B\right] = \max\left[19350.7725, 19105.7509\right] = 19350.773 \; psi\right\}$$
$$\leq \left\{H_f\left(\frac{S_a}{RSF_a}\right) = (1.0)\left(\frac{17500}{0.9}\right) = 19444.444 \; psi\right\}$$

Weight plus Thermal Case

$$\left\{\max\left[\sigma_e^A, \sigma_e^B\right] = \max\left[26721.1819, 25627.5647\right] = 26721.182 \; psi\right\}$$
$$\leq \left\{H_f\left(\frac{S_a}{RSF_a}\right) = (3.0)\left(\frac{17500}{0.9}\right) = 58333.333 \; psi\right\}$$

The circumferential extent of the flaw is acceptable.

Therefore, the equipment is acceptable for continued operation without repair

5.4 Example Problem 4

Inspection of a cylindrical pressure vessel indicates a region of localized corrosion. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1, 1992 Edition. Perform a Level 2 Assessment to evaluate the acceptability for continued operation.

Vessel Data

- Material = $SA-516\,Grade\,70\;Year\;1992$
- Design Conditions = $570\;psi\,@\,650\,^{\circ}F$
- Inside Diameter = $60\;in$
- Wall Thickness = $1.0\;in$
- Uniform Metal Loss = $0.0\;in$
- *FCA* = $0.0\;in$
- Longitudinal Weld Joint Efficiency = 1.0
- Circumferential Weld Joint Efficiency = 1.0
- Supplemental Loads = $0.0\;negligible$

Inspection Data

The critical thickness profile for the longitudinal plane is shown in the following table. The critical thickness profile for the circumferential plane can be approximated as a rectangular area of metal loss with a length of 20 in. This is the only region of localized metal loss found on the vessel during the inspection. The region of metal loss is located 72 in away from the nearest structural discontinuity.

Table E5.4-1

Inspection Location	Longitudinal Location (in)	Measured Thickness (in)
1	0	1.00
2	2	0.90
3	4	0.85
4	6	0.70
5	8	0.45
6	10	0.30
7	12	0.40
8	14	0.65
9	16	0.85
10	18	0.90
11	20	1.00

Perform a Level 2 Assessment per paragraph 5.4.3.2

a) STEP 1 – Determine the Critical Thickness Profiles (see paragraph 5.3.3.2) (see Table E5.4-1).

b) STEP 2 – Determine the wall thickness to be used in the assessment using equation (5.3).

$$t_{rd} = t_{nom} - LOSS = 1.0 - 0.0 = 1.0\;in$$

$$t_c = t_{nom} - LOSS - FCA = 1.0 - 0.0 - 0.0 = 1.0\;in$$

c) STEP 3 – Determine the minimum measured thickness, t_{mm}, and the dimension, s, for the longitudinal CTP.

There is only one LTA in the vessel; therefore, the spacing criteria in Part 4, paragraph 4.3.3.3.f.3 do not need to be checked.

$$t_{mm} = 0.30 \; in$$
$$s = 20.0 \; in \;\; based \;\; on \; t_{rd} = 1.0 \; in$$

d) STEP 4 – Determine the remaining thickness ratio, R_t, and the shell parameter, λ using equations (5.5) and (5.6).

$$R_t = \frac{t_{mm} - FCA}{t_c} = \frac{0.3 - 0.0}{1.0} = 0.3$$
$$D = 60 + 2 \times FCA = 60 + 2 \times 0.0 = 60 \; in$$
$$\lambda = \frac{1.285 s}{\sqrt{D t_c}} = \frac{1.285(20)}{\sqrt{60(1.0)}} = 3.3179$$

e) STEP 5 – Check the limiting flaw size criteria for a Level 1 Assessment using equations (5.7), (5.8), and (5.9).

$$(R_t = 0.3) \geq 0.20 \qquad True$$
$$(t_{mm} - FCA = 0.3 - 0.0 = 0.3 \; in) \geq 0.10 \; in \qquad True$$
$$(L_{msd} = 72 \; in) \geq \left(1.8\sqrt{D t_c} = 1.8\sqrt{60(1.0)} = 13.9427 \; in\right) \qquad True$$

f) STEP 6 – Check the criteria for a groove-like flaw. This step is not applicable because the region of localized metal loss is categorized as an LTA.

g) STEP 7 – Determine the $MAWP$ for the component using equations (A.10), (A.16), and (A.22).

$$R = \frac{D}{2} = \frac{60}{2} = 30 \; in$$
$$MAWP^C = \frac{SEt_c}{R + 0.6 t_c} = \frac{(17500)(1.0)(1.0)}{(30) + 0.6(1.0)} = 571.8954 \; psi$$
$$MAWP^L = \frac{2SE(t_c - t_{sl})}{R - 0.4(t_c - t_{sl})} = \frac{(2)(17500)(1.0)(1.0 - 0.0)}{(30) - 0.4(1.0 - 0.0)} = 1182.4 \; psi$$
$$MAWP = \min[571.8954, \; 1182.4] = 571.8954 \; psi$$

h) STEP 8 – Determine the Remaining Strength Factor for the longitudinal CTP

1) STEP 8.1 – Rank the thickness readings in ascending order based on metal loss – based on the CTP data, inspection location 6 would be the starting point for the assessment.

2) STEP 8.2 – Set the initial evaluation starting point as the location of maximum metal loss, this is the location in the thickness profile where t_{mm} is recorded – inspection location 6 has the minimum thickness equals to 0.30 in. Subsequent starting points should be in accordance with the ranking in STEP 8.1
3) STEP 8.3 – At the current evaluation starting point, subdivide the thickness profile into a series of subsections – the thickness profile will be subdivided into 10 sections each 2 inches in length .
4) STEP 8.4 – For each subsection, compute the Remaining Strength Factor using Equation (5.19) and the data tabulated in Table E5.4-2.

Table E5.4-2

Data For Starting Point At Location 6 Of The Longitudinal CTP								
Subsection I	s_s^i (1)	s_e^i (2)	s^i (3)	λ^i (4)	A^i (5)	A_o^i (6)	M_t^i (7)	RSF^i (8)
1	9.0	11.0	2.0	0.3318	1.3375	2.0	1.0250	0.9530
2	8.0	12.0	4.0	0.6636	2.5500	4.0	1.0952	0.8674
3	7.0	13.0	6.0	0.9954	3.5750	6.0	1.1978	0.8042
4	6.0	14.0	8.0	1.3271	4.3500	8.0	1.3229	0.7747
5	5.0	15.0	10.0	1.6589	4.9125	10.0	1.4632	0.7659
6	4.0	16.0	12.0	1.9907	5.3000	12.0	1.6138	0.7687
7	3.0	17.0	14.0	2.3225	5.5750	14.0	1.7709	0.7764
8	2.0	18.0	16.0	2.6543	5.8000	16.0	1.9322	0.7847
9	1.0	19.0	18.0	2.9861	5.9500	18.0	2.0958	0.7948
10	0.0	20.0	20.0	3.3179	6.0000	20.0	2.2607	0.8071

Notes:
1. Starting location of metal loss region under consideration.
2. Ending location of metal loss region under consideration.
3. Length of metal loss for the region under consideration.
4. Shell parameter evaluated using Equation (5.6) integration with $s = s^i$.
5. Area of metal loss evaluated using a numerical procedure.
6. Original metal area evaluated using Equation (5.20).
7. Folias factor evaluated using Table 5.2 with $\lambda = \lambda^i$.
8. Remaining strength factor; evaluated using Equations (5.19).

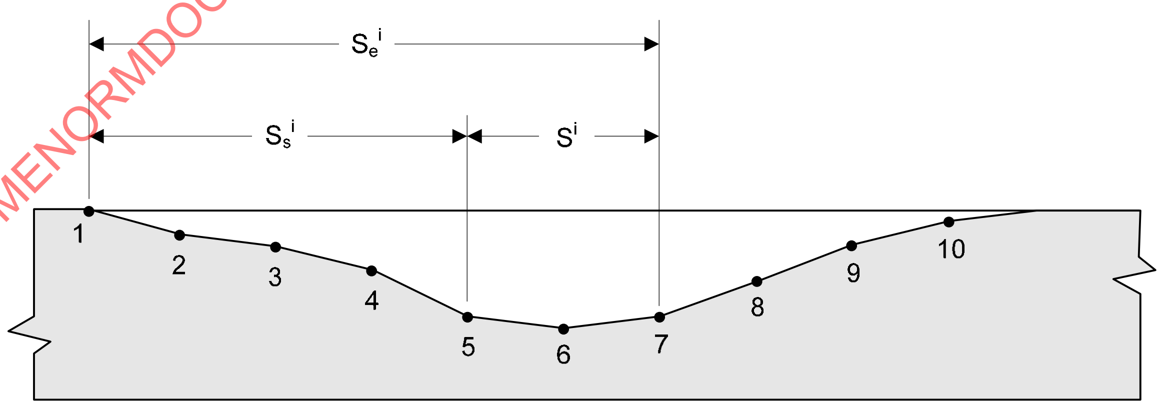


Figure E5.4-1 Thickness Profile

5) STEP 8.5 – Determine the minimum value of the Remaining Strength Factors, RSF^i, found in STEP 8.4 for all subsections. The minimum value of the Remaining Strength Factor for the current evaluation is found to be at subsection 5 when point 6 is used as the subdivision starting point.

$$RSF_{\min} = 0.7659$$

6) STEP 8.6 – Repeat STEPs 8.3 through 8.5 of this calculation for the next evaluation point that corresponds to the next thickness reading location in the ranked thickness profile list; this step is not shown here.

7) STEP 8.7 – After the calculation has been completed for all thickness reading locations (or evaluation points), determine the minimum value of the Remaining Strength Factor from all the calculated RSFs. It is found that the minimum RSF is associated with subsection 5 using point 6 as the subdivision starting point with a value of:

$$RSF = 0.7659$$

i) STEP 9 – Evaluate the longitudinal extent of the flaw and use equation (2.2) for calculating $MAWP_r$.

Since $\left(RSF = 0.7659\right) < \left(RSF_a = 0.9\right)$, the reduced $MAWP$ can be calculated as

$$MAWP_r = MAWP\frac{RSF}{RSF_a} = \left(571.8954\right)\left(\frac{0.7659}{0.9}\right) = 486.683 \ psi$$

$$\left(MAWP = 486.683 \ psi\right) < \left(P_{Design} = 570 \ psi\right)$$

Therefore the longitudinal extent of the flaw is unacceptable for the stated design conditions and a de-rate to 486.683 psi is required if no repair is done.

j) STEP 10 – Evaluate circumferential extent of the flaw. In this example, the Level 1 Assessment method is used because supplemental loads are negligible.

1) STEP 10.1 – From the circumferential CTP, determine λ_C using equation (5.12).

$$c = 20.0 \ in \qquad based \ \ on \ t_{rd} = 1.0 \ in$$

$$\lambda_C = \frac{1.285c}{\sqrt{Dt_c}} = \frac{1.285\left(20\right)}{\sqrt{\left(60\right)\left(1.0\right)}} = 3.3179$$

2) STEP 10.2 – Check the following conditions (equations (5.13) to (5.17)).

$$\left(\lambda_c = 3.3179\right) \le 9 \qquad True$$

$$\left(\frac{D}{t_c} = \frac{60}{1.0} = 60\right) \ge 20 \qquad True$$

$$0.7 \le \left(RSF = 0.7659\right) \le 1.0 \qquad True$$

$$0.7 \le \left(E_L = 1\right) \le 1.0 \qquad True$$

$$0.7 \le \left(E_C = 1\right) \le 1.0 \qquad True$$

3) STEP 10.3 – Calculate tensile strength factor using equation (5.18),

$$TSF = \frac{E_C}{2 \times RSF}\left(1 + \frac{\sqrt{4 - 3E_L^2}}{E_L}\right) = \frac{1}{2 \times 0.7659}\left(1 + \frac{\sqrt{4 - 3 \times 1^2}}{1}\right) = 1.3057$$

From Figure 5.8 with $\begin{Bmatrix} \lambda_C = 3.3179 \\ R_t = 0.3 \end{Bmatrix}$, the circumferential extent of the flaw is unacceptable. From Table 5.4,

$$R_{t\_min} = 0.42$$

Or from Table 5.4, calculate R_{t_min} for $TSF = 1.2$ and $TSF = 1.4$, then find R_{t_min} for $TSF = 1.3057$ through interpolation.

$$R_{t\_min|TSF=1.2} = C_1 + \frac{C_2}{\lambda_c} + \frac{C_3}{\lambda_c^2} + \frac{C_4}{\lambda_c^3} + \frac{C_5}{\lambda_c^4} + \frac{C_6}{\lambda_c^5}$$

$$= \left(7.8654 \times 10^{-1}\right) - \frac{2.5322 \times 10^{-1}}{3.3179} - \frac{5.7982}{(3.3179)^2} + \frac{1.3858 \times 10^1}{(3.3179)^3} - \frac{1.3118 \times 10^1}{(3.3179)^4} + \frac{4.6436}{(3.3179)^5}$$

$$= 0.4662$$

$$R_{t\_min|TSF=1.4} = C_1 + \frac{C_2}{\lambda_c} + \frac{C_3}{\lambda_c^2} + \frac{C_4}{\lambda_c^3} + \frac{C_5}{\lambda_c^4} + \frac{C_6}{\lambda_c^5}$$

$$= \left(7.2335 \times 10^{-1}\right) + \frac{1.1528 \times 10^{-2}}{3.3179} - \frac{9.3536}{(3.3179)^2} + \frac{2.6031 \times 10^1}{(3.3179)^3} - \frac{2.9372 \times 10^1}{(3.3179)^4} + \frac{1.2387 \times 10^1}{(3.3179)^5}$$

$$= 0.3783$$

$$R_{t\_min|TSF=1.304} = 0.4662 - \frac{0.4662 - 0.3783}{1.4 - 1.2} \times (1.3057 - 1.2) = 0.4198$$

$$\left(R_t = 0.3\right) < \left(R_{t\_min} = 0.4198\right)$$

The circumferential extent of the flaw is unacceptable.

Therefore, the Level 2 Assessment Criteria are not satisfied.

The equipment is unacceptable for continued operation under the design conditions, but may be operated at the reduced $MAWP$ of $486\ psi$ per this assessment.

Note that the circumferential extent can be re-assessed using the Level 2 procedure. The results will be improved because a certain level of supplemental loads is included in the Level 1 criteria which makes Level 1 procedure more conservative.

5.5 Example Problem 5

A region of local metal loss has been found on the inside surface of a cylindrical pressure vessel during an inspection. The vessel and inspection data are shown below. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1, 1989 Edition. Determine if the vessel is acceptable for continued operation.

Vessel Data

- Material = $SA-516\,Grade\,60\;Year\;1989$
- Design Conditions = $2.068\;MPa\,@\,340\,°C$
- Inside Diameter = $2438\;mm$
- Fabricated Thickness = $32\;mm$
- Uniform Metal Loss = $2.5\;mm$
- Future Corrosion Allowance = $3.2\;mm$
- Longitudinal Weld Joint Efficiency = 1.0
- Circumferential Weld Joint Efficiency = 1.0
- Supplemental Loads = $0.0\;negligible$

Inspection Data

Based on the inspection data, the critical thickness profile in the longitudinal direction has a length $s = 191\;mm$ and has a uniform measured thickness of 16 mm. The critical thickness profile in the circumferential direction has a length $c = 250\;mm$ with the same uniform thickness. The region of local metal loss is located 1520 mm away from the nearest structural discontinuity. This is the only region of local metal loss found in the vessel during the inspection.

Perform a Level 1 Assessment per paragraph 5.4.2.2

a) STEP 1 – Determine the CTP (Critical Thickness Profiles) (See Inspection Data above).

b) STEP 2 – Determine the wall thickness to be used in the assessment using equation (5.3).

$$t_{nom} = 32\;mm$$

$$LOSS = 2.5\;mm$$

$$FCA = 3.2\;mm$$

$$t_{rd} = t_{nom} - LOSS = 32 - 2.5 = 29.5\;mm$$

$$t_c = t_{nom} - LOSS - FCA = 32 - 2.5 - 3.2 = 26.3\;mm$$

c) STEP 3 – Determine the minimum measured thickness, t_{mm}, and the dimension, s, for the longitudinal CTP. There is only one LTA in the vessel; therefore, the spacing criteria in Part 4, paragraph 4.3.3.3.f.3 do not need to be checked.

$$t_{mm} = 16\;mm$$

$$s = 191\;mm$$

d) STEP 4 – Determine the remaining thickness ratio and the longitudinal flaw length parameter, λ using equations (5.5) and (5.6).

$$R_t = \frac{t_{mm} - FCA}{t_c} = \frac{16 - 3.2}{26.3} = 0.4867$$

$$D = 2438 + 2 \times (LOSS + FCA) = 2438 + 2 \times (2.5 + 3.2) = 2449.4\ mm$$

$$\lambda = \frac{1.285 s}{\sqrt{D t_c}} = \frac{1.285(191)}{\sqrt{2449.4(26.3)}} = 0.967$$

e) STEP 5 – Check the limiting flaw size criteria for a Level 1 Assessment using equations (5.7), (5.8), and (5.9).

$$(R_t = 0.4867) \geq 0.20 \qquad True$$

$$(t_{mm} - FCA = 16 - 3.2 = 12.8\ mm) \geq 2.5\ mm \qquad True$$

$$(L_{msd} = 1520\ mm) \geq \left(1.8\sqrt{D t_c} = 1.8\sqrt{2449.4(26.3)} = 456.857\ mm\right) \qquad True$$

f) STEP 6 – Check the criteria for a groove-like flaw. This step is not applicable because the region of localized metal loss is categorized as an LTA.

g) STEP 7 – Determine the $MAWP$ for the component (see A.3.4) using equations (A.10), (A.16), and (A.22).

$$R = \frac{D}{2} = \frac{2449.4}{2} = 1224.7\ mm$$

$$MAWP^C = \frac{SEt_c}{R + 0.6 t_c} = \frac{(103.42)(1.0)(26.3)}{(1224.7) + 0.6(26.3)} = 2.1927\ MPa$$

$$MAWP^L = \frac{2SE(t_c - t_{sl})}{R - 0.4(t_c - t_{sl})} = \frac{(2)(103.42)(1.0)(26.3 - 0.0)}{(1224.7) - 0.4(26.3 - 0.0)} = 4.4803\ MPa$$

$$MAWP = \min[2.1927,\ 4.4803] = 2.1927\ MPa$$

h) STEP 8 – Evaluate the longitudinal extent of the flaw.

From Figure 5.6 with $\left\{\begin{matrix} \lambda = 0.967 \\ R_t = 0.4867 \end{matrix}\right\}$, the longitudinal extent of the flaw is acceptable. Using Table 5.2 and equation (5.11):

$$M_t = 1.188$$

$$\left(RSF = \frac{R_t}{1 - \frac{1}{M_t}(1 - R_t)} = \frac{0.4867}{1 - \frac{1}{1.188}(1 - 0.4867)} = 0.857 \right) < (RSF_a = 0.9)$$

Since $RSF < RSF_a$, the reduced $MAWP$ can be calculated using equation (2.2)

$$MAWP_r = MAWP\frac{RSF}{RSF_a} = (2.1927)\left(\frac{0.857}{0.9}\right) = 2.0878\ MPa$$

$$(MAWP_r = 2.0878\ MPa) > (P_{Design} = 2.068\ MPa)$$

The longitudinal extent of the flaw is acceptable.

i) STEP 9 – Evaluate circumferential extent of the flaw.

1) STEP 9.1 – From the circumferential CTP, determine λ_C using equation (5.12).

$$c = 250\ mm \qquad based\ on\ t_{rd} = 29.5\ mm$$

$$\lambda_C = \frac{1.285c}{\sqrt{Dt_c}} = \frac{1.285(250)}{\sqrt{(2449.4)(26.3)}} = 1.2657$$

2) STEP 9.2 – Check the following conditions (equations (5.13) to (5.17)).

$$(\lambda_c = 1.2657) \le 9 \qquad True$$

$$\left(\frac{D}{t_c} = \frac{2449.4}{26.3} = 93.1331\right) \ge 20 \qquad True$$

$$0.7 \le (RSF = 0.857) \le 1.0 \qquad True$$

$$0.7 \le (E_L = 1) \le 1.0 \qquad True$$

$$0.7 \le (E_C = 1) \le 1.0 \qquad True$$

3) STEP 9.3 – Calculate tensile strength factor using equation (5.18),

$$TSF = \frac{E_C}{2 \times RSF}\left(1 + \frac{\sqrt{4 - 3E_L^2}}{E_L}\right) = \frac{1}{2 \times 0.857}\left(1 + \frac{\sqrt{4 - 3 \times 1^2}}{1}\right) = 1.1669$$

From Figure 5.8 with $\left\{\begin{matrix} \lambda_C = 1.2657 \\ R_t = 0.4867 \end{matrix}\right\}$, the circumferential extent of the flaw is acceptable. From Table 5.4,

$$R_{t\_min} = 0.2$$

$$(R_t = 0.4867) > (R_{t\_min} = 0.2)$$

The circumferential extent of the flaw is acceptable.

The Level 1 Assessment Criteria are satisfied.

The equipment is acceptable for continued operation.

5.6 Example Problem 6

A region of corrosion in a NPS-14, Schedule 140 nozzle has been found during the inspection of a pressure vessel. The corroded region is located in the nozzle (see inspection data). The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1, 1988 Edition and is not in the fatigue service. Determine if the vessel is acceptable for continued operation.

Vessel Data

- Shell Material = $SA-516\,Grade\,70\ Year\ 1988$
- Design Conditions = $185\ psi\ @350\ °F$
- Shell Inside Diameter = $60\ in$
- Shell Thickness = $0.60\ in$
- Shell Weld Joint Efficiency = 1.0
- Shell Uniform Metal Loss = $0.0\ in$
- Shell *FCA* = $0.125\ in$
- Nozzle Outside Diameter = $14.0\ in$
- Nozzle Thickness = $1.25\ in$
- Nozzle Neck Length = $5.0\ in$
- Nozzle Material = $SA-106\,Grade\,C\ Year\ 1988$
- Nozzle Weld Joint Efficiency = 1.0
- Nozzle Uniform Metal Loss = $0.0\ in$
- Nozzle *FCA* = $0.125\ in$
- Nozzle loads = *negligible*

Inspection Data

The region of localized metal loss is shown in the following figure. The opening is located 45 in from the nearest major structural discontinuity which is a NPS-12 nozzle.

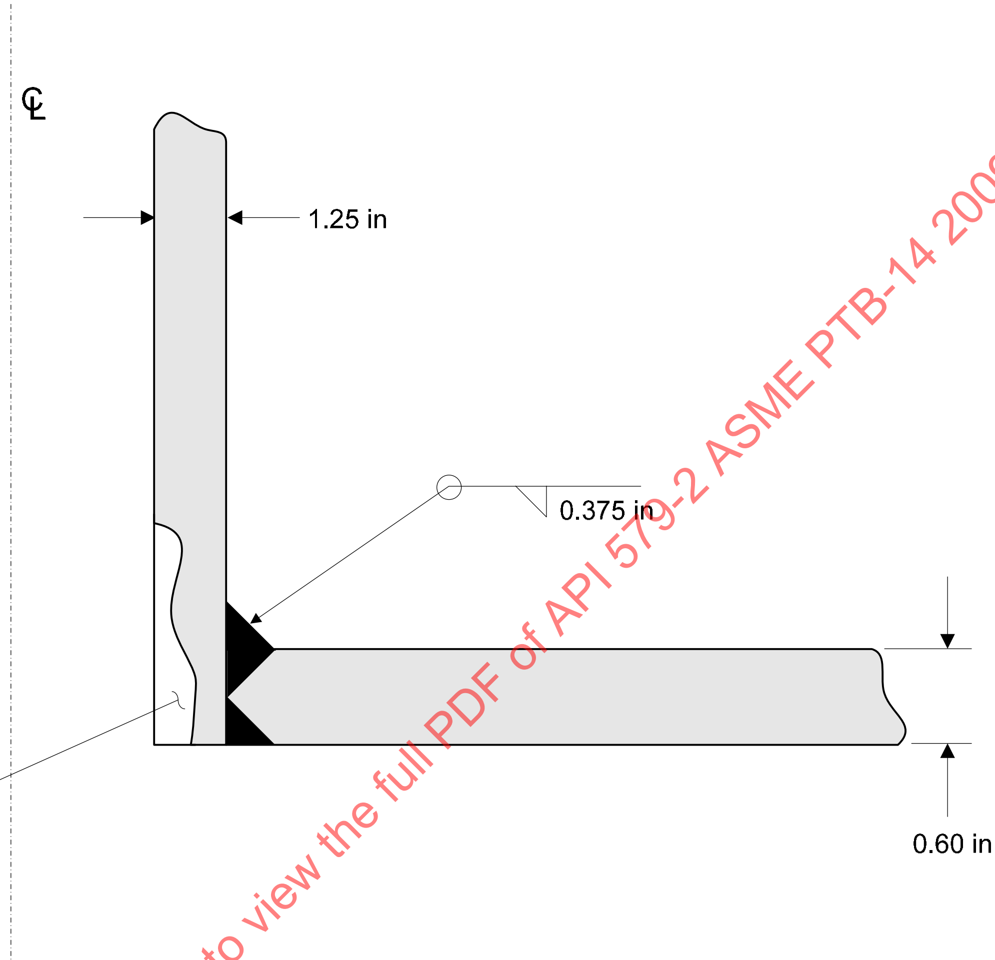


Figure E5.6-1

From the inspection data:

- The average thickness in the nozzle reinforcement zone is 0.875 in
- The corrosion is uniform for all inspection planes.

Perform a Level 2 Assessment per paragraph 5.4.3.5 because the corrosion is at a nozzle. The assessment procedure in Part 4, paragraph 4.4.3.3 is used.

From the inspection data:

$$t_{am}^{shell} = 0.60 \ in$$

$$t_{am}^{nozzle} = 0.875 \ in$$

Required thickness of the shell:

$$t_r = \frac{P(R_s + LOSS_s + FCA_s)}{SE - 0.6P} = \frac{(185)(30 + 0.0 + 0.125)}{(17500)(1.0) - 0.6(185)} = 0.3205 \ in$$

Determine the corroded shell and nozzle mean diameters:

$$D_o = 60 + 2t = 60 + 2 \times 0.6 = 61.2 \ in$$

$$D = 60 + 2\left(LOSS_s + FCA_s\right) = 60 + 2\left(0.0 + 0.125\right) = 60.25 \ in$$

$$D_m = \frac{D_o + D}{2} = \frac{61.2 + 60.25}{2} = 60.725 \ in$$

$$d_o = 14 \ in$$

$$d = d_o - 2t_{am}^{nozzle} + 2FCA_n = 14 - 2\left(0.875\right) + 2\left(0.125\right) = 12.5 \ in$$

$$d_m = \frac{d_o + d}{2} = \frac{14 + 12.5}{2} = 13.25 \ in$$

Perform the assessment using the limit analysis method (see paragraph A.3.11.b) of Annex A) (equations (A.110) to (A.116))

Check the limitations:

$$i.\ Nozzle\ material = SA106, Gr.C\ \ is\ a\ carbon\ steel$$

$$Temperature = 650^{\circ}F < 800^{\circ}F\ Limit\ in\ Table\ A.2 \qquad True$$

$$ii.\ \left(Shell - \frac{YS}{UTS} = \frac{38}{70} = 0.5429\right) < 0.8$$

$$\left(Nozzle - \frac{YS}{UTS} = \frac{40}{70} = 0.5714\right) < 0.8 \qquad True$$

$$iii.\ Nozzle\ is\ NPS-14 < NPS-24 \qquad True$$

$$iv.\ \left(\frac{d_m}{D_m} = \frac{13.25}{60.725} = 0.2182\right) \le 0.5,\ then\left(\frac{D_m}{t} = \frac{60.725}{0.6} = 101.2083\right) \le 250 \qquad True$$

$$v.\ The\ opening\ is\ not\ subject\ to\ cyclic\ loading \qquad True$$

$$vi.\ The\ opening\ is\ in\ a\ cylindrical\ vessel \qquad True$$

$$c_s = LOSS_s + FCA_s = 0.0 + 0.125 = 0.125\ in$$

$$\left(L_{msd} = 45\ in\right) > \left(1.8\sqrt{D_m\left(t-c_s\right)} = 1.8\sqrt{60.725\left(0.6-0.125\right)} = 9.6773\ in\right) \qquad True$$

$$vii.\ \left(Spacing\ between\ two\ openings = 45\ in\right) > \left(3\frac{d_1+d_2}{2} = 3\times\frac{14+12.75}{2} = 40.125\ in\right) \qquad True$$

$$viii.\ The\ opening\ is\ circular\ in\ cross\ section\ with\ its\ axis\ normal\ to\ the\ surface$$

$$of\ the\ cylindrical\ vessel \qquad True$$

$$ix.\ No\ significant\ nozzle\ loads \qquad True$$

$$x.\left(t_{am}^{nozzle} = 0.875\ in\right) > \left(0.875t_{std} = 0.875\times 0.375 = 0.3281\ in\right)$$

$$through\ an\ axial\ length\ of\left(0.5\sqrt{d_m t_{am}^{nozzle}} = 0.5\sqrt{13.25\times 0.875} = 1.7025\ in\right) \qquad True$$

$$xi.\left(L = 5\ in\right) > \left(0.5\sqrt{d_m t_{am}^{nozzle}} = 0.5\sqrt{13.25\times 0.875} = 1.7025\ in\right) \Rightarrow t_n = t_{am}^{nozzle} = 0.875\ in$$

$$c_n = LOSS_n + FCA_n = 0.0 + 0.125 = 0.125\ in$$

$$t_{am}^{nozzle} - c_n = 0.875 - 0.125 = 0.75\ in$$

$$t_{am}^{shell} - c_s = 0.6 - 0.125 = 0.475\ in$$

$$\frac{t_{am}^{nozzle} - c_n}{t_{am}^{shell} - c_s} = \frac{0.75}{0.475} = 1.5789 \quad \Rightarrow \quad A = 54\ \&\ B = 318$$

$$\lambda = \frac{d_m}{D_m}\sqrt{\frac{D_m}{t - c_s}} = \left(\frac{13.25}{60.725}\right)\sqrt{\frac{60.725}{0.6 - 0.125}} = 2.4671$$

$$\left(\begin{array}{l} \dfrac{2 + 2\left(\dfrac{d_m}{D_m}\right)^{3/2}\left(\dfrac{t_{am}^{nozzle} - c_n}{t_{am}^{shell} - c_s}\right)^{1/2} + 1.25\lambda}{1 + \left(\dfrac{d_m}{D_m}\right)^{1/2}\left(\dfrac{t_{am}^{nozzle} - c_n}{t_{am}^{shell} - c_s}\right)^{3/2}} \\ = \dfrac{2 + 2\left(\dfrac{13.25}{60.725}\right)^{3/2}(1.5789)^{1/2} + 1.25(2.4671)}{1 + \left(\dfrac{13.25}{60.725}\right)^{1/2}(1.5789)^{3/2}} = 2.7715 \end{array}\right)$$

$$\leq \left(2.95\left(\frac{t_{am}^{shell} - c_s}{t_r}\right) = 2.95\left(\frac{0.475}{0.3205}\right) = 4.3721\right) \qquad True$$

$$\left(\begin{array}{l} \dfrac{\left[A\left(\dfrac{t_{am}^{nozzle} - c_n}{t_{am}^{shell} - c_s}\right)^2 + 228\left(\dfrac{t_{am}^{nozzle} - c_n}{t_{am}^{shell} - c_s}\right)\left(\dfrac{d_m}{D_m}\right) + B\right]\lambda + 155}{108\lambda^2 + \left[228\left(\dfrac{d_m}{D_m}\right)^2 + 228\right]\lambda + 152} \\ = \dfrac{\left[54(1.5789)^2 + 228(1.5789)\left(\dfrac{13.25}{60.725}\right) + 318\right](2.4671) + 155}{108(2.4671)^2 + \left[228\left(\dfrac{13.25}{60.725}\right)^2 + 228\right](2.4671) + 152} = 1.0478 \end{array}\right)$$

$$\geq \left([0.93 + 0.005\lambda]\left(\frac{t_r}{t_{am}^{shell} - c_s}\right) = [0.93 + 0.005(2.4671)]\left(\frac{0.3205}{0.475}\right) = 0.6358\right) \qquad True$$

Analysis Results:

The area reinforcement calculation using the limit analysis approach is acceptable based on the corroded dimension of the nozzle configuration and the stated design conditions.

The Level 2 Assessment criteria are satisfied.

The vessel is acceptable for continued operation.

5.7 Example Problem 7

A region of corrosion in an atmospheric storage tank has been found during the inspection. The tank was constructed to API 650. Determine if the tank is acceptable for continued operation.

Tank Data

- Material = *ASTM A285 Grade C*
- Design Temperature = *Ambient*
- Design Liquid Height = $40\ ft$
- Diameter = $80\ ft$
- Shell Height = $40\ ft$
- Specific Gravity = 1.0
- Nominal Thickness = $0.58\ in$
- Uniform Metal Loss = $0.11\ in$
- *FCA* = $0.05\ in$
- Weld Joint Efficiency = 1.0

Inspection Data

The grid and data used for the inspection are shown below. The region of corrosion is located 57 inches from the nearest major structural discontinuity.

Table E5.7-1

Inspection Data (in)

Circumferential Inspection Planes		Meridional Inspection Planes												Meridional CTP
	(ft -in)	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	
C1	4-3	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
C2	4-6	0.47	0.47	0.47	0.45	0.45	0.43	0.43	0.43	0.43	0.45	0.46	0.47	0.43
C3	4-9	0.47	0.47	0.45	0.43	0.41	0.36	0.33	0.33	0.40	0.42	0.46	0.47	0.33
C4	5-0	0.47	0.47	0.40	0.36	0.30	0.26	0.33	0.34	0.34	0.35	0.39	0.47	0.26
C5	5-3	0.47	0.41	0.36	0.31	0.26	0.24	0.24	0.24	0.34	0.35	0.37	0.47	0.24
C6	5-6	0.47	0.41	0.38	0.33	0.27	0.23	0.24	0.29	0.33	0.38	0.37	0.47	0.23
C7	5-9	0.47	0.40	0.35	0.31	0.33	0.27	0.26	0.30	0.34	0.34	0.35	0.47	0.26
C8	6-0	0.47	0.42	0.35	0.36	0.33	0.29	0.31	0.30	0.32	0.37	0.39	0.47	0.29
C9	6-3	0.47	0.45	0.41	0.37	0.38	0.36	0.35	0.38	0.41	0.44	0.46	0.47	0.35
C10	6-6	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47	0.47
Circumferential CTP		0.47	0.40	0.35	0.31	0.26	0.23	0.24	0.24	0.32	0.34	0.35	0.47	

Notes:
1. Spacing of thickness readings in meridional or longitudinal direction is 3.0 in
2. Spacing of thickness readings in circumferential direction is 6.0 in

Perform a Level 1 Assessment per paragraph 5.4.2.2

a) STEP 1 – Determine the CTP (Critical Thickness Profiles) (see Table E5.7-1)

b) STEP 2 – Determine the wall thickness to be used in the assessment using equation (5.3).

$$t_{nom} = 0.58\ in$$
$$LOSS = 0.11\ in$$
$$FCA = 0.05\ in$$
$$t_{rd} = t_{nom} - LOSS = 0.58 - 0.11 = 0.47\ in$$
$$t_c = t_{nom} - LOSS - FCA = 0.58 - 0.11 - 0.05 = 0.42\ in$$

c) STEP 3 – Determine the minimum measured thickness, t_{mm}, and the dimension, s, for the longitudinal CTP.

There is only one LTA in the tank; therefore, the flaw-to-flaw spacing criteria do not need to be checked.

$$t_{mm} = 0.23\ in$$
$$s = 9 \times 3 = 27\ in$$

d) STEP 4 – Determine the remaining thickness ratio and the longitudinal flaw length parameter. λ using equations (5.5) and (5.6).

$$R_t = \frac{t_{mm} - FCA}{t_c} = \frac{0.23 - 0.05}{0.42} = 0.4286$$
$$D = 960 + 2 \times (LOSS + FCA) = 960 + 2 \times (0.11 + 0.05) = 960.32\ in$$
$$\lambda = \frac{1.285 s}{\sqrt{D t_c}} = \frac{1.285(27)}{\sqrt{960.32(0.42)}} = 1.7276$$

e) STEP 5 – Check the limiting flaw size criteria using equations (5.7), (5.8), and (5.9).

$$(R_t = 0.4286) \geq 0.20 \qquad True$$
$$(t_{mm} - FCA = 0.23 - 0.05 = 0.18\ in) \geq 0.10\ in \qquad True$$
$$(L_{msd} = 57\ in) \geq \left(1.8\sqrt{D t_c} = 1.8\sqrt{960.32(0.42)} = 36.1497\ in\right) \qquad True$$

f) STEP 6 – Check the criteria for a groove-like flaw. This step is not applicable because the region of localized metal loss is categorized as an LTA.

g) STEP 7 – Determine the MFH for the component (see A.6.3) using equation (A.322).

$$MFH = \frac{t_c \times S}{2.6GD} + 1 = \frac{(0.42)(23595)}{2.6(1.0)(80)} + 1 = 47.6437\ ft$$

h) STEP 8 – Evaluate the longitudinal extent of the flaw.

From Figure 5.6 with $\left\{\begin{matrix} \lambda = 1.7276 \\ R_t = 0.4286 \end{matrix}\right\}$, the longitudinal extent of the flaw is acceptable. Using Table 5.2 and equation (5.11):

$$M_t = 1.4937 \quad \textit{based on Table 5.2 equation}$$

$$\left(RSF = \frac{R_t}{1 - \frac{1}{M_t}(1 - R_t)} = \frac{0.4286}{1 - \frac{1}{1.4937}(1 - 0.4286)} = 0.6941 \right) < (RSF_a = 0.9)$$

$$MFH_r = MFH \frac{RSF}{RSF_a} = (47.6437)\left(\frac{0.6941}{0.9}\right) = 36.7448 \ ft$$

$$(MFH_r = 36.745 \ ft) < (MFH_{Design} = 40 \ ft)$$

Therefore the longitudinal extent of the flaw is unacceptable for the stated design conditions.

i) STEP 9 – Evaluate circumferential extent of the flaw.

1) STEP 9.1 – From the circumferential CTP, determine λ_C using equation (5.12)

$$c = 11 \times 6 = 66 \ in$$

$$\lambda_C = \frac{1.285c}{\sqrt{Dt_c}} = \frac{1.285(66)}{\sqrt{(960.32)(0.42)}} = 4.2229$$

2) STEP 9.2 – Check the following conditions (equations (5.13) to (5.17)).

$$(\lambda_c = 4.2229) \leq 9 \qquad \textit{True}$$

$$\left(\frac{D}{t_c} = \frac{960.32}{0.42} = 2286.5\right) \geq 20 \qquad \textit{True}$$

$$0.7 \leq (RSF = 0.6941) \leq 1.0 \qquad \textit{False}$$

$$0.7 \leq (E_L = 1) \leq 1.0 \qquad \textit{True}$$

$$0.7 \leq (E_C = 1) \leq 1.0 \qquad \textit{True}$$

The circumferential extent of the flaw is unacceptable.

The Level 1 Assessment criteria are not satisfied.

The tank is unacceptable for continued operation.

5.8 Example Problem 8

A region of internal corrosion and/or erosion has been found on the extrados of a seamless long radius piping elbow (90º bend) during an inspection. A piping stress analysis has been performed on this system and the results indicate that the forces and moments from the weight and thermal load cases which act on the elbow are negligible. The piping system was constructed to ASME B31.3 1980 Edition. Determine if the pipe bend is acceptable for continued operation.

Piping Data

- Material = $ASTM\ A234\ Grade\ WPB\ Year\ 1980$
- Design Conditions = $600\ psig\ @\ 700\ ^\circ F$
- Pipe Diameter = $NPS\ 12$
- Wall Thickness = $Schedule\ 40$
- Uniform Metal Loss = $0.0\ in$
- *FCA* = $0.05\ in$

Inspection Data

Thickness readings have been taken based on an inspection grid on the extrados of the elbow. The spacing to the nearest structural discontinuity is 32 in. The thickness readings indicate that the LTA is located in the middle one-third section of the elbow. The critical thickness profiles in the longitudinal and circumferential directions are 6.5 in and 3.0 in in length, respectively. Thickness readings indicate that the metal loss can be assumed to be uniform with the following minimum thickness reading.

$$t_{mm} = 0.18\ in$$

Perform a Level 1 Assessment per paragraph 5.4.2.2

Note that a Level 1 Assessment may be performed for piping bends subject to pressure loading only. In this example, it has been stated that the results of a piping stress analysis indicated that the forces and moments on the pipe bend are negligible.

a) STEP 1 – Determine the CTP (Critical Thickness Profiles) (see Inspection Data above) – the problem states that the metal loss is uniform with

$$t_{mm} = 0.18\ in$$

b) STEP 2 – Determine the wall thickness to be used in the assessment using equation (5.3).

$$D_o = 12.75\ in \qquad Outside\ diameter$$

$$t_{nom} = 0.406\ in \qquad Schedule\ 40$$

$$LOSS = 0.0\ in$$

$$FCA = 0.05\ in$$

$$D = D_o - 2t_{nom} + 2\times(LOSS + FCA) = 12.75 - 2(0.406) + 2\times(0.0 + 0.05) = 12.038\ in$$

$$t_{rd} = t_{nom} - LOSS = 0.406 - 0.0 = 0.406\ in$$

$$t_c = t_{nom} - LOSS - FCA = 0.406 - 0.0 - 0.05 = 0.356\ in$$

c) STEP 3 – Determine the minimum measured thickness, t_{mm}, and the dimension, *s*, for the longitudinal CTP.

There is only one LTA in the elbow; therefore, the flaw-to-flaw spacing criteria do not need to be checked.

$$t_{mm} = 0.18\ in$$
$$s = 6.5\ in$$

d) STEP 4 – Determine the remaining thickness ratio and the longitudinal flaw length parameter. λ using equations (5.5) and (5.6).

$$R_t = \frac{t_{mm} - FCA}{t_c} = \frac{0.18 - 0.05}{0.356} = 0.3652$$

$$\lambda = \frac{1.285s}{\sqrt{Dt_c}} = \frac{1.285(6.5)}{\sqrt{12.038(0.356)}} = 4.0347$$

e) STEP 5 – Check the limiting flaw size criteria using equations (5.7), (5.8), and (5.9).

$$(R_t = 0.3652) \geq 0.20 \qquad True$$
$$(t_{mm} - FCA = 0.18 - 0.05 = 0.13\ in) \geq 0.10\ in \qquad True$$
$$(L_{msd} = 32\ in) \geq \left(1.8\sqrt{Dt_c} = 1.8\sqrt{12.038(0.356)} = 3.7263\ in\right) \qquad True$$

f) STEP 6 – Check the criteria for a groove-like flaw. This step is not applicable because the region of localized metal loss is categorized as an LTA.

g) STEP 7 – Determine the $MAWP$ for the component equation (A.301).

Since this is a long radius elbow, the bend radius is 1.5 times of the pipe diameter. Calculate the Lorenz factor using Eqn. (A.305) for extrados.

$$R_b = 18\ in$$

$$R_m = \frac{D_o + D}{4} = \frac{12.75 + 12.038}{4} = 6.197$$

$$L_f = \frac{\frac{R_b}{R_m} + 0.5}{\frac{R_b}{R_m} + 1.0} = \frac{\frac{18}{6.197} + 0.5}{\frac{18}{6.197} + 1.0} = 0.8719$$

$$MAWP^C = \frac{2\left(\frac{SE}{L_f}\right)t_c}{D_o - 2Y_{B31}t_c} = \frac{2\left[\frac{(16500)(1.0)}{0.8719}\right](0.356)}{12.75 - 2(0.4)(0.356)} = 1080.8729\ psi$$

$$MAWP = MAWP^C = 1080.8729\ psi$$

h) STEP 8 – Evaluate the longitudinal extent of the flaw.

From Figure 5.6 with $\left\{\begin{matrix} \lambda = 4.0347 \\ R_t = 0.3652 \end{matrix}\right\}$, the longitudinal extent of the flaw is acceptable. Using Table 5.2 and equation (5.11):

$$M_t = 2.6172$$

$$\left(RSF = \frac{R_t}{1 - \frac{1}{M_t}(1 - R_t)} = \frac{0.3652}{1 - \frac{1}{2.6172}(1 - 0.3652)} = 0.4821 \right) < \left(RSF_a = 0.9 \right)$$

$$MAWP_r = MAWP \frac{RSF}{RSF_a} = (1080.8729)\left(\frac{0.4821}{0.9}\right) = 579.0022 \ psi$$

$$\left(MAWP_r = 579.002 \ psi \right) < \left(P_{Design} = 600 \ psi \right)$$

Therefore the longitudinal extent of the flaw is unacceptable for the stated design conditions.

i) STEP 9 – Evaluate circumferential extent of the flaw.

1) STEP 9.1 – From the circumferential CTP, determine λ_C using equation (5.12).

$$c = 3.0 \ in$$

$$\lambda_C = \frac{1.285c}{\sqrt{Dt_c}} = \frac{1.285(3)}{\sqrt{(12.038)(0.356)}} = 1.8622$$

2) STEP 9.2 – Check the following conditions (equations (5.13) to (5.17)).

$$\left(\lambda_c = 1.8622 \right) \le 9 \qquad \textit{True}$$

$$\left(\frac{D}{t_c} = \frac{12.038}{0.365} = 33.8146 \right) \ge 20 \qquad \textit{True}$$

$$\left(RSF = 0.4821 \right) \le 0.7 \qquad \textit{False}$$

$$0.7 \le \left(E_L = 1 \right) \le 1.0 \qquad \textit{True}$$

$$0.7 \le \left(E_C = 1 \right) \le 1.0 \qquad \textit{True}$$

The circumferential extent of the flaw is unacceptable.

The Level 1 Assessment criteria are not satisfied.

The pipe bend is unacceptable for continued operation.

5.9 Example Problem 9

A region of localized corrosion has been found in a pressure vessel in vacuum service during a scheduled turnaround. The corrosion is located on the inside surface of the vessel and between 2 stiffening rings that are 80 ft apart. The vessel and inspection data are provided below. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1, 1989 Edition. Determine if the vessel is acceptable for continued operation using a Level 2 Assessment.

Vessel Data

- Material = $SA-516\,Grade\,70\;Year\;1989$
- Design Conditions = $14.7\;psi\;@650\;°F\;(External\;Pressure)$
- Outside Diameter = $100.0\;in$
- Fabricated Thickness = $1.0\;in$
- Uniform Metal Loss (Internal) = $0.0\;in$
- *FCA* = $0.1\;in$
- Weld Joint Efficiency = 1.0
- Supplemental Loads = $0.0\;negligible$
- Out-of-roundness = $0.0\;negligible$

Inspection Data

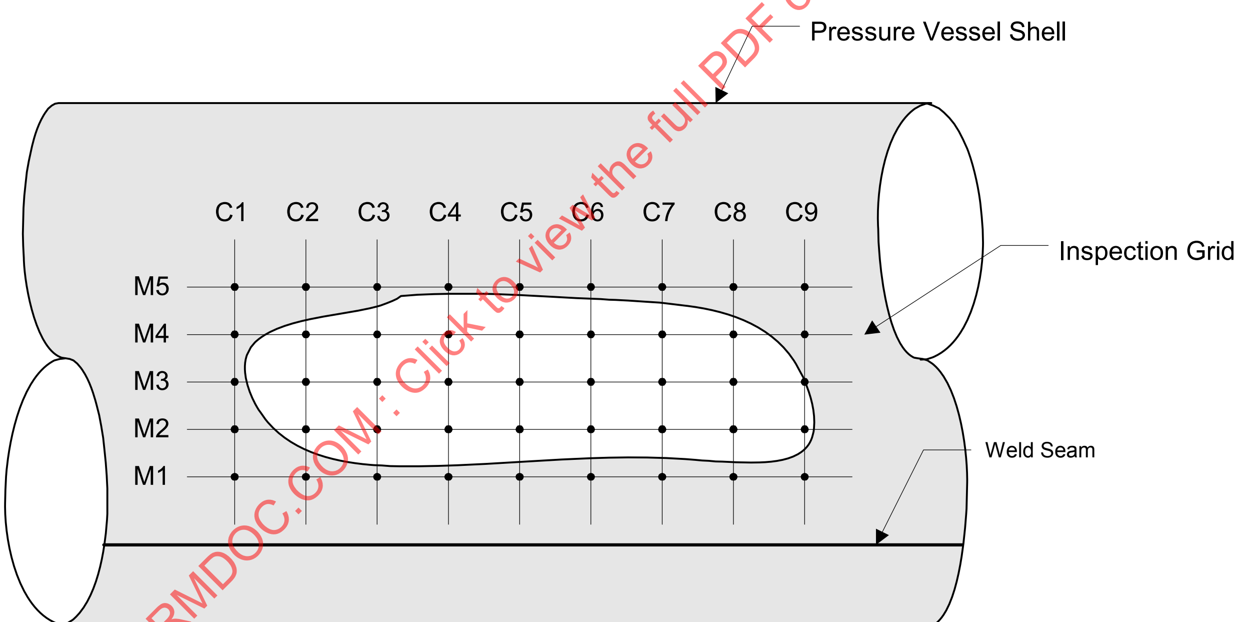


Figure E5.9-1 Inspection Grid

The thickness data and the grid used for the inspection are shown below.

Table E5.9-1

Inspection Data (in)										
Longitudinal Inspection Planes	Circumferential Inspection Planes									Circumferential CTP
	C1	C2	C3	C4	C5	C6	C7	C8	C9	
M1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
M2	1.0	0.87	0.75	0.70	0.76	0.80	0.85	0.94	1.0	0.70
M3	1.0	0.81	0.82	0.84	0.62	0.45	0.65	0.90	1.0	0.45
M4	1.0	0.85	0.88	0.81	0.84	0.83	0.90	0.91	1.0	0.81
M5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Longitudinal CTP	1.0	0.81	0.75	0.70	0.62	0.45	0.65	0.90	1.0	

Notes:
1. Spacing of thickness readings in longitudinal direction is 10 in.
2. Spacing of thickness readings in circumferential direction is 3.0 in.
3. These readings represent the minimum thickness reading within each 3 in X 10 in grid after scanning the entire grid area.

The distance from the edge of the metal loss to the nearest stiffening ring in the longitudinal direction is 310 in on one side and 580 in on another side.

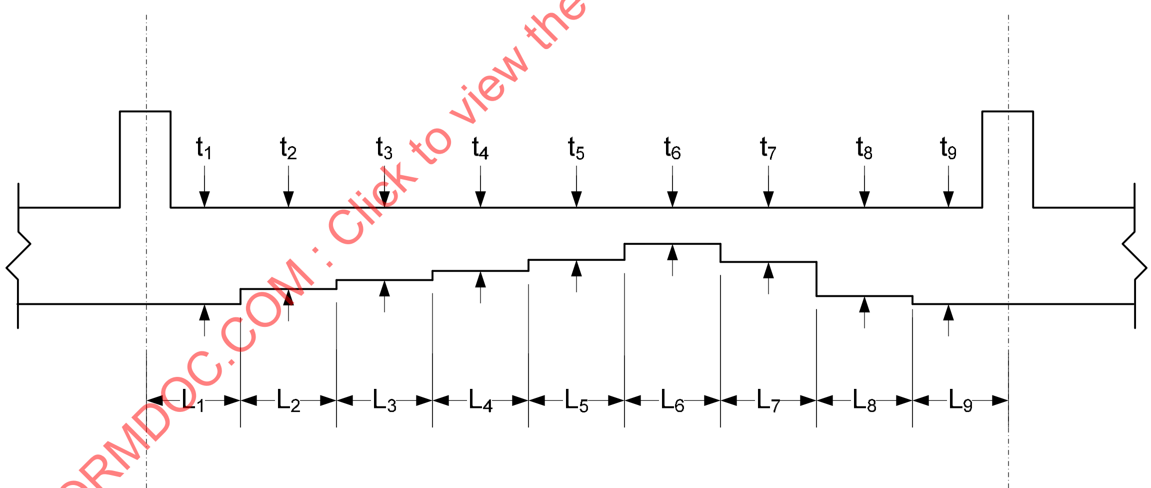


Figure E5.9-2 Thickness Profile

Perform a Level 2 Assessment per paragraph 5.4.3.3

a) STEP 1 – Determine the CTP (Critical Thickness Profiles) (see paragraph 5.3.3.2) – the thickness readings for the critical inspection planes are indicated in Table E5.9-1 and Figure E5.9-1.

b) STEP 2 – Subdivide the CTP in the longitudinal direction using a series of cylindrical shells that approximate the actual metal loss (see Figure E5.9-2). Determine the thickness and length of each of these cylindrical shells and designate them t_i and L_i. The metal loss can be subdivided into 9 regions in the longitudinal direction based on the table below.

Table E5.9-2

Subdivision, i	t_i (in)	L_i (in)
1	1.0	310
2	0.81	10
3	0.75	10
4	0.70	10
5	0.62	10
6	0.45	10
7	0.65	10
8	0.90	10
9	1.0	580

c) STEP 3 – Use the method in Annex A, Paragraph A.4 to calculate the allowable external pressure, P_i^e, for each subdivision (see Table E5.9-3).

$$t_{nom} = 1.0\ in$$

$$LOSS = 0.0\ in$$

$$FCA = 0.1\ in$$

$$D_o = 100\ in$$

$$R_o = \frac{D_o}{2} = \frac{100}{2} = 50\ in$$

$$L_T = 960\ in$$

$$E_y = 26.07 \times (10)^6\ \ psi @ 650\ ^\circ F$$

$$S_y = 28.48\ ksi @ 650\ ^\circ F$$

Check the applicability of the method (see paragraph A.4.1)

$$\left(t_c = t_{nom} - LOSS - FCA = 1 - 0 - 0.1 = 0.9\ in\right) \ge \left(3/16\ in = 0.1875\ in\right) \qquad True$$

$$\left(\frac{D_o}{t_c} = \frac{100}{0.9} = 111.1111\right) \le 2000 \qquad True$$

$$Temperature = 650\ ^\circ F \le 700\ ^\circ F\ \ for\, carbon\, steel\, with\, UTS \ge 60\ ksi \qquad True$$

$$SA516, Gr.70\, is\, carbon\, steel \qquad True$$

$$e = 0\ (Out - of - roundness) \qquad True$$

Supplemental load is negligible and does not need to be considered.

Detailed calculation of P_4^e for Subdivision 4 is given below.

Calculate the predicted elastic buckling stress, F_{he} (equations (A.176) – (A.181)).

$$t_4 = 0.7\ in$$

$$t_{c,4} = t_4 - FCA = 0.7 - 0.1 = 0.6\ in$$

$$D_o = 100\ in$$

$$M_x = \frac{L}{\sqrt{R_o t_{c,4}}} = \frac{960}{\sqrt{50 \times 0.6}} = 175.2712\ in$$

$$2\left(\frac{D_o}{t_{c,4}}\right)^{0.94} = 2\left(\frac{100}{0.6}\right)^{0.94} = 245.2267$$

$$Since\ 13 \le (M_x = 175.2712) < \left[2\left(\frac{D_o}{t_{c,4}}\right)^{0.94} = 245.2267\right]$$

$$C_h = 1.12 M_x^{-1.058} = 1.12 \times (175.2712)^{-1.058} = 4.7356 \times (10)^{-3}$$

$$F_{he} = \frac{1.6 C_h E_y t_{c,4}}{D_o} = \frac{1.6 \times (4.7356 \times (10)^{-3}) \times (26.07 \times (10)^6) \times 0.6}{100} = 1.1852 \times (10)^3\ psi$$

Calculate the predicted inelastic buckling stress, F_{ic} (equations (A.182) – (A.184)).

$$\left(\frac{F_{he}}{S_y} = \frac{1.1852 \times (10)^3}{2.848 \times (10)^4} = 0.0416\right) < 0.552$$

$$F_{ic} = 1.1852 \times (10)^3\ psi$$

Calculate the in-service margin, FS, (equations (A.163) – (A.165)).

$$\left(F_{ic} = 1.1852 \times (10)^3\ psi\right) \le (0.55 S_y = 1.5664 \times (10)^4\ psi)$$

$$SF = 2$$

Calculate the allowable external pressure, P_4^e, (equations (A.185) and (A.186)).

$$F_{ha} = \frac{F_{ic}}{FS} = \frac{1.1852 \times (10)^3}{2} = 592.5902\ psi$$

$$P_4^e = 2 F_{ha}\left(\frac{t_{c,4}}{D_o}\right) = 2 \times (592.5902) \times \left(\frac{0.6}{100}\right) = 7.1111\ psi$$

Calculated P_i^e for all subdivisions are given in Table E5.9-3 below.

Table E5.9-3

Subdivision, *i*	P_i^e (*psi*)
1	19.8276
2	10.8849
3	8.7066
4	7.1111
5	4.9518
6	1.8194
7	5.7065
8	14.7199
9	19.8276

d) STEP 4 – Determine the allowable external pressure using equation (5.22).

$$MAWP_r = \frac{L_T}{\sum_{i=1}^{9} \frac{L_i}{P_i^e}}$$

$$= \frac{960}{\frac{310}{19.8276} + \frac{10}{10.8849} + \frac{10}{8.7066} + \frac{10}{7.1111} + \frac{10}{4.9518} + \frac{10}{1.8194} + \frac{10}{5.7065} + \frac{10}{14.7199} + \frac{580}{19.8276}}$$

$$= 16.464 \ psi$$

e) STEP 5 – Compare $MAWP_r$ to design pressure

$$\left(MAWP_r = 16.464 \ psi\right) > (P_{design} = 14.7 \ psi)$$

The Level 2 Assessment Criteria are satisfied.
The equipment is acceptable for continued operation.

PART 6

ASSESSMENT OF PITTING CORROSION

EXAMPLE PROBLEMS

6.1 Example Problem 1

Widespread pitting on the ID surface has been discovered on the cylindrical section of a pressure vessel during an inspection. The vessel and inspection data are shown below. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1, 1985. Determine if the vessel is acceptable for continued operation at the current $MAWP$ and temperature. Perform a Level 1 assessment. Consider the pitting damage to be arrested.

<u>Vessel Data</u>

- Material = $SA-516\,Grade\,70\,Year\,1985$
- Design Conditions = $300\ psi\ @\ 250^{\circ}F$
- Inside Diameter = $60\ in$
- Wall Thickness = $0.75\ in$
- Uniform Metal Loss = $0.05\ in$
- Future Corrosion Allowance = $0.07\ in$
- Allowable Stress = $17500\ psi$
- Weld Joint Efficiency = 0.85

There are no supplemental loads on the section.

Figure E6.1-1 Example Problem E6.1 Pitting Damage

Perform a Level 1 Assessment per paragraph 6.4.2.

a) STEP 1 **-** Determine the following parameters: $D, D_O, FCA\, and\, either\, t_{rd}\, or\, t_{nom}\, and\, LOSS$

$$D = 60\ in$$

$$FCA = 0.07\ in$$

$$t_{nom} = 0.75\ in$$

$$LOSS = 0.05\ in$$

b) STEP 2 - Determine the wall thickness to be used in the assessment using Equation (6.1) or Equation (6.2), as applicable.

$$t_c = t_{nom} - LOSS - FCA = 0.75 - 0.05 - 0.07 = 0.63\ in$$

c) STEP 3 **-** Locate the area on the component that has the highest density of pitting damage based on the number of pits. Obtain photographs (include reference scale), or rubbings of this area to record the amount of surface damage. See Figure E6.1-1.

d) STEP 4 - Determine the maximum pit depth, $w_{\max}$, in the region of pitting damage being evaluated.

The maximum depth of pitting has been determined as $w_{\max} = 0.3\ in$

e) STEP 5 - Determine the ratio of the remaining wall thickness to the future wall thickness in the pitted region using Equation 6.3. In Equation (6.3), t_{rd} can be replaced by $t_{nom} - LOSS$. If $R_{wt} < 0.2$ the Level 1 assessment criteria are not met.

$$R_{wt} = \frac{t_c + FCA - w_{\max}}{t_c} = \frac{0.63 + 0.07 - 0.3}{0.63} = 0.6349$$

$$\text{Is } R_{wt} \geq 0.2 \text{ ?}$$

$$0.6349 \geq \ 0.2 \Rightarrow Yes$$

f) STEP 6 - Determine the $MAWP$ for the component (see Annex A, paragraph A.2) using the thickness from STEP 2

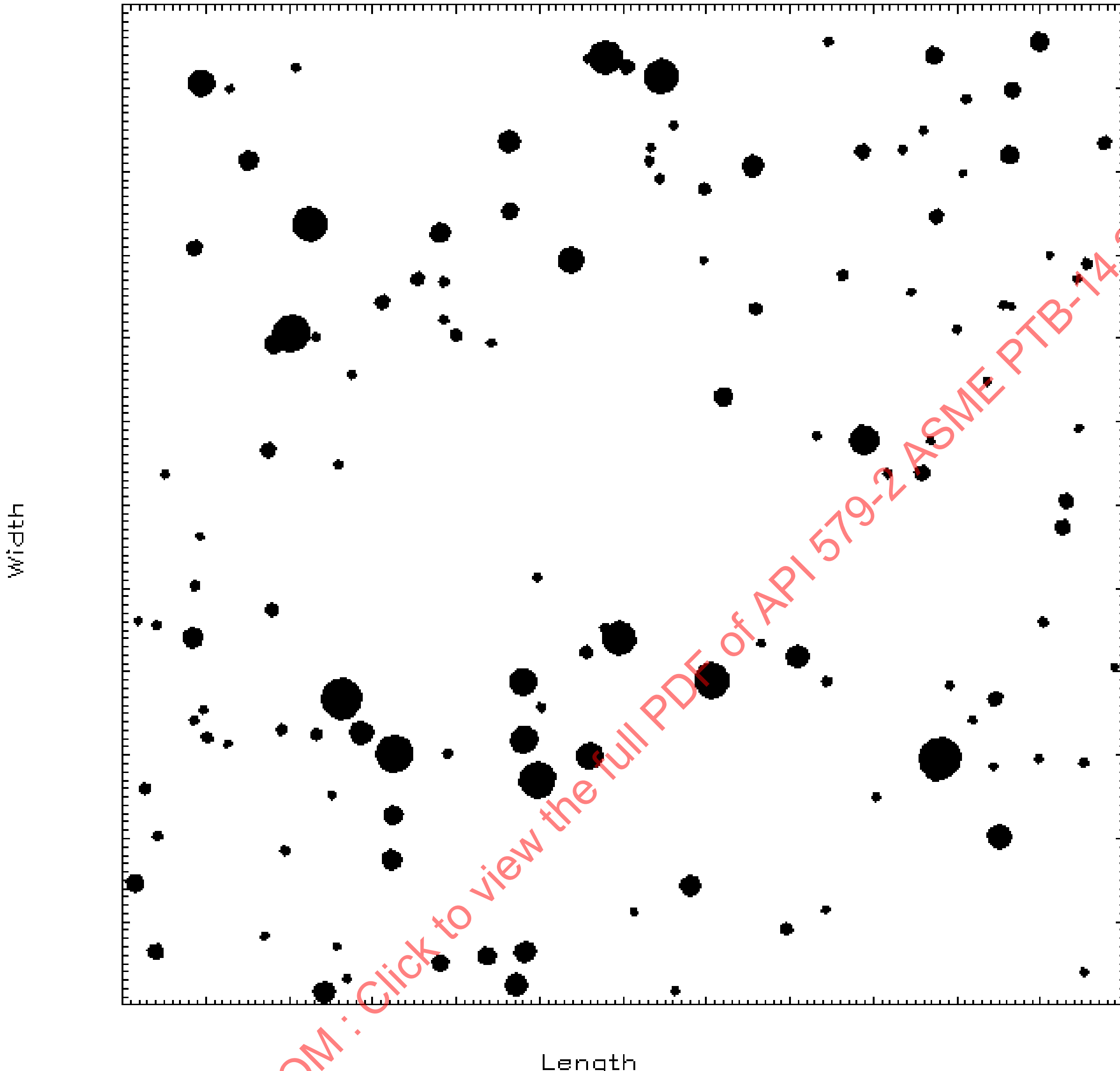
$$R_i = \frac{60}{2} = 30 \ in$$

$$R_c = R_i + LOSS + FCA = 30 + 0.05 + 0.07 = 30.12 \ in$$

$$MAWP = \frac{S_a E t_c}{R_c + 0.6 \cdot t_c} = \frac{(17500)(0.85)(0.63)}{30.12 + (0.6)(0.63)} = 307 \ psi$$

g) STEP 7 - Compare the surface damage from the photographs or rubbings to the standard pit charts shown in Figures 6.3 through 6.10. Select a pit chart that has a measure of surface damage that approximates the actual damage on the component. If the pitting damage is more extensive than that shown in Figure 6.10, then compute the RSF using Equation 6.4 and proceed to STEP 9.

Based on the picture, the closest Level 1 pitting chart is Figure E6.1-2



Note: The scale of this figure is 150 mm by 150 mm (6 in by 6 in)

R_{wt} (See Equation 6.3)	Level 1 RSF	
	Cylinder	Sphere
0.8	0.97	0.96
0.6	0.95	0.91
0.4	0.92	0.87
0.2	0.89	0.83

Figure E6.1-2 Pitting Chart for Grade 2 Pitting (API 579 Figure 6.4)

h) STEP 8 - Determine the RSF from the table shown at the bottom of the pit chart that was chosen in STEP 7 using the value of R_{wt} calculated in STEP 5. Interpolation of the RSF is acceptable for intermediate values of R_{wt}.

Calculations show interpolation in Figure 6.4.

Given $R_{wt} = 0.635$, from Figure 6.4

$$\text{From Figure 6.4, when } R_{wt} = 0.8 \quad \Rightarrow \quad RSF = 0.97$$
$$\text{and when } R_{wt} = 0.6 \quad \Rightarrow \quad RSF = 0.95$$
$$\text{thus the difference in } RSF = |0.95 - 0.97| = 0.02$$
$$\text{and the difference in } R_{wt} = |0.6 - 0.8| = 0.2$$

Solving for the RSF

$$RSF = (0.02)\left(\frac{0.635 - 0.6}{0.2}\right) + 0.95 = 0.9535$$

i) STEP 9 - Since the $RSF \geq RSF_a$, then the pitting damage is acceptable for operation at the $MAWP$ determined in STEP 6. To illustrate the Part 2 calculation, determine $MAWP_r$ for the case of $RSF < RSF_a$. Using the equations in Part 2, paragraph 2.4.2.2. The $MAWP$ from STEP 6 shall be used in this calculation.

$$MAWP_r = 307\ psi$$

The Design Pressure is $300\ psi$, and the $MAWP_r = 307\ psi$; therefore, the vessel passes the Level 1 assessment and is acceptable for the design pressure.

6.2 Example Problem 2

Widespread pitting on the outside surface has been discovered on the cylindrical straight section of a piping component during an external inspection. The piping and inspection data are shown below. The pipe was constructed to the ASME B31.3 code 1992. Determine if the pipe is acceptable for continued operation at the current $MAWP$ and temperature. Consider the pitting damage to be arrested.

Pipe Data

- Material = $SA-106\ Grade\ B\ Year\ 1992$
- Design Conditions = $17.24\,\text{bar} @ 150^{\circ}C$
- Outside Diameter = $168.3\,mm$
- Wall Thickness = $10.97\,mm$
- Uniform Metal Loss = $0.0\,mm$
- Future Corrosion Allowance = $0.76\,mm$
- Allowable Stress = $137.89\,MPa$
- Weld Joint Efficiency = 1
- Maximum pitting depth = $5.6\,mm$

There are no supplemental loads on the section.

Figure E6.2-1 Example Problem E6.2 Pitting Damage

Perform a Level 1 Assessment per paragraph 6.4.2

a) STEP 1 - Determine the following parameters: $D_O, FCA\, and\, either\, t_{rd}\, or\, t_{nom}\, and\, LOSS$

$$D_O = 168.3\, mm$$
$$FCA = 0.76\, mm$$
$$LOSS = 0.0\, mm$$
$$t_{rd} = t_{nom} - LOSS$$
$$t_{rd} = 10.97 - 0 = 10.97\, mm$$

b) STEP 2 - Determine the wall thickness to be used in the assessment using Equation 6.1 or Equation 6.2 as applicable.

$$t_c = t_{rd} - FCA$$
$$t_c = 10.97 - 0.76 = 10.21\, mm$$

c) STEP 3 - Locate the area on the component that has the highest density of pitting damage based on the number of pits. Obtain photographs (include reference scale), or rubbings of this area to record the amount of surface damage. See Figure E6.2-1

d) STEP 4 - Determine the maximum pit depth, $w_{\max}$, in the region of pitting damage

$$w_{\max} = 5.6\,mm$$

e) STEP 5 - Determine the ratio of the remaining wall thickness to the future wall thickness in the pitted region using Equation 6.3. In Equation (6.3), t_{rd} can be replaced by $t_{nom} - LOSS$. If $R_{wt} < 0.2$ the Level 1 assessment criteria are not met.

$$R_{wt} = \frac{t_c + FCA - w_{\max}}{t_c} = \frac{10.21 + 0.76 - 5.6}{10.21} = 0.5260$$

$$\text{Is } R_{wt} \geq 0.2 \text{ ?}$$

$$0.5260 \geq \ 0.2 \Rightarrow \text{Yes}$$

f) STEP 6 **-** Determine the $MAWP$ for the component (see Annex A, paragraph A.5) using the thickness from STEP 2.

$$D = D_o - 2 \cdot t_{nom} = 168.3 - (2)(10.97) = 146.36\,mm$$

$$R_c = \frac{D}{2} + LOSS + FCA = \frac{146.36}{2} + 0.0 + 0.76 = 73.94\,mm$$

circumferential

$$MAWP^C = \frac{2S_a E(t_c - MA)}{D_o - 2Y_{B31}(t_c - MA)} = \frac{2(137.89)(1)(10.21-0)}{168.3 - 2(0.4)(10.21-0)} = 17.583\,bar$$

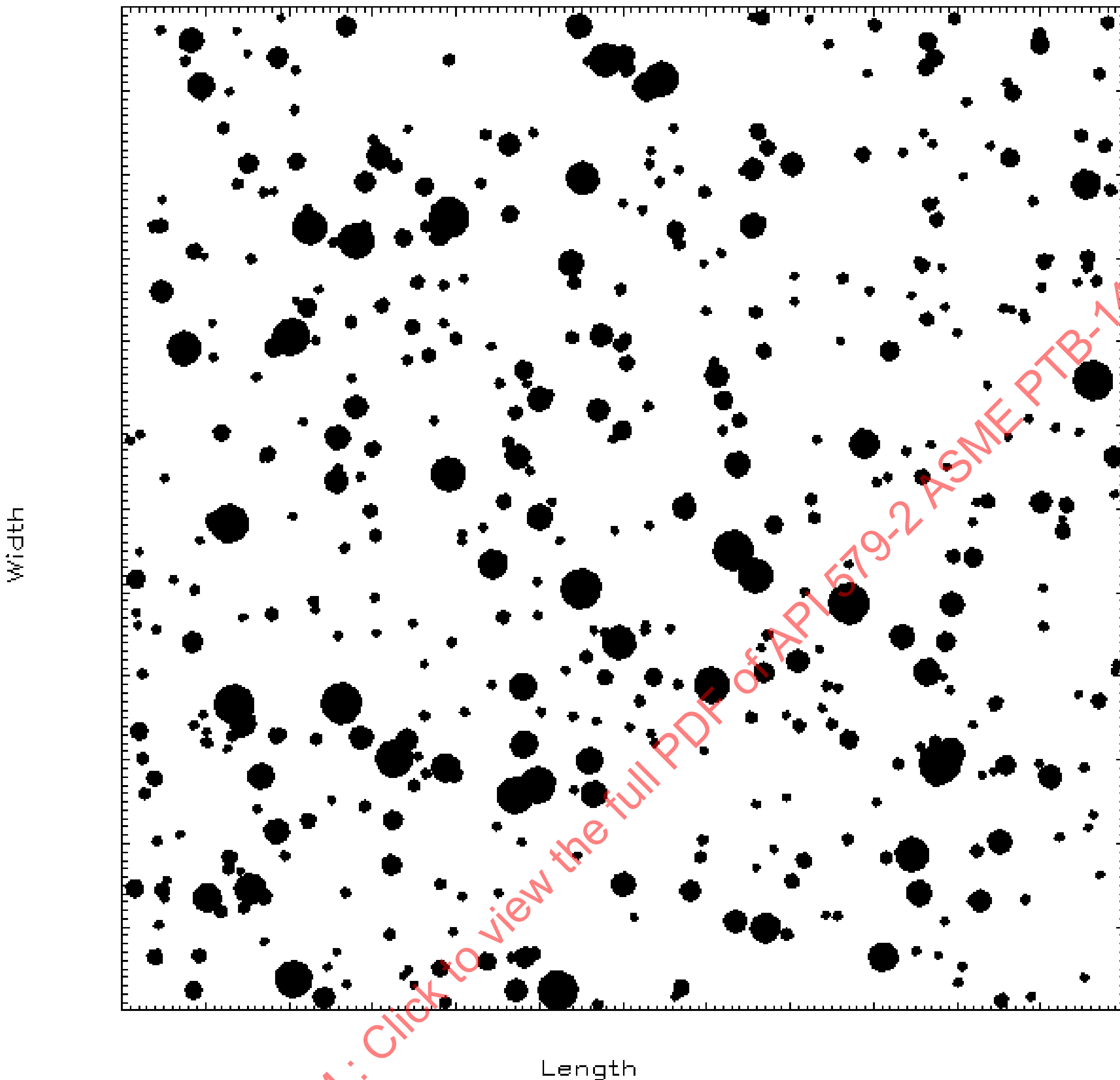
longitudinal

$$MAWP^L = \frac{4S_a E(t_c - t_{sl} - MA)}{D_o - 4Y_{B31}(t_c - t_{sl} - MA)} = \frac{4(137.89)(1)(10.21-0-0)}{168.3 - 4(0.4)(10.21-0-0)} = 37.057\,bar$$

$$MAWP = \min(MAWP^C, MAWP^L) = \min(17.583,\ 37.057) = 17.583\ bar$$

g) STEP 7 - Compare the surface damage from the photographs or rubbings to the standard pit charts shown in Figures 6.3 through 6.10. Select a pit chart that has a measure of surface damage that approximates the actual damage on the component. If the pitting damage is more extensive than that shown in Figure 6.10, then compute the RSF using Equation 6.4 and proceed to STEP 9.

Based on the picture, the closest Level 1 pitting chart is Figure E6.2-2



Note: The scale of this figure is 150 mm by 150 mm (6 in by 6 in)

R_{wt} (See Equation 6.3)	Level 1 RSF	
	Cylinder	Sphere
0.8	0.95	0.93
0.6	0.90	0.86
0.4	0.85	0.79
0.2	0.79	0.72

Figure E6.2-2– Pitting Chart for Grade 4 Pitting (API 579 Figure 6.6)

h) STEP 8 - Determine the RSF from the table shown at the bottom of the pit chart that was chosen in STEP 7 using the value of R_{wt} calculated in STEP 5. Interpolation of the RSF is acceptable for intermediate values of $R_{wt} = 0.526$

Calculations show interpolation in Figure 6.6.
Given

When $R_{wt} = 0.6$	$RSF = 0.9$
and when $R_{wt} = 0.4$	$RSF = 0.85$

thus the difference in $RSF = |0.9 - 0.85| = 0.05$

when the difference in $R_{wt} = |0.6 - 0.4| = 0.2$

Solve for RSF

$$RSF = (0.05)\left(\frac{0.526 - 0.4}{0.2}\right) + 0.85 = 0.8815$$

i) STEP 9 - Since $RSF < RSF_a$, calculate the $MAWP_r$ as applicable using the equations in Part 2, paragraph 2.4.2.2. Acceptability for continued service is determined from $MAWP_r$.

$$MAWP_r = MAWP \frac{RSF}{RSF_a} = 17.583\left(\frac{0.8815}{0.9}\right) = 17.222\,bar$$

Since the $\text{Design Pressure} = 17.24\ bar$ **and the** $MAWP_r = 17.222\ bar$ **, the pipe fails the Level 1 assessment.**

6.3 Example Problem 3

Widely scattered pitting has been discovered on the bottom cylindrical section of a pressure vessel midway between two saddle locations during an internal inspection. The vessel and inspection data are shown below. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1, 1980. Determine if the vessel is acceptable for continued operation at the current $MAWP$ and temperature.

Vessel Data

- Material = $SA-516\,Grade\,70\ Year\ 1980$
- Design Conditions = $500\ psi\,@\,450^{\circ}F$
- Inside Diameter = $60\ in$
- Wall Thickness = $1.125\ in$
- Uniform Metal Loss = $0.03\ in$
- Future Corrosion Allowance = $0.05\ in$
- Allowable Stress = $17500\ psi$
- Weld Joint Efficiency = 0.85
- Saddle Reaction Force = $34690\,lbf$
- Mid Span Bending Moment = $1312600\ in-lbf$
- Tangent-to-Tangent Length = $30\ ft$
- Depth of Head = $15\ in$
- Distance from Support to Tangent = $4\ ft$

The region of pitting extends through a girth weld.

A Level 2 assessment is required since the equipment has supplemental loads.

Table E6.3-1 Inspection Data

$Pit - Couple_k$	P_k ,in	θ_k Degrees	$d_{i,k}$,in	$w_{i,k}$,in	$d_{j,k}$,in	$w_{j,k}$,in
1	3.5	10	0.5	0.5	0.6	0.4
2	4.2	15	1.6	0.6	1.8	0.65
3	2.7	22	0.9	0.5	0.9	0.75
4	2.1	30	1.0	0.7	1.2	0.6
5	4.6	5	0.7	0.6	1.2	0.5
6	3.1	15	1.1	0.5	2.2	0.45
7	2.9	20	0.8	0.65	0.5	0.6
8	3.1	45	0.5	0.4	1.0	0.75
9	2.6	60	1.3	0.5	0.8	0.2
10	2.2	0	0.4	0.55	0.3	0.75
11	1.8	10	1.5	0.4	0.8	0.5
12	2.5	20	0.6	0.75	0.5	0.7
13	3.8	35	2.4	0.5	1.6	0.75
14	1.9	90	0.4	0.25	0.8	0.5
15	1.8	0	1.0	0.7	0.8	0.5
16	1.0	22	0.6	0.75	0.2	0.7
17	2.5	45	0.9	0.3	1.2	0.4
18	1.5	67	0.6	0.5	0.6	0.7
19	1.3	90	0.8	0.4	0.5	0.7

Perform a Level 2 Assessment per paragraph 6.4.3.

Determine acceptability for the Circumferential Stress Direction per 6.4.3.2

a) STEP 1 – Determine the following parameters.

$t_{nom} = 1.125\ in$ | $D = 60\ in$ | $Q_s = 34690\ \ lbf$

$LOSS = 0.03\ in$ | $S_a = 17500\ psi$ | $L = 30\ ft$

$FCA = 0.05\ in$ | $E_c = 0.85$ | $H = 15\ in$

$P = 500\ psi$ | $RSF_a = 0.9$ | $A = 4\ ft$

$E_L = 0.85$ | $M = 1.312(10)^6\ \ in-lbf$ | $\alpha = 0\deg$

$$t_{rd} = t_{nom} - LOSS = 1.125 - 0.03 = 1.095\ in$$

$$D_O = D + 2t_{nom} = 60 + (2)(1.125) = 62.25\ in$$

$$R_c = \frac{D}{2} + LOSS + FCA = 30 + 0.03 + 0.05 = 30.08\ in$$

b) STEP 2 – Determine the wall thickness to be used in the assessment using Equation (6.1) or Equation (6.2), as applicable.

$$t_c = t_{rd} - FCA = 1.095 - 0.05 = 1.045\ in$$

c) STEP 3 – Determine the pit-couple sample for the assessment (see 6.3.3.2), and the following parameters for each pit-couple, $k, d_{i,k}, d_{j,k}, P_k, w_{i,k}, and\ w_{j,k}$. In addition, determine the orientation of the pit-couple measured from the direction of the σ_2 stress component, θ_k (see Figure 6.11)

<u>For the first pit-couple</u> (Other calculations will be summarized in Table E6.3-2).

$$\theta_1 = 10^\circ$$

$$d_{11} = 0.5\ in \qquad w_{11} = 0.5\ in \qquad P_1 = 3.5\ in$$

$$d_{21} = 0.6\ in \qquad w_{21} = 0.4\ in$$

d) STEP 4 – Determine the depth of each pit below t_c in all pit-couples, $w_{i,k}$ and $w_{j,k}$ (see Figure 6.11.b) and compute the average pit depth, w_{avg} , considering all readings. In Equation (6.5), the subscript k represents a calculation for pit-couple k .

$$w_{avg1} = \frac{w_{11} + w_{21}}{2} = \frac{0.5 + 0.4}{2} = 0.45\ in$$

e) STEP 5 – Calculate the components of the membrane stress field, σ_1 and σ_2 (see Figure 6.11). Membrane stress equations for shell components are included in Annex A.

$$R_m = \frac{R_c + \frac{D_0}{2}}{2} = \frac{30.08 + \frac{62.25}{2}}{2} = 30.6025\ in$$

For the location of the defects given in the example which is at the center section of the lower shell centered between the two saddle supports. Using Annex A, determine the membrane stress values considering supplemental loads.

Using Annex A.7.3 Horizontal Vessels Subject to Weight Loads

$$t_{sl} = \left(\frac{(3)Q_s L}{S_a E_L (\pi) R_m^{\;2}}\right)\left[\frac{1+\dfrac{(2)\left(R_m^{\;2}-H^2\right)}{L^2}}{1+\dfrac{4H}{3L}} - (4)\left(\frac{A}{L}\right)\right]$$

$$t_{sl} = \left(\frac{(3)(34690)(30)}{(17500)(0.85)(\pi)(30.6025)^2}\right)\left[\frac{1+\dfrac{(2)\left((30.6025)^2-(15)^2\right)}{(30)^2}}{1+\dfrac{(4)(15)}{(3)(30)}} - (4)\left(\frac{4}{30}\right)\right] = 0.3633\ in$$

$$\sigma_1 = \left(\frac{P}{E_c}\right)\left(\frac{R_c}{t_c}+0.6\right)$$

$$\sigma_1 = \left(\frac{500}{0.85}\right)\left(\frac{30.08}{1.045}+0.6\right) = 17285.1112\, psi$$

$$\sigma_2 = \left(\frac{P}{2E_L}\right)\left(\frac{R_c}{t_c - t_{sl}}-0.4\right)$$

$$\sigma_2 = \left(\frac{500}{2(0.85)}\right)\left(\frac{30.08}{1.045-0.3633}-0.4\right) = 12861.1738\, psi$$

f) STEP 6 – Determine the $MAWP$ for the component (see Annex A, paragraph A.2) using the thickness from STEP 2.

$$MAWP^C = \frac{S_a E_c t_c}{R_c + 0.6 t_c} = \frac{(17500)(0.85)(1.045)}{30.08+(0.6)(1.045)} = 506.2\, psi$$

$$MAWP^L = \frac{2 S_a E_c (t_c - t_{sl})}{R_c - 0.4(t_c - t_{sl})} = \frac{2(17500)0.85(1.045-0.3633)}{30.08-0.4(1.045-0.3633)} = 680.3\, psi$$

The $MAWP$ is the lowest of the longitudinal and circumferential $MAWPs$

$$MAWP = \min[506.2,\ 680.3] = 506\, psi$$

g) STEP 7 – For pit-couple k , calculate the Remaining Strength Factor:

Single Layer Analysis – This analysis can be used when the pitting occurs on one side of the component (see Figure 6.11).

For pit-couple 1

$$d_{avg1} = \frac{d_{11} + d_{21}}{2} = \frac{0.5 + 0.6}{2} = 0.55\ in \qquad \mu_{avg1} = \frac{P_1 - d_{avg,1}}{P_1} = \frac{3.5 - 0.55}{3.5} = 0.8429$$

$$\rho_{11} = \frac{\sigma_1}{\mu_{avg1}} = \frac{17285}{0.8429} = 20507.7590\ psi \qquad \rho_{21} = \frac{\sigma_2}{\mu_{avg1}} = \frac{12860}{0.8429} = 15259.0197\ psi$$

$$\psi_1 = \left(\begin{array}{l} \left(\cos^4[\theta_1] + \sin^2[2\theta_1]\right)(\rho_{11})^2 - \\ \dfrac{3\sin^2[2\theta_1](\rho_{11})(\rho_{21})}{2} + \\ \left(\sin^4[(10)] + \sin^2[(2)(10)]\right)(\rho_{21})^2 \end{array} \right)$$

$$\psi_1 = \left(\begin{array}{l} \left(\cos^4[(10)] + \sin^2[(2)(10)]\right)(20507.7590)^2 - \\ \dfrac{3\sin^2[(2)(10)](20507.7590)(15259.0197)}{2} + \\ \left(\sin^4[(10)] + \sin^2[(2)(10)]\right)(15259.0197)^2 \end{array} \right) = 4.1732(10)^8\ psi^2$$

$$\Phi_1 = \mu_{avg1} \max\left[|\rho_{11}|, |\rho_{21}|, |\rho_{11} - \rho_{21}| \right]$$

$$\Phi_1 = 0.8429 \max\left[|20507.7590|, |15259.0197|, |20507.7590 - 15259.0197| \right] = 17285.1112\ psi$$

$$E_{avg1} = \min\left(\frac{\Phi_1}{\sqrt{\Psi_1}}, 1 \right) \qquad RSF_1 = 1 - \frac{w_{avg1}}{t_c}\left(1 - E_{avg1}\right)$$

$$E_{avg1} = \min\left(\frac{17285.1112}{\sqrt{4.1732(10)^8}}, 1 \right) = 0.8461 \qquad RSF_1 = 1 - \left(\frac{0.45}{1.045} \right)(1 - 0.8461) = 0.9337$$

h) STEP 8 – Repeat STEP 7 for all pit-couples, n , recorded at the time of the inspection. Determine the average value of the Remaining Strength Factors, RSF_k , determined in STEP 7 and designate this value as RSF_{pit} for the region of pitting.

The calculation results for all pit-couples are shown in Table E6.3-2.

Table E6.3-2 Pit-Couple Results

$Pit-Couple,_k$	$w_{avg,k}$	$d_{avg,k}$	$\mu_{avg,k}$	$\rho_{1,k}$	$\rho_{2,k}$	Ψ_k	Φ_k	$E_{avg,k}$	RSF_k
1	0.4500	0.5500	0.8429	2.0508E+04	1.5258E+04	4.1732E+08	1.7285E+04	0.8461	0.9337
2	0.6250	1.7000	0.5952	2.9039E+04	2.1605E+04	8.2840E+08	1.7285E+04	0.6006	0.7611
3	0.6250	0.9000	0.6667	2.5928E+04	1.9290E+04	6.4607E+08	1.7285E+04	0.6800	0.8086
4	0.6500	1.1000	0.4762	3.6299E+04	2.7007E+04	1.2191E+09	1.7285E+04	0.4951	0.6859
5	0.5500	0.9500	0.7935	2.1784E+04	1.6207E+04	4.7364E+08	1.7285E+04	0.7942	0.8917
6	0.4750	1.6500	0.4677	3.6954E+04	2.7494E+04	1.3416E+09	1.7285E+04	0.4719	0.7600
7	0.6250	0.6500	0.7759	2.2279E+04	1.6575E+04	4.8049E+08	1.7285E+04	0.7885	0.8735
8	0.5750	0.7500	0.7581	2.2802E+04	1.6965E+04	4.2941E+08	1.7285E+04	0.8341	0.9087
9	0.3500	1.0500	0.5962	2.8994E+04	2.1572E+04	5.9017E+08	1.7285E+04	0.7115	0.9034
10	0.6500	0.3500	0.8409	2.0555E+04	1.5293E+04	4.2252E+08	1.7285E+04	0.8409	0.9010
11	0.4500	1.1500	0.3611	4.7866E+04	3.5613E+04	2.2735E+09	1.7285E+04	0.3625	0.7255
12	0.7250	0.5500	0.7800	2.2160E+04	1.6488E+04	4.7541E+08	1.7285E+04	0.7928	0.8562
13	0.6250	2.0000	0.4737	3.6491E+04	2.7149E+04	1.1938E+09	1.7285E+04	0.5003	0.7011
14	0.3750	0.6000	0.6842	2.5263E+04	1.8796E+04	3.5328E+08	1.7285E+04	0.9196	0.9712
15	0.6000	0.9000	0.5000	3.4570E+04	2.5721E+04	1.1951E+09	1.7285E+04	0.5000	0.7129
16	0.7250	0.4000	0.6000	2.8809E+04	2.1434E+04	7.9762E+08	1.7285E+04	0.6120	0.7308
17	0.3500	1.0500	0.5800	2.9802E+04	2.2173E+04	7.3355E+08	1.7285E+04	0.6382	0.8788
18	0.6000	0.6000	0.6000	2.8809E+04	2.1434E+04	5.3708E+08	1.7285E+04	0.7458	0.8541
19	0.5500	0.6500	0.5000	3.4570E+04	2.5721E+04	6.6155E+08	1.7285E+04	0.6720	0.8274

$$RSF_{pit} = \frac{1}{19}\sum_{k=1}^{19} RSF_k = 0.8256$$

i) STEP 9 – Evaluate results based on the type of pitting damage:

Widespread Pitting – For widespread pitting that occurs over a significant region of the component, if $RSF_{pit} \geq RSF_a$, then the pitting damage is acceptable for operation at the $MAWP$ determined in STEP 6. If $RSF_{pit} < RSF_a$, then the region of pitting damage is acceptable for operation at $MAWP$r, where $MAWP$r is computed using the equations in Part 2, paragraph 2.4.2.2. The $MAWP$ from STEP 6 shall be used in this calculation.

Since $RSF_{pit} < RSF_a$, determine the reduced $MAWP$ for the average RSF

$$MAWP_r = MAWP\frac{RSF}{RSF_a} = 506.2\left(\frac{0.8256}{0.9}\right) = 464.3475\ psi$$

See 6.4.3.3 calculations following STEP 10.

j) STEP 10 – Check the recommended limitations on the individual pit dimensions:

(1) Pit Diameter – If the following equation is not satisfied for an individual pit, then the pit should be evaluated as a local thin area using the assessment methods of Part 5. The size of the local thin area is the pit diameter and the remaining thickness ratio is defined below. This check is required for larger pits to ensure that a local ligament failure at the base of the pit does not occur. In this example, the check is performed at the pit-couple with the maximum average diameter.

$$d \le Q\sqrt{Dt_c}$$

The value of Q in Equation (6.18) shall be determined using Part 4, Table 4.4 and is a function of the remaining thickness ratio, R_t , for each pit as given by either of the following equations where, $w_{i,k}$ is the depth of the pit under evaluation.

$$R_t = \left(\frac{t_c + FCA - w_{i,k}}{t_c}\right)$$

(2) Pit Depth – The following limit on the remaining thickness ratio is recommended to prevent a local failure characterized by pinhole type leakage. The criterion is expressed in terms of the remaining thickness ratio as follows:

$$R_t \ge 0.20$$

Calculations

<u>For the first pit</u>

$$R_t = \left(\frac{t_c + FCA - w_{i,k}}{t_c}\right) \qquad Q_1 = (1.123)\left[\left(\frac{1-R_{t1}}{1-\frac{R_{t1}}{RSF_a}}\right)^2 - 1\right]^{0.5}$$

$$R_{t1} = \frac{1.045 + 0.05 - 0.5}{1.045} = 0.5694 \qquad Q_1 = (1.123)\left[\left(\frac{1-0.5694}{1-\frac{0.5694}{0.9}}\right)^2 - 1\right]^{0.5} = 0.6869$$

$$Q\sqrt{Dt_c} = (0.6869)\sqrt{(60)(1.045)} = 5.4388\ in$$

Is diameter less than allowable?

$$D_{11} \le Q_k\sqrt{Dt_c}$$

$$0.5 \le 5.4388 \Rightarrow Yes$$

All the pit-couple calculations are presented in Table E6.3-3.

Table E6.3-3 Limitations on Individual Pit Sizes

$Pit-Couple_k$	$R_{t,1}$	$Q_{1,k}$	$Q_{1,k}\sqrt{Dt_c}$	Single Pit Diameter Ok?	$R_{t,2}$	$Q_{2,k}$	$Q_2\sqrt{D\cdot t_c}$	Single Pit Diameter Ok?	Is $R_t \ge 0.2$
1	0.5694	0.6869	5.4388	Yes	0.6651	0.9028	7.1489	Yes	Yes
2	0.4737	0.5439	4.3067	Yes	0.4258	0.4865	3.8523	Yes	Yes
3	0.5694	0.6869	5.4388	Yes	0.3301	0.3878	3.0704	Yes	Yes
4	0.3780	0.4350	3.4447	Yes	0.4737	0.5439	4.3067	Yes	Yes
5	0.4737	0.5439	4.3067	Yes	0.5694	0.6869	5.4388	Yes	Yes
6	0.5694	0.6869	5.4388	Yes	0.6172	0.7814	6.1876	Yes	Yes
7	0.4258	0.4865	3.8523	Yes	0.4737	0.5439	4.3067	Yes	Yes
8	0.6651	0.9028	7.1489	Yes	0.3301	0.3878	3.0704	Yes	Yes
9	0.5694	0.6869	5.4388	Yes	0.8565	3.1370	24.8400	Yes	Yes
10	0.5215	0.6095	4.8264	Yes	0.3301	0.3878	3.0704	Yes	Yes
11	0.6651	0.9028	7.1489	Yes	0.5694	0.6869	5.4388	Yes	Yes
12	0.3301	0.3878	3.0704	Yes	0.3780	0.4350	3.4447	Yes	Yes
13	0.5694	0.6869	5.4388	Yes	0.3301	0.3878	3.0704	Yes	Yes
14	0.8086	1.7942	14.2069	Yes	0.5694	0.6869	5.4388	Yes	Yes
15	0.3780	0.4350	3.4447	Yes	0.5694	0.6869	5.4388	Yes	Yes
16	0.3301	0.3878	3.0704	Yes	0.3780	0.4350	3.4447	Yes	Yes
17	0.7608	1.3246	10.4889	Yes	0.6651	0.9028	7.1489	Yes	Yes
18	0.5694	0.6869	5.4388	Yes	0.3780	0.4350	3.4447	Yes	Yes
19	0.6651	0.9028	7.1489	Yes	0.3780	0.4350	3.4447	Yes	Yes

Determine acceptability for the LONGITUDINAL Stress Direction per paragraph 6.4.3.3

a) STEP 1 – Determine the following parameters: D, D_O, FCA, either t_{rd} or t_{nom} and $LOSS$.

$$D = 60\ in$$

$$D_O = 60 + (2)(1.125) = 62.25\ in$$

$$FCA = 0.05\ in$$

$$LOSS = 0.03\ in$$

$$t_{rd} = 1.095\ in$$

$$R_c = 30 + 0.05 + 0.03 = 30.08\ in$$

b) STEP 2 – Determine the wall thickness to be used in the assessment using Equation (6.1) or Equation (6.2), as applicable.

$$t_c = 1.045\ in$$

c) STEP 3 – Determine the remaining strength factor, RSF, the allowable remaining strength factor, RSF_a, the permissible maximum allowable working pressure, $MAWP_r$, and supplemental loads on the circumferential plane. The remaining strength factor, allowable remaining strength factor, and the permissible maximum allowable working pressure for the region with pitting damage can be established using the procedures in paragraph 6.4.3.2. The supplemental loads are determined in accordance with paragraphs 6.4.3.3.a and 6.4.3.3.b.

$$RSF_{pit} = 0.8256 \qquad RSF_a = 0.9$$

$$MAWP_r = 464.3475\ psi \qquad t_{sl} = 0.3633\ in$$

Weight Case

$$Q_s = 34690\, lbf \qquad M = 1.312(10)^6\ in-lbf$$

Thermal Case
There are no thermal loads

d) STEP 4 – Compute the equivalent thickness of the cylinder with pitting damage

$$B = \min\left[\frac{RSF_{pit}}{RSF_a}, 1.0\right]$$

$$B = \min\left[\frac{0.8256}{0.9}, 1.0\right] = 0.9173$$

$$t_{eq} = Bt_c$$

$$t_{eq} = (0.917)(1.045) = 0.9586\ in$$

e) STEP 5 – For the supplemental loads determined in STEP 3, compute the components of the resultant bending moment and torsion. This should be done for the weight and the weight plus thermal load cases. There is no thermal load case. For the weight case a Zick analysis was performed to determine the reaction load and maximum bending load at the midspan. These values are:

Weight Case

$$Q_s = 34690\, lbf \qquad M = 1.312(10)^6\ in-lbf$$

f) STEP 6 – Compute the maximum circumferential stress.

$$\sigma_{cm} = \left(\frac{MAWP_r}{RSF_{pit}\cos\alpha}\right)\left(\frac{R_c}{t_{eq}} + 0.6\right)$$

$$\sigma_{cm} = \left(\frac{464.3475}{(0.8256)\cos[0]}\right)\left(\frac{30.08}{0.9586} + 0.6\right) = 17987.5791\, psi$$

g) STEP 7 – Compute the maximum section longitudinal membrane stress and the shear stress for both the weight and the weight plus thermal load cases. All credible load combinations should be considered in the calculation. The section properties required for the calculations are provided in Table 6.2.

$$D_f = D_o - (2)t_{eq}$$

$$D_f = 62.25 - (2)(0.959) = 60.3329\ in$$

$$A_m = \left(\frac{\pi}{4}\right)\left(D_o^{\,2} - D_f^{\,2}\right)$$

$$A_m = \left(\frac{\pi}{4}\right)\left((62.25)^2 - (60.33)^2\right) = 184.5751\ in^2$$

$$a = \frac{D_0}{2} = \frac{62.25}{2} = 31.1250\ in$$

$$I_x = \left(\frac{\pi}{64}\right)\left(D_o^{\,4} - D_f^{\,4}\right)$$

$$I_x = \left(\frac{\pi}{64}\right)\left(62.25^4 - 60.33^4\right) = 86693.9751\ in^4$$

$$A_t = \left(\frac{\pi}{16}\right)\left(D_o + D_f\right)^2$$

$$A_t = \left(\frac{\pi}{16}\right)\left(62.25 + 60.33\right)^2 = 2950.4577\ in^2$$

$$A_a = \left(\frac{\pi}{4}\right)\left(D_f\right)^2 = \left(\frac{\pi}{4}\right)(60.33)^2 = 2858.8918\ in^2$$

<u>Shear Stress</u>

There is no torsion loading and the shear load at the midspan is zero

$$M_T = 0\ in-lbf \qquad V = 0\ lbf$$

$$\tau = \frac{M_T}{2A_t t_{eq}} + \frac{V}{A_m}$$

$$\tau = \frac{0}{(2)(2951)(0.959)} + \frac{0}{184.6} = 0$$

<u>Longitudinal Membrane Stress</u>

F is the applied section axial force for the weight or weight plus thermal load case, as applicable.

$$F = 0\ lbf$$

<u>Tensile</u>

$$\sigma_{lmt} = \left(\frac{1}{E_c \cos[\alpha]}\right)\left(\left(\frac{A_a}{A_m}\right)MAWP_r + \frac{F}{A_m} + \frac{Ma}{I_x}\right)$$

$$\sigma_{lmt} = \left(\frac{1}{(0.85)\cos[0]}\right)\left(\left(\frac{2858.9}{184.6}\right)(464.3) + \frac{0}{184.6} + \frac{1.312(10)^6(31.13)}{86690}\right) = 9015.6874\ psi$$

<u>Compressive</u>

$$\sigma_{lmc} = \left(\frac{1}{E_c \cos[\alpha]}\right)\left(\left(\frac{A_a}{A_m}\right)MAWP_r + \frac{F}{A_m} - \frac{Ma}{I_x}\right)$$

$$\sigma_{lmc} = \left(\frac{1}{(0.85)\cos[0]}\right)\left(\left(\frac{2859}{184.6}\right)(464.3) + \frac{0}{184.6} - \frac{1.312(10)^6(31.13)}{86690}\right) = 7907.3607\ psi$$

h) STEP 8 – Compute the equivalent membrane stress for the weight and the weight plus thermal load cases

Weight Case - Tensile

$$\sigma_{et} = \left(\sigma_{cm}^{2} - \sigma_{cm}\sigma_{lmt} + \sigma_{lmt}^{2} + 3\tau^{2}\right)^{0.5}$$

$$\sigma_{et} = \left((17990)^{2} - (17990)(9016) + (9016)^{2} + (3)(0)^{2}\right)^{0.5} = 15577.7314\ psi$$

Weight Case - Compressive

$$\sigma_{ec} = \left(\sigma_{cm}^{2} - \sigma_{cm}\sigma_{lmc} + \sigma_{lmc}^{2} + 3\tau^{2}\right)^{0.5}$$

$$\sigma_{ec} = \left((17990)^{2} - (17990)(7907) + (7907)^{2} + (3)(0)^{2}\right)^{0.5} = 15615.5554\ psi$$

Thermal Case

There are no thermal loads

i) STEP 9 – Evaluate the results as follows:

The following relationship should be satisfied for either a tensile and compressive longitudinal stress for both the weight and the weight plus thermal load cases:

$$\sigma_{e} \le H_{f}\left(\frac{S_{a}}{RSF_{a}}\right)$$

$$H_{f} = 1.0 \qquad \text{for the weight case}$$

$$\sigma_{e} \le 1.0\left(\frac{17500}{0.9}\right)$$

$$\max\left[\sigma_{et},\ \sigma_{ec}\right]$$

$$\max\left[15577.7314,\ 15615.5554\right] = 15615.5554\ psi$$

$$H_{f}\left(\frac{S_{a}}{RSF_{a}}\right)$$

$$1.0\left(\frac{17500}{0.9}\right) = 19444.4444\ psi$$

The maximum of the tensile or compressive equivalent stress must be less than or equal to the allowable stress $H_{f}\left(\frac{S_{a}}{RSF_{a}}\right)$

$$Acceptable\ if\ \ \max\left[\sigma_{et},\sigma_{ec}\right] \le H_{f}\left(\frac{S_{a}}{RSF_{a}}\right)$$

$$Is\ \left(\max\left[15577.7314,\ 15615.5554\right] \le 1.0\left(\frac{17500}{0.9}\right)\right) \rightarrow "Yes"$$

If the maximum longitudinal stress computed in STEP 7 is compressive, then this stress should be less than or equal to the allowable compressive stress computed using the methodology in Annex A, paragraph A.4.4 or the allowable tensile stress, whichever is smaller. When using this methodology to establish an allowable compressive stress, an average thickness representative of the region of pitting damage in the compressive stress zone should be used in the calculations.

The maximum longitudinal stress in STEP 7 is NOT compressive.

j) STEP 10 – If the equivalent stress criterion of STEP 9 is not satisfied, the $MAWP$ and/or supplemental loads determined in STEP 3 should be reduced, and the evaluation outlined in STEPs 1 through 9 should be repeated. Alternatively, a Level 3 Assessment can be performed.

SUMMARY

$$MAWP_r = 464\,psi$$

The longitudinal stress is acceptable. The equipment fails the level 2 assessment at $500\,psig$,but it is fit for service at a reduced $MAWP$ of $464\,psig$.

6.4 Example Problem 4

Localized pitting has been discovered on the cylindrical shell section of a pressure vessel during a corrosion under insulation external inspection. There is no internal corrosion on this vessel. The vessel and inspection data are shown below. The vessel was constructed to the ASME B&PV Code, Section VIII Division 1, 1986. Determine if the vessel is acceptable for continued operation at the current MAWP and temperature. There are no supplemental loads. Perform a Level 2 Assessment.

Vessel Data

- Material = $SA-516\ Grade\ 70\ Year\ 1986$
- Design Conditions = $320\ psi\ @\ 450^{\circ}F$
- Inside Diameter = $84\ in$
- Wall Thickness = $1.0\ in$
- Uniform Metal Loss = $0.0\ in$
- Future Corrosion Allowance = $0.0625\ in$
- Allowable Stress = $17500\ psi$
- Weld Joint Efficiency = 0.85
- Distance to Nearest Discontinuity = $37\ in$

The region of pitting extends through a girth weld and is 25 in longitudinal by 15 in circumferential.

Table E6.4-1 Inspection Data

$Pit-Couple_{,k}$	$P_k\ ,in$	$\theta_k\ ,\deg$	$d_{i,k}\ ,in$	$w_{i,k}\ ,in$	$d_{j,k}\ ,in$	$w_{j,k}\ ,in$
1	3.5	10	0.7	0.27	0.6	0.5
2	2.8	0	0.9	0.6	1.1	0.65
3	2.7	22	0.9	0.5	0.9	0.75
4	2.1	30	1	0.7	1.2	0.6
5	3.1	5	0.7	0.6	1.2	0.5
6	4.1	25	1.1	0.55	2.2	0.45
7	2.9	20	0.8	0.65	0.8	0.6
8	3.1	45	1.2	0.4	1.5	0.75
9	2.6	60	1.3	0.5	0.8	0.2
10	2.2	0	0.4	0.55	0.3	0.75
11	1.8	10	1.5	0.5	0.8	0.5
12	2.5	20	0.6	0.75	0.5	0.7
13	3.8	35	2.4	0.5	1.6	0.7
14	1.9	25	0.7	0.35	0.8	0.5
15	1.8	0	1	0.7	0.8	0.5

a) STEP 1 - Determine the following parameters: D, D_O, FCA, $LOSS$, RSF_a, and either t_{rd} or t_{nom} and $LOSS$

$$D = 84\ in \qquad RSF_a = 0.9$$

$$FCA = 0.0625\ in \qquad LOSS = 0.0\ in$$

$$t_{nom} = 1\ in$$

$$t_{rd} = t_{nom} - LOSS = 1 - 0.0 = 1.0\ in$$

$$D_O = D + (2)t_{nom} = 84 + (2)(1) = 86\ in$$

b) STEP 2 - Determine the wall thickness to be used in the assessment using Equation (6.1) or Equation (6.2), as applicable.

$$t_c = t_{rd} - FCA$$

$$t_c = 1 - 0.0625 = 0.9375\ in$$

c) STEP 3 - Determine the pit-couple sample for the assessment (see 6.3.3.2), and the following parameters for each pit-couple. In addition, determine the orientation of the pit-couple measured from the direction of the σ_2 stress component, θ_k (see Figure 6.11)

For the first pit-couple.

$$\theta_1 = 10^\circ$$

$$d_{11} = 0.7\ in \qquad w_{11} = 0.27\ in \qquad P_1 = 3.5\ in$$

$$d_{21} = 0.6\ in \qquad w_{21} = 0.5\ in$$

d) STEP 4 - Determine the depth of each pit in all pit-couples , $w_{i,k}$ and $w_{j,k}$ (See Figure 6.11b) and compute the average pit depth, w_{avg}, considering all readings. In the following equations the subscript 1 represents a calculation for pit-couple 1. The remaining calculations are performed in an embedded matrix

$$w_{avg1} = \frac{w_{11} + w_{21}}{2} = \frac{0.27 + 0.5}{2} = 0.385\ in$$

e) STEP 5 - Calculate the components of the membrane stress field σ_1 and σ_2 (see Figure 6.11). Membrane stress equations for shell components are included in Annex A.

$$R_c = \frac{D}{2} = 42\ in$$ External metal loss only

There are no supplemental loads

$$t_{sl} = 0\ in$$

$$\sigma_1 = \left(\frac{P}{E_c}\right)\left(\frac{R_c}{t_c} + 0.6\right)$$

$$\sigma_1 = \left(\frac{320}{0.85}\right)\left(\frac{42}{0.9375} + 0.6\right) = 17091.7647\ psi$$

$$\sigma_2 = \left(\frac{P}{2E_L}\right)\left(\frac{R_c}{t_c - t_{sl}} - 0.4\right)$$

$$\sigma_2 = \left(\frac{320}{(2)(0.85)}\right)\left(\frac{42}{0.9375 - 0} - 0.4\right) = 8357.6471\ psi$$

f) STEP 6 - Determine the $MAWP$ for the component using the thickness from STEP 2. See Annex A paragraph A.2.

$$MAWP^C = \frac{S_a E_c t_c}{R_c + 0.6 t_c}$$

$$MAWP^C = \frac{(17500)(0.85)(0.9375)}{42 + (0.6)(0.9375)} = 327.6432\ psi$$

$$MAWP^L = \frac{2 S_a E_L (t_c - t_{sl})}{R_c - 0.4(t_c - t_{sl})}$$

$$MAWP^L = \frac{(2)(17500)(0.85)(0.9375 - 0)}{42 - (0.4)(0.9375 - 0)} = 670.0450\ psi$$

The $MAWP$ is the lowest of the longitudinal and circumferential $MAWPs$

$$MAWP = \min\left[327.6432,\ 670.0450\right] = 327.6432\ psi$$

g) STEP 7 - For pit-couple 1, calculate the Remaining Strength Factor

Show the individual calculations for the first pit-couple. Remainder of the pit-couples are shown in Table E6.4-2.

Single Layer Analysis - This analysis can be used when the pitting occurs on one side of the component (See Figure 6.11).

$$d_{avg1} = \frac{d_{11} + d_{21}}{2} = \frac{0.7 + 0.6}{2} = 0.65\ in \qquad \mu_{avg1} = \frac{P_1 - d_{avg1}}{P_1} = \frac{3.5 - 0.65}{3.5} = 0.8143$$

$$\rho_{11} = \frac{\sigma_1}{\mu_{avg1}} = \frac{17091.7674}{0.8143} = 20989.8865\ psi \qquad \rho_{21} = \frac{\sigma_2}{\mu_{avg1}} = \frac{8357.6471}{0.8143} = 10263.7771\ psi$$

$$\psi_1 = \begin{pmatrix} \left(\cos^4[\alpha]+\sin^2[2\alpha]\right)(\rho_{11})^2 - \\ \dfrac{3\sin^2[2\alpha](\rho_{11})(\rho_{21})}{2} + \\ \left(\sin^4[\alpha]+\sin^2[(2\alpha)]\right)(\rho_{21})^2 \end{pmatrix}$$

$$\psi_1 = \begin{pmatrix} \left(\cos^4[(10)]+\sin^2[2(10)]\right)(20989.8865)^2 - \\ \dfrac{3\sin^2[2(10)](20989.8865)(10263.7771)}{2} + \\ \left(\sin^4[((10))]+\sin^2[((2)(10))]\right)(10263.7771)^2 \end{pmatrix} = 4.4056(10)^8\ psi^2$$

$$\Phi_1 = \mu_{avg1}\cdot\max\left[|\rho_{11}|,\ |\rho_{21}|,\ |\rho_{11}-\rho_{21}|\right]$$

$$\Phi_1 = 0.8143\max\left[|20989.8865|,\ |10263.7771|,\ |20989.8865-10263.7771|\right] = 17091.7647\ psi$$

$$E_{avg1} = \min\left[\frac{\Phi_1}{\sqrt{\Psi_1}},1\right] \qquad RSF_1 = 1-\left(\frac{w_{avg1}}{t_c}\right)\left(1-E_{avg1}\right)$$

$$E_{avg1} = \min\left[\frac{17091.7647}{\sqrt{4.4056(10)^8}},1\right] = 0.8143 \qquad RSF_1 = 1-\left(\frac{0.385}{0.9375}\right)(1-0.8143) = 0.9237$$

h) STEP 8 - Repeat STEP 7 for all pit-couples, n, recorded at the time of the inspection. Results are shown in Table E6.4-2.

Table E6.4-2 Pit-Couple Calculations

$Pit-Couple_k$	$w_{avg,k}$	$d_{avg,k}$	$\mu_{avg,k}$	ρ_{1k}	ρ_{2k}	Ψ_k	Φ_k	$E_{avg,k}$	RSF_k
1	0.3850	0.6500	0.8143	2.0990E+04	1.0264E+04	4.4056E+08	1.7092E+04	0.8143	0.9237
2	0.6250	1.0000	0.6429	2.6587E+04	1.3001E+04	7.0688E+08	1.7092E+04	0.6429	0.7619
3	0.6250	0.9000	0.6667	2.5638E+04	1.2536E+04	6.4923E+08	1.7092E+04	0.6708	0.7805
4	0.6500	1.1000	0.4762	3.5893E+04	1.7551E+04	1.2325E+09	1.7092E+04	0.4869	0.6442
5	0.5500	0.9500	0.6935	2.4644E+04	1.2051E+04	6.0740E+08	1.7092E+04	0.6935	0.8202
6	0.5000	1.6500	0.5976	2.8603E+04	1.3986E+04	8.0095E+08	1.7092E+04	0.6039	0.7888
7	0.6250	0.8000	0.7241	2.3603E+04	1.1542E+04	5.5259E+08	1.7092E+04	0.7271	0.8181
8	0.5750	1.3500	0.5645	3.0277E+04	1.4805E+04	7.4747E+08	1.7092E+04	0.6252	0.7701
9	0.3500	1.0500	0.5962	2.8670E+04	1.4019E+04	4.7364E+08	1.7092E+04	0.7854	0.9199
10	0.6500	0.3500	0.8409	2.0325E+04	9.9388E+03	4.1312E+08	1.7092E+04	0.8409	0.8897
11	0.5000	1.1500	0.3611	4.7331E+04	2.3144E+04	2.2402E+09	1.7092E+04	0.3611	0.6593
12	0.7250	0.5500	0.7800	2.1913E+04	1.0715E+04	4.7628E+08	1.7092E+04	0.7832	0.8323
13	0.6000	2.0000	0.4737	3.6083E+04	1.7644E+04	1.2012E+09	1.7092E+04	0.4931	0.6756
14	0.4250	0.7500	0.6053	2.8239E+04	1.3808E+04	7.8069E+08	1.7092E+04	0.6117	0.8240
15	0.6000	0.9000	0.5000	3.4184E+04	1.6715E+04	1.1685E+09	1.7092E+04	0.5000	0.6800

$$RSF_{pit} = \frac{1}{15}\sum_{k=1}^{15} RSF_k = 0.7859$$

i) STEP 9 - Evaluate results based on the type of pitting damage (see Figure 6.2).

Localized Pitting –The pitting damage is localized, then the damaged area is evaluated as an equivalent region of localized metal loss (LTA, see Part 5 and Figure 5.13). The meridional and circumferential dimensions of the equivalent LTA should be based on the physical bounds of the observed pitting. The equivalent thickness, t_{eq}, for the LTA can be established using the following equation. To complete the analysis, the LTA is then evaluated using the Level 1 or Level 2 assessment procedures in Part 5 with $t_{mm} = t_{eq}$, where t_{eq} is given by Equation (6.16).

$$t_{eq} = RSF_{pit}\left(t_c\right)$$

$$t_{eq} = (0.7859)(0.9375) = 0.7368\ in$$

Determine if the vessel is acceptable for the current $MAWP$ using a Part 5 Level 1 paragraph 5.4.2 Assessment.

a) STEP 1 – Determine the CTP (Critical Thickness Profiles) – the thickness and the size of the local thin area is given as:

$$t_{eq} = 0.7368\ in \qquad s = 25\ in \qquad c = 15\ in$$

b) STEP 2 – Determine the wall thickness to be used in the assessment. This is the same as Level 2 STEP 2

$$t_c = 0.9375\ in$$

c) STEP 3 – Determine the minimum measured thickness in the LTA and the dimension, s, (see paragraph 5.3.3.2.b) for the CTP.

$$t_{mm} = t_{eq} = 0.7368\ in$$
$$s = 25\ in$$

d) STEP 4 – Determine the remaining thickness ratio using Equation (5.5) and the longitudinal flaw length parameter using Equation (5.6). Note in this case t_{eq} is based on t_c and already includes the FCA.

$$t_{mm} - FCA = t_{eq}$$
$$R_t = \frac{t_{mm} - FCA}{t_c} = \frac{0.7368}{0.9375} = 0.7859$$
$$\lambda = \frac{1.285s}{\sqrt{Dt_c}} = \frac{(1.285)(25)}{\sqrt{(84)(0.9375)}} = 3.6201$$

e) STEP 5 – Check the limiting flaw size criteria; if the following requirements are satisfied, proceed to STEP 6; otherwise, the flaw is not acceptable per the Level 1 Assessment procedure.

$$\left(R_t = 0.7859\right) \geq 0.2 \qquad True$$
$$\left(t_{mm} - FCA = 0.7368 in\right) \geq 0.1 in \qquad True$$
$$\left(L_{msd} = 23.5\ in\right) \geq \left((1.8)\sqrt{(84)(0.9375)} = 15.9734\ in\right) \qquad True$$

f) STEP 6 – The region of metal loss is categorized as an LTA, so proceed to STEP 7

g) STEP 7 – Determine the $MAWP$ for the component (see Annex A, paragraph A.2) using the thickness from STEP 2.

The MAWP calculation has been performed in STEP 6 of the pitting evaluation.

$$MAWP = 327\ psi$$

h) STEP 8 – Enter Figure 5.6 for a cylindrical shell or Figure 5.7 for a spherical shell with the calculated values of λ and R_t.

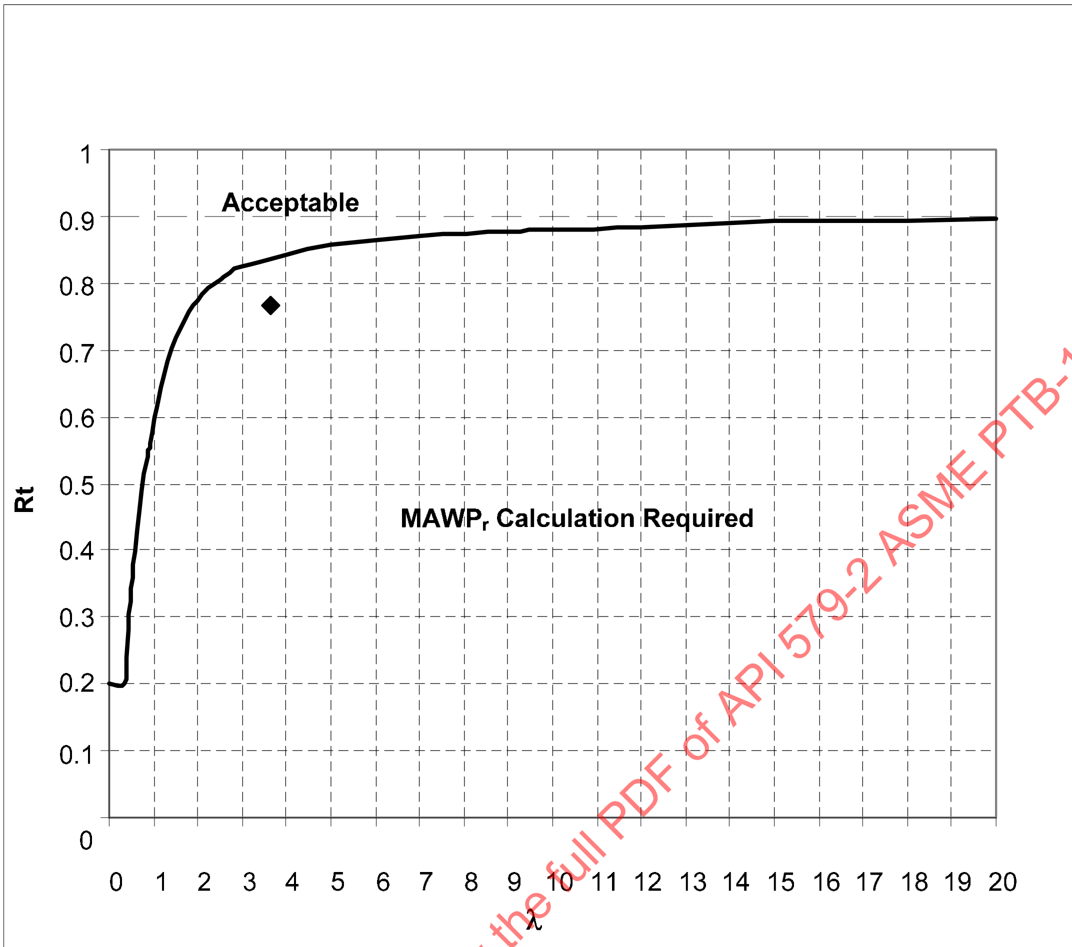


Figure E6.4-1 Level 1 Screening Curve (API 579 Figure 5.6)

The RSF can be determined by Equation 5.11 with $R_t = 0.7859$ and $\lambda = 3.6201$

$$M_t = \begin{pmatrix} 1.0010 - 0.014195\lambda + 0.29090\lambda^2 - 0.096420\lambda^3 + \\ 0.020890\lambda^4 - 0.0030540\lambda^5 + 2.9570\left(10^{-4}\right)\lambda^6 - \\ 1.8462\left(10^{-5}\right)\lambda^7 + 7.1553\left(10^{-7}\right)\lambda^8 - \\ 1.5631\left(10^{-8}\right)\lambda^9 + 1.4656\left(10^{-10}\right)\lambda^{10} \end{pmatrix} = 2.4109$$

$$RSF = \frac{R_t}{1 - \dfrac{1}{M_t}\left(1 - R_t\right)}$$

$$RSF = \frac{0.7859}{1 - \left(\dfrac{1}{2.4109}\right)\left(1 - 0.7859\right)} = 0.8625$$

i) STEP 9 – The component is a cylindrical shell so that the circumferential extent of the flaw must be evaluated using the following procedure.

1) STEP 9.1 – Determine the circumferential flaw length parameter

$$\lambda_c = \frac{(1.285)c}{\sqrt{Dt_c}}$$

$$\lambda_c = \frac{(1.285)(15)}{\sqrt{(84)(0.9375)}} = 2.1720$$

2) STEP 9.2 – If all of the following conditions are satisfied, proceed to STEP 9.3; otherwise, the flaw is not acceptable per the Level 1 Assessment procedure.

$$(\lambda_c = 2.1720) \le 9 \qquad True$$

$$\left(\frac{D}{t_c} = 89.6\right) \ge 20 \qquad True$$

$$0.7 \le (RSF = 0.8625) \le 1 \qquad True$$

$$0.7 \le (E_L = 0.85) \le 1 \qquad True$$

$$0.7 \le (E_c = 0.85) \le 1 \qquad True$$

3) STEP 9.3 – Determine the tensile stress factor using Equation (5.18).

$$TSF = \left(\frac{E_c}{2RSF}\right)\left(1 + \frac{\sqrt{4 - 3E_L^2}}{E_L}\right)$$

$$TSF = \left(\frac{0.85}{(2)(0.8625)}\right)\left(1 + \frac{\sqrt{4 - (3)(0.85)^2}}{0.85}\right) = 1.2775$$

4) STEP 9.4 – Determine the screening curve in Figure 5.8 based on TSF. Enter Figure 5.8 with the calculated values of λ_c and R_t. If the point defined by the intersection of these values is on or above the screening curve, then the circumferential extent of the flaw is acceptable per Level 1

$TSF = 1.2775$ $\qquad R_t = 0.7859$ $\qquad \lambda_c = 2.1720$

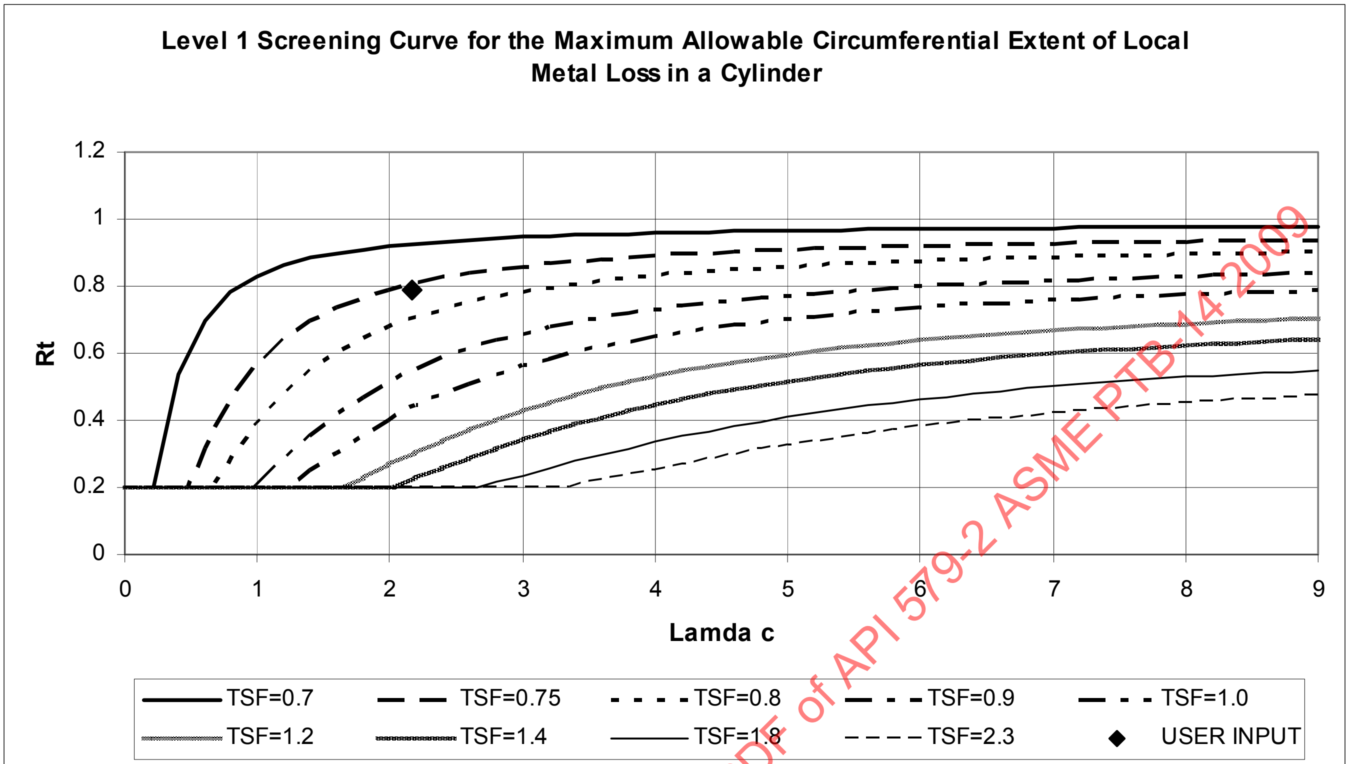


Figure E6.4-2 Level 1 Screening Curve – Circumferential Extent

The point is between the interpolated $TSF = 0.75 \,/\, TSF = 0.8$ screening curve, so that the circumferential extent is acceptable.

SUMMARY

The equipment fails the longitudinal extent of the Part 5 Level 1 criteria. The rerated $MAWP$ is

$$RSF = 0.8625$$

$$MAWP_r = MAWP\frac{RSF}{RSF_a} = 327.6432\frac{0.8625}{0.9} = 313.9846\ psi$$

Return to and complete the assessment.

j) STEP 10 - Check the recommended limitations on the individual pit diameters

1) For the first pit

$$R_{t1} = \frac{t_c + FCA - w_{11}}{t_c} = \frac{0.9375 + 0.0625 - 0.27}{0.9375} = 0.7787$$

$$Q_1 == (1.123)\left[\left(\frac{1-R_{t1}}{1-\dfrac{R_{t1}}{RSF_a}}\right)^2 - 1\right]^{0.5} = (1.123)\left[\left(\frac{1-0.7787}{1-\dfrac{0.7787}{0.9}}\right)^2 - 1\right]^{0.5} = 1.4622$$

$$Q_1\sqrt{Dt_c} = (1.462)\sqrt{(84)(0.9375)} = 12.9759\, in$$

Is diameter less than allowable?

$$D_1 \le Q_1\sqrt{Dt_c}$$

$$0.5 \le = 12.9759 \;\Rightarrow\; \text{Yes}$$

2) Pit Depth – The following limit on the remaining thickness ratio is recommended to prevent a local failure characterized by pinhole type leakage. The criterion is expressed in terms of the remaining thickness ratio as follows:

$$R_t \ge 0.20$$

The calculations are summarized in Table E6.4-**3** for all pit-couples.

Table E6.4-3 Pit-Couple Calculations

$Pit-Couple,_k$	$R_{t,i}$	$Q_{1,k}$	$Q_1\sqrt{Dt_c}$	Single Pit da_1 Ok?	$R_{t,j}$	$Q_{2,k}$	$Q_2\sqrt{Dt_c}$	Single Pit da_1 Ok?	$R_t \le 0.2$
1	0.779	1.462	12.98	Yes	0.533	0.627	5.567	Yes	Yes
2	0.427	0.487	4.326	Yes	0.373	0.430	3.818	Yes	Yes
3	0.533	0.627	5.567	Yes	0.267	0.329	2.922	Yes	Yes
4	0.320	0.378	3.356	Yes	0.427	0.487	4.326	Yes	Yes
5	0.427	0.487	4.326	Yes	0.533	0.627	5.567	Yes	Yes
6	0.480	0.552	4.899	Yes	0.587	0.719	6.377	Yes	Yes
7	0.373	0.430	3.818	Yes	0.427	0.487	4.326	Yes	Yes
8	0.640	0.835	7.410	Yes	0.267	0.329	2.922	Yes	Yes
9	0.533	0.627	5.567	Yes	0.853	2.971	26.368	Yes	Yes
10	0.480	0.552	4.899	Yes	0.267	0.329	2.922	Yes	Yes
11	0.533	0.627	5.567	Yes	0.533	0.627	5.567	Yes	Yes
12	0.267	0.329	2.922	Yes	0.320	0.378	3.356	Yes	Yes
13	0.533	0.627	5.567	Yes	0.320	0.378	3.356	Yes	Yes
14	0.693	0.994	8.821	Yes	0.533	0.627	5.567	Yes	Yes
15	0.320	0.378	3.356	Yes	0.533	0.627	5.567	Yes	Yes

The equipment fails the Level 2 assessment; the re-rated pressure is 313 psig

6.5 Example Problem 5

Pitting in a local thin area has been discovered on the cylindrical section on a horizontal pressure vessel during an external inspection. The local thin area is 12 inches longitudinal by 18 inches circumferential and is centered on the bottom of the vessel with a minimum thickness of 0.39 inches. The region is located midway between the two saddles. The vessel is insulated and filled with an oil product with specific gravity of 0.9.

The vessel and inspection data are shown below. The pitting depths are measured from the undamaged surface $\left(t_{rd} = 0.50 \text{ inches}\right)$. Figure E6.5-1 shows a sketch of the pitting / LTA damage. The vessel was constructed to the ASME B&PV Section VIII Division 1 code 1999. Determine if the vessel is acceptable for continued operation at the current $MAWP$ and temperature. Since there are supplemental loads a Level 2 Assessment is required. There is no internal corrosion.

Vessel Data

- Material = $SA-516\ Grade\ 70\ Year\ 1999$
- Design Conditions = $125\ psi @ 450^{\circ} F$
- Inside Diameter = $120\ in$
- Wall Thickness = $0.5\ in$
- Uniform Metal Loss = $0.0\ in$
- Future Corrosion Allowance (on OD) = $0.1\ in$
- Allowable Stress = $20000\ psi$
- Weld Joint Efficiency = 1
- Tangent to Tangent Distance = $70\ in$
- Total Weight = $80000\ lbf$
- Saddle Reaction Force = $40000\ lbf$
- Length from the tangent line of the horizontal vessel to the centerline of a saddle support = $18\ in$
- Height of the Horizontal Vessel Head = $30\ in$

A Zick analysis has determined the supplemental loads acting at the pitting / LTA.

The inspection data is shown in Table E6.5-1.

Table E6.5-1 Inspection Data

$Pit-Couple,_k$	P_k ,in	θ_k ,deg	$d_{i,k}$,in	$w_{i,k}$,in	$d_{j,k}$,in	$w_{j,k}$,in
1	3.5	10	0.3	0.21	0.4	0.18
2	2.8	0	0.9	0.2	1.1	0.22
3	2.7	22	0.9	0.17	0.9	0.19
4	2.1	30	0.5	0.21	1	0.135
5	3.1	5	0.7	0.17	1.2	0.22
6	3	25	1.1	0.165	2.2	0.21
7	2.9	20	0.8	0.18	0.8	0.24
8	3.1	45	1.2	0.123	1.5	0.17
9	2.6	60	1.3	0.145	0.8	0.16
10	2.2	0	0.4	0.21	0.3	0.135
11	1.8	10	1.5	0.22	0.8	0.19
12	2.5	20	0.6	0.25	0.5	0.175
13	2.5	35	2.4	0.18	1.6	0.205
14	1.9	25	0.7	0.2	0.8	0.2
15	1.8	0	1	0.17	0.8	0.22

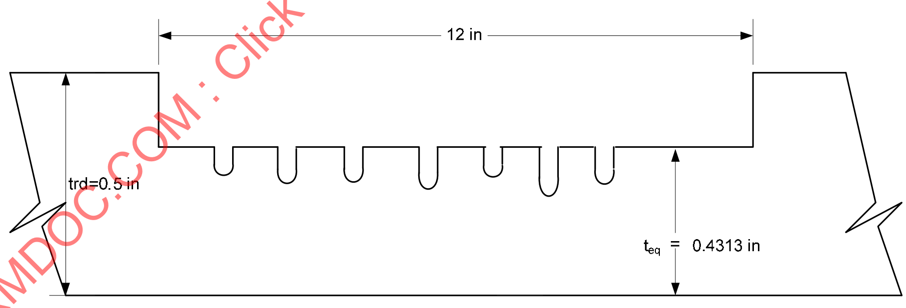


Figure E6.5-1: Sketch of LTA and Pitting (longitudinal direction)

a) STEP 1 - Determine the following parameters: $D, D_O, FCA, LOSS, RSF_a$, and either t_{rd} or t_{nom} and $LOSS$

$$D = 120\ in$$
$$t_{nom} = 0.5\ in$$
$$FCA = 0.1\ in$$
$$LOSS = 0.0\ in$$
$$RSF_a = 0.9$$
$$D_O = D + 2t_{nom} = 120 + (2)(0.5) = 121\ in$$
$$t_{rd} = t_{nom} - LOSS = 0.5 - 0.0 = 0.5\ in$$

Additional Required Variables

$S_a = 20000\ psi$	$E_c = 1$	$E_L = 1$
$P = 125\ psi$	$\alpha = 0\deg$	$L = 70\ in$
$s = 12\ in$	$c = 18\ in$	$A = 18\ in$
$H = 30\ in$	$Q_s = 40000\ lb$	

$$t_{mm} = 0.39\ in \text{ minimum thickness in the LTA}$$
$$R_c = \frac{D}{2} = 60\ in$$
$$L_{msd} = \frac{70}{2} = 35\ in$$

b) STEP 2 - Determine the RSF for the local thin area per Part 5 Level 1 paragraph 5.4.2 Assessment.

a) PART 5 STEP 1 – Determine the CTP (Critical Thickness Profiles) – the thickness and the size of the local thin area is given as:

$s = 12\ in$ $\qquad$ $c = 18\ in$

b) PART 5 STEP 2 – Determine the wall thickness to be used in the assessment.

$$t_c = t_{rd} - FCA = 0.5 - 0.1 = 0.4\ in$$

c) PART 5 STEP 3 – Determine the minimum measured thickness in the LTA, and the dimension, s, (see paragraph 5.3.3.2.b) for the CTP.

$t_{mm} = 0.39\ in$ $\qquad$ $s = 12\ in$

d) PART 5 STEP 4 – Determine the remaining thickness ratio using Equation (5.5) and the longitudinal flaw length parameter using Equation (5.6)

$$R_t = \frac{t_{mm} - FCA}{t_c} = \frac{0.39 - 0.1}{0.4} = 0.725$$
$$\lambda = \frac{(1.285)s}{\sqrt{Dt_c}} = \frac{(1.285)(12)}{\sqrt{(120)(0.4)}} = 2.2257$$

e) PART 5 STEP 5 – Check the limiting flaw size criteria; if the following requirements are satisfied, proceed to PART 5 STEP 6; otherwise, the flaw is not acceptable per the Level 1 Assessment procedure.

$$\left(R_t = 0.7250\right) \geq 0.2 \qquad True$$

$$\left(t_{mm} - FCA = 0.29\ in \geq 0.1\ in\right) \qquad True$$

$$\left(L_{msd} = 35\ in\right) \geq \left(\left(1.8\right)\sqrt{\left(120\right)\left(0.4\right)} = 12.4708\ in\right) \qquad True$$

f) PART 5 STEP 6 – The region of metal loss is categorized as an LTA, so proceed to PART 5 STEP 7

g) PART 5 STEP 7 - Determine the $MAWP$ for the component using the thickness from PART 5 STEP 2. See Annex A paragraph A.5

$$R_m = \frac{\dfrac{D}{2} + \left(\dfrac{D_o}{2} - LOSS - FCA\right)}{2} = \frac{\dfrac{120}{2} + \left(\dfrac{121}{2} - 0.0 - 0.1\right)}{2} = 60.2\,in$$

$$t_{sl} = \frac{QL}{4SE\pi R_m^2}\left[\frac{1 + \dfrac{2\left(R_m^2 - H^2\right)}{L^2}}{1 + \dfrac{4H}{3L}} - \frac{4A}{L}\right]$$

$$= \frac{8000(70)}{4(20000)(1)\pi(60.2)^2}\left[\frac{1 + \dfrac{2((60.2)^2 - (30)^2)}{(70)^2)}}{1 + \dfrac{4(30)}{3(70)}} - \frac{4(15)}{70}\right] = 0.001\ in$$

$$MAWP^C = \frac{S_a E_c t_c}{R_c + 0.6t_c} = \frac{\left(20000\right)\left(1\right)\left(0.4\right)}{60 + \left(0.6\right)\left(0.4\right)} = 132.8021\,psi$$

$$MAWP^L = \frac{2S_a E_L\left(t_c - t_{sl}\right)}{R_c - 0.4\left(t_c - t_{sl}\right)} = \frac{\left(2\right)\left(20000\right)\left(1\right)\left(0.4 - 0.0025\right)}{60 - \left(0.4\right)\left(0.4 - 0.0025\right)} = 265.6731\,psi$$

The $MAWP$ is the lowest of the longitudinal and circumferential $MAWPs$

$$MAWP = \min\left[132.8021,\ 265.6731\right] = 132.8021\,psi$$

h) PART 5 STEP 8 – Enter Figure 5.6 for a cylindrical shell or Figure 5.7 for a spherical shell with the calculated values of λ and R_t.

This is not required since the RSF for the LTA is only needed for the combined assessment. The RSF can be determined by Equation 5.11.

Using $R_t = 0.725$ and $\lambda = 2.2257$, determine the RSF for the LTA

Determine M_t using Table 5.2

$$M_t = \begin{pmatrix} 1.0010 - 0.014195\lambda + 0.29090\lambda^2 - 0.096420\lambda^3 + 0.020890\lambda^4 - \\ 0.0030540\lambda^5 + 2.9570(10)^{-4}\lambda^6 - 1.8462(10)^{-5}\lambda^7 + \\ 7.1553(10)^{-7}\lambda^8 - 1.5631(10)^{-8}\lambda^9 + 1.4656(10)^{-10}\lambda^{10} \end{pmatrix} = 1.7245$$

$$RSF_{lta} = \frac{R_t}{1-\left(\frac{1}{M_t}\right)(1-R_t)} = \frac{0.7250}{1-\left(\frac{1}{1.7245}\right)(1-0.7250)} = 0.8625$$

Determine the equivalent thickness for the pitting assessment

$$t_{eq} = t_{rd} \bullet RSF_{lta} = 0.5(0.8625) = 0.4313\,in$$

i) PART 5 STEP 9 – The component is a cylindrical shell so that the circumferential extent of the flaw must be evaluated using the following procedure.

NOTE: This needs to be assessed with the combined RSF due to pitting and LTA and will be performed after the RSF for pitting is determined.

c) STEP 3 - Assess the Pitting Damage using the equivalent thickness from PART 5 STEP 8 as t_c.

a) PART 6 STEP 1 - Determine the following parameters: $D, D_O, FCA, LOSS, RSF_a$, and either t_{rd} or t_{nom} and $LOSS$. These values have been calculated in STEP 1

b) PART 6 STEP 2 - Determine the wall thickness to be used in the assessment using Equation (6.1) or Equation (6.2) as applicable. Use the equivalent thickness calculated in PART 5 STEP 8. Do not adjust pit depth to the depth below the equivalent thickness, pit depth is measured from the corroded surface.

$$t_c = t_{eq} = 0.4313\,in$$

c) PART 6 STEP 3 **-** Determine the pit-couple sample for the assessment (see 6.3.3.2), and the following parameters for each pit-couple. In addition, determine the orientation of the pit-couple measured from the direction of the σ_2 stress component, θ_k (see Figure 6.11)

For the first pit-couple:

$$\theta_{10} = 10^\circ$$

$d_{11} = 0.3\ in$ $\quad$ $w_{11} = 0.21\ in$ $\quad$ $P_1 = 3.5\ in$

$d_{21} = 0.4\ in$ $\quad$ $w_{21} = 0.18\ in$

d) PART 6 STEP 4 - Determine the depth of each pit in all pit-couples, w_{ik} and w_{jk} (See Figure 6.11b) and compute the average pit depth, w_{avg}, considering all readings. In the following equations the subscript 1 represents a calculation for pit-couple 1. The remaining calculations are shown in Table E6.5-2.

$$w_{avg1} = \frac{w_{11} + w_{21}}{2} = \frac{0.21 + 0.18}{2} = 0.195\ in$$

e) PART 6 STEP 5 - Calculate the components of the membrane stress field σ_1 and σ_2 (see Figure 6.11). Membrane stress equations for shell components are included in Annex A.

$$\sigma_1 = \left(\frac{P}{E_c}\right)\left(\frac{R_c}{t_c}+0.6\right) \qquad \sigma_1 = \left(\frac{125}{1}\right)\left(\frac{60}{0.4313}+0.6\right) = 17465.4199\ psi$$

$$\sigma_2 = \left(\frac{P}{2E_L}\right)\left(\frac{R_c}{t_c-t_{sl}}-0.4\right) \qquad \sigma_2 = \left(\frac{125}{(2)(1)}\right)\left(\frac{60}{0.4313-0.001}-0.4\right) = 8689.7986\ psi$$

f) PART 6 STEP 6 - Determine the $MAWP$ for the component using the thickness from PART 5 STEP 2. See Annex A paragraph A.5.

This is not required since the RSF for the LTA is only needed for the combined assessment.

g) PART 6 STEP 7 - For pit-couple 1, calculate the Remaining Strength Factor

Show the individual calculations for the first pit-couple.

Single Layer Analysis - This analysis can be used when the pitting occurs on one side of the component

(See Figure 6.11).

$$d_{avg1} = \frac{d_{11}+d_{21}}{2} = \frac{0.3+0.4}{2} = 0.35\ in \qquad \mu_{avg1} = \frac{P_1 - d_{avg1}}{P_1} = \frac{3.5-0.35}{3.5} = 0.9$$

$$\rho_{11} = \frac{\sigma_1}{\mu_{avg1}} = \frac{17465.4199}{0.9} = 19406.0221\ psi \qquad \rho_{21} = \frac{\sigma_2}{\mu_{avg1}} = \frac{8689.7986}{0.9} = 9655.3317\ psi$$

$$\psi_1 = \left(\begin{array}{l} \left(\cos^4[\alpha]+\sin^2[2\alpha]\right)(\rho_{11})^2 - \\ \dfrac{3\sin^2[2\alpha](\rho_{11})(\rho_{21})}{2} + \\ \left(\sin^4[\alpha]+\sin^2[(2\alpha)]\right)(\rho_{21})^2 \end{array}\right)$$

$$\psi_1 = \left[\begin{array}{l} \left(\cos^4[(10)]+\sin^2[(2)(10)]\right)(19406.0221)^2 - \\ \dfrac{3\sin^2[(2)(10)](19406.0221)(9655.3317)}{2} + \\ \left(\sin^4[(10)]+\sin^2[(2)(10)]\right)(9655.3317)^2 \end{array}\right] = 3.7639(10)^8\ psi^2$$

$$\Phi_1 = 0.9\max\left[|\rho_{11}|,|\rho_{21}|,|\rho_{11}-\rho_{21}|\right]$$

$$\Phi_1 = 0.9\max\left[|19406.0221|,|9655.3317|,|19406.0221-9655.3317|\right] = 17465.4199\ psi$$

$$E_{avg1} = \min\left[\frac{\Phi_1}{\sqrt{\psi_1}},1\right] \qquad RSF_1 = 1-\left(\frac{w_{avg1}}{t_c}\right)\left(1-E_{avg1}\right)$$

$$E_{avg1} = \min\left[\frac{17465.4199}{\sqrt{3.7635(10)^8}},1\right] = 0.9002 \qquad RSF_1 = 1-\left(\frac{0.195}{0.4313}\right)(1-0.9002) = 0.9549$$

h) PART 6 STEP 8 - Repeat PART 6 STEP 7 for all pit-couples, n, recorded at the time of the inspection. Results are in Table E6.5-2.

Table E6.5-2 Pit-Couple Calculations

$Pit-Couple_k$	$w_{avg,k}$	$d_{avg,k}$	$\mu_{avg,k}$	ρ_{1k}	ρ_{2k}	ψ_k	Φ_k	$E_{avg,k}$	RSF_k
1	0.195	0.35	0.900	20951	10475	4.387E+08	18856.3	0.900	0.951
2	0.210	1	0.643	29332	14664	8.604E+08	18856.3	0.643	0.813
3	0.180	0.9	0.667	28284	14141	7.882E+08	18856.3	0.672	0.852
4	0.173	0.75	0.643	29332	14664	8.200E+08	18856.3	0.658	0.853
5	0.195	0.95	0.694	27188	13593	7.392E+08	18856.3	0.694	0.851
6	0.188	1.65	0.450	41903	20949	1.714E+09	18856.3	0.455	0.745
7	0.210	0.8	0.724	26040	13018	6.711E+08	18856.3	0.728	0.857
8	0.147	1.35	0.565	33403	16699	9.065E+08	18856.3	0.626	0.863
9	0.153	1.05	0.596	31630	15813	5.784E+08	18856.3	0.784	0.918
10	0.173	0.35	0.841	22424	11211	5.028E+08	18856.3	0.841	0.931
11	0.205	1.15	0.361	52217	26106	2.725E+09	18856.3	0.361	0.673
12	0.213	0.55	0.780	24175	12086	5.784E+08	18856.3	0.784	0.885
13	0.193	2	0.200	94281	47135	8.168E+09	18856.3	0.209	0.619
14	0.200	0.75	0.605	31154	15575	9.474E+08	18856.3	0.613	0.806
15	0.195	0.9	0.500	37713	18854	1.422E+09	18856.3	0.500	0.756

Determine the average RSF for all the pit-couples specified

$$RSF_{pit} = \frac{1}{15}\sum_{k=1}^{15} RSF_k = 0.8375$$

i) PART 6 STEP 9 - Evaluate results based on the type of pitting damage (see Figure 6.2): In this case pitting is confined within a **region of localized metal loss.**

(1) Pitting Confined Within A Region Of Localized Metal Loss – If the pitting damage is confined within a region of localized metal loss (see Figure 6.14), then the results can be evaluated using the methodology in subparagraph 2) (below)

(2) Region Of Local Metal Loss Located In An Area Of Widespread Pitting – If a region of local metal loss (LTA) is located in an area of widespread pitting, then a combined Remaining Strength Factor can be determined using the following equation.

$$RSF_{comb} = RSF_{pit} RSF_{lta}$$

Combined Analysis

$$RSF_{pit} = 0.8375$$

$$RSF_{lta} = 0.8625$$

$$RSF_{comb} = RSF_{pit} RSF_{lta} = (0.8375)(0.8625) = 0.7224$$

The reduced $MAWP$ of the damaged component is

$$MAWP_r = \min\left[MAWP\left(\frac{RSF_{comb}}{RSF_a}\right), MAWP\right]$$

$$= \min\left[132.8021\left(\frac{0.7224}{0.9}\right), 132.8021\right] = 106.5978\ psi$$

k) PART 6 STEP 10 - Check the recommended limitations on the individual pit dimensions
For the first pit of the first pit-couple
1) Pit Diameter

$$R_{t1} = \frac{t_c + FCA - w_{11}}{t_c} = \frac{0.4313 + 0.1 - 0.21}{0.4313} = 0.7449$$

$$Q_1 = (1.123)\left[\left(\frac{1 - R_{t1}}{1 - \frac{R_{t1}}{RSF_a}}\right)^2 - 1\right]^{0.5} = (1.123)\left[\left(\frac{1 - 0.7449}{1 - \frac{0.7449}{0.9}}\right)^2 - 1\right]^{0.5} = 1.2259$$

$$Q_1\sqrt{Dt_c} = (1.123)\sqrt{(120)(0.4313)} = 8.819\ in$$

Is diameter less than allowable?

$$D_1 \le Q_1\sqrt{Dt_c}$$

$$0.3 \le 8.819 \quad \Rightarrow \text{ Yes}$$

2) Pit Depth – The following limit on the remaining thickness ratio is recommended to prevent a local failure characterized by pinhole type leakage. The criterion is expressed in terms of the remaining thickness ratio as follows:

$$R_t \ge 0.20$$

Repeat for all pit-couples. The calculations are summarized in Table E6.5-3.

Table E6.5-3 Pit-Couple Sizing Calculations

$Pit-Couple_k$	$R_{t,i}$	$Q_{1,k}$	$Q_1\sqrt{Dt_c}$	Single Pit diameter Ok?	$R_{t,j}$	$Q_{2,k}$	$Q_2\sqrt{Dt_c}$	Single Pit diameter Ok?	$R_t \geq 0.2$
1	0.725	1.123	5.502	Yes	0.800	1.681	8.234	Yes	Yes
2	0.750	1.256	6.151	Yes	0.700	1.018	4.989	Yes	Yes
3	0.825	2.074	10.159	Yes	0.775	1.431	7.012	Yes	Yes
4	0.725	1.123	5.502	Yes	0.913	6.985	34.220	Yes	Yes
5	0.825	2.074	10.159	Yes	0.700	1.018	4.989	Yes	Yes
6	0.838	2.376	11.639	Yes	0.725	1.123	5.502	Yes	Yes
7	0.800	1.681	8.234	Yes	0.650	0.861	4.217	Yes	Yes
8	0.943	0.780	3.822	Yes	0.825	2.074	10.159	Yes	Yes
9	0.888	9.027	44.222	Yes	0.850	2.816	13.798	Yes	Yes
10	0.725	1.123	5.502	Yes	0.913	6.985	34.220	Yes	Yes
11	0.700	1.018	4.989	Yes	0.775	1.431	7.012	Yes	Yes
12	0.625	0.799	3.914	Yes	0.813	1.852	9.072	Yes	Yes
13	0.800	1.681	8.234	Yes	0.738	1.185	5.806	Yes	Yes
14	0.750	1.256	6.151	Yes	0.750	1.256	6.151	Yes	Yes
15	0.825	2.074	10.159	Yes	0.700	1.018	4.989	Yes	Yes

d) STEP 4 - Return to the PART 5 analysis to check the circumferential extent of the flaw

j) PART 5 STEP 9 – The component is a cylindrical shell so that the circumferential extent of the flaw must be evaluated using the following procedure.

1) STEP 9.1 – Determine the circumferential flaw length parameter

$$\lambda_c = \frac{1.285c}{\sqrt{Dt_c}} = \frac{(1.285)(18)}{\sqrt{(120)(0.4313)}} = 3.2152$$

2) STEP 9.2 – If all of the following conditions are satisfied, proceed to STEP 9.3; otherwise, the flaw is not acceptable per the Level 1 Assessment procedure.

$$(\lambda_c = 3.2152) \leq 9 \qquad True$$

$$\left(\frac{D}{t_c} = 278.2467\right) \geq 20 \qquad True$$

$$0.7 \leq (RSF_{comb} = 0.7224) \leq 0.1 \; True$$ Use the combined RSF for the circumferential extent

$$0.7 \leq (E_L = 1) \leq 1 \qquad True$$

$$0.7 \leq (E_c = 1) \leq 1 \qquad True$$

3) STEP 9.3 – Determine the tensile stress factor using Equation (5.18).

$$TSF = \left(\frac{1}{2RSF_{comb}}\right)\left(1+\frac{\sqrt{4-3E_L^{\,2}}}{E_L}\right)$$

$$TSF = \left(\frac{1}{(2)(0.7224)}\right)\left(1+\frac{\sqrt{4-(3)(1)^2}}{1}\right)=1.3842$$

4) STEP 9.4 – Determine the screening curve in Figure 5.8 based on TSF. Enter Figure 5.8 with the calculated values of λ_c and R_t (See Figure E6.5-2). If the point defined by the intersection of these values is on or above the screening curve, then the circumferential extent of the flaw is acceptable per Level 1.

$TSF = 1.3842$ $\quad\quad$ $R_t = 0.7250$ $\quad\quad$ $\lambda_c = 3.2152$

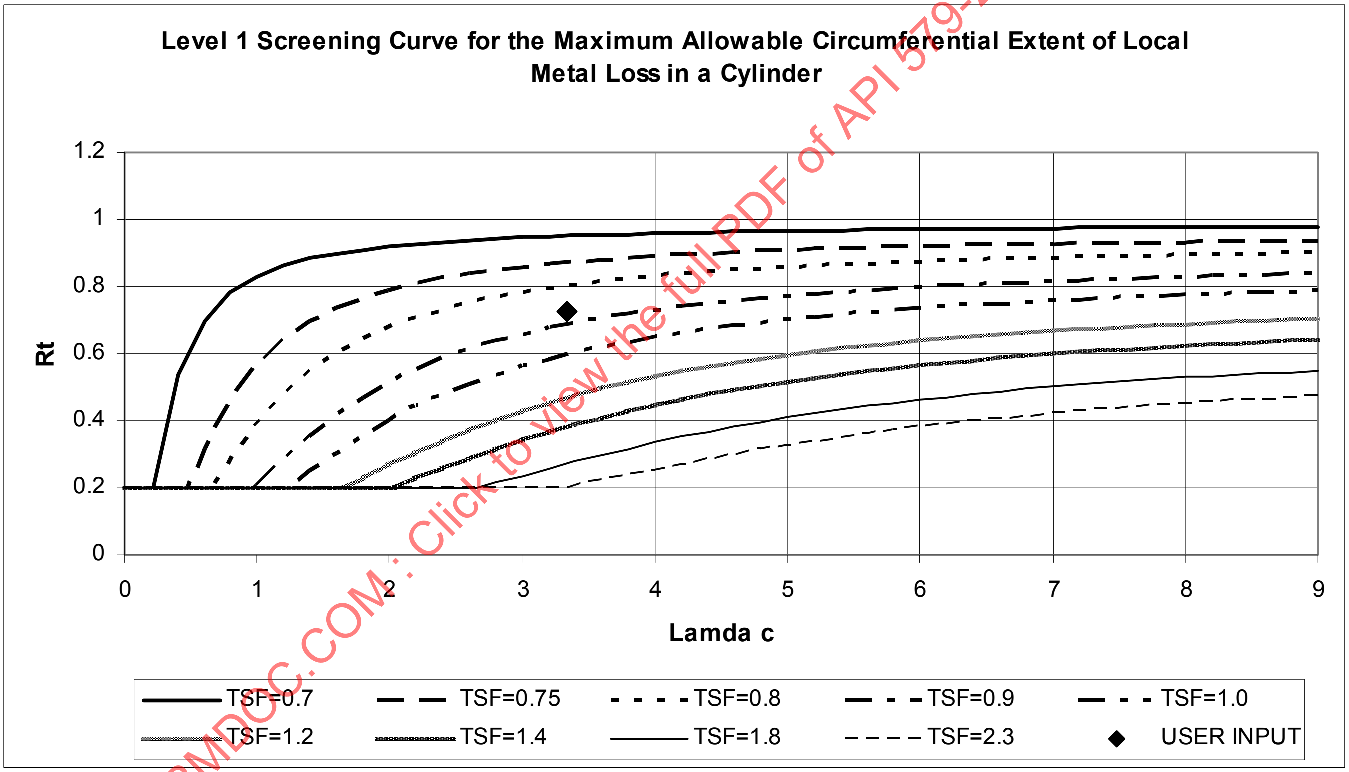


Figure E6.5-2 Level 1 Screening Curve – Circumferential Extent

The point shown is between the $TSF = 0.8$ / $TSF = 0.9$ screening curve which is above the curve for $TSF = 1.3842$, so that the circumferential extent is ACCEPTABLE

e) STEP 5 Summarize and calculate the combined RSF and $MAWP$

The RSF for the combined LTA and pitting damage is

$$RSF_{pit} = 0.8376$$

$$RSF_{lta} = 0.8625$$

$$RSF_{comb} = RSF_{pit} RSF_{lta} = (0.8376)(0.8625) = 0.7224$$

The region of pitting and local thin area fails the Level 2 Assessment procedure. Determine the reduced $MAWP$ of the damaged component

$$MAWP_r = \min\left[MAWP\left(\frac{RSF_{comb}}{RSF_a}\right), MAWP\right]$$

$$= \min\left[132.8021\left(\frac{0.7224}{0.9}\right), 132.8021\right] = 106.6015\ psi$$

6.6 Example Problem 6

Inspection of a pressure vessel during a scheduled turnaround has detected widespread pitting on both ID and OD surfaces. The vessel and inspection data are shown below. The vessel was constructed to the ASME B&PV Code, Section VIII Division 1 1972. Determine if the vessel is acceptable for continued operation at the current $MAWP$ and temperature.

<u>Vessel Data</u>

- Material = $SA-516\ Grade\ 70\ Year\ 1972$
- Design Conditions = $300\ psi @\ 450^{\circ} F$
- Inside Diameter = $96\ in$
- Wall Thickness = $1\ in$
- Uniform Metal Loss = $0.0\ in$
- Future Corrosion Allow. = $0.0\ in$
- Allowable Stress = $17500\ psi$
- Weld Joint Efficiency = 0.85
- Distance to Nearest Discontinuity = $96\ in$
- Supplemental Loads = $0\ (Negligible)$

The inspection data taken from the ID and OD surfaces is shown in Table E6.6-1. Depths of the pitting are measured from each respective surface.

Table E6.6-1 Inspection Data

$Pit-Couple_k$	P_k ,in	θ_k ,deg	$d_{i,k}$,in	$w_{i,k}$,in	$d_{j,k}$,in	$w_{j,k}$,in
ID Surface						
1	3.5	10	0.3	0.21	0.4	0.32
2	2.8	0	0.9	0.2	1.1	0.2
3	2.7	22	0.9	0.17	0.9	0.2
4	2.1	30	0.5	0.25	1	0.135
5	3.1	5	0.7	0.17	1.2	0.2
6	3	25	1.1	0.165	2.2	0.2
7	2.9	20	0.8	0.18	0.8	0.25
8	3.1	20	1.2	0.123	1.5	0.17
9	2.6	30	1.3	0.25	0.8	0.3
10	2.2	0	0.86	0.3	0.9	0.21
OD Surface						
11	1.8	10	1.5	0.22	0.8	0.19
12	2.5	20	0.6	0.25	0.5	0.175
13	2.5	35	2	0.18	1.6	0.2
14	1.9	25	0.75	0.35	1.1	0.24
15	1.8	0	1	0.17	0.8	0.2
16	2.2	30	0.8	0.2	1.2	0.22
17	1.8	15	0.95	0.17	0.8	0.2
18	1.8	55	1.3	0.22	1.35	0.3
19	1.75	25	1.25	0.17	1.4	0.25
20	3	0	1.45	0.15	1.5	0.3

Since the pitting is on both sides of the component a Level 2 assessment per 6.4.3 is required.

a) STEP 1 - Determine the following parameters: $D, D_O, FCA, LOSS, RSF_a$, and either t_{rd} or t_{nom} and $LOSS$

$$D = 96\ in$$
$$D_O = 96 + (2)(1) = 98\ in$$
$$FCA = 0.0\ in$$
$$LOSS = 0.0\ in$$
$$RSF_a = 0.9$$
$$t_{nom} = 1.0\ in$$

Additional Variables

$$S_a = 17500\ psi \qquad P = 300\ psi$$
$$E_L = 0.85 \qquad E_c = 0.85$$
$$R_c = 48 + 0.0 + 0.0 = 48\ in \qquad L_{msd} = 30\ in$$

b) STEP 2 - Determine the wall thickness to be used in the assessment using Equation (6.1) or Equation (6.2), as applicable.

$$t_c = t_{nom} - LOSS - FCA = 1.0 - 0.0 = 1.0\ in$$

c) STEP 3 - Determine the pit-couple sample for the assessment (see 6.3.3.2), and the following parameters for each pit-couple. In addition, determine the orientation of the pit-couple measured from the direction of the σ_2 stress component, θ_k (see Figure 6.11)

For the first Pit-Couple. All results for the other pit-couples are shown in the embedded tables.

$$\theta_1 = 10^\circ \qquad P_1 = 3.5\ in$$
$$d_{1,1} = 0.3\ in \qquad w_{1,1} = 0.21\ in$$
$$d_{2,1} = 0.4\ in \qquad w_{2,1} = 0.32\ in$$

d) STEP 4 - Determine the depth of each pit in all pit-couples, w_{ik} and w_{jk} (See Figure 6.11b) and compute the average pit depth, w_{avg}, considering all readings. In the following equations the subscript 1 represents a calculation for pit-Couple 1. The remaining calculations are performed in an embedded matrix

$$w_{avg1} = \frac{w_{11} + w_{21}}{2} = \frac{0.21 + 0.32}{2} = 0.265\ in$$

e) STEP 5 - Calculate the components of the membrane stress field σ_1 and σ_2 (see Figure 6.11). Membrane stress equations for shell components are included in Annex A.

$$t_{sl} = 0.0\ in$$

$$\sigma_1 = \frac{P}{E_c}\left(\frac{R_c}{t_c} + 0.6\right) = \left(\frac{300}{0.85}\right)\left(\frac{48}{1} + 0.6\right) = 17152.9412\ psi$$

$$\sigma_2 = \frac{P}{2E_L}\left(\frac{R_c}{t_c - t_{sl}} - 0.4\right) = \left(\frac{300}{(2)(0.85)}\right)\left(\frac{48}{1 - 0.0} - 0.4\right) = 8400\ psi$$

f) STEP 6 - Determine the $MAWP$ for the component using the thickness from STEP 2. See Annex A paragraph A.5

$$MAWP^C = \frac{S_a E_c t_c}{R_c + 0.6t_c} = \frac{(17500)(0.85)(1)}{48 + (0.6)(1)} = 306.07\ psi$$

$$MAWP^L = \frac{2S_a E_L (t_c - t_{sl})}{R_c - 0.4(t_c - t_{sl})} = \frac{(2)(17500)(0.85)(1 - 0.0)}{48 - (0.4)(1 - 0.0)} = 625\ psi$$

The $MAWP$ is the lowest of the longitudinal and circumferential $MAWPs$

$$MAWP = \min[306.07,\ 625] = 306.07\ psi$$

g) STEP 7 - For pit-couple 1, calculate the Remaining Strength Factor.
Calculations are shown for the first pit-couple. Use subpart 2 for multiple layer analysis.
Multiple Layer Analysis – This analysis is used to account for pitting on both sides of the component (see Figure 6.15). In this analysis, $E_{avg,k}$, is calculated for each pit-couple using Equations (6.7) through (6.13). The value of $E_{avg,k}$ is then used along with the thickness of all layers that the pit-couple penetrates to calculate a value of RSF_k for the pit-couple. The selection of the number of layers, N, is based on the depth of pits on both sides of the component. The component thickness is divided into layers based on the pitting damage (see Figure 6.15), and the RSF_k is computed using Equation (6.14) considering all layers containing the pit-couple. Each layer thickness, t_L, is determined by the depth of the deeper of the two pits in the pit-couple that establishes the layer. For layers where a pit-couple does not penetrate the layer, and the solid layer for all pit-couples, $E_{avg,k}$ in Equation (6.14) equals 1.0. The $MAWP$ used with this expression should be based on t_c. If the pitting damage is overlapped from both surfaces (Figure 6.15), it is not acceptable per Level 2. A Level 3 assessment or the recommendations provided in paragraph 6.4.3.5 can be used.

$$RSF_k = 1 - \sum_{L=1}^{N}\left(\frac{t_L}{t_c}\right)\left(1 - E_{avg,k}\right)_L \qquad (6.14)$$

$$d_{avg1} = \frac{d_{11} + d_{21}}{2} = \frac{0.3 + 0.4}{2} = 0.35 \ in$$

$$\mu_{avg1} = \frac{P_1 - d_{avg1}}{P} = \frac{3.5 - 0.35}{3.5} = 0.9$$

$$\rho_{11} = \frac{\sigma_1}{\mu_{avg1}} = \frac{17152.9412}{0.9} = 19058.8235 \ psi$$

$$\rho_{21} = \frac{\sigma_2}{\mu_{avg1}} = \frac{8400}{0.9} = 9333.3333 \ psi$$

$$\psi_1 = \left[\begin{array}{l} \left(\cos^4[\alpha] + \sin^2[2\alpha]\right)\rho_{11}^2 - \\ \dfrac{3\sin^2[2\alpha]\rho_{11}\rho_{21}}{2} + \\ \left(\sin^4[\alpha] + \sin^2[2\alpha]\right)\rho_{21}^2 \end{array} \right]$$

$$\psi_1 = \left[\begin{array}{l} \left(\cos^4[(10)] + \sin^2[(2)(10)]\right)(19058.8235)^2 - \\ \dfrac{3\sin^2[(2)(10)](19058.8235)(9333.3333)}{2} + \\ \left(\sin^4[(10)] + \sin^2[(2)(10)]\right)(9333.3333)^2 \end{array} \right] = 3.6321(10)^8 \ psi^2$$

$$\Phi_1 = \mu_{avg1} \cdot \max\left[|\rho_{11}|, |\rho_{21}|, |\rho_{11} - \rho_{21}|\right]$$
$$= 0.9 \cdot \max\left[|19058.8235|, |9333.3333|, |19058.8235 - 9333.3333|\right]$$
$$= 17152.9412 \ psi$$

$$E_{avg1} = \min\left(\frac{\Phi_1}{\sqrt{\Psi_1}}, 1\right) \min\left[\frac{17152.94120}{\sqrt{3.6321(10)^8}}, 1\right] = 0.9$$

Determine the maximum pit depth of each pit-couple.

Table 6.6-3 Maximum Pit Depth for each Pit-Couple

ID Surface		**OD Surface**	
Pit-Couple	w_{max}	**Pit-Couple**	w_{max}
1	0.32	11	0.22
2	0.2	12	0.25
3	0.2	13	0.2
4	0.25	14	0.35
5	0.2	15	0.2
6	0.2	16	0.22
7	0.25	17	0.2
8	0.17	18	0.3
9	0.3	19	0.25
10	0.3	20	0.3

Based on reviewing the maximum pit depth data for all pit-couples, 11 layers of the following thicknesses are required for the evaluation (Refer to Figure 6.15).

Table 6.6-4 Layers

Layer # (from ID)	Thickness (in)
1	0.17
2	0.03
3	0.05
4	0.05
5	0.02
6	0.33
7	0.05
8	0.05
9	0.03
10	0.02
11	0.2

Compute the RSF for the first pit-couple using equation 6.14

$$RSF_1 = 1 - \sum_{L=1}^{N} \left(\frac{t_L}{t_c} \right) \left(1 - E_{avg,k}\right)_L$$

$$RSF_1 = 1 - \frac{1}{1} \sum_{L=1}^{11} \begin{bmatrix} 0.17(1-0.9) + 0.03(1-0.9) + 0.05(1-0.9) + \\ 0.05(1-0.9) + 0.02(1-0.9) + 0.33(1-1) + \\ 0.05(1-1) + 0.05(1-1) + 0.03(1-1) + \\ 0.02(1-1) + 0.2(1-1) \end{bmatrix}$$

$$RSF_1 = 0.9680$$

h) STEP 8 - Repeat STEP 7 for all pit-couples, n, recorded at the time of the inspection. Determine the average value of the Remaining Strength Factors, RSF_k, found in STEP 7 and designate this value as RSF_{pit} for the region of pitting. Results are shown in Table E6.6-5.

Table E6.6-5 Pit-Couple Calculations

$Pit\text{-}Couple,k$	$w_{avg,k}$ (in)	$d_{avg,k}$ (in)	$\mu_{avg,k}$	ρ_{1k} (psi)	ρ_{2k} (psi)	ψ_k $(psi)^2$	Φ_k (psi)	$E_{avg,k}$	RSF_k
1	0.265	0.35	0.900	19059	9333	3.6321E+08	17152.9	0.900	0.9680
2	0.200	1	0.643	26682	13067	7.119E+08	17152.9	0.643	0.9286
3	0.185	0.9	0.667	25729	12600	6.538E+08	17152.9	0.671	0.9342
4	0.193	0.75	0.643	26682	13067	6.809E+08	17152.9	0.657	0.9143
5	0.185	0.95	0.694	24732	12112	6.117E+08	17152.9	0.694	0.9387
6	0.183	1.65	0.450	38118	18667	1.422E+09	17152.9	0.455	0.8910
7	0.215	0.8	0.724	23687	11600	5.565E+08	17152.9	0.727	0.9318
8	0.147	1.35	0.565	30385	14880	9.157E+08	17152.9	0.567	0.9264
9	0.275	1.05	0.596	28773	14090	7.918E+08	17152.9	0.610	0.8829
10	0.255	0.88	0.600	28588	14000	8.173E+08	17152.9	0.600	0.8800
11	0.205	1.15	0.361	47500	23262	2.256E+09	17152.9	0.361	0.8594
12	0.213	0.55	0.780	21991	10769	4.796E+08	17152.9	0.783	0.9458
13	0.190	1.8	0.280	61261	30000	3.461E+09	17152.9	0.292	0.8583
14	0.295	0.925	0.513	33426	16369	1.094E+09	17152.9	0.519	0.8315
15	0.185	0.9	0.500	34306	16800	1.177E+09	17152.9	0.500	0.9000
16	0.210	1	0.545	31447	15400	9.458E+08	17152.9	0.558	0.9027
17	0.185	0.875	0.514	33379	16346	1.112E+09	17152.9	0.514	0.9029
18	0.260	1.325	0.264	65001	31832	2.799E+09	17152.9	0.324	0.7973
19	0.210	1.325	0.243	70630	34588	4.883E+09	17152.9	0.245	0.8114
20	0.225	1.475	0.508	33743	16525	1.139E+09	17152.9	0.508	0.8525

$$RSF_{pit} = \frac{1}{n}\sum_{k=1}^{n} RSF_k$$

$$RSF_{pit} = \frac{1}{20}\sum_{k=1}^{20} RSF_k = 0.8929$$

i) STEP 9 - Evaluate results based on the type of pitting damage (see Figure 6.2):

Widespread Pitting – For widespread pitting that occurs over a significant region of the component, if $RSF_{pit} \geq RSF_a$, then the pitting damage is acceptable for operation at the MAWP determined in STEP 6. If $RSF_{pit} < RSF_a$, then the region of pitting damage is acceptable for operation at $MAWP_r$, where $MAWP_r$ is computed using the equations in Part 2, paragraph 2.4.2.2. The MAWP from STEP 6 shall be used in this calculation.

In this case $RSF_{pit} < RSF_a$, thus the reduced MAWP can be determined from equation 2.2 as:

$$MAWP_r = MAWP\left(\frac{RSF_{pit}}{RSF_a}\right)$$

$$MAWP_r = 306.07\left(\frac{0.8929}{0.9}\right) = 303.6488\ psi$$

j) STEP 10 - Check the recommended limitations on the individual pit dimensions

1) Pit Diameter – If the following equation is not satisfied for an individual pit, then the pit should be evaluated as a local thin area using the assessment methods of Part 5. The size of the local thin area is the pit diameter and the remaining thickness ratio is defined below. This check is required for larger pits to ensure that a local ligament failure at the base of the pit does not occur.

$$d \leq Q\sqrt{D \cdot t_c}$$

The value of Q shall be determined using Part 4, Table 4.5 and is a function of the remaining thickness ratio, R_t, for each pit as given by either of the following equations where $w_{i,k}$ is the depth of the pit under evaluation.

$$R_t = \left(\frac{t_c + FCA - w_{i,k}}{t_c}\right)$$

For the first pit of the first pit-couple

$$R_{t1} = \frac{1 + 0.0 - 0.21}{1} = 0.7900$$

$$Q_1 = (1.123)\left[\left(\frac{1-0.79}{1-\dfrac{0.79}{0.9}}\right)^2 - 1\right]^{0.5} = 1.5690$$

$$Q_1\sqrt{Dt_c} = (1.5690)\sqrt{(96)(1)} = 15.3735\ in$$

Is diameter less than allowable?

$$D_1 \leq Q_1\sqrt{Dt_c}$$

$$0.3 \leq 15.3735 \;\Rightarrow\; \text{Yes}$$

2) Pit Depth – The following limit on the remaining thickness ratio is recommended to prevent a local failure characterized by pinhole type leakage. The criterion is expressed in terms of the remaining thickness ratio as follows:

$$R_t \geq 0.20$$

The calculations are summarized in Table E6.6-6 for all Pit-Couples

Table E6.6-6 Pit-Couple Sizing Calculations

$Pit-Couple,_k$	$R_{t,i}$	$Q_{1,k}$	$Q_1\sqrt{Dt_c}$	Single Pit Dia. Ok?	$R_{t,j}$	$Q_{2,k}$	$Q_2\sqrt{Dt_c}$	Single Pit Dia Ok?	$R_t \geq 0.2$
1	0.7900	1.5690	15.3735	Yes	0.6800	0.9487	9.2956	Yes	Yes
2	0.8000	1.6808	16.4679	Yes	0.8000	1.6808	16.4679	Yes	Yes
3	0.8300	2.1826	21.3850	Yes	0.8000	1.6808	16.4679	Yes	Yes
4	0.7500	1.2556	12.3018	Yes	0.8650	3.7332	36.5774	Yes	Yes
5	0.8300	2.1826	21.3850	Yes	0.8000	1.6808	16.4679	Yes	Yes
6	0.8350	2.3068	22.6019	Yes	0.8000	1.6808	16.4679	Yes	Yes
7	0.8200	1.9774	19.3749	Yes	0.7500	1.2556	12.3018	Yes	Yes
8	0.8770	5.2871	51.8028	Yes	0.8300	2.1826	21.3850	Yes	Yes
9	0.7500	1.2556	12.3018	Yes	0.7000	1.0185	9.9789	Yes	Yes
10	0.7000	1.0185	9.9789	Yes	0.7900	1.5690	15.3735	Yes	Yes
11	0.7800	1.4739	14.4409	Yes	0.8100	1.8143	17.7761	Yes	Yes
12	0.7500	1.2556	12.3018	Yes	0.8250	2.0738	20.3185	Yes	Yes
13	0.8200	1.9774	19.3749	Yes	0.8000	1.6808	16.4679	Yes	Yes
14	0.6500	0.8608	8.4344	Yes	0.7600	1.3194	12.9276	Yes	Yes
15	0.8300	2.1826	21.3850	Yes	0.8000	1.6808	16.4679	Yes	Yes
16	0.8000	1.6808	16.4679	Yes	0.7800	1.4739	14.4409	Yes	Yes
17	0.8300	2.1826	21.3850	Yes	0.8000	1.6808	16.4679	Yes	Yes
18	0.7800	1.4739	14.4409	Yes	0.7000	1.0185	9.9789	Yes	Yes
19	0.8300	2.1826	21.3850	Yes	0.7500	1.2556	12.3018	Yes	Yes
20	0.8500	2.8165	27.5957	Ok	0.7000	1.0185	9.9789	Yes	Yes

SUMMARY

The pitting fails the level 2 assessment; the reduced MAWP is 303 psi

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PART 7

ASSESSMENT OF HYDROGEN BLISTERS AND HYDROGEN DAMAGE ASSOCIATED WITH HIC AND SOHIC

EXAMPLE PROBLEMS

7.1 Example Problem 1

HIC damage has been discovered on a cylindrical pressure vessel. Both subsurface and surface breaking HIC damage are present. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1. Determine if the vessel is acceptable for continued operation fully pressurized at 50°F.

Vessel Data

- Material = SA-516 Grade70 Year 1984
- Design Conditions = $300\ psig\ @\ 600\ °F$
- Inside Diameter = $96\ in$
- Fabricated Thickness = $1.25\ in$
- FCA = $0.125\ in$
- Weld Joint Efficiency = 0.85
- PWHT = *Yes*

Inspection Data

A schematic of a pressure vessel containing the HIC damage is shown in Figure E7.1-1. The inspection data for the HIC damage is in Table E7.1-1.

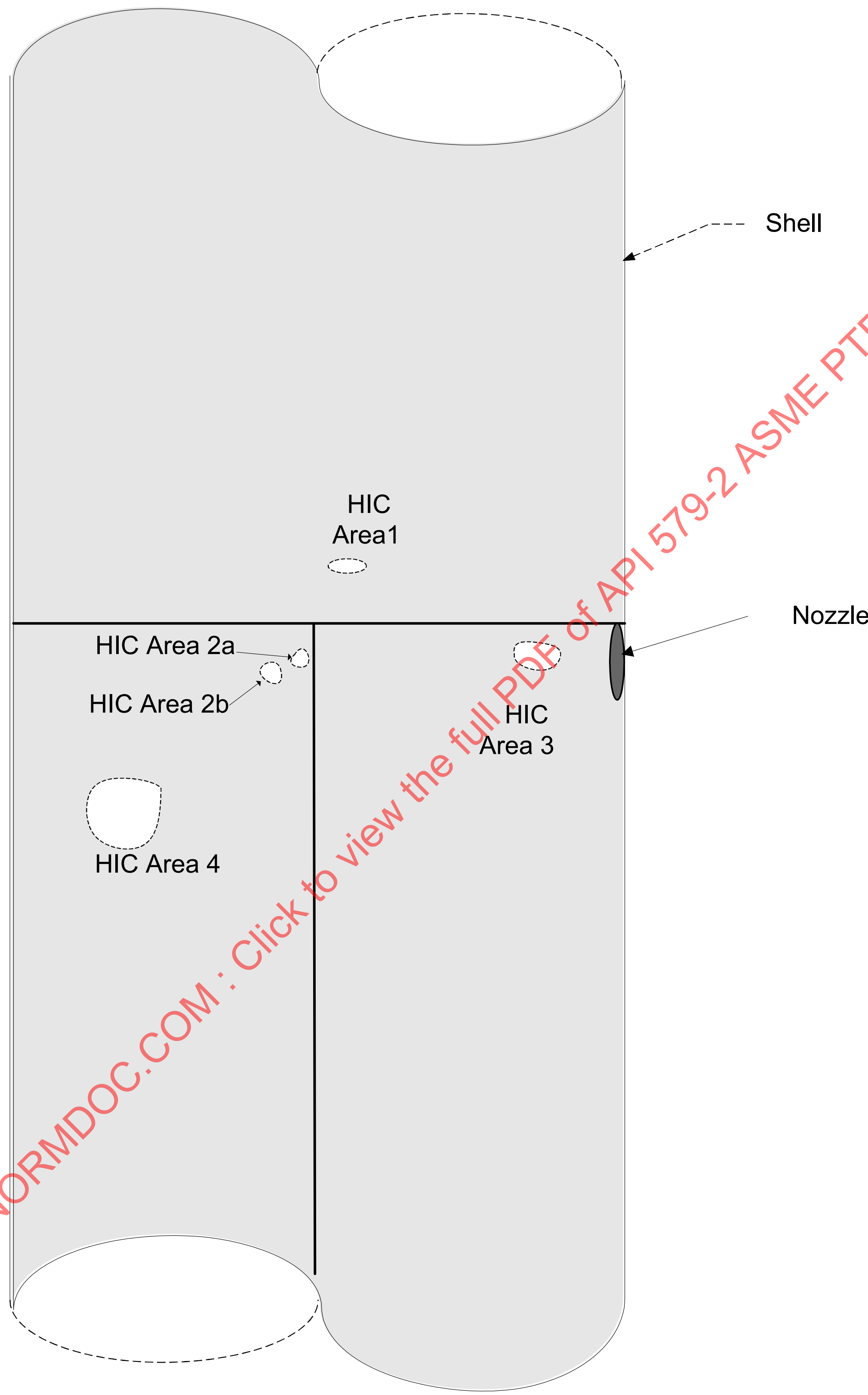

Figure E7.1-1 - HIC Damage

Table E7.1-1
Size, Location, Condition, and Spacing for HIC Damage

Enter the data obtained from a field inspection on this form.

Inspection Date: ____________________

Equipment Identification: ____________________

Equipment Type: __X__ Pressure Vessel ______ Storage Tank ______ Piping Component

Component Type & Location: ____________________

t_{nom} : 1.25

$LOSS$: ____________________

FCA : 0.125

t_{rd} : 1.25

Data Required for Level 1 and Level 2 Assessment

HIC Identification	HIC Area 1	HIC Area 2a	HIC Area 2b	HIC Area 3	HIC Area 4
Diameter s (1)	3	2	1	3	7
Dimension c (1)	5	2	1	5.5	4.5
Edge-To-Edge Spacing To Nearest HIC or Blister L_H (2)	20	2	2	28.5	32
Minimum Measured Thickness to Internal Surface t_{mm-ID} (3)	0.1	0.0	0.45	0.2	0.25
Minimum Measured Thickness to External Surface t_{mm-OD} (3)	0.55	0.475	0.475	0.65	0.575
Minimum Measured Thickness ; Total of Both Sides t_{mm} (3)	0.65	0.475	0.925	0.85	0.825
Spacing To Nearest Weld Joint L_W (2)	10	1.5	6	9	28
Spacing To Nearest Major Structural Discontinuity L_{msd}	50	50	50	12	50
Depth of HIC damage w_H	0.475	0.65	0.2	0.275	0.3

Notes:
1. The HIC-to-HIC spacing may affect the size of the HIC damage to be used in the evaluation (see paragraph 7.3.3.1.i.).
2. See Figure 7.3.
3. See Figure 7.2

Perform a Level 1 Assessment per paragraph 7.4.2 on HIC Area 1

a) STEP 1 – Determine the wall thickness to be used in the assessment.

$$t_c = t_{rd} - FCA$$
$$t_c = 1.25 - 0.125 = 1.125\ in$$

b) STEP 2 – Determine the information in paragraph 7.3.3.1.

$$D = ID + 2FCA = 96.25\ in$$

$$t_{mm-ID} = 0.1\ in$$
$$t_{mm-OD} = 0.55\ in$$
$$w_H = 0.475\ in$$
$$(L_H = 20.0\ in) \geq (8t_c = 9.0\ in)$$

c) STEP 3 - Satisfy the following requirements, then proceed to STEP 4. Otherwise, the Level 1 Assessment is not satisfied.

1) The planar dimensions of the HIC damage satisfy Equations (7.7) and (7.8).

$$\left(s = 3.0\ in\right) \leq \left(0.6\sqrt{D \cdot t_c} = 6.243\ in\right) \qquad True$$

$$\left(c = 5.0\ in\right) \leq \left(0.6\sqrt{D \cdot t_c} = 6.243\ in\right) \qquad True$$

2) The through-thickness extent of the damage satisfies Equation (7.9).

$$\left(w_H = 0.475\ in\right) \leq \min\left[\left(\frac{t_c}{3} = 0.375\ in\right), 0.5\ in\right] \qquad False$$

3) HIC Damage must not be surface breaking in accordance with paragraph 7.3.3.1.h

$$\left(t_{mm-ID} = 0.1\ in\right) \geq \left(0.2t_c = 0.225\ in\right) \qquad False$$
$$\left(t_{mm-OD} = 0.55\ in\right) \geq \left(0.2t_c = 0.225\ in\right) \qquad True$$

4) Distance between the edge of the HIC damage and the nearest weld seam satisfies the following equation.

$$\left(L_w = 10.0\ in\right) > \max\left[\left(2t_c = 2.25\ in\right), 1.0\ \ in\right] \qquad True$$

5) Distance from edge of HIC damage to the nearest major structural discontinuity satisfies following the equation.

$$\left(L_{msd} = 50.0\ in\right) \geq \left(1.8\sqrt{D \cdot t_c} = 18.73\ in\right) \qquad True$$

6) Further hydrogen charging of the metal has been stopped. *False*

The Level 1 Assessment Criteria are not satisfied. A Level 2 assessment must be performed.

Perform a Level 2 Assessment per paragraph 7.4.3.1 on HIC Damage Area 1.

a) STEP 1 – See Level 1, STEP 1

b) STEP 2 – See Level 1, STEP 2

c) STEP 3 – See Level 1, STEP 3, item 4)

d) STEP 4 – See Level 1, STEP 3, item 5)

e) STEP 5 – See Level 1, STEP 3, item 3) – damage is classified as surface breaking, therefore

$$w_H = w_H + \min[t_{mm-ID}, t_{mm-OD}]$$
$$w_H = 0.475 + \min[0.1, 0.55] = 0.475 + 0.1 = 0.575\ in$$

f) STEP 6 – Determine the $MAWP$ of the component per Annex A, paragraph A.2. E is set to1.0 because the damage is in the base metal.

$$MAWP = \frac{SEt_c}{R + 0.6t_c} = \frac{(17500)(1.0)(1.125)}{48.125 + 0.6(1.125)} = 403\ psi$$

g) STEP 7 – Calculate the RSF based on surface breaking HIC damage

$$\lambda = \frac{1.285s}{\sqrt{Dt_c}} = \frac{1.285(3.0)}{\sqrt{(96.25)(1.125)}} = 0.3705$$
$$M_t = 1.0311 \qquad Part\,5,\ Table\,5.2$$
$$RSF = \frac{1 - \left[\dfrac{w_H \cdot D_H}{t_c}\right]}{1 - \dfrac{1}{M_t}\left[\dfrac{w_H \cdot D_H}{t_c}\right]} = \frac{1 - \left[\dfrac{(0.575)(0.8)}{1.125}\right]}{1 - \dfrac{1}{1.0311}\left[\dfrac{(0.575)(0.8)}{1.125}\right]} = 0.980$$

h) STEP 8 – Evaluate the longitudinal extent of the flaw. Since

$$(RSF = 0.980) \geq (RSF_a = 0.9) \qquad True$$

then the longitudinal extent of the HIC damage satisfies the LTA portion of the assessment. with the $MAWP$ from STEP 6:

$MAWP_r = MAWP = 403\ psi$ but the $MAWP$ is limited by $MAWP$ adjusted for weld joint efficiency of 0.85=343 psi

i) STEP 9 – Evaluate the circumferential extent of the HIC damage as an LTA using the procedures in Part 5, paragraph 5.4.3.4. See Example Problem 5.3 STEP 10 for the complete procedure. The depth used in this analysis is given by

$$d_{HIC} = w_H D_H = (0.475 + 0.1)(0.8) = 0.46\ in.$$

Per the results of the LTA analysis of the circumferential extent of the HIC damage, $MAWP = 506\ psi$. Since $MAWP$ from STEP 9 is greater than $P_{Design} = 300\,psi$ then the circumferential extent of the flaw is acceptable.

j) STEP 10 – Determine whether a fracture assessment is required. This is the case if any of the following are true.

1) The equipment will remain in hydrogen service. *True*

2) The HIC damage is surface breaking. *True*

3) $(w_H = 0.575\ in) \geq \min\left[\left(\dfrac{t_c}{3} = 0.375\ in\right),\ 0.5\ in\right]$ *True*

k) STEP 11 – Evaluate the HIC as a crack like flaw in accordance with the procedures in Part 9. An example of this procedure and the associated calculations is provided in the Part 9 example problems. The parameters used in the crack like flaw assessment are specified below.

1) Flaw Size – two crack like flaw assessments must be performed, one for the circumferential extent of the HIC damage and one for the longitudinal extent. The crack dimensions are as follows.

i) Circumferential crack

$$a = w_H = 0.575\ in$$
$$2c = c = 5.0\ in$$

ii) Longitudinal crack

$$a = w_H = 0.575\ in$$
$$2c = s = 3.0\ in$$

2) Fracture Toughness – If hydrogen charging of the steel has not been halted by means of a barrier coating, overlay, or process change, the lower bound arrest fracture toughness as specified in Annex F must be used in the assessment.

l) STEP 12 – Confirm that further HIC damage has been either prevented or is limited to a known or verifiable rate based on one of the methods provided.

The Level 2 Assessment Criteria are satisfied.

$\left(MAWP = 403\,psi\right) > \left(P_{Design} = 300\,psi\right)$ but the $MAWP$ is limited by $MAWP$ adjusted for weld joint efficiency of 0.85=343 psi

The equipment is fit for continued operation at design stress and temperature pending the outcome of a fracture assessment following procedures listed in Part 9 and the outcome of the assessments of other damaged areas.

Perform a Level 1 Assessment per paragraph 7.4.2 on HIC Area 2a.

a) STEP 1 – Determine the wall thickness to be used in the assessment.

$$t_c = 1.125\ in$$

b) STEP 2 – Determine the information in paragraph 7.3.3.1.

$$t_{mm-ID} = 0.0\ in$$
$$t_{mm-OD} = 0.475\ in$$
$$\left(L_H = 2.0\ in\right) \geq 9.0\ in \qquad False$$

HIC Area 2a is within $8t_c$ of HIC Area 2b, therefore; according to the procedures described in Part 4, Figure 4-7, the two areas are combined for analysis.

$$s = 3.0\ in$$
$$c = 5.0\ in$$

Repeating STEP 1 satisfies the requirements and the Level 1 Assessment can continue.

c) STEP 3 - Satisfy the following requirements, then proceed to STEP 4. Otherwise, the Level 1 Assessment is not satisfied.

1) The planar dimensions of the HIC damage satisfy Equations (7.7) and (7.8).

$(s = 3.0\ in) \le 6.243\ in$ *True*

$(c = 5.0\ in) \le 6.243\ in$ *True*

2) The through-thickness extent of the damage satisfies Equation (7.9).

$(w_H = 0.65\ in) \le 0.375\ in$ *False*

3) HIC Damage must not be surface breaking in accordance with paragraph 7.3.3.1.h

$\left(t_{mm-ID} = 0.0\ in\right) \ge 0.225\ in$ *False*

$(t_{mm-OD} = 0.475\ in) \ge 0.225\ in$ *True*

4) Distance between the edge of the HIC damage and the nearest weld seam satisfies the following equation.

$(L_w = 1.5\ in) > 2.25\ in$ *False*

5) Distance from edge of HIC damage to the nearest major structural discontinuity satisfies following the equation.

$\left(L_{msd} = 50.0\ in\right) \ge 18.73\ in$ *True*

6) Further hydrogen charging of the metal has been stopped. *False*

Therefore, Level 1 Assessment criteria are not satisfied. Since item 4) is also required for a Level 2 Assessment, a Level 3 analysis must be conducted.

Perform a Level 1 Assessment per paragraph 7.4.2 on HIC Area 3.

a) STEP 1 – Determine the wall thickness to be used in the assessment.

$$t_c = 1.125\ in$$

b) STEP 2 – Determine the information in paragraph 7.3.3.1

$t_{mm-ID} = 0.2\ in$

$t_{mm-OD} = 0.65\ in$

$(L_H = 28.5\ in) \ge 9.0\ in$ *True*

c) STEP 3 - Satisfy the following requirements, then proceed to STEP 4. Otherwise, the Level 1 Assessment is not satisfied.

1) The planar dimensions of the HIC damage satisfy Equations (7.7) and (7.8).

$(s = 3.0\ in) \le 6.243\ in$ *True*

$(c = 5.5\ in) \le 6.243\ in$ *True*

2) The through-thickness extent of the damage satisfies Equation (7.9).

$(w_H = 0.275\ in) \le 0.375\ in$ *True*

3) HIC Damage must not be surface breaking in accordance with paragraph 7.3.3.1.h

$(t_{mm-ID} = 0.20\ in) \ge 0.225\ in$ *False*

$(t_{mm-OD} = 0.65\ in) \ge 0.225\ in$ *True*

4) Distance between the edge of the HIC damage and the nearest weld seam satisfies the following equation.

$$\left(L_w = 9.0\ in\right) > 2.25\ in \qquad True$$

5) Distance from edge of HIC damage to the nearest major structural discontinuity satisfies following the equation.

$$\left(L_{msd} = 12.0\ in\right) \ge 18.73\ in \qquad False$$

6) Further hydrogen charging of the metal has been stopped. *False*

Therefore, Level 1 Assessment criteria are not satisfied. Since item 5) is also required for a Level 2 Assessment, a Level 3 analysis must be conducted.

Perform a Level 1 Assessment per paragraph 7.4.2.1 on HIC Damage Area 4.

a) STEP 1 – Determine the wall thickness to be used in the assessment.

$$t_c = 1.125\ in$$

b) STEP 2 – Determine the information in paragraph 7.3.3.1.

$$t_{mm-ID} = 0.25\ in$$

$$t_{mm-OD} = 0.575\ in$$

$$\left(L_H = 32.0\ in\right) \ge 9.0\ in \qquad True$$

c) STEP 3 - Satisfy the following requirements, then proceed to STEP 4. Otherwise, the Level 1 Assessment is not satisfied.

1) The planar dimensions of the HIC damage satisfy Equations (7.7) and (7.8).

$$\left(s = 7.0\ in\right) \le 6.243\ in \qquad False$$

$$\left(c = 4.5\ in\right) \le 6.243\ in \qquad True$$

2) The through-thickness extent of the damage satisfies Equation (7.9).

$$\left(w_H = 0.3\ in\right) \le 0.375\ in \qquad True$$

3) HIC Damage must not be surface breaking in accordance with paragraph 7.3.3.1.h

$$\left(t_{mm-ID} = 0.25\ in\right) \ge 0.225\ in \qquad True$$

$$\left(t_{mm-OD} = 0.575\ in\right) \ge 0.225\ in \qquad True$$

4) Distance between the edge of the HIC damage and the nearest weld seam satisfies the following equation.

$$\left(L_w = 28.0\ in\right) > 2.25\ in \qquad True$$

5) Distance from edge of HIC damage to the nearest major structural discontinuity satisfies following the equation.

$$\left(L_{msd} = 50.0\ in\right) \ge 18.73\ in \qquad True$$

6) Further hydrogen charging of the metal has been stopped. *False*

The Level 1 Assessment criteria are not satisfied; therefore, a Level 2 Assessment per paragraph 7.4.3.1 must be conducted on HIC Damage Area 4.

Perform a Level 2 Assessment per paragraph 7.4.3.1 on HIC Damage Area 4.

a) STEP 1 – See Level 1, STEP 1

b) STEP 2 – See Level 1, STEP 2

c) STEP 3 – See Level 1, STEP 3, item 4)

d) STEP 4 – See Level 1, STEP 3, item 5)

e) STEP 5 – See Level 1, STEP 3, item 3) – damage is classified as sub surface

f) STEP 6 – Determine the $MAWP$ of the component per Annex A, paragraph A.2

$$MAWP = \frac{SEt_c}{R + 0.6t_c} = \frac{(17500)(1.0)(1.125)}{48.125 + 0.6(1.125)} = 403 \ psi$$

g) STEP 7 – Calculate the RSF based on the subsurface HIC damage. The minimum longitudinal distance to the nearest region of HIC damage is 22 inches.

$$L_R = \min\left[\frac{L_{Hs}}{2}, 8t_c\right] = \min\left[\frac{22.0}{2}, 8(1.125)\right] = 9.0 \ in$$

$$RSF = \frac{2L_R + s\left[1 - \frac{w_H \cdot D_H}{t_c}\right]}{2L_R + s} = \frac{2(9) + (7)\left[1 - \frac{(0.3)(0.8)}{1.125}\right]}{2(9) + 7} = 0.94$$

h) STEP 8 – Evaluate the longitudinal extent of the flaw. Since

$$(RSF = 0.940) \geq (RSF_a = 0.9) \qquad \textit{True}$$

then the longitudinal extent of the HIC damage satisfies the LTA portion of the assessment. with the $MAWP$ from STEP 6:

$MAWP_r = MAWP = 403 \ psi$ but the $MAWP$ is limited by $MAWP$ adjusted for weld joint efficiency of 0.85=343 psi

i) STEP 9 – Evaluate the circumferential extent of the HIC damage as an LTA using the procedures in Part 5, paragraph 5.4.3.4. See Example Problem 5.3 STEP 10 for the complete procedure. The depth used in this analysis is given by

$$d_{HIC} = w_H D_H = (0.3)(0.8) = 0.24 \ in.$$

Per the results of the LTA analysis of the circumferential extent of the HIC damage, $MAWP = 487 \ psi$. Since $MAWP$ from STEP 9 is greater than $P_{Design} = 300 \ psi$ then the circumferential extent of the flaw is acceptable.

j) STEP 10 – Determine whether a fracture assessment is required. This is the case if any of the following are true.

1) The equipment will remain in hydrogen service. *True*

2) The HIC damage is surface breaking. *False*

3) $(w_H = 0.3 \ in) \geq 0.375 \ in$ *False*

k) STEP 11 – Evaluate the HIC as a crack like flaw in accordance with the procedures in Part 9. An example of this procedure and the associated calculations is provided in the Part 9 example problems. The parameters used in the crack like flaw assessment are specified below.

1) Flaw Size – two crack like flaw assessments must be performed, one for the circumferential extent of the HIC damage and one for the longitudinal extent. The crack dimensions are as follows.

i) Circumferential crack

$$2a = w_H = 0.3\ in$$

$$2c = c = 4.5\ in$$

$$d = 0.25\ in$$

ii) Longitudinal crack

$$2a = w_H = 0.3\ in$$

$$2c = s = 7.0\ in$$

$$d = 0.25\ in$$

2) Fracture Toughness – If hydrogen charging of the steel has not been halted by means of a barrier coating, overlay, or process change, the lower bound arrest fracture toughness as specified on Annex F must be used in the assessment.

l) STEP 12 – Confirm that further HIC damage has been either prevented or is limited to a known or verifiable rate based on one of the methods provided.

The Level 2 Assessment Criteria are satisfied.

$\left(MAWP = 403\,psi\right) > \left(P_{Design} = 300\,psi\right)$ but the $MAWP$ is limited by $MAWP$ adjusted for weld joint efficiency of 0.85=343 psi

The equipment is fit for continued operation at design stress and temperature pending the outcome of a fracture assessment following procedures listed in Part 9. and the outcome of the assessments of other damaged areas.

7.2 Example Problem 2

A cylindrical vessel with both internal and external blisters is shown below. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1. Determine if the vessel is suitable for continued operation at the current $MAWP$ and temperature using the Level 1 Assessment criteria and Level 2 Assessment criteria if necessary.

Vessel Data

- Material = $SA-516\ Grade 70\ Year\ 1980$
- Design Conditions = $250\ psig\ @180\ ^{\circ}F$
- Inside Diameter = $96\ in$
- Nominal Wall Thickness = $1.14\ in$
- Future Corrosion Allowance = $0.125\ in$
- $LOSS$ = $0.0\ in$
- Allowable Stress = $17,500\ psi$
- Weld Joint Efficiency = 0.85

Inspection Data

The pressure vessel section containing the blisters is shown below. The inspection data for the blisters is shown in the following table.

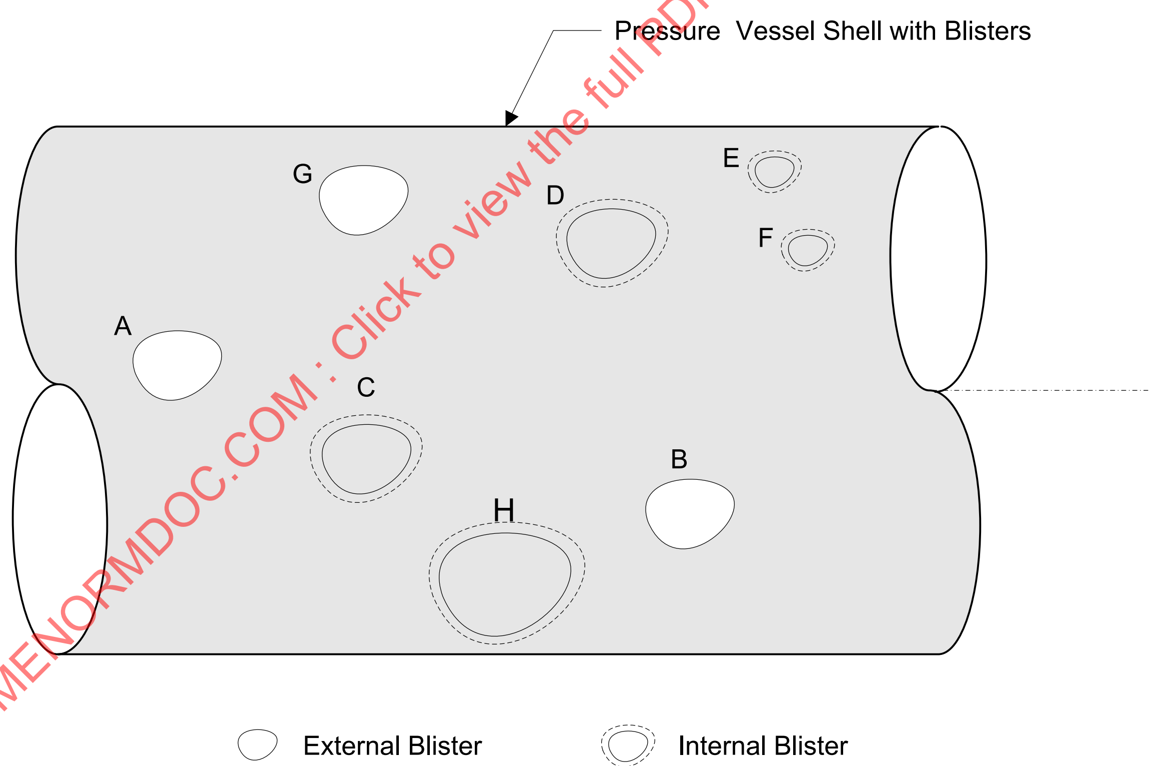

Figure E7.2-1 Blister Damage

Table E7.2-1
Size, Location, Condition, and Spacing for Blisters

Enter the data obtained from a field inspection on this form.

Inspection Date: ____________________

Equipment Identification: ____________________

Equipment Type: __X__ Pressure Vessel _____ Storage Tank _____ Piping Component

Component Type & Location: ____________________

Data Required for Level 1 and Level 2 Assessment

Blister Identification	A	B	C	D	E
Diameter s, in (1)	10	5.5	5	12	2
Dimension c, in (1)	8	5	5	10	4
Edge-To-Edge Spacing To Nearest Blister L_B, in (1)	18	18	12	10	6
Bulge Direction (inside/ outside)	outside	outside	inside	inside	Inside
Blister Projection B_p, in	1.5	0.3	0.4	0.8	0.1
Minimum Measured Thickness t_{mm}, in	0.70	0.80	0.60	0.60	0.90
Cracking At Periphery (Yes/No)	No	No	No	No	No
Crown Cracking or Venting (Yes/No) (2)	Crack	Vent	Vent	Crack	Vent
Length Of Crown Crack or Diameter of Vent Hole s_c, in (2)	6	0.125	2	6	0.125
Spacing To Nearest Weld Joint L_W, in (3)	10	5	6	8	10
Spacing To Nearest Major Structural Discontinuity L_{msd}, in	25	20	30	30	40

Notes:

1. The blister-to-blister spacing may affect the size of the blister to be used in the evaluation (see paragraph 7.3.3.3.a & b)
2. If the blister has crown cracks, enter the length of the crack, see dimension s_c in Figure 7.6. If the blister has a vent hole, indicate as such with the diameter of the hole (see Figure 7.7).
3. See Figure 7.8.

Table E7.2-1
Size, Location, Condition, and Spacing for Blisters

Enter the data obtained from a field inspection on this form.

Inspection Date: ____________________

Equipment Identification: ______

Equipment Type: __X__ Pressure Vessel _____ Storage Tank _____ Piping Component

Component Type & Location: ______

____

____

____

Data Required for Level 1 and Level 2 Assessment

Blister Identification	F	G	H		
Diameter s, in (1)	2	11	24		
Dimension c, in (1)	2	8	18		
Edge-To-Edge Spacing To Nearest Blister L_B, in (1)	6	12	8		
Bulge Direction (inside/ outside)	inside	outside	outside		
Blister Projection B_p, in	0.1	0.3	1.5		
Minimum Measured Thickness t_{mm}, in	0.60	0.60	0.55		
Cracking At Periphery (Yes/No)	No	Yes(inward)	No		
Crown Cracking or Venting (Yes/No) (2)	No	Crack	Vent		
Length Of Crown Crack or Diameter of Vent Hole s_c, in (2)	-	5	0.125		
Spacing To Nearest Weld Joint L_W, in (3)	6	3	6		
Spacing To Nearest Major Structural Discontinuity L_{msd}, in	40	24	25		

Notes:
1. The blister-to-blister spacing may affect the size of the blister to be used in the evaluation (see paragraph 7.3.3.3.a & b)
2. If the blister has crown cracks, enter the length of the crack, see dimension s_c in Figure 7.6. If the blister has a vent hole, indicate as such with the diameter of the hole (see Figure 7.7).
3. See Figure 7.8.

Perform a Level 1 Assessment per paragraph 7.4.2.3 on Blister A

a) STEP 1 – Determine the wall thickness to be used in the assessment.

$$t_c = t_{rd} - FCA$$
$$t_c = 1.14 - 0.125 = 1.015\,in$$

b) STEP 2 – Determine the information in paragraph 7.3.3.3.

$$D = ID + 2FCA = 96.0 + 2(0.125) = 96.25\ in$$

The blister-to-blister spacing check satisfies "$2s\,x\,2c$" box criteria

$$(L_b = 18.0\ in) \ge (2t_c = 2.03\,in)$$
$$s = 10.0\,in$$
$$c = 8.0\,in$$

c) STEP 3 – Check the blister acceptance criteria, blisters are acceptable without repair if all of the following are satisfied:

1) The blister diameter and venting requirements meet one of the following:

$$\left(\max[s,c] = 10.0\ in\right) \le 2.0\ in \qquad False$$

$$\left(\max[s,c] = 10.0\ in\right) \le \left(0.6\sqrt{D \cdot t_c} = 5.93\ in\right)\ and\ is\ vented \quad False$$

2) The minimum measured undamaged thickness measured from the non-bulged surface satisfies the follow.

$$(t_{mm} = 0.70\,in) \ge (0.5t_c = 0.5075\ in) \qquad True$$

3) The blister projection satisfies the following.

$$(B_p = 1.5\ in) \le \left(0.1 \cdot \min[s,c] = 0.8\ in\right) \qquad False$$

4) The blister has no periphery cracks. *True*

5) The distance between the edge of the blister and the nearest weld seam satisfies Equation (7.10).

$$(L_w = 10.0\ in) \ge \max[2t_c = 2.03\ in,\ 1.0\ in] \qquad True$$

6) The distance from the blister edge to the nearest major structural discontinuity satisfies Equation (7.11).

$$(L_{msd} = 25.0\ in) \ge \left(1.8\sqrt{D \cdot t_c} = 17.79\ in\right) \qquad True$$

Therefore, Level 1 Assessment criteria are not satisfied.

Perform a Level 2 Assessment per paragraph 7.4.3.3 on Blister A.

a) STEP 1 – See Level 1, STEP 1
b) STEP 2 – See Level 1, STEP 2
c) STEP 3 – See Level 1, STEP 3, item 6)
d) STEP 4 – The blister has no periphery cracks. Proceed to STEP 6.
e) STEP 6 – The blister has a crown crack. Proceed to STEP 9.
f) STEP 9 – Evaluate the blister as an equivalent local thin area using the procedures in Part 5.
   1) STEP 9.1 Determine the remaining thickness ratio and the longitudinal flaw length parameter. λ.

$$D = 96\ in \qquad t_{mm} = 0.70\ in$$
$$FCA = 0.125\ in \qquad s = 10\ in$$
$$L_{msd} = 25\ in \qquad t_c = 1.015\,in$$
$$Design\ Pressure = 250\ \ psig \qquad RSFa = 0.90$$

$$R_t = \frac{t_{mm} - FCA}{t_c} = \frac{0.70 - 0.125}{1.015} = 0.5665$$
$$D = 96 + 2\times(FCA) = 96 + 2\times(0.125) = 96.25in$$
$$\lambda = \frac{1.285s}{\sqrt{Dt_c}} = \frac{1.285(10)}{\sqrt{96.25(1.015)}} = 1.3$$

   2) STEP 9.2 – Check the limiting flaw size criteria.

$$(R_t = 0.5665) \geq 0.20 \qquad True$$
$$(t_{mm} - FCA = 0.70 - 0.125 = 0.575\ in) \geq 0.10\ in \qquad True$$
$$(L_{msd} = 25\,in) \geq \left(1.8\sqrt{Dt_c} = 1.8\sqrt{96.25(1.015)} = 17.79\ in\right) \qquad True$$

   3) STEP 9.3 – Determine the $MAWP$ for the component (see A.3.4).
   Note that $E = 1.0$ since the LTA is remote from weld seams (see paragraph A.2.5.b) of Annex A)

$$R = \frac{D}{2} = \frac{96.25}{2} = 48.125\ in$$
$$MAWP^C = \frac{SEt_c}{R + 0.6t_c} = \frac{17500(1.0)(1.015)}{48.125 + 0.6(1.015)} = 364.48\ \ psi$$
$$MAWP^L = \frac{2SE(t_c - t_{sl})}{R - 0.4(t_c - t_{sl})} = \frac{17500(1.0)(1.015 - 0.0)}{48.125 - 0.4(1.015 - 0.0)} = 744.46\ \ psi$$
$$MAWP = \min\left[MAWP^C, MAWP^L\right] = \min[364\ \ psi, 744\ \ psi] = 364\ \ psi$$

4) STEP 9.4 – Evaluate the longitudinal extent of the flaw.

From Part 5 Figure 5.6 with $\begin{Bmatrix} \lambda = 1.3 \\ R_t = 0.5665 \end{Bmatrix}$, the longitudinal extent of the flaw is not acceptable. Using Table 5.2 and equation (5.11):

$$M_t = 1.316$$

$$\left(RSF = \frac{R_t}{1 - \frac{1}{M_t}\left(1 - R_t\right)} = \frac{0.5665}{1 - \frac{1}{1.316}\left(1 - 0.5665\right)} = 0.8448 \right) < \left(RSF_a = 0.9 \right)$$

$$MAWP_r = MAWP\left(\frac{RSF}{RSF_a}\right) = 364\left(\frac{.8448}{.9}\right) = 341\ psig$$

The LTA is acceptable at a $MAWP_r$ of $341\ psig$.

g) STEP 10 – Evaluate circumferential extent of the flaw.

1) STEP 10.1 – From the circumferential CTP,

$$c = 8\ in$$

$$\lambda_C = \frac{1.285c}{\sqrt{Dt_c}} = \frac{1.285(8)}{\sqrt{(96.25)(1.015)}} = 1.06$$

2) STEP 10.2 – Check the following conditions

$\left(\lambda_c = 1.06\right) \le 9$ *True*

$\left(\frac{D}{t_c} = \frac{96.25}{1.015} = 94.83\right) \ge 20$ *True*

$0.7 \le \left(RSF = 0.8448\right) \le 1.0$ *True*

$0.7 \le \left(E_L = 1\right) \le 1.0$ *True*

$0.7 \le \left(E_C = 1\right) \le 1.0$ *True*

3) STEP 10.3 – Calculate tensile strength factor,

$$TSF = \frac{E_C}{2 \times RSF}\left(1 + \frac{\sqrt{4 - 3E_L^2}}{E_L}\right) = \frac{1}{2 \times 0.8448}\left(1 + \frac{\sqrt{4 - 3 \times 1^2}}{1}\right) = 1.18$$

From Part 5, Figure 5.8 with $\begin{Bmatrix} \lambda_C = 1.06 \\ R_t = 0.5665 \end{Bmatrix}$, the circumferential extent of the flaw is acceptable. From Table 5.4,

$$R_{t\_min} = 0.2$$

$$\left(R_t = 0.5665\right) > \left(R_{t\_min} = 0.2\right)$$

The circumferential extent of the flaw is acceptable.

h) STEP 11 – See Level 1, STEP 3, item 5)

i) STEP 12 – An in-service monitoring program should be developed to monitor potential blister growth.

The Level 2 Assessment Criteria are satisfied.

$\left(MAWP = 341\ psi\right) > \left(P_{Design} = 250\ psi\right)$ but the $MAWP$ is limited by $MAWP$ adjusted for weld joint efficiency of 0.85=310 psi

The equipment is fit for continued operation.

Perform a Level 1 Assessment per paragraph 7.4.2.3 on Blister B

a) STEP 1 – Determine the wall thickness to be used in the assessment.

$$t_c = 1.015\ in$$

b) STEP 2 – Determine the information in paragraph 7.3.3.3.

The blister-to-blister spacing check satisfies "$2s\ x\ 2c$" box criteria

$$\left(L_b = 18.0\ in\right) \geq 2.03\ in$$

$$s = 5.5\ in$$

$$c = 5.0\ in$$

c) STEP 3 – Check the blister acceptance criteria, blisters are acceptable without repair if all of the following are satisfied:

1) The blister diameter and venting requirements meet one of the following:

$$\left(\max\left[s,c\right] = 5.5\ in\right) \leq 2.0\ in \qquad False$$

$$\left(\max\left[s,c\right] = 5.5\ in\right) \leq 5.93\ in\ and\ is\ vented \qquad True$$

2) The minimum measured undamaged thickness measured from the non-bulged surface satisfies the follow.

$$\left(t_{mm} = 0.80\ in\right) \geq 0.5075\ in \qquad True$$

3) The blister projection satisfies the following.

$$\left(B_p = 0.3\ in\right) \leq \left(0.1 \cdot \min\left[s,c\right] = 0.5\ in\right) \qquad True$$

4) The blister has no periphery cracks.

5) The distance between the edge of the blister and the nearest weld seam satisfies Equation (7.10).

$$\left(L_w = 5.0\ in\right) \geq 2.03\ in \qquad True$$

6) The distance from the blister edge to the nearest major structural discontinuity satisfies Equation (7.11).

$$\left(L_{msd} = 20.0\,in\right) \geq 17.79\ in \qquad True$$

Therefore, Level 1 Assessment criteria are satisfied.

Perform a Level 1 Assessment per paragraph 7.4.2.3 on Blister C

a) STEP 1 – Determine the wall thickness to be used in the assessment.

$$t_c = 1.015\ in$$

b) STEP 2 – Determine the information in paragraph 7.3.3.3.

The blister-to-blister spacing check satisfies $"2s\,x\,2c"$ box criteria

$$\left(L_b = 12\ in\right) \ge 2.03\ in$$

$$s = 5.0\ in$$

$$c = 5.0\ in$$

c) STEP 3 – Check the blister acceptance criteria, blisters are acceptable without repair if all of the following are satisfied:

1) The blister diameter and venting requirements meet one of the following:

$$\left(\min\left[s,c\right] = 5.0\ in\right) \le 2.0\ in \qquad False$$

$$\left(\min\left[s,c\right] = 5.0\ in\right) \le 5.93\ in\ and\ is\ vented \qquad True$$

2) The minimum measured undamaged thickness measured from the non-bulged surface satisfies the follow.

$$\left(t_{mm} = 0.80\ in\right) \ge 0.5075\ in \qquad True$$

3) The blister projection satisfies the following.

$$\left(B_p = 0.4\ in\right) \le \left(0.1 \cdot \min\left[s,c\right] = 0.5\ in\right) \qquad True$$

4) The blister has no periphery cracks. $True$

5) The distance between the edge of the blister and the nearest weld seam satisfies Equation (7.10).

$$\left(L_w = 5.0\ in\right) \ge 2.03\ in \qquad True$$

6) The distance from the blister edge to the nearest major structural discontinuity satisfies Equation (7.11).

$$\left(L_{msd} = 20.0\ in\right) \ge 17.79\ in \qquad True$$

Therefore, Level 1 Assessment criteria are satisfied.

Perform a Level 1 Assessment per paragraph 7.4.2.3 on Blister D

a) STEP 1 – Determine the wall thickness to be used in the assessment.

$$t_c = 1.015\ in$$

b) STEP 2 – Determine the information in paragraph 7.3.3.3.

The blister-to-blister spacing check satisfies $"2s\,x\,2c"$ box criteria

$$\left(L_b = 10.0\ in\right) \ge 2.03\ in$$

$$s = 12.0 \ in$$

$$c = 10.0 \ in$$

c) STEP 3 – Check the blister acceptance criteria, blisters are acceptable without repair if all of the following are satisfied:

1) The blister diameter and venting requirements meet one of the following:

$$\left(\max\left[s,c\right] = 12.0 \ in\right) \le 2.0 \ in \qquad False$$

$$\left(\max\left[s,c\right] = 12.0 \ in\right) \le 5.93 \ in \ and \ is \ vented \qquad False$$

2) The minimum measured undamaged thickness measured from the non-bulged surface satisfies the follow.

$$\left(t_{mm} = 0.60 \ in\right) \ge 0.5075 \ in \qquad True$$

3) The blister projection satisfies the following.

$$\left(B_p = 0.8 \ in\right) \le \left(0.1 \cdot \min\left[s,c\right] = 1.0 \ in\right) \qquad True$$

4) The blister has no periphery cracks. *True*

5) The distance between the edge of the blister and the nearest weld seam satisfies Equation (7.10).

$$\left(L_w = 8.0 \ in\right) \ge 2.03 \ in \qquad True$$

6) The distance from the blister edge to the nearest major structural discontinuity satisfies Equation (7.11).

$$\left(L_{msd} = 30.0 \ in\right) \ge 17.79 \ in \qquad True$$

Therefore, Level 1 Assessment criteria are not satisfied.

Perform a Level 2 Assessment per paragraph 7.4.3.3 on Blister D.

a) STEP 1 – See Level 1, STEP 1
b) STEP 2 – See Level 1, STEP 2
c) STEP 3 – See Level 1, STEP 3, item 6)
d) STEP 4 – The blister has no periphery cracks. Proceed to STEP 6.
e) STEP 6 – The blister has a crown crack. Proceed to STEP 9.
f) STEP 9 – Evaluate the blister as an equivalent local thin area using the procedures in Part 5. Perform a Level 1 Assessment per paragraph 5.4.2.2 for STEP 9

1) STEP 9.1 – Determine the CTP (Critical Thickness Profiles) (see paragraph 5.3.3.2) –

$D = 96\ in$ $\quad t_c = 1.015\ in$

$FCA = 0.125\ in$ $\quad t_{mm} = 0.60\ in$

$L_{msd} = 25\ in$ $\quad s = 12\ in$

$Design\ \Pr essure = 250\ \ psig$ $\quad RSFa = 0.90$

2) STEP 9.2 – Determine the remaining thickness ratio and the longitudinal flaw length parameter. λ.

$$R_t = \frac{t_{mm}}{t_c} = \frac{0.6}{1.015} = 0.5911$$

$$D = 96 + 2\times(FCA) = 96 + 2\times(0.125) = 96.25\ in$$

$$\lambda = \frac{1.285s}{\sqrt{Dt_c}} = \frac{1.285(12)}{\sqrt{96.25(1.015)}} = 1.56$$

3) STEP 9.3 – Check the limiting flaw size criteria.

$$\left(R_t = 0.5911\right) \geq 0.20 \qquad True$$

$$\left(t_{mm} = 0.6in\right) \geq 0.10\ in \qquad True$$

$$\left(L_{msd} = 30in\right) \geq \left(1.8\sqrt{Dt_c} = 1.8\sqrt{96.25(1.015)} = 17.42\ in\right) \qquad True$$

4) STEP 9.4 – Determine the $MAWP$ for the component (see A.3.4).

Note that $E = 1.0$ since the LTA is remote from weld seams (see paragraph A.2.5.b) of Annex A)

$$R = \frac{D}{2} = \frac{96.25}{2} = 48.125\ in$$

$$MAWP^C = \frac{SEt_c}{R + 0.6t_c} = \frac{17500(1.0)(1.015)}{48.125 + 0.6(1.015)} = 364.48\ \ psi$$

$$MAWP^L = \frac{2SE(t_c - t_{sl})}{R - 0.4(t_c - t_{sl})} = \frac{17500(1.0)(1.015 - 0.0)}{48.125 - 0.4(1.015 - 0.0)} = 744.46\ \ psi$$

$$MAWP = \min\left[MAWP^C, MAWP^L\right] = \min\left[364\ \ psi, 744\ \ psi\right] = 364\ \ psi$$

5) STEP 9.5 – Evaluate the longitudinal extent of the flaw.

From Part 5 Figure 5.6 with $\left\{ \begin{matrix} \lambda = 1.56 \\ R_t = 0.5911 \end{matrix} \right\}$, the longitudinal extent of the flaw is not acceptable. Using Table 5.2 and equation (5.11):

$$M_t = 1.421$$

$$\left(RSF = \frac{R_t}{1 - \frac{1}{M_t}\left(1 - R_t\right)} = \frac{0.5911}{1 - \frac{1}{1.421}\left(1 - 0.5911\right)} = 0.83 \right) < \left(RSF_a = 0.9 \right)$$

Since the calculated $RSF < RSF_a$, a $MAWP_r$ must be calculated using the equations in Part 2, paragraph 2.4.2.2.

$$MAWP_r = MAWP\left(\frac{RSF}{RSF_a}\right) = 364\left(\frac{0.83}{0.9}\right) = 336 \ psig$$

The LTA is acceptable at a $MAWP_r$ of $336 \ psig$.

g) STEP 10 – Evaluate circumferential extent of the flaw.

1) STEP 10.1 – From the circumferential CTP,

$$c = 8 \ in$$

$$\lambda_C = \frac{1.285c}{\sqrt{Dt_c}} = \frac{1.285(10)}{\sqrt{(96.25)(1.015)}} = 1.3$$

2) STEP 10.2 – Check the following conditions

$(\lambda_c = 1.3) \le 9$ *True*

$\left(\frac{D}{t_c} = \frac{96.25}{1.015} = 94.83 \right) \ge 20$ *True*

$0.7 \le (RSF = 0.83) \le 1.0$ *True*

$0.7 \le (E_L = 1) \le 1.0$ *True*

$0.7 \le (E_C = 1) \le 1.0$ *True*

3) STEP 10.3 – Calculate tensile strength factor,

$$TSF = \frac{E_C}{2 \times RSF}\left(1 + \frac{\sqrt{4 - 3E_L^2}}{E_L}\right) = \frac{1}{2 \times 0.83}\left(1 + \frac{\sqrt{4 - 3 \times 1^2}}{1}\right) = 1.205$$

From Part 5, Figure 5.8 with $\left\{ \begin{matrix} \lambda_C = 1.3 \\ R_t = 0.5911 \end{matrix} \right\}$, the circumferential extent of the flaw is acceptable. From Table 5.4,

$$R_{t\_min} = 0.2$$

$$\left(R_t = 0.5911\right) > \left(R_{t\_\min} = 0.2\right)$$

The circumferential extent of the flaw is acceptable.

h) STEP 11 – See Level 1, STEP 3, item 5)

i) STEP 12 – An in-service monitoring program should be developed to monitor potential blister growth.

The Level 2 Assessment Criteria are satisfied.

$\left(MAWP_r = 336\,psi\right) > \left(P_{Design} = 250\,psi\right)$ but the $MAWP_r$ is limited by $MAWP$ adjusted for weld joint efficiency of 0.85=310 psi

The equipment is fit for continued operation.

Perform a Level 1 Assessment per paragraph 7.4.2.3 on Blister E

a) STEP 1 – Determine the wall thickness to be used in the assessment.

$$t_c = 1.015\ in$$

b) STEP 2 – Determine the information in paragraph 7.3.3.3.

The blister-to-blister spacing check satisfies "$2s\,x\,2c$" box criteria

$$\left(L_b = 6.0\ in\right) \geq 2.03\ in$$

$$s = 2.0\ in$$

$$c = 4.0\ in$$

c) STEP 3 – Check the blister acceptance criteria, blisters are acceptable without repair if all of the following are satisfied:

1) The blister diameter and venting requirements meet one of the following:

$$\left(\max\left[s,c\right] = 4.0\ in\right) \leq 2.0\ in \qquad False$$

$$\left(\max\left[s,c\right] = 4.0\ in\right) \leq 5.93\ in\ and\ is\ vented \qquad True$$

2) The minimum measured undamaged thickness measured from the non-bulged surface satisfies the follow.

$$\left(t_{mm} = 0.9\ in\right) \geq 0.5075\ in \qquad True$$

3) The blister projection satisfies the following.

$$\left(B_p = 0.1\ in\right) \leq \left(0.1 \cdot \min\left[s,c\right] = 0.2\ in\right) \qquad True$$

4) The blister has no periphery cracks. *True*

5) The distance between the edge of the blister and the nearest weld seam satisfies Equation (7.10).

$$\left(L_w = 10.0\ in\right) \geq 2.03\ in \qquad True$$

6) The distance from the blister edge to the nearest major structural discontinuity satisfies Equation (7.11).

$$\left(L_{msd} = 40.0\ in\right) \geq 17.79\ in \qquad True$$

Therefore, Level 1 Assessment criteria are satisfied.

Perform a Level 1 Assessment per paragraph 7.4.2.3 on Blister F

a) STEP 1 – Determine the wall thickness to be used in the assessment.

$$t_c = 1.015\ in$$

b) STEP 2 – Determine the information in paragraph 7.3.3.3.

The blister-to-blister spacing check satisfies "$2s\,x\,2c$" box criteria

$$\left(L_b = 6.0\ in\right) \geq 2.03\ in$$

$$s = 2.0\ in$$

$$c = 2.0\ in$$

c) STEP 3 – Check the blister acceptance criteria, blisters are acceptable without repair if all of the following are satisfied:

1) The blister diameter and venting requirements meet one of the following:

$$\left(\max\left[s,c\right] = 2.0\ in\right) \leq 2.0\ in \qquad True$$

$$\left(\max\left[s,c\right] = 2.0\ in\right) \leq 5.93\ in\ and\ is\ vented \qquad False$$

2) The minimum measured undamaged thickness measured from the non-bulged surface satisfies the follow.

$$\left(t_{mm} = 0.60\ in\right) \geq 0.5075\ in \qquad True$$

3) The blister projection satisfies the following.

$$\left(B_p = 0.1\ in\right) \leq \left(0.1 \cdot \min\left[s,c\right] = 0.2\ in\right) \qquad True$$

4) The blister has no periphery cracks. *True*

5) The distance between the edge of the blister and the nearest weld seam satisfies Equation (7.10).

$$\left(L_w = 6.0\ in\right) \geq 2.03\ in \qquad True$$

6) The distance from the blister edge to the nearest major structural discontinuity satisfies Equation (7.11).

$$\left(L_{msd} = 40.0\ in\right) \geq 17.79\ in \qquad True$$

Therefore, Level 1 Assessment criteria are satisfied.

Perform a Level 1 Assessment per paragraph 7.4.2.3 on Blister G

a) STEP 1 – Determine the wall thickness to be used in the assessment.

$$t_c = 1.015\ in$$

b) STEP 2 – Determine the information in paragraph 7.3.3.3.

The blister-to-blister spacing check satisfies "$2s\,x\,2c$" box criteria

$$\left(L_b = 12.0\ in\right) \geq 2.03\ in$$

$$s = 11.0\ in$$

$$s = 8.0\ in$$

c) STEP 3 – Check the blister acceptance criteria, blisters are acceptable without repair if all of the following are satisfied:

1) The blister diameter and venting requirements meet one of the following:

$$\left(\max\left[s,c\right] = 11.0\ in\right) \leq 2.0\ in \qquad False$$

$$\left(\max\left[s,c\right] = 11.0\ in\right) \leq 5.93\ in\ and\ is\ vented \qquad False$$

2) The minimum measured undamaged thickness measured from the non-bulged surface satisfies the follow.

$$\left(t_{mm} = 0.6\ in\right) \geq 0.5075\ in \qquad True$$

3) The blister projection satisfies the following.

$$\left(B_p = 0.3\ in\right) \leq \left(0.1 \cdot \min\left[s,c\right] = 0.8\ in\right) \qquad True$$

4) The blister has no periphery cracks. *False*

5) The distance between the edge of the blister and the nearest weld seam satisfies Equation (7.10).

$$\left(L_w = 3.0\ in\right) \geq 2.03\ in \qquad True$$

6) The distance from the blister edge to the nearest major structural discontinuity satisfies Equation (7.11).

$$\left(L_{msd} = 24.0\ in\right) \geq 17.79\ in \qquad True$$

Therefore, Level 1 Assessment criteria are not satisfied.

Perform a Level 2 Assessment per paragraph 7.4.3.3 on Blister G

a) STEP 1 – See Level 1, STEP 1
b) STEP 2 – See Level 1, STEP 2
c) STEP 3 – See Level 1, STEP 3, item 6)
d) STEP 4 – Inspection information gathered indicates periphery cracking inward from an external blister; therefore, a Level 2 Assessment cannot be performed.

Level 2 Assessment criteria are not satisfied; therefore, a Level 3 Assessment consisting of a detailed stress analysis must be conducted.

Perform a Level 1 Assessment per paragraph 7.4.2.3 on Blister H

a) STEP 1 – Determine the wall thickness to be used in the assessment.

$$t_c = 1.015\ in$$

b) STEP 2 – Determine the information in paragraph 7.3.3.3.

The blister-to-blister spacing check satisfies "$2s\ x\ 2c$" box criteria

$$\left(L_b = 8.0\ in\right) \geq 2.03\ in$$

$$s = 24.0\ in$$

$$s = 18.0\ in$$

c) STEP 3 – Check the blister acceptance criteria, blisters are acceptable without repair if all of the following are satisfied:

1) The blister diameter and venting requirements meet one of the following:

$$\left(\max\left[s,c\right] = 24.0\ in\right) \leq 2.0\ in \qquad False$$

$$\left(\max\left[s,c\right] = 24.0\ in\right) \leq 5.93\ in\ and\ is\ vented \qquad False$$

2) The minimum measured undamaged thickness measured from the non-bulged satisfies the follow.

$$\left(t_{mm} = 0.55\ in\right) \geq 0.5075\ in \qquad True$$

3) The blister projection satisfies the following.

$$\left(B_p = 1.5\ in\right) \leq \left(0.1 \cdot \min\left[s,c\right] = 1.8\ in\right) \qquad True$$

4) The blister has no periphery cracks. *True*

5) The distance between the edge of the blister and the nearest weld seam satisfies Equation (7.10).

$$\left(L_w = 6.0\ in\right) \geq 2.03\ in \qquad True$$

6) The distance from the blister edge to the nearest major structural discontinuity satisfies Equation (7.11).

$$\left(L_{msd} = 25.0\ in\right) \geq 17.79\ in \qquad True$$

Therefore, Level 1 Assessment criteria are not satisfied. A Level 2 Assessment is required.

Perform a Level 2 Assessment per paragraph 7.4.3.3 on Blister H

a) STEP 1 – See Level 1, STEP 1
b) STEP 2 – See Level 1, STEP 2
c) STEP 3 – See Level 1, STEP 3, item 6)
d) STEP 4 – The blister has no periphery cracks. Proceed to STEP 6.
e) STEP 6 – The blister does not have a crown crack. Proceed to STEP 7.
f) STEP 7 – The blister projection criteria is satisfied. See Level 1, STEP 3, item 3). Proceed to STEP 8.
g) STEP 8 – The blister is vented. Proceed to STEP 10.
h) STEP 10 – See Level 1, STEP 3, item 5)
i) STEP 11 – An in-service monitoring program should be developed to monitor potential blister growth.

Therefore, Level 2 Assessment criteria are satisfied.

7.3 Example Problem 3

An AUT (Automated UT) inspection was performed on a pressure vessel in hydrogen charging service. Two areas with a varying degree of HIC damage were identified by AUT. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1, 1989 Edition. The plant has decided to use weld overlay to stop future hydrogen charging of the steel. Determine if the vessel is fit for continued operation.

Vessel Data

- Material = $SA\text{-}516\ Grade\ 70\ \ Year\ 1980$
- Design Conditions = $148\ psi @ 350\ °F$
- Inside Diameter = $174\ in$
- Nominal Thickness = $1.0\ in$
- Measured Uniform Thickness = $0.9\ in$
- FCA = $0.0\ in$
- Weld Joint Efficiency = 0.85
- Supplemental Loads = $0\ (negligible)$
- Fracture Evaluation Temp = $100\ °F$

Inspection Data

Data on HIC damaged areas with increasing severity are given below. These 2 HIC areas are at least 50 in from one another. Each of the HIC area is located a minimum distance of 30 in away from the nearest structural discontinuity and 10 in away from a weld.

HIC Area 1

- Longitudinal Length = $6\ in$
- Circumferential Length = $7\ in$
- HIC to ID surface = $0.25\ in$
- HIC to OD surface = $0.35\ in$

HIC Area 2

- Longitudinal Length = $12\ in$
- Circumferential Length = $20\ in$
- HIC to ID surface = $0.25\ in$
- HIC to OD surface = $0.35\ in$

Perform a Level 1 Assessment per paragraph 7.4.2.1 – HIC Area 1

a) STEP 1 – Determine the wall thickness to be used in the assessment.

$$t_c = t_{rd} - FCA = 0.9\ in$$

$$(L_H = 50.0\ in) \geq (8t_c = 7.2\ in)$$

Therefore,

$$s = 6.0\ in$$

$$c = 7.0\ in$$

b) STEP 2 – Determine the information in paragraph 7.3.3.1.

HIC spacing to the nearest HIC or blister

$$L_H = 50.0\ in$$

HIC spacing to weld joints

$$L_w = 10.0\ in$$

HIC spacing to major structural discontinuities

$$L_{msd} = 30.0\ in$$

Minimum remaining wall thickness of undamaged metal, internal side,

$$t_{mm-ID} = 0.25\ in$$

Minimum remaining wall thickness of undamaged metal, external side,

$$t_{mm-OD} = 0.35\ in$$

HIC through-wall extent of damage

$$w_H = t_c - t_{mm-ID} - t_{mm-OD} = 0.3\ in$$

c) STEP 3 – Check all the conditions listed below.

1) The planar dimensions of the HIC damage

$$LOSS = t_{nom} - t_{rd} = 0.1\ in$$

$$D = ID + 2(LOSS + FCA) = 174.2\ in$$

$$(s = 6.0\ in) \leq \left(0.6\sqrt{D \cdot t_c} = 7.51\ in\right) \qquad True$$

$$(c = 7.0\ in) \leq \left(0.6\sqrt{D \cdot t_c} = 7.51\ in\right) \qquad True$$

2) The through-thickness extent of the damage

$$(w_H = 0.3\ in) \leq \left(\min\left[\frac{t_c}{3}, 0.5\ in\right] = 0.3\ in\right) \qquad True$$

3) The HIC damage is not surface breaking

$$\left(t_{mm-ID} = 0.25\ in\right) \geq \left(0.2t_c = 0.18\ in\right) \qquad True$$

$$\left(t_{mm-OD} = 0.35\ in\right) \geq \left(0.2t_c = 0.18\ in\right) \qquad True$$

4) The distance between the edge of the HIC damage and the nearest weld seam

$$\left(L_w = 10.0\ in\right) > \left(\max\left[2t_c, 1.0\,in\right] = 1.8\ in\right) \qquad True$$

5) The distance from the edge of the HIC damage to the nearest major structural discontinuity

$$\left(L_{msd} = 30.0\ in\right) \geq \left(1.8\sqrt{D \cdot t_c} = 22.54\ in\right) \qquad True$$

6) Further HIC damage has been prevented

Weld overlay will be applied $\qquad$ *True*

The Level 1 Assessment Criteria are Satisfied.

Perform a Level 1 Assessment per paragraph 7.4.2.1 – HIC Area 2

a) STEP 1 – Determine the wall thickness to be used in the assessment.

$$t_c = 0.9\ in$$

$$\left(L_H = 50.0\ in\right) \geq 7.2\ in$$

Therefore,

$$s = 12.0\ in$$

$$c = 20.0\ in$$

b) STEP 2 – Determine the information in paragraph 7.3.3.1.

HIC spacing to the nearest HIC or blister

$$L_H = 50.0\ in$$

HIC spacing to weld joints

$$L_w = 10.0\ in$$

HIC spacing to major structural discontinuities

$$L_{msd} = 30.0\ in$$

Minimum remaining wall thickness of undamaged metal, internal side,

$$t_{mm-ID} = 0.25\ in$$

Minimum remaining wall thickness of undamaged metal, external side,

$$t_{mm-OD} = 0.35\ in$$

HIC through-wall extent of damage

$$w_H = t_c - t_{mm-ID} - t_{mm-OD} = 0.3\ in$$

c) STEP 3 – Check all the conditions listed below.

1) The planar dimensions of the HIC damage

$$(s = 12.0\ in) \le 7.51\ in \qquad False$$

$$(c = 20.0\ in) \le 7.51\ in \qquad False$$

2) The through-thickness extent of the damage

$$(w_H = 0.3\ in) \le 0.3\ in \qquad True$$

3) The HIC damage is not surface breaking

$$(t_{mm-ID} = 0.25\ in) \ge 0.18\ in \qquad True$$

$$(t_{mm-OD} = 0.35\ in) \ge 0.18\ in \qquad True$$

4) The distance between the edge of the HIC damage and the nearest weld seam

$$(L_w = 10.0\ in) > 1.8\ in \qquad True$$

5) The distance from the edge of the HIC damage to the nearest major structural discontinuity

$$(L_{msd} = 30.0\ in) \ge 22.54\ in \qquad True$$

6) Further HIC damage has been prevented

Weld overlay will be applied *True*

HIC Area 2 is not acceptable per the Part 7 Level 1 Assessment Criteria.

Perform a Level 2 Assessment per paragraph 7.4.3.1 – HIC Area 2

a) STEP 1 – See Level 1, STEP 1

b) STEP 2 – See Level 1, STEP 2

c) STEP 3 – See Level 1, STEP 3, item 4)

d) STEP 4 – See Level 1, STEP 3, item 5)

e) STEP 5 – See Level 1, STEP 3, item 3) – damage is classified as sub surface

f) STEP 6 – Determine the $MAWP$ of the component per Annex A, paragraph A.2

$$MAWP = \frac{SEt_c}{R + 0.6t_c} = \frac{(17500)(0.9)}{87 + 0.6(0.9)} = 180\ psi$$

g) STEP 7 – Calculate the RSF based on the sub surface HIC damage. The minimum longitudinal distance to the nearest region of HIC damage is 22 inches.

$$L_R = \min\left[\frac{L_{Hs}}{2}, 8t_c\right] = \min\left[\frac{50.0}{2}, 8(0.9)\right] = 7.2\ in$$

$$RSF = \frac{2L_R + s\left[1 - \frac{w_H \cdot D_H}{t_c}\right]}{2L_R + s} = \frac{2(7.2) + (12)\left[1 - \frac{(0.3)(0.8)}{0.9}\right]}{2(7.2) + 12} = 0.8788$$

h) STEP 8 – Evaluate the longitudinal extent of the flaw. Since

$$\left(RSF = 0.8788\right) \geq \left(RSF_a = 0.9\right) \qquad \textit{False}$$

$$MAWP_r = MAWP\left(\frac{RSF}{RSF_a}\right) = 180\left(\frac{0.8788}{0.9}\right) = 175.76\ psi$$

then the longitudinal extent of the HIC damage satisfies the LTA portion of the assessment. with the $MAWP_r$ from STEP 8.

i) STEP 9 – Evaluate the circumferential extent of the HIC damage as an LTA using the procedures in Part 5, paragraph 5.4.3.4. See Example Problem 5.3 STEP 10 for the complete procedure. The depth used in this analysis is given by

$$d_{HIC} = w_H D_H = (0.3)(0.8) = 0.24\ in.$$

Per the results of the LTA analysis of the circumferential extent of the HIC damage, $MAWP = 202\ psi$. Since $MAWP$ from STEP 9 is greater than $P_{Design} = 148\,psi$ then the circumferential extent of the flaw is acceptable.

j) STEP 10 – Determine whether a fracture assessment is required. This is the case if any of the following are true.

1) The equipment will remain in hydrogen service (overlay applied). *False*
2) The HIC damage is surface breaking. *False*
3) $\left(w_H = 0.3\ in\right) > 0.3\ in$ *False*

A crack like flaw assessment does not need to be performed. Proceed to STEP 12.

k) STEP 12 – Confirm that further HIC damage has been either prevented or is limited to a known or verifiable rate based on one of the methods provided.

The Level 2 Assessment Criteria are satisfied.

$\left(MAWP_r = 175\,psi\right) \geq \left(P_{Design} = 148\,psi\right)$ but the $MAWP_r$ is limited by $MAWP$ adjusted for weld joint efficiency of 0.85=153 psi

The equipment is fit for continued operation.

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PART 8

ASSESSMENT OF WELD MISALIGNMENT AND SHELL DISTORTIONS

EXAMPLE PROBLEMS

8.1 Example Problem 1

A NPS 36 long seam welded pipe is to be used on a refinery project. Inspection of the pipe indicates peaking at the long seam weld. The pipe was constructed to ASME B31.3. Determine if the pipe is suitable for service.

Pipe Data

- Material = ASTM A-691 Grade 1-1/4Cr *Year* 1990
- Pipe Outside Diameter = $36\ in$
- Wall Thickness = $0.5\ in$
- Design Pressure = $315\ psig$
- Design Temperature = $800\ ^\circ F$
- Joint Efficiency = $100\ \%$
- Future Corrosion Allowance = $0.05\ in$

Inspection Data

- Peaking distortion δ = $0.31\ in$

Perform a Level 1 Assessment per Part 8 paragraph 8.4.2.1

Limitations for weld peaking misalignment are not specified in ASME B31.3 (see Part 8 Table 8.4). Typically, the rules for out-of-roundness are applied to this type of misalignment.

$$\left(D_{\max}-D_{\min}\right)=\left(36.31-36\right)=0.31\ \ in\quad\le\quad\left(0.01D\right)=0.36\ \ in\qquad \text{True}$$

The Level 1 Assessment is Satisfied if the Out-Of-Roundness Criterion is Applied

Perform A Level 2 Assessment per Part 8 paragraph 8.4.3.2

a) STEP 1 – Identify the component and weld misalignment type (see Part 8 Table 8.10) and determine the following variables as applicable (see Figures 8.2, 8.3, and 8.4) – The weld misalignment is peaking which occurs on a longitudinal weld seam. The following data is required for the assessment:

$D_o = 36\ in$ $\quad$ $LOSS = 0.0\ in$

$t_{nom} = 0.5\ in$ $\quad$ $FCA = 0.05\ in$

$P = 315\ psig$ $\quad$ $\delta = 0.31\ in$

$E_y = 25.2(10^6)\ psi$ $\quad$ $S_a = 16{,}800\ psi$

$\nu = 0.3$ $\quad$ $H_f = 3.0$

b) STEP 2 - Determine the wall thickness to be used in the assessment

$$t_c = t_{nom} - LOSS - FCA = 0.5 - 0.0 - 0.05 = 0.45\ in$$

c) STEP 3 – Determine the membrane stress based on the current design pressure (see Annex A, Equation (A.290)).

$$MA = 0.0\ in$$

$$Y_{B31} = 0.4$$

$$\sigma_m^c = \frac{(315)}{1.0}\left[\frac{36}{(2)(0.45-0.0)} - 0.4\right] = 12{,}474\ psi$$

d) STEP 4 – Calculate the ratio of the induced bending stress to the applied membrane stress using the equations in Part 8 Table 8.10 based on local peaking.

$$R = \frac{36}{2} - 0.5 + 0.05 + \frac{0.45}{2} = 17.775\ in$$

$$S_p = \sqrt{\frac{12\left\{\left(1-\nu^2\right)PR^3\right\}}{E_y t_c^3}} = \sqrt{\frac{12\left\{1-(0.3)^2\right\}(315)((17.775)^3}{\left\{25.5\cdot(10)^6\right\}(0.45)^3}} = 2.88$$

$$\frac{\delta}{R} = \frac{0.31}{(17.775)} = 0.0174$$

From Figure 8.13, with $\left\{\begin{array}{l} S_p = 2.88 \\ \dfrac{\delta}{R} = 0.0174 \end{array}\right\} \Rightarrow C_f \approx 0.83$, and

$$R_b^{clja} = \frac{(6)(0.31)}{(0.45)}(0.83) = 3.43$$

$$R_b = R_b^{cljc} + R_b^{clja} = 0.0 + 3.43$$

$$R_{bs} = -1.0$$

e) STEP 5 – Determine the remaining strength factors – set $H = 3.0$ (the induced bending stress is evaluated as a secondary stress)

$$RSF = \min\left[\frac{(3.0)(16,800)}{(12,474)(1+3.43)+(0.0)(1+(-1.0))},\ 1.0\right] = 0.91$$

f) STEP 6 – Evaluate the results.

$$(RSF = 0.91) \quad \geq \quad (RSF_a = 0.90) \qquad \qquad True$$

The Level 2 Assessment Criterion is Satisfied.

8.2 Example Problem 2

Determine if the pipe in the Example Problem 1 can operate for 2,000 cycles at 315 psig.

Perform A Level 2 Assessment – Fatigue Analysis per Part 8 Paragraph 8.4.3.8.

Paragraph 8.4.3.8 permits a Level 2 assessment as long as the geometric flaw satisfies the requirements of the Part 8 paragraph 8.4.3.2. The results of Example Problem 1 shows that this restriction is met by the flaw since the Level 2 criterion for the assessment of the weld misalignment was satisfied.

Additional Pipe Data

- Material Yield Strength = $25,200\ psi @ 800\,^{\circ}F$

a) STEP 1 – Determine the nature of the loading, the associated membrane stress and the number of operating cycles.

- The loading consists of pressure loading.
- From Example Problem 1 the circumferential membrane stress is $\sigma_m = 12,474$ psi.
- The desired number of operating cycles is 2000.

b) STEP 2 – Determine the ratio of the induced bending stress to the applied membrane stress, R_b.

$R_b^{cljc} = 0.0$ since centerline offset is not present

$R_b^{clja} = 3.43$

$R_b^{or} = 0.0$ since neither general or arbitrary out-of-roundness is present.

$$R_b = R_b^{cljc} + R_b^{clja} + R_b^{or} = 0.0 + 3.43 + 0.0 = 3.43$$

c) STEP 3 – Using the loading history and membrane stress from STEP 1 and the R_b from STEP 2, calculate the stress range for the fatigue analysis using Table 8.12.

From Table 8.12, for a cylinder with a longitudinal weld joint with weld misalignment:

$$\Delta\sigma_m = \sigma_m = 12474\ psi$$

$$\Delta\sigma_b = \sigma_m\left(R_b^{cljc} + R_b^{clja} + R_b^{or}\right) = (12,747)(0.0 + 3.43 + 0.0) = 42,756\ psi$$

$$\Delta S_P = \sigma_m\left(1 + R_b^{cljc} + R_b^{clja} + R_b^{or}\right)\left(K_f\right)$$

Since we apply the fatigue strength reduction factor when using Equation (B.130) below, we will set $K_f = 1.0$ in the equation for ΔS_P

$$\Delta S_P = \sigma_m\left(1 + R_b^{cljc} + R_b^{clja} + R_b^{or}\right)(1.0) = (12,474)(1 + 0.0 + 3.43 + 0.0)(1.0) = 55,260\ psi$$

d) STEP 4 – Compute the number of allowed cycles using the stress range determined in STEP 3.

Table 8.12 references Annex B1, paragraph B1.5. Paragraph B1.5 provides three methods for determining the permissible number of cycles:

1) Elastic Stress Analysis and Equivalent Strength in accordance with paragraph B1.5.3
2) Elastic-Plastic Stress Analysis and Equivalent Strain in accordance with paragraph B1.5.4
3) Elastic Stress Analysis and Structural Stress in accordance with paragraph B1.5.5

Since an elastic-plastic stress analysis has not been conducted, the permitted number of cycles will be determined using Methods 1 and 3. In both cases the stresses considered consist of those due to pressure loading, stresses from supplementary loads and thermal gradients are considered negligible.

Method 1:

For a fatigue assessment using an elastic stress analysis and equivalent stresses, STEPS 1 through 3 in paragraph B1.5.3.1 are similar to STEPS 1 through 3 in paragraph 8.4.3.8 with the exception that the elastic stress range is calculated from the stress tensors and that the stress state from both mechanical and thermal loading are considered. For this example problem the stress range due to thermal loading is considered negligible and the mechanical loading consists of internal pressure. Thus the stress range is given by STEP 3 and is 55,260 psi.

STEP 4 – Determine the effective alternating stress from Equation (B1.30), modified to ignore cyclic thermal stress, (i.e., $\Delta S_{LT} = 0.0$):

$$S_{alt} = \frac{K_f \cdot K_e \cdot \Delta S_P}{2}$$

K_f is a fatigue strength reduction factor determined from Table B1.10 based on type of weld and the quality level determined from Table B.11. The quality level in Table B1.11 is based on the type of inspection performed on the weld.

For the pipe material, the specification called for full volumetric and full visual examination, but neither MT nor PT were performed on the weld. Thus from Table B1.11 the quality level is 4.

The weld being assessed is a full penetration weld. For a full penetration weld inspected to quality level 4, Table B1.10 stipulated a weld fatigue reduction factor of $K_f = 2.0$.

The factor K_e is a fatigue penalty factor that may be determined from Equations (B1.31) to (B1.33) depending on the value of the stress range ΔS_P compared to the permitted primary plus secondary stress range, S_{PS}. The value of S_{PS} is the larger of three times the allowable stress at temperature or two times the material yield strength at the average temperature during a stress cycle. The allowable stress at temperature, S_a, equals 16,800 psi and the yield strength for the A-691 Grade 1-1/4Cr material, S_y, equals 25,200 psi at 800° F and 35,000 at ambient temperature. The average yield stress during the cycle is thus 30,100 psi.

$$S_{PS} = \max\left[3.0S_a, 2S_y\right] = \max\left[(3)(16,800),(2)(30,100)\right] = 60,200 \ psi$$

Compare the value of ΔS_P to S_{PS}:

$$(\Delta S_P = 55,260) \quad \le \quad (S_{PS} = 60,200) \qquad\qquad True$$

Therefore from Equation (B1.31) $K_e = 1$

$$S_{alt} = \frac{K_f \cdot K_e \cdot \Delta S_P}{2} = \frac{(2)(1)(55,260)}{2} = 55,260 \ psi$$

STEP 5 – Determine the permitted number of cycles, N, for the alternating stress computed in STEP 4 and the smooth bar fatigue curves as provided in Annex F, paragraph F.6.2.1. For temperatures not in the creep range, the permitted number of cycles is given by Equation (F.214) and Equation (F.215):

$$N = (10)^X \cdot \left(\frac{E_T}{E_{FC}}\right)$$

where

$$X = \frac{C_1 + C_3\left(\frac{S_{alt}}{C_{us}}\right) + C_5\left(\frac{S_{alt}}{C_{us}}\right)^2 + C_7\left(\frac{S_{alt}}{C_{us}}\right)^3 + C_9\left(\frac{S_{alt}}{C_{us}}\right)^4 + C_{11}\left(\frac{S_{alt}}{C_{us}}\right)^5}{1 + C_2\left(\frac{S_{alt}}{C_{us}}\right) + C_4\left(\frac{S_{alt}}{C_{us}}\right)^2 + C_6\left(\frac{S_{alt}}{C_{us}}\right)^3 + C_8\left(\frac{S_{alt}}{C_{us}}\right)^4 + C_{10}\left(\frac{S_{alt}}{C_{us}}\right)^5}$$

The values of the coefficients C_i are given in Table F.13 for low allow steels where $\sigma_{UTS} \le 80$ ksi. Examining Table F.13, the values of C_6 through C_{11} all equal zero.

Substituting the values for C_1 through C_5, $S_{alt} = 55.26$ ksi, $C_{us} = 1$, $E_T = 25.2(10)^3$ ksi, and $E_{FC} = 28.3(10)^3$ ksi,

$$X = \frac{7.999502 + (1.50085)(10)^{-1}(55.26) + (-5.263661)(10)^{-5}(55.26)^2}{1 + (5.832491)(10)^{-2}(55.26) + (1.273659)(10)^{-4}(55.26)^2} = 3.498$$

and

$$N = (10)^{3.498}\left(\frac{25.2(10)^3}{28.3(10)^3}\right) = 2,802\ cycles$$

<u>Method 3:</u>

a) STEP 1 – Determine the load history for the component, considering all significant operating loads. The load applied to the pipe consists of internal pressure, P, of 315 psig.

b) STEP 2 – For the weld joint subject to fatigue evaluation determine the individual number of stress-strain cycles. The desired number of cycles, N, is 2,000.

c) STEP 3 – Determine the elastically calculated membrane and bending stress normal to the hypothetical crack plane at the start and end of the cycle. Using this data calculate the membrane and bending stress ranges between the time of maximum and minimum stress for the cycle.

From Example Problem 1 the maximum membrane stress for the cycle occurs at a pressure of 315 psig, and the minimum membrane stress for the cycle occurs at zero pressure. Similarly, the maximum bending stress for the cycle occurs at a pressure of 315 psig, and the minimum bending stress for the cycle occurs at zero pressure. The values of the two stress ranges given by Equations (B1.46) through (B1.50) are:

$$\Delta\sigma_m = {}^m\sigma_m^e - {}^n\sigma_m^e = 12.474 - 0 = 12.474\ ksi$$

$$\Delta\sigma_b = {}^m\sigma_b^e - {}^n\sigma_b^e = (R_b)\left({}^m\sigma_m^e - {}^n\sigma_m^e\right) = (3.43)(12.474 - 0) = 42.786\ ksi$$

$$\sigma_{\max} = \max\left[\left({}^m\sigma_m^e + {}^m\sigma_b^e\right), \left({}^n\sigma_m^e + {}^n\sigma_b^e\right)\right] = \max\left[(12.474 + 42.786), (0+0)\right] = 55.26\ ksi$$

$$\sigma_{\min} = \min\left[\left({}^m\sigma_m^e + {}^m\sigma_b^e\right), \left({}^n\sigma_m^e + {}^n\sigma_b^e\right)\right] = \min\left[(12.474 + 42.786), (0+0)\right] = 0\ ksi$$

$$\sigma_{mean} = \frac{\sigma_{\max}^e + \sigma_{\min}^e}{2} = \frac{55.26 + 0}{2} = 27.63\ ksi$$

d) STEP 4 – Determine the elastically calculated structural stress range, $\Delta\sigma^e$, for the cycle using Equation (B1.51)

$$\Delta\sigma^e = \Delta\sigma_m^e + \Delta\sigma_b^e = 12.474 + 42.786 = 55.26\ ksi$$

e) STEP 5 – Determine the elastically calculated structural strain, $\Delta\varepsilon^e$, from the elastically calculated structural stress range, $\Delta\sigma^e$, using Equation (B1.52) and the elastic modulus for the material at the average temperature of 435° F,

$$\Delta\varepsilon^e = \frac{\Delta\sigma^e}{E_{ya}} = \frac{55.26}{27.79(10)^4} = 1.9885(10)^{-4}$$

and the values of the stress range, $\Delta\sigma$, and strain range, $\Delta\varepsilon$, by correcting $\Delta\sigma^e$ and $\Delta\varepsilon^e$ for hysteresis stress-strain loop by solving Equations (B1.53) and (B1.54) simultaneously,

$$\Delta\sigma \cdot \Delta\varepsilon = \Delta\sigma^e \cdot \Delta\varepsilon^e = (55.26)\left(1.9885(10)^{-4}\right) = 1.0988(10)^{-1}$$

$$\Delta\varepsilon = \frac{\Delta\sigma}{E_{ya}} + 2\left(\frac{\Delta\sigma}{K_{css}}\right)^{\frac{1}{n_{css}}}$$

where

K_{css} and n_{css} are determined from Table F.8 in Annex F for the average temperature during the cycle. The closest material to the ASTM A691 Grade 41 is the 1Cr-1-Mo-1/4V material. The average value of K_{css} is given by,

$$K_{css} = \frac{K_{css_{70^\circ}} + K_{css_{800^\circ}}}{2} = \frac{156.9 + 132.3 + \dfrac{(118.2 - 132.3)(800 - 750)}{(930 - 750)}}{2} = 142.503$$

The average value of n_{css} is given by,

$$n_{css} = \frac{n_{css_{70^\circ}} + n_{css_{800^\circ}}}{2} = \frac{0.128 + 0.128 + \dfrac{(0.143 - 0.128)(800 - 750)}{(930 - 750)}}{2} = 0.1301$$

Substituting these values into the Equations (B1.54) and (B1.54) for $\Delta\sigma$ and $\Delta\varepsilon$, and solving them simultaneously gives,

$$\Delta\sigma = 53.283\ ksi$$

$$\Delta\varepsilon = 2.0623(10)^{-3}.$$

Modify the value of $\Delta\sigma$ for low-cycle fatigue using Equation (B1.55),

$$\Delta\sigma = \left(\frac{E_{ya}}{1-\nu^2}\right)\Delta\varepsilon = \left(\frac{2.779(10)^4}{1-(0.3)^2}\right)\left(2.0623(10)^{-3}\right) = 62.979\ ksi$$

f) STEP 6 – Compute the equivalent structural stress range ΔS_{ess} using Equation (B1.56) where the input parameters are as follows:

$$\Delta\sigma = 62.979\ ksi$$

$t_{ess} = 0.625\ in$ since the component thickness, $t_c = 0.45 \le 0.625\ in$

$$R_b = \frac{|\Delta\sigma_b|}{|\Delta\sigma_m| + |\Delta\sigma_b|} = \frac{42.786}{12.474 + 42.786} = 0.7743$$

$$I^{\frac{1}{m_{ss}}} = \frac{1.23 - 0.364R_b - 0.17R_b^2}{1.007 - 0.306R_b - 0.178R_b^2} = \frac{1.23 - 0.364(0.7743) - 0.17(0.7743)^2}{1.007 - 0.306(0.7743) - 0.178(0.7743)^2} = 1.2757$$

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} = \frac{0}{55.26} = 0$$

$f_M = 1.0$, since $R = 0 \le 0$ (see Equations (B1.63) and (B1.64))

$$m_{ss} = 3.6$$

$$\Delta S_{ess} = \frac{\Delta\sigma}{t_{ess}^{\left(\frac{2-m_{ss}}{2\cdot m_{ss}}\right)} \cdot I^{\frac{1}{m_{ss}}} \cdot f_M} = \frac{62.979}{(0.625)^{\left(\frac{2-3.6}{2\cdot 3.6}\right)} \cdot 1.2757 \cdot 1} = 44.472\ ksi$$

g) STEP 7 – Determine the permitted number of cycles, N, using the value of ΔS_{ess} from STEP 6 and the welded component fatigue curves in Annex F. The welded component fatigue curves are represented in Annex F by Equation (F.218):

$$N = \frac{f_1}{f_E}\left(\frac{f_{MT} \cdot C}{\Delta S_{ess}}\right)^{\frac{1}{h}}$$

where

$f_1 = 1.0$, since no work has been done to improve the fatigue of the pipe longitudinal weld

$f_E = 4.0$, since the process fluid is considered mildly aggressive

$$f_{MT} = \frac{E_{ACS}}{E_T} = \frac{2.94(10)^4}{2.56(10)^4} = 1.1484$$

From Table F.29, for a lower 99% prediction interval (-3σ), the values of C and h for low alloy steel are,

$$C = 818.3$$

$$h = 0.3195$$

$$N = \frac{f_1}{f_E}\left(\frac{f_{MT} \cdot C}{\Delta S_{ess}}\right)^{\frac{1}{h}} = \frac{1.0}{4.0}\left(\frac{(1.1484)(818.3)}{44.472}\right)^{\frac{1}{0.3195}} = 3,505\ cycles$$

h) STEP 8 – Evaluate the component by comparing the number of permitted cycles to the number of desired cycles:

Method 1:

$$N = 2,802 \geq \quad 2,000 \qquad \textit{True}$$

Method 3:

$$N = 3,505 \quad \geq \quad 2,000 \qquad \textit{True}$$

The Level 2 assessment for fatigue is satisfied by both Method 1 and Method 3

8.3 Example Problem 3

An existing pressure vessel is being repaired during a shutdown. After field PWHT, inspection of the vessel indicates that out-of-roundness along the length of the cylindrical section of the vessel has occurred. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1. Determine if the vessel is suitable for service.

Vessel Data

- Material = $SA-516\ Grade\,70\ \ Year\,1998$
- Design Conditions = $500\ psig\ @\ 650\,^{\circ}F$
- Wall Thickness = $1.875\ in$
- Inside Diameter, D_{in} = $120\ in$
- Joint Efficiency = $100\,\%$
- FCA = $0.125\ in$

Inspection Data

- $D_{\max}$ = $120.5\ in$
- $D_{\min}$ = $119.4\ in$
- Based on other measurements, the deformed shape significantly deviates from the perfect oval shape.

Perform A Level 1 Assessment per Part 8 paragraph 8.4.2

$$\left(D_{\max}-D_{\min}\right)=\left(120.5-119.4\right)=1.1\ \ in\ \ \le\ \ \left(0.01D\right)=\left(\left(0.01\right)\left(120\right)\right)=1.2\ \ in\qquad True$$

The Level 1 Assessment Criterion Is Satisfied

Perform A Level 2 Assessment per Part 8 paragraph 8.4.3.3

a) STEP 1 – Determine the following variables based on the type of out-of-roundness.

$R_{in} = D_{in}/2 = 120/2 = 60\ in$ $\qquad LOSS = 0.0\ in$

$t_{nom} = 1.875\ in$ $\qquad FCA = 0.125\ in$

$P = 500\ \ psig$ $\qquad \theta = 0^{\circ}$ (chosen because this is the location of the longitudinal weld seam)

$E_y = 26.1\left(10\right)^6\ \ psig$ $\qquad S_a = 17,500\ \ psi$

$\nu = 0.3$ $\qquad H_f = 3.0$

$D_{\max} = 120.5\ in$ $\qquad D_{\min} = 119.4\ in$

$C_s = 0.1$ (the deformed shape significantly deviates from a perfect oval)

b) STEP 2 – Determine the wall thickness to be used in the assessment.

$$t_c = t_{nom} - LOSS - FCA = 1.875 - 0.0 - 0.125 = 1.75\ in$$

c) STEP 3 – Determine the circumferential membrane stress based on the current design pressure (see Annex A).

$$\sigma_m = \frac{(500)}{(1.0)}\left(\frac{(60+0.125)}{(1.75)}+0.6\right) = 17,479\ \ psi$$

d) STEP 4 – Determine the ratio of the induced circumferential bending stress to the circumferential membrane stress from Equation (8.22):

$$R_b^{or} = abs\left[\frac{(1.5)(120.5-119.4)\left(\cos\left((2.)(0.)\right)\right)}{(1.75)\left(1+\left[\frac{(0.1)(500)\left(1-(0.3)^2\right)}{26.1(10)^6}\right]\left(\frac{120.25+1.75}{1.75}\right)^3\right)}\right] = 0.593$$

e) STEP 5 – Determine the remaining strength factor using Equation (8.21):

$$RSF = \min\left[\frac{(3.0)(17,500)}{(17479)(1+0.593)},\ 1.0\right] = \min\left[1.8855,\ 1.0\right] = 1.0$$

f) STEP 6 – Evaluate the results. If $RSF \geq RSF_a$, the out-of-roundness is acceptable per Level 2; otherwise, refer to Part 8 paragraph 8.4.3.7.

$$\left(RSF = 1.0\right) \geq \left(RSF_a = 0.90\right) \qquad True$$

The Level 2 Assessment Criterion Is Satisfied

8.4 Example Problem 4

On further inspection of the vessel in Example Problem Number 3, the out-of-roundness was reclassified as weld misalignment on one of the longitudinal seams. The weld misalignment is categorized as centerline offset and local peaking. Determine if the vessel is suitable for operation, and the maximum allowable working pressure.

Inspection Data

$$D_{\max} = 120.5\ in$$

$$D_{\min} = 119.4\ in$$

Based on additional field measurements, the deformed shape significantly deviates from the perfect oval shape. The centerline offset and local peaking were measured to be:

$$e = 0.25\ in\,(centerline\,offset)$$

$$\delta = 0.60\ in\ (peaking)$$

Perform A Level 2 Assessment per Part 8 paragraph 8.4.3.2

a) STEP 1 – The component is a cylindrical shell with centerline offset and peaking (angular) weld misalignment. The variables necessary to perform a Level 2 Assessment were determined as part of Example Problem 3.

b) STEP 2 – The wall thickness to use in the assessment was determined in Example Problem 3, STEP 2, and equals 1.75 in

c) STEP 3 – Determine the circumferential membrane stress based on the current design pressure (see Annex A) – from Example Problem 3:

$$\sigma_m = 17,479 \text{ psi}$$

d) STEP 4 – Calculate the ratio of the induced bending stress to the applied circumferential membrane stress for weld misalignment using Part 8, paragraph 8.4.3.2.

R_b^{cljc} for centerline offset misalignment, (see Table 8.9 for the equation to calculate S_p and Table 8.10 for the equation to calculate R_b^{cljc}):

$$S_p = \sqrt{\frac{12\left\{\left(1-\nu^2\right)PR^3\right\}}{E_y t_c^3}} = \sqrt{\frac{(12)\left(1-(0.3)^2\right)(500)\left(60+0.125+(0.5)(1.75)\right)^3}{\left(26.1(10)^6\right)(1.75)^3}} = 2.98$$

$$C_1 = 3.8392(10)^{-3} + 3.1636\left(\frac{0.25}{1.75}\right) + 1.2377\left(\frac{0.25}{1.75}\right)^2 -$$
$$4.0582(10)^{-3}(2.98) + 3.4647(10)^{-4}(2.98)^2 +$$
$$3.1205(10)^{-6}(2.98)^3 = 0.4721$$

$$C_2 = 1.0 + 0.41934\left(\frac{0.25}{1.75}\right) + 9.7390(10)^{-3}(2.98) = 1.0888$$

$$R_b^{cljc} = \frac{C_1}{C_2} = \frac{0.4721}{1.0888} = 0.434$$

R_b^{clja} for peaking misalignment (see Table 8.10)

$$S_p = 2.98$$

$$\frac{\delta}{R} = \frac{0.60}{61} = 0.010$$

From Figure 8.13, with $\left\{ \begin{matrix} S_p = 2.98 \\ \dfrac{\delta}{R} = 0.010 \end{matrix} \right\} \Rightarrow C_f \approx 0.87$, and

$$R_b^{clja} = \frac{6(0.60)}{(1.75)}(0.87) = 1.79$$

R_b for centerline offset misalignment and peaking weld misalignment is:

$$R_b = R_b^{clja} + R_b^{cljc} = 1.79 + 0.434 = 2.224$$

e) STEP 5 – Determine the remaining strength factor.

$$RSF = \min\left[\frac{(3.0)(17500)}{(17479)(1+2.224)},\ 1.0\right] = \min[0.927,\ 1.0] = 0.93$$

f) STEP 6 – Evaluate the results.

$$(RSF = 0.927) \quad \geq \quad (RSF_a = 0.90) \qquad\qquad True$$

The Level 2 Assessment Criterion is Satisfied.

Thus, from Equation (2.3), $MAWP_r = MAWP = 500$ **psig**

8.5 Example Problem 5

A vertical, cylindrical pressure vessel subjected to an upset condition has been inspected and found to have deformed to an out-of-round shape along the length of about a third of the vessel. From the measurements, it appears that the deformation can be classified as arbitrary out-of-roundness. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1. Determine if the vessel is suitable for service.

Vessel Data

- Material = SA-542 Grade B Year 2004
- Design Conditions = $265\ psig @ 625\,^{\circ}F$
- t_{nom} = $1.5\ in$
- D = $228\ in$
- Joint Efficiency = 100% (*both circumferential and longituidinal*)
- FCA = $0.125\ in$
- $LOSS$ = $0.0\ in$
- Allowable Stress = $23,200\ psi$

Inspection Data

As part of the inspection, twenty-four measurements of the distance to the vessel inside surface were made from a point near the center of the vessel. The distance from the point to the equally spaced locations at the vessel inside surface, taken at fifteen degree increments are shown in Table E8.5-1. Table E8.5-1 also shows the diameter obtained by adding the radii of two points on opposite sides of the vessel, and the percent the diameter varies from the design diameter.

Table E8.5-1 Measured Distances To Vessel Inside Surface

Point	Angle (degrees)	Radius (in)	Point	Angle (degrees)	Radius (in)	Diameter (in)	% Out-Of-Round
1	0	83.90	13	180	148.40	232.30	1.88
2	15	85.65	14	195	145.15	230.80	1.22
3	30	88.65	15	210	140.15	228.80	0.35
4	45	93.90	16	225	132.27	226.17	-0.80
5	60	101.27	17	240	124.27	225.54	-1.08
6	75	108.52	18	255	114.77	223.29	-2.07
7	90	116.52	19	270	106.27	222.79	-2.28
8	105	125.52	20	285	99.27	224.79	-1.41
9	120	133.02	21	300	94.52	227.54	-0.20
10	135	141.15	22	315	89.15	230.30	1.01
11	150	146.15	23	330	85.40	231.55	1.55
12	165	148.52	24	345	83.65	232.17	1.83

Perform a Level 1 Assessment

Table 8.3 shows that for a cylindrical shell under internal pressure, the value of $D_{max} - D_{min}$ shall not exceed one percent of the design diameter. For this to be satisfied, the absolute value of the algebraic difference between two values in the last column should not exceed 1.0. The maximum absolute algebraic difference between any two values occurs between the 0° - 180° diameter and the 90° - 270° diameter and is equal to [(1.88) – (-2.28)] = 4.16.

Therefore, the vessel out-of-roundness does not satisfy the Level 1 assessment criterion.

Perform a Level 2 Assessment

Classify the shell deformation as arbitrary out-of-roundness.

a) STEP 1 – Using the measured radii from the inspection results calculate the Fourier series coefficients that represent the shape of the cylindrical shell using the method provided in Part 8, Table 8.2.

Before we can calculate the Fourier coefficients we must apply Equations (8.5) through (8.9) to correct the measurements so that they account for the difference between the center of the vessel and the point from which the measurements were made. This may be done using a spreadsheet or a computer program written for this purpose, as shown in sub-steps 1. through 6. below:

1) Apply Equation (8.7), $R_m = \frac{1}{M}\sum_{i=1}^{M} R_i$, to the twenty-four measured radii, to determine the mean inside radius, R_m, equals 114 in.

2) Determine the values of A_1 and B_1, the coefficients of the second terms in the Fourier series for the cosine and sine functions respectively. For A_1 apply Equation (8.8)

$$A_n = \frac{2}{M}\sum_{i=1}^{M} R_i \cos\left[\frac{2\pi(i-1)}{M} n\right]$$

and for B_1 Equation (8.9)

$$B_n = \frac{2}{M}\sum_{i=1}^{M} R_i \sin\left[\frac{2\pi(i-1)}{M} n\right]$$

with the value of n equal to 1. Doing this gives $A_1 = -32.0762$ in and $B_1 = 4.8868$ in

3) Use the values of A_1 and B_1 in Equation (8.5)

$$R_i^c = R_i - A_1 \cos\left[\frac{2\pi(i-1)}{M}\right] - B_1 \sin\left[\frac{2\pi(i-1)}{M}\right]$$

to determine the radii of the twenty-four measured points adjusted for the true center of the vessel R_i^c.

4) Determine the value of the correction to each of the twenty-four measured radii, ε_i, from Equation (8.6)

$$\varepsilon_i = R_i^c - R_m .$$

5) Using the previously determined values, calculate the adjusted radius at each of the twenty-four locations using Equation (8.4)

$$R(\theta) = R_m + A_1 \cos\theta + B_1 \sin\theta + \varepsilon$$

The values of i, θ_i, R_i^c, ε_i, and $R(\theta)$ at each of the twenty-four measured locations are shown in Table E8.5-2.

Table E8.5-2 Corrections To Measured Radii

i	θ_i (degrees)	R_i^c (in)	ε_i (in)	$R(\theta)$ (in)
1	0	83.90	1.9721	115.9720
2	15	85.65	1.3643	115.3642
3	30	88.65	-0.0188	113.9812
4	45	93.90	-0.8783	113.1216
5	60	101.27	-0.9231	113.0768
6	75	108.52	-1.8975	112.1024
7	90	116.52	-2.3660	111.6340
8	105	125.52	-1.5014	112.4986
9	120	133.02	-1.2494	112.7506
10	135	141.15	1.0091	115.0090
11	150	146.15	1.9236	115.9236
12	165	148.52	2.2728	116.2728
13	180	148.40	2.3197	116.3196
14	195	145.15	1.4274	115.4274
15	210	140.15	0.8105	114.8104
16	225	132.27	-0.9549	113.0450
17	240	124.27	-1.5351	112.4648
18	255	114.77	-2.8108	111.1892
19	270	106.27	-2.8423	111.1576
20	285	99.27	-1.7069	112.2930
21	300	94.52	0.7911	114.7910
22	315	89.15	1.2827	115.2826
23	330	85.40	1.6181	115.6180
24	345	83.65	1.8939	115.8938

6) Using the values shown in the last column of this table (i.e., $R(\theta)$) as a new value for R_i in Equations (8.8) and (8.9) determine the values of A_n and B_n for n = 2 to 24. This may be accomplished with either a spreadsheet or computer program that implements the pseudo-code of Table 8.2. Because there are 24 measurement points, there can only be twenty-six values total for both A_n and B_n, where A_0 equals 2 times the mean radius R_m and $B_0 = 0$ (i.e., A_1 to A_{12} and B_1 to B_{12}).

The values of the twenty-six coefficients for the thirteen terms of the Fourier series are shown in Table E8.5-3.

Table E8.5-3 Fourier Coefficients To Calculate The True Shape Of The Vessel Shell

Index	Fourier Term	A_n	B_n
1	0	227.9999	0.0000
2	1	-32.0762	4.8868
3	2	2.1673	-0.8063
4	3	-0.3384	-0.1423
5	4	-0.2135	-0.0451
6	5	0.1902	0.1821
7	6	0.1875	0.1042
8	7	0.1366	-0.0598
9	8	-0.0573	0.0632
10	9	-0.1616	0.0244
11	10	0.0202	-0.1207
12	11	-6.633E-04	0.1705
13	12	0.0836	-1.087E-06

b) STEP 2 – Determine the wall thickness to be used in the assessment, t_c, using Equation (8.10) or (8.11) as applicable.

$$t_c = t_{nom} - LOSS - FCA = 1.5 - 0.0 - 0.125 = 1.375\ in$$

c) STEP 3 – Determine the circumferential membrane stress using the thickness from STEP 2 (see Annex A).

$$\sigma_m^C = \frac{P}{E}\left(\frac{R}{t_c} + 0.6\right) = \frac{265}{1.0}\left(\frac{114 + 0.125}{1.375} + 0.6\right) = 22{,}154\ psi$$

d) STEP 4 – Determine the ratio of the induced circumferential bending stress to the circumferential membrane stress at the circumferential position (denoted by the angle θ) of interest using Equation (8.23).

$$R_b^{or}(\theta) = \left(\frac{6}{t_c}\right)\sum_{n=2}^{N}\left\{\frac{\left(A_n\cos(n\theta) + B_n\sin(n\theta)\right)}{1 + k_n}\right\}$$

where

$$k_n = \frac{PR^3}{\left(n^2 - 1\right)D_c}$$

and

$$D_c = \frac{E_y t_c^3}{12\left(1 - \nu^2\right)}.$$

Calculate D_c, and k_n as a function of n,

$$D_c = \frac{E_y t_c^3}{12\left(1-\nu^2\right)} = \frac{(27,520,000)(1.375)^3}{12\left(1-(0.3)^2\right)} = 6,624,189.8 \text{ in-lb}$$

$$k_n(n) = \frac{PR^3}{\left(n^2-1\right)D_c} = \frac{(265)(114.125)^3}{\left(n^2-1\right)(6,624,189.8)} = \frac{59.4642}{\left(n^2-1\right)}$$

Substitute the appropriate values of t_c, A_n, B_n and k_n into Equation (8.23) for each value of θ.

$$R_b^{or}(\theta) = \left(\frac{6}{1.375}\right)\sum_{n=2}^{24}\left\{\frac{\left(A_n\cos(n\theta)+B_n\sin(n\theta)\right)}{1+\dfrac{59.4642}{\left(n^2-1\right)}}\right\}$$

Determine the maximum value of $R_b^{or}(\theta)$.

The maximum value occurs at $\theta = 300$ degrees, where $R_b^{or}{}_{\max} = 1.6607$ and the minimum value occurs at $\theta = 120$ degrees where $R_b^{or}{}_{\min} = -1.3377$

e) STEP 5 – Determine the remaining strength factor RSF using Equation (8.21) and the value of

$$R_b = \max\left(abs\left(R_b^{or}{}_{\max}\right), abs\left(R_b^{or}\min\right)\right) = \max(1.6607, 1.3377) = 1.6607,$$

$$R_{bs} = -1.0,$$

$$H_f = 3, \text{ and}$$

$\sigma_{ms} = 0.0$ psi (supplemental loads are negligible)

$$RSF = \min\left[\left\{\frac{H_f S_a}{\sigma_m\left(1+R_b\right)+\sigma_{ms}\left(1+R_{bs}\right)}\right\},\ 1.0\right]$$

$$= \min\left[\left\{\frac{(3)(23,200)}{(22,154)(1+1.6607)+(0)(1.0-1.0)}\right\},\ 1.0\right]$$

$$= \min[1.1807,\ 1.0] = 1.0$$

f) STEP 6 – Evaluate the results,

$$\left(RSF = 1.0\right) \geq \left(RSF_a = 0.90\right) \qquad True$$

$$MAWP = \frac{SEt_c}{R+0.6t_c} = \frac{(23200)(1.0)(1.375)}{(114+0.125)+0.6(1.375)} = 277.5\ psi \geq 265\ psi \qquad True$$

The vessel satisfies the Level 2 criteria.

8.6 Example Problem 6

A pressure vessel has experienced general shell distortion in the ring stiffened cylindrical section. The vessel is subject to both internal pressure and external pressure. In addition, the stiffening rings provided for vacuum service have also been distorted. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1. Determine if the vessel is suitable for continued service.

Vessel Data

- Shell and Head Material = $SA-285-C\ FBX\quad Year\ 1965$
- Design Pressure (top) = $25\ \text{psig}$
- (bottom) = $50.7\ \text{psig}$
- (entire vessel) = $-5\ \text{psig (external)}$
- Design Temperature = $650\ ^{\circ}F$
- Inside Diameter of Cylinder = $180\ in$
- Cone Height = $163\ in$
- Cylinder Tangent-Tangent = $938\ in$
- Cone Small Inside Diameter = $17\ in$
- Shell Wall Thickness = $0.875\ in$
- Cone Wall Thickness = $0.625\ in$
- Hemispherical Head Thickness = $0.5625\ in$
- Future Corrosion Allowance = $0.125\ in$
- Allowable Stress = $13,750\ psi$
- Yield Stress = $32\ ksi$
- Tensile Stress = $55\ ksi$
- Joint Efficiency = 0.85

Inspection Data

The vessel was 360 degrees scanned by laser along its length from tangent line to tangent line. The inspection revealed that the largest radial deformation was 2.5 in inwards and 5.5 in outward. Figure E8.6-2 shows the mapped laser scan data on the north side (top plots) and south side (bottom plots) of the model. Figure E8.6-3 shows the shell distortion built into a finite element model.

Perform a Level 1 Assessment

Table 8.3 shows that for a cylindrical shell under internal pressure, the value of $D_{max} - D_{min}$ shall not exceed one percent of the design diameter. For the cylindrical shell this would be 1.8 in. Assuming that the cylinder opposite the maximum inward or outward deformation is a true cylinder, the diametrical deviation would equal the maximum radial deformation. The maximum radial deformation of 5.5 in exceeds the permitted one percent deviation.

Therefore, the Level 1 assessment criteria are not satisfied.

Perform a Level 2 Assessment

Based on the measured shell deformation, the shell distortion was classified as general shell distortion. Therefore it was decided to forgo a Level 2 assessment and conduct a Level 3 assessment.

Perform a Level 3 Assessment

A Level 3 FFS assessment was conducted in accordance with Annex B1. The assessment used a three-dimensional shell finite element model as shown in Figure E8.6-3. Four procedures were followed:

1) A Limit Load analysis in accordance with paragraph B1.2.3 using elastic-perfectly plastic material behavior and linear geometry
2) A check of local strain criteria in accordance with paragraph B1.3.3 using a model with elastic-plastic material properties that included strain hardening.
3) An elastic buckling analysis in accordance with paragraph B1.4 to determine the structural stability of the deformed shell
4) A check of the fatigue requirements in accordance with paragraph B1.5.2.4

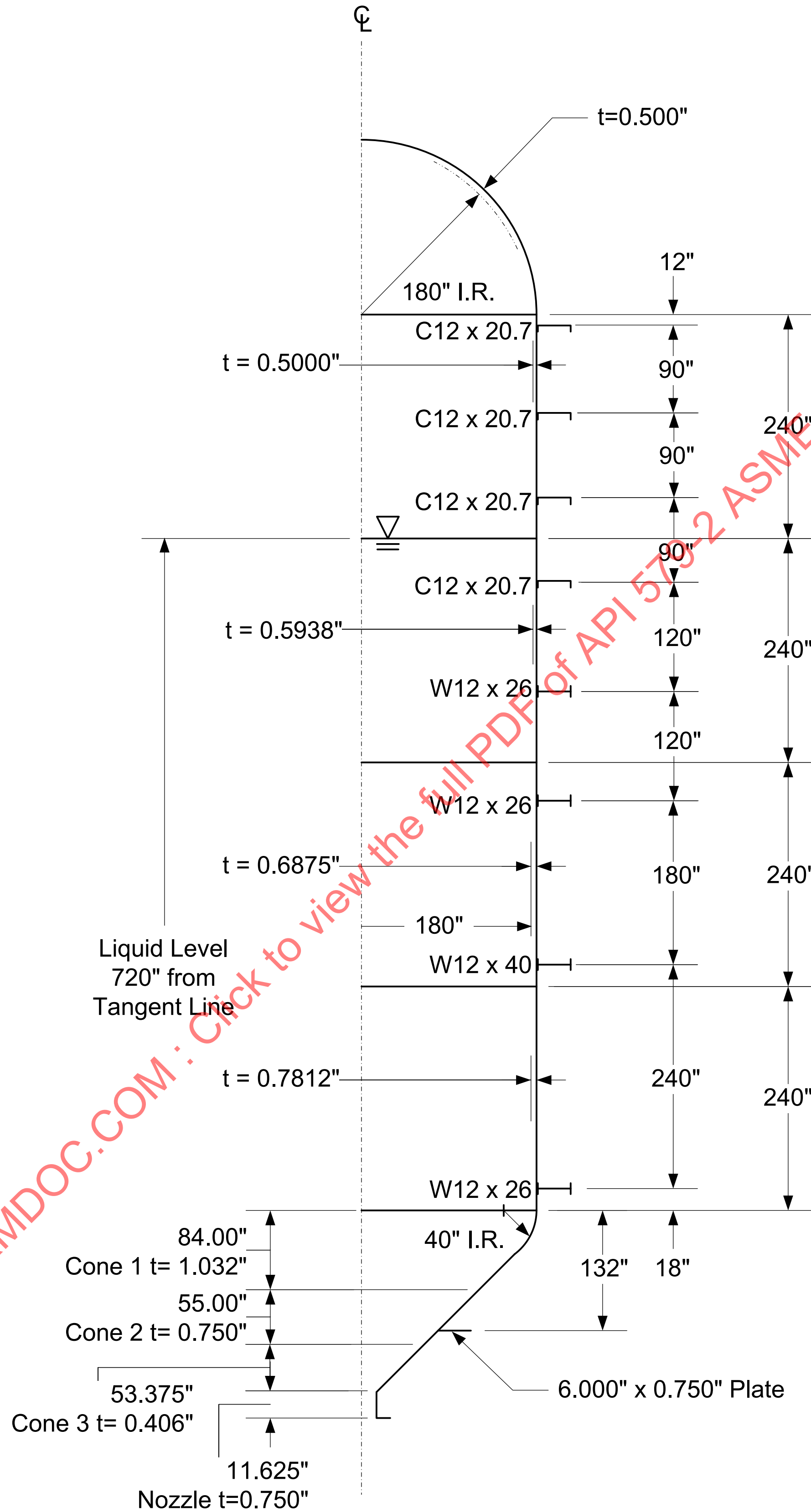


Figure E8.6-1 Vessel Drawing

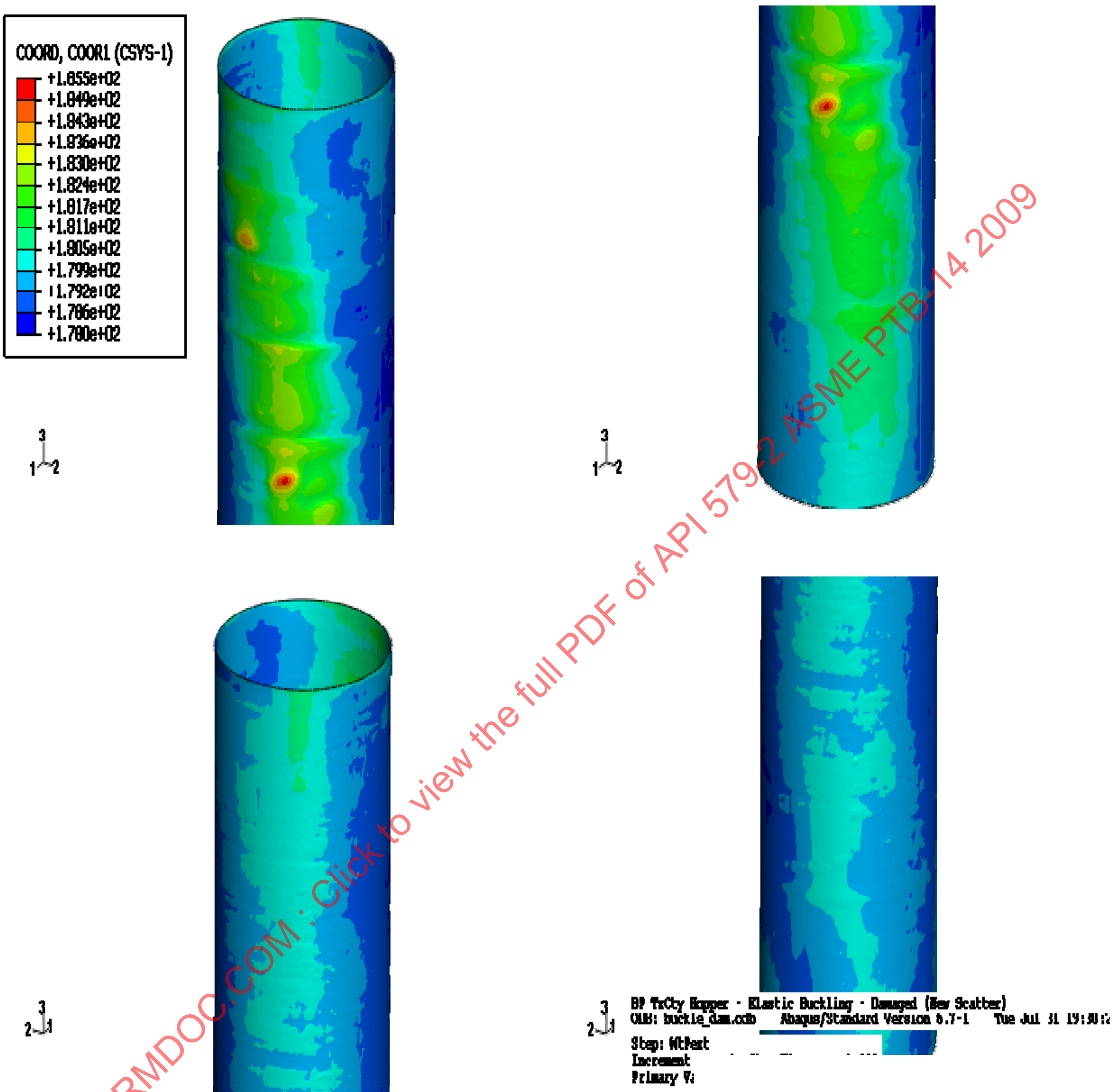


Figure E8.6-2 - Mapped Laser Scan Data

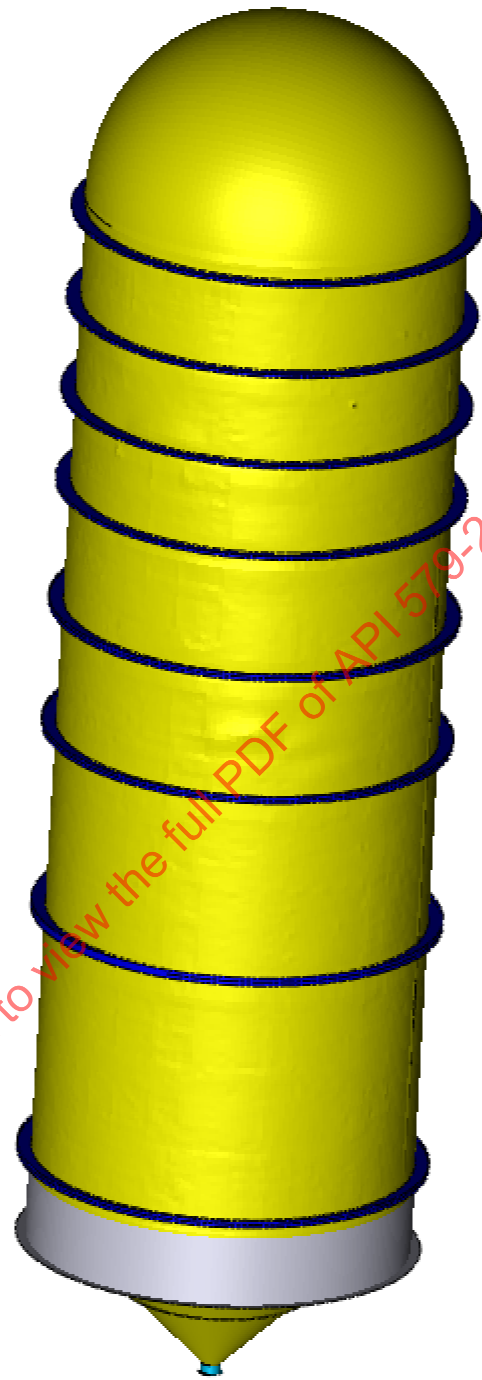


Figure E8.6-3 3 Dimensional Shell Finite Element Model

Limit Load Analysis

An elastic-perfectly plastic limit load stress analysis was performed on the model of the damaged cylinder. In the model and analysis it was assumed that the damaged stiffening rings would be replaced or repaired to adequately reinforce the shell. The loads applied to the model included the vessel weight, static head from the contents, and the internal pressure. These loads were increased in accordance with Table B1.3 by a factor of 1.35. This factor is 1.5 RSF_a where the allowable remaining strength factor RSF_a is taken equal to 0.9. In the model the applied loads were:

- Weight of 517,100 lb, based on a shipping weight of 383,000 lb.
- A 34.7 psig (1.35 x 25.7 psig) hydrostatic load applied beginning at an elevation of 924 inches from the bottom tangent line
- A 33.75 psig (1.35 x 25 psig) constant pressure, applied to the model in addition to the static head
- The Limit Load finite element analysis converged to a solution indicating that the deformed shell was adequate for the imposed loading.

Local Strain Criteria

An elastic-plastic analysis was performed using the loads stipulated for local strain criteria in Table B1.4. The local strain criteria require that the loads be factored by 1.7 times the allowable remaining strength factor, giving a factored load of 1.53. Thus the factored loads were:

- Weight of 586,000 lb, based on a shipping weight of 383,000 lb.
- A 39.4 psig (1.53 x 25.7 psig) hydrostatic load applied beginning at an elevation of 924 in from the bottom tangent line
- A 38.3 psig (1.53 x 25 psig) constant pressure, applied to the model in addition to the static head

The equivalent maximum plastic strain was determined and shown to be $\varepsilon_{peq} = 0.00732$. From Equation (B1.6) the permitted strain from fabrication and applied loading is given by,

$$\varepsilon_L = \varepsilon_{Lu} \cdot \exp\left(-\left(\frac{\alpha_{sl}}{1+m_2}\right)\left(\left[\frac{\sigma_1+\sigma_2+\sigma_3}{3\sigma_e}\right]-\frac{1}{3}\right)\right)$$

From Table B1.6,

$$\varepsilon_{Lu} = m_2 = 0.6\left(1-\frac{\sigma_{ys}}{\sigma_{uts}}\right) = 0.6\left(1-\frac{32}{55}\right) = 0.349$$

$$\alpha_{sl} = 2.2$$

From the elastic-plastic analysis, the values of the principal stresses and equivalent stress at the point of evaluation were:

$$\sigma_1 = 32.34\ ksi$$

$$\sigma_2 = 26.73\ ksi$$

$$\sigma_3 = 16.18\ ksi$$

$$\sigma_e = 14.21\ ksi$$

Substituting into the equation for ε_{Lu} resulted in

$$\varepsilon_L = 0.349 \cdot \exp\left(-\left(\frac{2.2}{1+0.349}\right)\left(\left[\frac{32.34+26.73+16.18}{3(14.21)}\right]-\frac{1}{3}\right)\right) = 0.0338$$

The cold forming strain was calculated from the radius of curvature, ρ, and the thickness, t, as

$$\varepsilon_{cf} = \frac{t}{2 \cdot \rho} = \frac{0.875}{2 \cdot 90} = 0.00486$$

Check the criteria of Equation (B1.7).

$$\varepsilon_{peq} + \varepsilon_{cf} \quad \leq \quad \varepsilon_L$$

$$(0.00732 + 0.00486) = 0.01218 \quad \leq \quad 0.0338 \qquad True$$

The local strain criterion of Equation (B1.7) is met.

Buckling Analysis

Since the pressure vessel is subject to external pressure, it was necessary to determine the deformed shells stability. For this purpose a linear elastic buckling analysis in accordance with Paragraph B1.4 was conducted to determine the critical eigenvalue buckling modes and associated buckling pressures for the vessel.

The buckling analysis was accomplished in two steps. The first step consisted of a preload that included the vessel weight of 383,000 lb, applied as a body load, along with an initial external pressure of -1 psig. This first step produced displacements in the vessel that formed the basis for linear perturbation eigenvalue buckling analysis. In the second step a perturbation external pressure of -1 psig was applied and a linear eigenvalue buckling analysis that sought the first three buckling modes and eigenvalues was conducted. In the linear perturbation analysis the finite element program scales the perturbation load by multipliers that produce a solution to the eigenvalue problem (i.e., the eigenvalues). The critical buckling loads were then obtained by adding the preload pressure of -1 psig to the perturbation load scaled by the eigenvalue.

The first buckling mode was identified as the critical mode and its eigenvalue plus the initial -1 psig as the critical buckling pressure. The first three buckling modes are shown in Figure E8.6-4.

The critical buckling pressure for the deformed shell geometry was calculated as -16.9 psig. For bifurcation buckling performed using an elastic stress analysis without geometric non-linearities, a capacity reduction factor

$$\Phi_B = 2 / \beta_{cr}$$

shall be used to determine the permissible external load. The permissible external pressure is the critical buckling pressure divided by the capacity reduction factor. For unstiffened and ring stiffened cylinders,

$$\beta_{cr} = 0.80 .$$

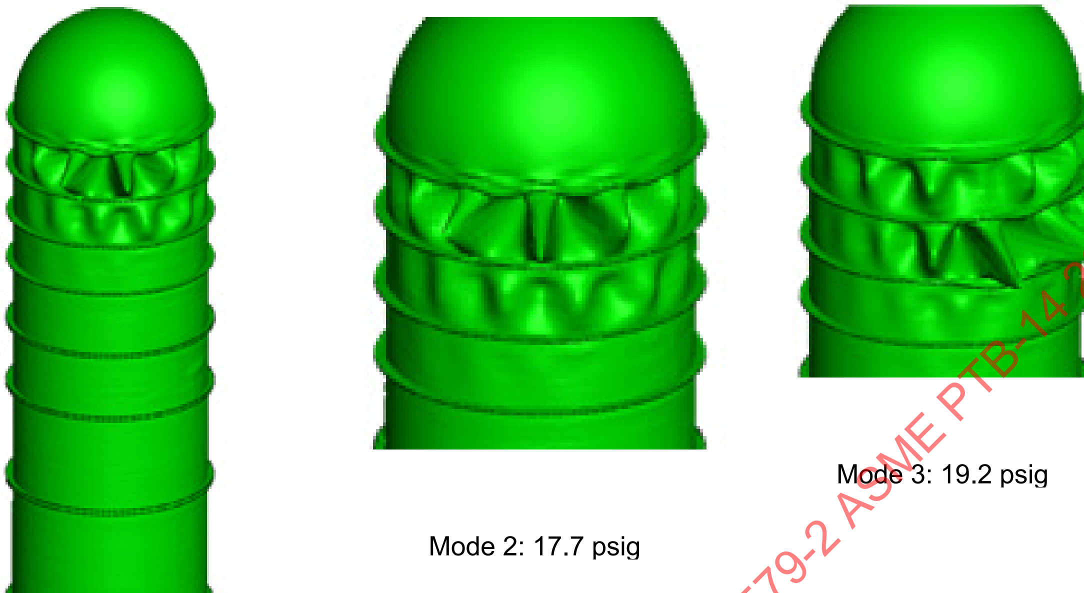
Therefore,

$$\Phi_B = 2 / 0.80 = 2.5 .$$

Using this factor, the permissible external pressure is

$$P_{ext} = 16.9 / 2.5 = 6.75 > 5 \ \ psig \ external \ design \ pressure$$

Since the permissible external pressure P_{ext} exceeds the design external pressure of 5 psig, the deformed cylindrical shell is adequate for continued service.



Mode 1: 16.9 psig

Mode 2: 17.7 psig

Mode 3: 19.2 psig

Figure E8.6-4 - Lowest Three Buckling Modes

Fatigue Assessment

To determine whether fatigue was a concern a fatigue screening in accordance with B1.5.2.4, Fatigue Analysis Screening – Method B was performed. Only pressure loads were considered. The smooth bar fatigue curves in Annex F were used for this purpose. Thermal stresses were considered to be neglible.

a) STEP 1 – Determine the number of full range pressure cycles for the vessel

The pressure vessel is filled with catalyst once a week and emptied once every three weeks. During filling operations, the vessel experiences its -5 psig external pressure and while it is emptied, the pressure at the top of the vessel is 25 psig. Thus the pressure vessel experiences 52 vacuum pressure cycles and 17 internal pressure cycles per year for a total of 69 pressure cycles per year.

b) STEP 2 – Determine the fatigue screening factors, C_1 and C_2 based on the type of construction in accordance with Table B1.9.

Table B1.9 shows that for components with a flaw as characterized by Part 8, the values of C_1 and C_2 are given by:

$$C_1 = \frac{3}{RSF_a} = \frac{3}{0.90} = 3.33$$

$$C_2 = \frac{2}{RSF_a} = \frac{2}{0.90} = 2.22$$

c) STEP 3 – Based on the number of cycles determined in STEP 1, and the allowable stress of the material S_m compare the number of full range cycles to the number of permitted cycles:

$$N_{\Delta FP} \quad \leq \quad N\left(C_1 S_m\right) = N\left(\left(3.33\right)\left(13,750\right)\right) = N\left(45,833\right)$$

$N(45,833)$ may be determined from Equation (F.214) and (F.215) or from logarithmic interpolation using the data from Table (F.22) adjusted for the modulus of elasticity at the assessment temperature of 650° F to the fatigue curve modulus at 700° F.

For carbon steel the coefficients of Equation (F.215) for an alternating stress between 31 ksi and 580 ksi are:

$$C_1 = 7.999502 \qquad C_2 = 5.832491 \cdot (10)^{-2} \qquad C_3 = 1.500851 \cdot (10)^{-1}$$

$$C_4 = 1.273659 \cdot (10)^{-4} \qquad C_5 = -5.263661 \cdot (10)^{-5}$$

Substituting into Equation (F.215) and Equation (2.14) respectively

$$X = \frac{(7.999502) + \left(1.500851 \cdot (10)^{-1}\right)(45.833) + \left(-5.263661 \cdot (10)^{-5}\right)(45.833)^2}{1 + \left(5.832491 \cdot (10)^{-2}\right)(45.833) + \left(1.273659 \cdot (10)^{-4}\right)(45.833)^2} = 3.747446$$

$$N = 10^{3.747446} \frac{26.07 \cdot (10)^6}{25.53 \cdot (10)^6} = 5,708 \ cycles$$

Dividing N by $N_{\Delta FP}$ we can determine the number of years that the vessel may be used,

$$\frac{N}{N_{\Delta FP}} = \frac{5,708}{69} = 82.7 \ years$$

Based on this and the other assessment criteria, the vessel satisfies the Level 3 criteria and may be put back in service.

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PART 9

ASSESSMENT OF CRACK-LIKE FLAWS

EXAMPLE PROBLEMS

9.1 Example Problem 1

A crack-like flaw has been found on a cylindrical shell of a pressure vessel during a scheduled turnaround. The vessel and inspection data are provided below. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1, 2001 Edition. Determine if the vessel is acceptable for continued operation using a Level 1 Assessment.

<u>Vessel Data</u>

- Material = $SA\text{-}516\ Grade\ 70\ Year\ 2001$
- Design Conditions = $300\ psig\ @\ 650°F$
- Inside Diameter = $96\ in$
- Fabricated Thickness = $1.25\ in$
- Uniform Metal Loss = $0.10\ in$
- FCA = $0.125\ in$
- Weld Joint Efficiency = 1.0
- PWHT = Yes, Original Fabrication Requirement

<u>Operating Conditions</u>

The vessel is not fully pressurized until the temperature is 100°F. Below this temperature, the startup pressure remains under 140 psig. At shutdown, the pressure is decreased to 140 psig before letting the temperature drop below 100°F.

<u>Inspection Data</u>

The flaw is located in a longitudinal weld seam on the inside surface of a cylindrical vessel. The flaw is parallel to the weld joint. The longitudinal seam is a double V-groove weld. The depth of the flaw was established by UT; however, many different values were obtained during the inspection with a maximum value of 0.25 in being reported. The flaw length was established by MT and is 1.1 in. The distance of the crack-like flaw to the nearest structural discontinuity is 60 in.

Perform a Level 1 Assessment per paragraph 9.4.2.2

First, check that the conditions to perform a Level 1 Assessment are satisfied

<u>Geometry:</u>

Component is a flat plate, cylinder or sphere: (cylinder) *True*

Cylinder with $R/t \geq 5$ (t being the current thickness)

$$\left\{\begin{array}{l} t = t_{nom} - LOSS = 1.25 - 0.10 = 1.15\ in \\ R = D/2 = 96/2 = 48\ in \end{array}\right\} \Rightarrow R/t = 48/1.15 = 41.7391 \qquad \textit{True}$$

Wall thickness at the location of the flaw is less than 1.5 in: $(1.15\ in < 1.50\ in)$ *True*

Flaw of surface or through-thickness type with a maximum crack-length of 8 in:

Surface crack with length equal to 1.1 in *True*

Cylindrical shell: flaw oriented in the axial or circumferential direction: (longitudinal = axial) *True*

With a distance to the nearest structural discontinuity greater than or equal to $1.8\sqrt{Dt}$

$$\left\{\begin{array}{l} L_{msd} = 60\ in \\ 1.8\sqrt{Dt} = 1.8\sqrt{(96)(1.15)} = 18.9129\ in \end{array}\right\} \Rightarrow L_{msd} \geq 1.8\sqrt{Dt} \qquad \textit{True}$$

<u>Loads:</u>

Pressure producing only a membrane stress field *True*

Membrane stress within the design limits of original construction code *True*

Welded joint is single or double V: (double V-groove weld) *True*

<u>Material:</u>

Carbon Steel (P1, Group 1 or 2) with $S \leq 25\ ksi$, $\sigma_{ys} \leq 40\ ksi$ and $\sigma_{uts} \leq 70\ ksi$

(From ASME Section II, Part D, SA-516 Grade 70 is a carbon steel, P1, Group 2,

With $S = 20\ ksi$, $\sigma_{ys} = 38\ ksi$ and $\sigma_{uts} = 70\ ksi$) *True*

Fracture toughness greater than or equal to the lower-bound K_{IC} in Annex F

Carbon steel not degraded because of environmental damage *True*

a) STEP 1 – Determine the temperature to be used in the assessment based on operating and design conditions – The primary membrane tensile stress σ_m^C due to startup or shutdown pressure (140 psig), calculated per formula in paragraph A.3.4 of Annex A is less than 8 ksi. Per Part 3 paragraph 3.1.2, a brittle fracture assessment is not needed for these pressures. The temperature used in the assessment will be the minimum temperature for which the pressure is above 140 psig. Therefore

$$T = 100\,^{o}F$$

b) STEP 2 – Determine the length and depth of the crack-like flaw from inspection data.

$$a = 0.25\ in$$

$$2c = 1.10\ in$$

c) STEP 3 – Determine the figure to be used in the assessment – The flaw is located in a longitudinal weld seam in a cylindrical vessel and is parallel to the weld joint; therefore Figure 9.13 will be used.

d) STEP 4 – Determine the screening curve.

- The maximum flaw depth reported from UT measurements is $0.25\ in$.
- The current component thickness is $t = 1.25 - 0.10 = 1.15\ in$ which is greater than $1\ in$; therefore, the maximum permissible flaw depth for an assessment with ¼-t screening curve is $0.25\ in$. Based on NDE results, this is the maximum flaw depth reported.
- The flaw is in a weldment and the vessel was subject to PWHT at the time of construction.

Based on the above, the ¼-t (solid line) Curve B of Figure 9.13 will be used.

e) STEP 5 – Determine the Reference Temperature – T_{ref} is established using Table 9.2. Inputs for this table are the exemption curve as per Table 3.2 in Part 3 and the minimum specified yield strength at ambient temperature based on the original construction code. SA-516 Grade 70 is a Curve B Carbon Steel with $\sigma_{ys} = 38\ ksi$, therefore:

$$\left\{ \begin{array}{l} Curve\ B\ Carbon\ \ Steel \\ \sigma_{ys} = 38\ ksi \end{array} \right\} \Rightarrow T_{ref} = 43°F$$

f) STEP 6 – Determine the maximum permissible crack-flaw length using Figure 9.13 (see STEP 3).

$$\left\{ \begin{array}{l} \left(T - T_{ref} + 100\right) = (100 - 43 + 100) = 157°F \\ \tfrac{1}{4}\text{-}t\ - Curve\ B\ of\ \ Figure\ 9.13 \end{array} \right\} \Rightarrow 2c = 8.00\ in$$

g) STEP 7 – Evaluate Results.

Since $\left(2c\big|_{Screening\ Curve} = 8.00\ in\right) > \left(2c\big|_{Measured} = 1.10\ in\right)$, the flaw is acceptable.

The Level 1 Assessment Criteria are Satisfied. The vessel is acceptable for continued operation.

9.2 Example Problem 2

A crack-like flaw was found on a spherical pressure vessel that was constructed to the ASME B&PV Code, Section VIII, Division 1, 1998 Edition. The vessel and inspection data are provided below. Determine if the vessel is acceptable for continued operation using a Level 1 Assessment.

<u>Vessel Data</u>

- Material = $SA\text{-}516\ Grade\ 70\ Year\ 1998$
- Design Conditions = $2.0\ MPa\ (20\ bar)\ @\ 350°C$
- Operating Conditions = $1.5\ MPa\ (15\ bar)\ @\ 300°C$
- Inside Diameter = $2.4\ m$
- Fabricated Thickness = $30\ mm$
- Uniform Metal Loss = $2.5\ mm$
- FCA = $3\ mm$
- Weld Joint Efficiency = 1.0
- PWHT = Yes, Original Fabrication Requirement

<u>Operating Conditions</u>

At startup the vessel is warmed up to 30°C prior to pressurizing. At shutdown, the vessel is depressurized before letting the temperature drop below 30°C.

<u>Inspection Data</u>

The flaw is located in a circumferential weld seam on the inside surface of a spherical vessel. The flaw is perpendicular to the weld joint. The seam is a single V-groove weld. The maximum measured depth of the flaw using UT is 10 mm. A flaw length of 30 mm is established by MT. The distance of the crack-like flaw to the nearest structural discontinuity is 1500 mm.

Perform a Level 1 Assessment per paragraph 9.4.2.2

First, check that the conditions to perform a Level 1 Assessment are satisfied

<u>Geometry:</u>

Component is a flat plate, cylinder or sphere: (sphere) *True*

Sphere with $R/t \geq 5$ (t is the current thickness)

$$\left\{\begin{array}{l} t = t_{nom} - LOSS = 30.00 - 2.50 = 27.50\ mm \\ R = D/2 = 2400/2 = 1200\ mm \end{array}\right\} \Rightarrow R/t = 1200/27.50 = 43.6364$$ *True*

Wall thickness at the location of the flaw is less than 38 mm: $(27.50\ mm < 38.00\ mm)$ *True*

Flaw of surface or through-thickness type with a maximum crack-length of *200 mm:*

Surface crack with length equal to *30 mm* *True*

Spherical shell: flaw oriented in the axial or circumferential direction:

Perpendicular to circumferential weld = axial direction *True*

With a distance to the nearest structural discontinuity greater than or equal to $1.8\sqrt{Dt}$

$$\left\{\begin{array}{l} L_{msd} = 1500\ mm \\ 1.8\sqrt{Dt} = 1.8\sqrt{(2400)(27.50)} = 462.4284\ mm \end{array}\right\} \Rightarrow L_{msd} \geq 1.8\sqrt{Dt} \qquad \textit{True}$$

Loads:

Pressure produces only a membrane stress field *True*

Membrane stress from operation is within the design limits of original construction code *True*

Welded joint is single or double V: (single V-groove weld) *True*

Material:

Carbon Steel (P1, Group 1 or 2) with $S \leq 172\ MPa$, $\sigma_{ys} \leq 276\ MPa$ and $\sigma_{uts} \leq 483\ MPa$

(From ASME Section II, Part D, SA-516 Grade 70 is a carbon steel, P1, Group 2,

With $S = 138\ MPa$, $\sigma_{ys} = 260\ MPa$ and $\sigma_{uts} = 485\ MPa$

Fracture toughness greater than or equal to the lower-bound K_{IC} in Annex F

Carbon steel not degraded because of environmental damage *True*

a) STEP 1 – Determine the temperature to be used in the assessment based on operating and design conditions – Based on the operating conditions:

$$T = 30°C$$

b) STEP 2 – Determine the length and depth of the crack-like flaw from inspection data.

$$a = 10.0\ mm$$

$$2c = 30.0\ mm$$

c) STEP 3 – Determine the figure to be used in the assessment – The flaw is located at a circumferential weld seam of a spherical vessel and is perpendicular to the joint; therefore Figure 9.18M will be used.

d) STEP 4 – Determine the screening curve.

- The maximum flaw depth reported from UT measurements is 10.0 mm.
- The current component thickness is 27.5 mm which is greater than 25.0 mm; therefore, the maximum permissible flaw depth for an assessment with ¼-t screening curve is 6.0 mm. Since the maximum flaw depth is 10.0 mm, then the 1-t screening curves are to be used.
- The flaw is in a weldment and the vessel was subject to PWHT at the time of construction.

Based on the above, the 1-t (dashed line) Curve B of Figure 9.18M will be used.

e) STEP 5 – Determine the Reference Temperature – T_{ref} is established using Table 9.2M. Inputs for this table are the exemption curve as per Table 3.2 in Part 3 and the minimum specified yield strength at ambient temperature based on the original construction code. SA-516 Grade 70 is a Curve B Carbon Steel with $\sigma_{ys} = 260\ MPa$, therefore:

$$\left\{\begin{array}{l} Curve\ B\ Carbon\ \ Steel \\ \sigma_{ys} = 260\ MPa \end{array}\right\} \Rightarrow T_{ref} = 6°C$$

f) STEP 6 – Determine the maximum permissible crack-flaw length using Figure 9.18M (see STEP 3).

$$\left\{\begin{matrix} \left(T - T_{ref} + 56\right) = (30 - 6 + 56) = 80°C \\ 1\text{–}t \ \ -Curve\ B\ of\ \ Figure\ 9.18M \end{matrix}\right\} \Rightarrow 2c = 37.5\ mm$$

g) STEP 7 – Evaluate Results.

Since the maximum permissible flaw length from the screening curve of 37.5 mm is greater than the measured flaw length of 30.0 mm, the flaw is acceptable.

The Level 1 Assessment Criteria are Satisfied. The vessel is acceptable for continued operation.

9.3 Example Problem 3

A crack-like flaw has been found on a cylindrical shell of a pressure vessel during a schedule turnaround. The vessel and inspection data are provided below. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1, 2001 Edition. In order to determine if the vessel is acceptable for continued operation using a Level 1 or Level 2 Assessment, the flaw length used in the assessment must be computed.

Vessel Data

- Material = $SA\text{-}516\ Grade\ 70\ Year\ 2001$
- Design Conditions = $300\ psig\ @\ 650°F$
- Inside Diameter = $96\ in$
- Fabricated Thickness = $1.25\ in$
- Uniform Metal Loss = $0.10\ in$
- FCA = $0.125\ in$
- Weld Joint Efficiency = 1.0
- PWHT = Yes, Original Fabrication Requirement

Operating Conditions

The vessel is not fully pressurized until the temperature is 100°F. Below this temperature, the startup pressure remains under 140 psig. At shutdown, the pressure is decreased to 140 psig before letting the temperature drop below 100°F.

Inspection Data

The flaw is located primarily in a longitudinal weld seam on the inside surface of a cylindrical vessel. The flaw is perpendicular to the inside surface and oriented at 30° with respect to the horizontal seam weld joint. The longitudinal seam is a double V-groove weld. The depth of the flaw was established by UT with a maximum value of 0.25 in being reported. The flaw length was established by MT and is 1.18 in. The distance of the crack-like flaw to the nearest structural discontinuity is about 60 in.

Before performing a Level 1 or Level 2 Assessment per paragraph 9.4.2.2, the equivalent flaw length onto the principal plane needs to be computed first.

Compute the equivalent flaw length parallel to the seam weld.

a) The 2 principal stresses are the hoop stress due to pressure (σ_1) and the axial stress due to the end effect (σ_2). Both of them are positive and $\sigma_1 > \sigma_2$. This leads to a biaxiality ratio B

$$B = \frac{\sigma_2}{\sigma_1} = 0.50$$

b) From Equation (9.1), for the plane of the flaw projected onto the plane normal to the hoop stress, σ_1:

$$\frac{c}{c_m} = \cos^2[\alpha] + \frac{(1-B)\sin[\alpha]\cos[\alpha]}{2} + B^2\sin^2[\alpha]$$

In the above equation, the dimension c corresponds to the half flaw length to be used in calculations and c_m is the measured half length for the flaw oriented at an angle α from the σ_1 plane

Thus in this case,

$$c_m = 1.18/2 = 0.59\ in$$

$$\alpha = 30°$$

$$\frac{c}{c_m} = \cos^2\left[30\right] + \frac{\left(1-0.5\right)\sin\left[30\right]\cos\left[30\right]}{2} + (0.5)^2 \sin^2\left[30\right] = 0.9208$$

For $2\,c_m = 1.18\,in$, $2c = 1.0865\,in$

The equivalent flaw length, parallel to the seam weld, to be taken into account in a Level 1 or a Level 2 Assessment is rounded to 1.10 in.

9.4 Example Problem 4

A crack-like flaw has been found in the longitudinal seam on the inside surface of a cylindrical pressure vessel during a scheduled turnaround. The vessel and inspection data are provided below. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1, 2001 Edition. In order to determine if the vessel is acceptable for continued operation using a Level 1 or Level 2 Assessment, the flaw depth used in the assessment must be computed.

Vessel Data

- Material = $SA\text{-}516\ Grade\ 70\ Year\ 2001$
- Design Conditions = $200\ psig\ @\ 750°F$
- Inside Diameter = $120.0\ in$
- Fabricated Thickness = $1.0\ in$
- Uniform Metal Loss = 0.0
- FCA = $0.0\ in$
- Weld Joint Efficiency = 1.0
- PWHT = No

Inspection Data

The flaw is located in a longitudinal weld seam on the inside surface of the vessel. The longitudinal seam is a double V-groove weld with bevel angle of 25 degrees. The depth of the flaw was established by UT; consistent readings were noted and a final value for the flaw depth was established at 0.17 in. The flaw length was established by MT and is 3.2 in. The distance of the crack-like flaw to the nearest structural discontinuity is 30 in.

Before performing a Level 1 or Level 2 Assessment per paragraph 9.4.2.2, since the flaw is not normal to the surface (due to a lack of fusion, the flaw is oriented parallel to the bevel angle as shown in Figure 9.4, the flaw depth dimension, a, must be computed first.

Compute the flaw depth to be used in the assessment.

a) STEP 1 – Project the flaw onto a plane that is normal to the plate surface, designate this flaw depth as a_m.

$$a_m = 0.17\ in$$

b) STEP 2 – Determine W using the Equations (9.6) and (9.7) in which the angle, θ, expressed in degrees and defined in Figure 9.4, is the bevel angle of the weld (25° in this case)

$$W = \max[W_{Theta},\ 1.0]$$

$$W_{Theta} = \begin{pmatrix} 0.99999 + 1.0481\left(10^{-5}\right)\theta + 1.5471\left(10^{-4}\right)\theta^2 + \\ 3.4141\left(10^{-5}\right)\theta^3 - 2.0688\left(10^{-6}\right)\theta^4 + 4.4977\left(10^{-8}\right)\theta^5 - \\ 4.5751\left(10^{-10}\right)\theta^6 + 1.8220\left(10^{-12}\right)\theta^7 \end{pmatrix}$$

$$= \begin{pmatrix} 0.99999 + 1.0481\left(10^{-5}\right)25 + 1.5471\left(10^{-4}\right)25^2 + \\ 3.4141\left(10^{-5}\right)25^3 - 2.0688\left(10^{-6}\right)25^4 + 4.4977\left(10^{-8}\right)25^5 - \\ 4.5751\left(10^{-10}\right)25^6 + 1.8220\left(10^{-12}\right)25^7 \end{pmatrix} = 1.1609$$

c) STEP 3 – Multiply a_m by W to obtain the dimension a, which is used in flaw calculations.

$$a = a_m W = (0.17)(1.1609) = 0.1974 \, in$$

The flaw depth to be taken into account in a Level 1 or a Level 2 Assessment is rounded to 0.20 in.

9.5 Example Problem 5

A crack-like flaw has been found in the longitudinal seam on the inside surface of a cylindrical pressure vessel during a scheduled turnaround. The vessel and inspection data are provided below. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1, 1998 Edition. Determine if the vessel is acceptable for continued operation.

Vessel Data

- Material = $SA\text{-}516\ Grade\ 70\ Year\ 1998$
- Design Conditions = $200\ psig\ @\ 750°F$
- Inside Diameter = $120.0\ in$
- Fabricated Thickness = $1.0\ in$
- Uniform Metal Loss = $0.0\ in$
- FCA = $0.0\ in$
- Weld Joint Efficiency = 1.0
- PWHT = No

Operating Conditions

The vessel is not fully pressurized until the temperature is 40°F. Below this temperature, the startup pressure remains under 100 psig. At shutdown, the pressure is decreased to 100 psig before letting the temperature drop below 40°F.

Inspection Data

The flaw is located in the HAZ of a longitudinal weld seam on the inside surface of the vessel. The longitudinal seam is a double V-groove weld. The flaw is parallel to the weld seam. The depth of the flaw was established by UT; consistent readings were noted and a final value for the flaw depth was established at 0.20 in. The flaw length was established by MT and is 3.2 in. The distance of the crack-like flaw to the nearest structural discontinuity is 30 in.

Perform a Level 1 Assessment per paragraph 9.4.2.2

First, check that the conditions to perform a Level 1 Assessment are satisfied: See Example 9.1

a) STEP 1 – Determine the temperature to be used in the assessment based on operating and design conditions –The primary membrane tensile stress σ_m^C due to startup or shutdown pressure ($100\ psig$), calculated per formula in paragraph A.3.4 of Annex A is less than 8 ksi. Per Part 3 paragraph 3.1.2, a brittle fracture assessment is not needed for these pressures. The temperature used in the assessment will be the minimum temperature for which the pressure is above 100 psig. Therefore

$$T = 40°F$$

b) STEP 2 – Determine the length and depth of the crack-like flaw from inspection data.

$$a = 0.20\ in$$

$$2c = 3.20\ in$$

c) STEP 3 – Determine the figure to be used in the assessment – The flaw is located in a longitudinal weld seam in a cylindrical vessel and is parallel to the weld joint; therefore Figure 9.13 will be used.

d) STEP 4 – Determine the screening curve.

- The maximum flaw depth reported from UT measurements is $0.20\ in$.
- The current component thickness is $1\ in$; therefore, the maximum permissible flaw depth for an assessment with ¼-t screening curve is $(1.00)/4 = 0.25\ in$. Based on NDE results, the maximum flaw depth reported is $0.20\ in$
- The flaw is in a weldment and the vessel was not subject to PWHT at the time of construction.

Based on the above, the ¼-t (solid line) Curve C of Figure 9.13 will be used.

e) STEP 5 – Determine the Reference Temperature – T_{ref} is established using Table 9.2. Inputs for this table are the exemption curve as per Table 3.2 in Part 3 and the minimum specified yield strength at ambient temperature based on the original construction code. SA-516 Grade 70 is a Curve B Carbon Steel with $\sigma_{ys} = 38\ ksi$, therefore:

$$\begin{Bmatrix} Curve\ B\ Carbon\ \ Steel \\ \sigma_{ys} = 38\ ksi \end{Bmatrix} \Rightarrow T_{ref} = 43°F$$

f) STEP 6 – Determine the maximum permissible crack-flaw length using Figure 9.13 (see STEP 3).

$$\begin{Bmatrix} \left(T - T_{ref} + 100\right) = (40 - 43 + 100) = 97°F \\ \text{¼-}t - Curve\ C\ of\ \ Figure\ 9.13 \end{Bmatrix} \Rightarrow 2c \approx 0.2\ in$$

g) STEP 7 – Evaluate Results.

Since, $(2c\,|_{Screening\,Curve} = 0.2\ in) < (2c\,|_{Measured} = 3.20\ in)$ the flaw is not acceptable.

The Level 1 Assessment Criteria are Not Satisfied

Perform a Level 2 Assessment per paragraph 9.4.3.2

a) STEP 1 – Evaluate operating conditions and determine the pressure, temperature and supplemental loading combinations to be evaluated – There are no significant supplemental loads, pressure is the only significant load.

$$T = 40°F$$

$$P = 200\, psig$$

b) STEP 2 – Determine the stress distribution at the location of the flaw - The primary stress distribution is based on the applied loads.

1) Primary Stress

The flaw is located away from all major structural discontinuities. Therefore, the primary stress at the weld joint perpendicular to the crack face is a membrane hoop stress. From Annex C, Table C.1, the flaw geometry, component geometry, and loading condition correspond to KCSCLE1 and RCSCLE1, Cylinder - Surface Crack, Longitudinal Direction - Semi-Elliptical Shape, Internal Pressure. The stress intensity factor solution for KCSCLE1 is provided in Annex C, paragraph C.5.10. The reference stress solution for RCSCLE1 is provided in Annex D, paragraph D.5.10.

$$R_i = D/2 = 120.00/2 = 60.00\, in$$

$$R_o = R_i + t = 60.00 + 1.00 = 61.00\, in$$

$$t/R_i = 1.00/60.00 = 0.0167$$

The membrane and bending components of the primary stress for the calculation of the reference stress are given by Equations (D.47) and (D.48):

$$P_m = P\,R_i/t = (200)\,(60.00)/(1.00) = 12000.0000\; psi$$

$$P_b = \frac{P\,R_o^2}{R_o^2 - R_i^2}\left[\left(\frac{t}{R_i}\right) - 1.5\left(\frac{t}{R_i}\right)^2 + 1.8\left(\frac{t}{R_i}\right)^3\right]$$

$$= \frac{(200)\,(61.00)^2}{(61.00)^2 - (60.00)^2}\left[(0.0167) - 1.5(0.0167)^2 + 1.8(0.0167)^3\right] = 99.9955\; psi$$

The bending component is less than 1% of the membrane component and, therefore, will be neglected. The calculations will be performed with:

$$P_m = \sigma_m^C = 12000\; psi$$

$$P_b = 0\; psi$$

2) Secondary Stress

Thermal gradients do not exist in the vessel at the location of the flaw, and the flaw is located away from all major structural discontinuities. Therefore, there are no secondary stresses.

3) Residual Stress

The flaw is located at a weldment in a vessel that was not subject to PWHT at the time of fabrication. From Annex E, paragraph E.3.2.

$$\sigma_{ys}^r = \sigma_{ys} + 10 = 38 + 10 = 48\; ksi$$

The flaw is located at the limit between the weld seam and the base metal. The residual stress field used in the assessment can be based on the surface distribution or the through-thickness distribution. The more conservative stress distribution is chosen (see Example 9.6 or 9.7 for an assessment using a less conservative residual stress field based on the through-thickness distribution) .The residual stress is calculated from Annex E, paragraph E.4.4.1.a with $y = w/2$

It has been verified that the crack-like flaw was in the vessel during a field hydrotest previously performed as part of a rerate. Therefore the residual stress may be reduced. The circumferential membrane stress during hydrotest is calculated:

$$S_{750F} = 14800\ psi @ 750°F$$

$$S_{RT} = 20000\ psi @ Ambient$$

$$\sigma_{mc,t} = 1.3\,\sigma_m^C\left(\frac{S_{RT}}{S_{750F}}\right) = (1.3)(12000)\left(\frac{20.0}{14.8}\right) = 21081.0811\ psi$$

The percentage of yield strength reached during hydrotest is:

$$T_p = \left(\frac{\sigma_{mc,t}}{\sigma_{ys}^r}\right)(100) = \left(\frac{21.0811}{48.0000}\right)(100) = 43.9189\ \%$$

Since $T_p < 75\ \%$, then the reduction factor on the residual stress is $R_r = 1.0$. Therefore:

$$Q_m = \sigma_{ys}^r . R_r = (48000)(1.0) = 48000\ psi$$

$$Q_b = 0\ psi$$

c) STEP 3 – Determine the material properties; yield strength, tensile strength and fracture toughness. Material properties for the plate containing the flaw are not available; therefore, the specified minimum specified yield and tensile strength are used. Based on the material specification and grade, the material fracture toughness is established using the lower-bound curve in Annex F, paragraph F.4.4.1.

$$\sigma_{ys} = 38\ ksi$$

$$\sigma_{uts} = 70\ ksi$$

$$T_{ref} = 43°F \quad (see\ STEP\ 5\ of\ the\ Level\ 1\ Assessment)$$

$$K_{IC} = 33.2 + 2.806\exp\left[0.02\left(T - T_{ref} + 100\right)\right]$$

$$= 33.2 + 2.806\exp\left[0.02\left(40 - 43 + 100\right)\right] = 52.7263\ ksi\sqrt{in}$$

d) STEP 4 – Determine the crack-like flaw dimensions from inspection data.

$$a = 0.20\ in$$

$$2c = 3.20\ in$$

e) STEP 5 – Modify the primary stress, material fracture toughness, and flaw size using Partial Safety Factors. Based on a risk assessment, it was decided that the most appropriate probability of failure to use in the FFS assessment would be $p_f = 10^{-3}$. The mean fracture toughness to specified minimum yield strength ratio, R_{ky}, is required to determine the Partial Safety Factors. Using the information in Notes 5 and 6 of Table 9.3 (Note that $sigma = 1$ is used in calculating the K_{mat}^{mean} / K_{IC} ratio per Table F.11 of Annex F):

$$\Delta T = T - T_{ref} = 40 - 43 = -3 \approx 0°F$$

$$\left.\frac{K_{mat}^{mean}}{K_{IC}}\right|_{sigma=1} = \frac{1.0}{0.61401} = 1.6286$$

$$K_{mat}^{mean} = 1.6286\, K_{IC} = (1.6286)\,(52.7263) = 85.8720\ ksi\sqrt{in}$$

$$R_{ky} = \frac{K_{mat}^{mean}}{\sigma_{ys}} = \frac{85.8720}{38.0} = 2.2598\ \sqrt{in}$$

From Table 9.3, with $\left(R_{ky} = 2.2598\right) > \left(R_c = 1.9\right)$, the Partial Safety Factors are:

$$\begin{Bmatrix} (a = 0.20\ in) \ge 0.20\ in \\ COV_s = 0.10 \\ R_c = 1.9 \end{Bmatrix} \Rightarrow \begin{Bmatrix} PSF_s = 1.50 \\ PSF_k = 1.00 \\ PSF_a = 1.00 \end{Bmatrix}$$

The primary stress, pressure on the crack face, fracture toughness, and flaw size are factored by the Partial Safety Factors as follows:

$$P_m = P_m\ PSF_s = (12000)\,(1.5) = 18000\ psi$$

$$P_b = P_b\ PSF_s = (0)\,(1.5) = 0\ psi$$

$$p = p\ PSF_s = (200)\,(1.5) = 300\ psig$$

$$K_{mat} = K_{mat}\ /\ PSF_k = (85.8720)\,/\,(1.0) = 85.8720\ ksi\sqrt{in}$$

$$a = a\ PSF_a = (0.20)\,(1.0) = 0.20\ \ in$$

Note: The fracture toughness data is the lower-bound estimate in Annex F. Therefore, per Table 9.3 Note 6, the Partial Safety Factor on fracture toughness is applied on K_{mat}^{mean}.

f) STEP 6 – Compute the reference stress for the primary stress. The reference stress solution for RCSCLE1 is provided in Annex D, paragraph D.5.10.

$$a = 0.20\ \ in$$

$$c = 3.20\,/\,2 = 1.60\ \ in$$

$$\lambda_a = \frac{1.818\,c}{\sqrt{R_i\ a}} = \frac{(1.818)(1.60)}{\sqrt{(60)\ (0.20)}} = 0.8397$$

$$M_t(\lambda_a) = \left[\frac{1.02 + 0.4411\,\lambda_a^{\ 2} + 0.006124\,\lambda_a^{\ 4}}{1.0 + 0.02642\,\lambda_a^{\ 2} + 1.533\,(10^{-6})\,\lambda_a^{\ 4}}\right]^{0.5}$$

$$= \left[\frac{1.02 + 0.4411(0.8397)^2 + 0.006124\,(0.8397)^4}{1.0 + 0.02642\,(0.8397)^2 + 1.533\,(10^{-6})\,(0.8397)^4}\right]^{0.5} = 1.1444$$

$$M_s^{NS} = \frac{1}{1 - \left(\dfrac{a}{t}\right) + \left(\dfrac{a}{t}\right)\left(\dfrac{1}{M_t(\lambda_a)}\right)} = \frac{1}{1 - \left(\dfrac{0.20}{1.00}\right) + \left(\dfrac{0.20}{1.00}\right)\left(\dfrac{1}{1.1444}\right)} = 1.0259$$

$$\alpha = \frac{\frac{a}{t}}{1+\frac{t}{c}} = \frac{\frac{0.20}{1.00}}{1+\frac{1.00}{1.60}} = 0.1231$$

$$\sigma_{ref}^{P} = \frac{gP_b + \left\{ (gP_b)^2 + 9\left[M_s P_m (1-\alpha)^2 \right]^2 \right\}^{0.5}}{3(1-\alpha)^2}$$

$$= \frac{0 + \left\{ (0)^2 + 9\left[(1.02659)(18000)(1-0.1231)^2 \right]^2 \right\}^{0.5}}{3(1-0.1231)^2} = 18466.0216\ psi$$

In the above formula $M_s = M_s^{NS}$ (as recommended).

g) STEP 7 – Compute the Load Ratio (L_r^P) or abscissa of the FAD.

$$\sigma_{ys} = 38000\ psi$$

$$L_r^P = \frac{\sigma_{ref}^P}{\sigma_{ys}} = \frac{18466.0216}{38000.0000} = 0.4859$$

h) STEP 8 – Compute K_1^P - The stress intensity factor for KCSCLE1 is provided in Annex C, paragraph C.5.10. Note that because the applied loading is a membrane stress, only the data required to evaluate the G_0 influence coefficient is needed to compute the stress intensity factor.

The flaw ratios and parameters to determine the G_0 influence coefficient from Annex C Table C.12 are:

$$\left\{ \begin{array}{l} \dfrac{t}{R_i} = \dfrac{1.0}{60} = 0.01667 \\ \dfrac{a}{c} = \dfrac{0.2}{1.6} = 0.125 \\ \dfrac{a}{t} = \dfrac{0.2}{1.0} = 0.2 \end{array} \right\} \Rightarrow \left\{ \begin{array}{ll} A_{0,0} = & 0.4141982 \\ A_{1,0} = & 1.1344888 \\ A_{2,0} = & 1.7439464 \\ A_{3,0} = & -6.2232541 \\ A_{4,0} = & 7.7907137 \\ A_{5,0} = & -4.9072442 \\ A_{6,0} = & 1.2389750 \end{array} \right\}$$

The influence coefficients required for the assessment are:

At the base of the flaw $\varphi = 90^o$: $\varphi = 90° = \left(\frac{\pi}{2}\right) rad \Rightarrow \beta = \frac{2\varphi}{\pi} = \frac{2}{\pi}\left(\frac{\pi}{2}\right) = 1 \Rightarrow G_0 = 1.1918238$

At the edge of the flaw $\varphi = 0^o$: $\varphi = 0° = (0) rad \Rightarrow \beta = \frac{2\varphi}{\pi} = \frac{2}{\pi}(0) = 0 \Rightarrow G_0 = 0.4141982$

The stress intensity factors are:

$$Q = 1.0 + 1.464\left(\frac{a}{c}\right)^{1.65} = 1.0 + 1.464\left(\frac{0.2}{1.6}\right)^{1.65} = 1.0474$$

At the base of the flaw $\varphi = 90^o$:

$$K_I^P = \frac{2\,p\,R_o^2\,G_0}{R_o^2 - R_i^2}\sqrt{\frac{\pi a}{Q}} = \frac{2(300)(61)^2(1.1918238)}{(61)^2-(60)^2}\sqrt{\frac{\pi(0.20)}{1.0474}} = 17.0325\ ksi\sqrt{in}$$

At the edge of the flaw $\varphi = 0^o$:

$$K_I^P = \frac{2\,p\,R_o^2\,G_0}{R_o^2 - R_i^2}\sqrt{\frac{\pi a}{Q}} = \frac{2(300)(61)^2(0.4141982)}{(61)^2-(60)^2}\sqrt{\frac{\pi(0.20)}{1.0474}} = 5.9194\ ksi\sqrt{in}$$

i) STEP 9 – Compute the reference stress for secondary stresses. Note that σ_{ref}^{SR} used in this calculation is based on the residual stress (σ^r) from STEP 2. From Annex C, Table C.1, the flaw geometry, component geometry, and loading condition correspond to KCSCLE2 and RCSCLE2, Cylinder - Surface Crack, Longitudinal Direction - Semi-Elliptical Shape, Through-Wall Fourth Order Polynomial Stress Distribution. The reference stress solution for RCSCLE2 is provided in Annex D, paragraph D.5.11 which references paragraph D.5.10. Details regarding the calculation of the reference stress are provided in STEP 6.

$$\sigma_{ref}^{SR} = \frac{gQ_b + \left\{(gQ_b)^2 + 9\left[M_s\,Q_m\,(1-\alpha)^2\right]^2\right\}^{0.5}}{3(1-\alpha)^2}$$

$$= \frac{0 + \left\{(0)^2 + 9\left[(1.0259)(48000)(1-0.1231)^2\right]^2\right\}^{0.5}}{3(1-0.1231)^2} = 49242.7243\ psi$$

j) STEP 10 – Compute K_1^{SR}. The stress intensity factor solution for KCSCLE2 is provided in Annex C, paragraph C.5.11. Details regarding the calculation of coefficients Q and G_0 used in the formula for the stress intensity factor are provided in STEP 8.

The stress intensity factors are:

At the base of the flaw $\varphi = 90^o$:

$$K_I^{SR} = G_0\sigma_0\sqrt{\frac{\pi a}{Q}} = (1.1918238)(48.0)\sqrt{\frac{\pi(0.2)}{1.0474}} = 44.3093\ ksi\sqrt{in}$$

At the edge of the flaw $\varphi = 0^o$:

$$K_I^{SR} = G_0\sigma_0\sqrt{\frac{\pi a}{Q}} = (0.4141982)(48.0)\sqrt{\frac{\pi(0.2)}{1.0474}} = 15.3989\ ksi\sqrt{in}$$

k) STEP 11 – Compute the plasticity interaction factor, with L_r^P from STEP 7

$$L_r^{SR} = \frac{\sigma_{ref}^{SR}}{\sigma_{ys}} = \frac{49242.7243}{38000.0000} = 1.2959$$

ψ and φ are calculated from Tables 9.3 and 9.5 respectively

$$\begin{Bmatrix} L_r^P = 0.4859 \\ L_r^{SR} = 1.2959 \end{Bmatrix} \Rightarrow \begin{Bmatrix} \psi = 0.09086 \\ \varphi = 0.62739 \end{Bmatrix}$$

and,

$$\frac{\Phi}{\Phi_0} = 1.0 + \frac{\psi}{\varphi} = 1.0 + \frac{0.09086}{0.62739} = 1.1448$$

Since $0 < \left(L_r^{SR} = 1.2959\right) \le 4.0$, then $\Phi_o = 1.0$ and $\Phi = 1.1448$

l) STEP 12 – Determine toughness ratio or ordinate of the FAD assessment point.

At the base of the flaw $\varphi = 90^o$: $K_r = \dfrac{K_I^P + \Phi\, K_I^{SR}}{K_{mat}} = \dfrac{17.0325 + (1.1448)(44.3093)}{85.8720} = 0.7891$

At the edge of the flaw $\varphi = 0^o$: $K_r = \dfrac{K_I^P + \Phi\, K_I^{SR}}{K_{mat}} = \dfrac{5.9194 + (1.1448)(15.3989)}{85.8720} = 0.2742$

m) STEP 13 – Evaluate the results.

1) STEP 13.1 – Determine the cut-off for the L_r^P -axis of the FAD – Since the hardening characteristics of the material are not known, the following value can be used (see Figure 9.20, Note 2):

$$L_{r(\max)}^P = 1.0$$

2) STEP 13.2 – Plot the assessment point on the FAD shown in Figure 9.20.

At the base of the flaw $\varphi = 90^o$: $(L_r^P, K_r) = (0.486, 0.789)$

the point is inside the FAD (see Figure E9.5-1)

At the edge of the flaw $\varphi = 0^o$: $(L_r^P, K_r) = (0.486, 0.274)$

the point is inside the FAD (see Figure E9.5-1)

Note: Equation (9.33) under Figure 9.20 gives the maximum allowable K_r for $L_r^P = 0.4859$:

$$K_{r,\max} = \left[1 - 0.14\left(L_r^P\right)^2\right]\left\{0.3 + 0.7\exp\left[-0.65\left(L_r^P\right)^6\right]\right\}$$

$$= \left[1 - 0.14\left(0.4859\right)^2\right]\left\{0.3 + 0.7\exp\left[-0.65\left(0.4859\right)^6\right]\right\} = 0.9612$$

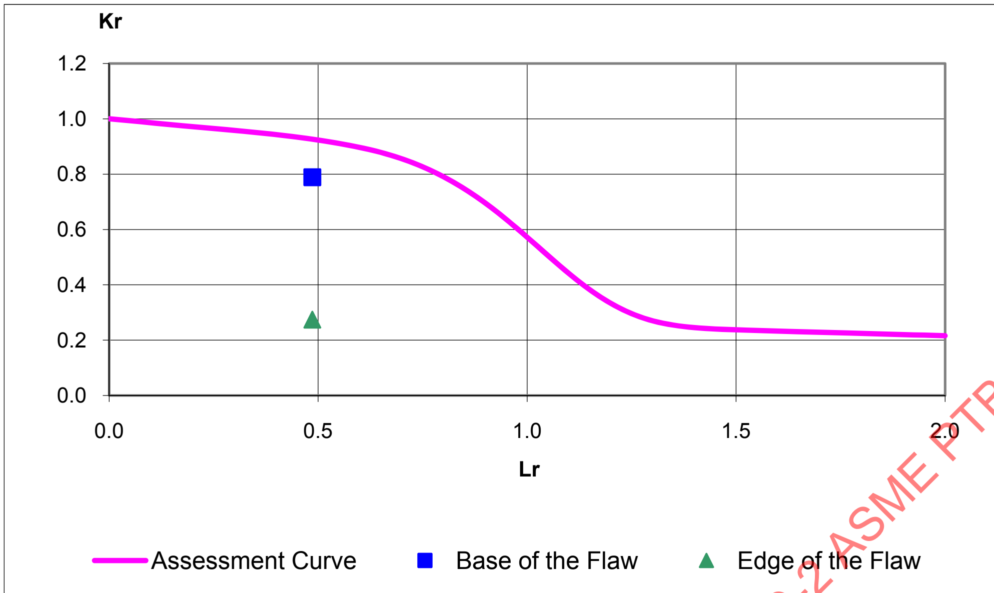


Figure E9.5-1 - FAD with Assessment Points

The Level 2 Assessment Criteria are Satisfied. The vessel is acceptable for continued operation.

Note: Should the Level 2 criteria not be satisfied, then the assessment could be repeated with a less conservative residual stress field based on the through-thickness distribution (see Example 9.6 or 9.7)

9.6 Example Problem 6

A crack-like flaw has been found in the circumferential seam on the outside surface of a pipe during a scheduled turnaround. The pipe and inspection data are provided below. The piping system was constructed to the ASME B31.3 Code, 2003 Edition. Determine if the pipe is acceptable for continued operation.

<u>Pipe Data</u>

- Material = $SA\text{-}106\ Grade\ B\ Year\ 2003$
- Design Conditions = $3.0\ MPa\ (30\ bar)\ @\ 250°C$
- Fluid Density = 0.8
- Pipe Outside Diameter = $508\ mm\ (NPS\ 20)$
- Pipe Thickness = $9.53\ mm\ (Schedule\ 20)$
- Uniform Metal Loss = $0.0\ mm$
- FCA = $0.0\ mm$
- Weld Joint Efficiency = 1.0
- PWHT = No

<u>Operating Conditions</u>

The piping system is not fully pressurized until the temperature is 20°C. Below this temperature, the startup pressure remains under 2.0 MPa (20 bar). At shutdown, the pressure is decreased to 2.0 MPa (20 bar) before letting the temperature drop below 20°C.

<u>Inspection Data</u>

The flaw is located in a circumferential weld seam on the outside surface of the pipe. The seam is a single V-groove weld. The flaw is parallel to the weld seam. The depth of the flaw was established by UT; consistent readings were noted and a final value for the flaw depth was established at 3.0 mm. The flaw length is such that the flaw may be considered as a 360 degree crack. The crack-like flaw is situated midway between 2 supports, the distance of which is 10.5 m.

Perform a Level 1 Assessment per paragraph 9.4.2.2

First, check that the conditions to perform a Level 1 Assessment are satisfied

<u>Geometry:</u>

Component is a flat plate, cylinder or sphere: (cylinder) *True*

Cylinder with $R/t \geq 5$ (t being the current thickness)

$$\left.\begin{cases} t = 9.53\ mm \\ R = D/2 - t = (508/2) - 9.53 = 244.47\ mm \end{cases}\right\} \Rightarrow R/t = 244.47/9.53 = 25.6527$$ *True*

Wall thickness at the location of the flaw is less than $38\,mm$: ($9.53\ mm < 38\ mm$) *True*

Flaw of surface or through-thickness type with a maximum crack-length of $200\,mm$

Surface crack with length equal to $\left(508\pi = 1595.9291\,mm\right) \leq 200\,mm$ *False*

Cylindrical shell: flaw oriented in the axial or circumferential direction: (longitudinal = axial) *True*

Loads:

Membrane stress field produced by pressure only *False*

Considering the location of the flaw, a global bending moment shall be taken into account.

Membrane stress within the design limits of original construction code *True*

Welded joint is single or double V: (single V-groove weld) *True*

Material:

Carbon Steel (P1, Group 1 or 2) with $S \le 172\ MPa$, $\sigma_{ys} \le 276\ MPa$ and $\sigma_{uts} \le 483\ MPa$

(From ASME Section II, Part D, SA-106 Grade B is a carbon steel, P1, Group 1,

With $S = 118\ MPa$, $\sigma_{ys} = 240\ MPa$ and $\sigma_{uts} = 415\ MPa$) *True*

Fracture toughness greater than or equal to the lower-bound K_{IC} in Annex F

(Carbon steel not degraded because of environmental damage) *True*

The Level 1 Assessment Criteria are Not Satisfied

Perform a Level 2 Assessment per paragraph 9.4.3.2

a) STEP 1 – Evaluate operating conditions and determine the pressure, temperature and supplemental loading combinations to be evaluated:

Due to the location of the flaw, a global bending moment shall be considered. The pipe section is considered as simply supported at both ends

The circumferential primary membrane tensile stress σ_m^C due to startup or shutdown pressure (2.0 MPa) calculated per formula in paragraph A.3.4 of Annex A are less than 55 MPa.

The longitudinal primary membrane tensile stress σ_m^L due to startup or shutdown pressure and to the global bending moment, calculated per formula in paragraph A.3.4 of Annex A is less than 55 MPa too.

Per Part 3 paragraph 3.1.2, a brittle fracture assessment is not needed for these loads. Therefore, the temperature used in the assessment will be the minimum temperature for which the pressure is above 2.0 MPa.

$$T = 20°C$$

$$P = 3.0\ MPa$$

$$M = (36.8)(10)^6\ N\text{–}mm$$

b) STEP 2 – Determine the stress distribution at the location of the flaw - The primary stress distribution is based on the applied loads.

1) Primary Stress

The flaw is located away from all major structural discontinuities. From Annex C, Table C.1, the flaw geometry, component geometry, and loading condition correspond to KCSCCL1 and RCSCCL1, Cylinder - Surface Crack, Circumferential Direction - 360 Degrees, Pressure with a Net Section Axial Force and Bending Moment. The stress intensity factor solution for KCSCCL1 is provided in Annex C, paragraph C.5.7. The reference stress solution for RCSCCL1 is provided in Annex D, paragraph D.5.7 .

$$R_o = D/2 = 508.00/2 = 254.00\ mm$$

$$R_i = R_o - t = 254.00 - 9.53 = 244.47\ mm$$

$$M/\pi(R_o^4 - R_i^4) = (36.8)(10)^6/\pi\left\{(254.00)^4 - (244.47)^4\right\} = 0.01984\ N/mm^3$$

The membrane and bending components of the primary stress for the calculation of the stress intensity factor are (with $F = 0$):

$$\sigma_m^P = \left\{ \frac{pR_i^2}{(R_o^2 - R_i^2)} \right\} + \left\{ 2 \frac{M}{\pi(R_o^4 - R_i^4)} (R_o + R_i) \right\}$$

$$= \left\{ \frac{(3.0)\,(244.47)^2}{(254.00)^2 - (244.47)^2} \right\} + \left\{ 2\,(0.01984)\,(254.00 + 244.47) \right\}$$

$$= 57.5234\ MPa$$

$$\sigma_b^P = 2 \frac{M}{\pi(R_o^4 - R_i^4)} (R_o - R_i) = 2\,(0.01984)\,(254.00 - 244.47) = 0.3782\ MPa$$

The membrane and bending components of the primary stress for the calculation of the reference stress are (with $F = 0$):

$$P_m = \frac{pR_i^2}{(R_o^2 - R_i^2)} = \frac{(3.0)\,(244.47)^2}{(254.00)^2 - (244.47)^2} = 37.7434\ MPa$$

$$P_{bg} = \frac{M}{\pi(R_o^4 - R_i^4)} \frac{R_o}{0.25} = (0.01984) \frac{254.00}{0.25} = 20.1583\ MPa$$

2) Secondary Stress

Thermal gradients do not exist in the pipe at the location of the flaw, and the flaw is located away from all major structural discontinuities. Therefore, there are no secondary stresses.

3) Residual Stress

The flaw is located at a girth in a pipe that was not subject to PWHT at the time of fabrication. From Annex E, paragraph E.3.2.

$$\sigma_{ys}^r = \sigma_{ys} + 69 = 240 + 69 = 309\ MPa$$

The flaw is located at the limit between the weld seam and the base metal. The weld is a single V-groove. The through-thickness residual stress field is calculated from Annex E, paragraph E.4.1.1.b

The basic parameters used in the equation representing the through-thickness residual stress field are $\bar{\sigma}_m^r$ and $\bar{\sigma}_b^r$.

$$\bar{\sigma}_m^r = 0.30$$

$\bar{\sigma}_b^r$ is a function of the mean radius to thickness ratio and of the heat input of the welding process. It has been established that the first pass was a GTAW one and that all subsequent passes were SMAW ones. Since the crack is on the opposite side of the root, the selected heat input corresponds to the SMAW passes recorded as $\dot{q} = 1500\ J/mm$

The parameters in the $\bar{\sigma}_b^r$ equations are:

$$\hat{Q} = 0.7441 \left(\frac{\dot{q}}{t^2} \right) = (0.7441) \left(\frac{1500}{(9.53)^2} \right) = 12.2896\ J/mm^3 \quad (between\ 1.5\ and\ 25.0)$$

$$\hat{R} = \frac{r}{t} = \frac{249.235}{9.53} = 26.1527 \quad < 30.0 \quad \Rightarrow \quad \hat{R} = 30.0$$

$$\ln\left[\hat{R}\right] = 3.4012$$

Leading to:

$$\bar{\sigma}_b^r = \begin{pmatrix} 1.5161198 - 0.4523099\ln\left[\hat{R}\right] - 7.25919(10)^{-2}\,\hat{Q} + \\ 5.0417213(10)^{-2}\left(\ln\left[\hat{R}\right]\right)^2 + 9.2862457(10)^{-4}\,\hat{Q}^2 - \\ 1.0999481(10)^{-2}\,\hat{Q}\ln\left[\hat{R}\right] - 2.7500406(10)^{-3}\left(\ln\left[\hat{R}\right]\right)^3 - \\ 2.0566152(10)^{-5}\,\hat{Q}^3 - 2.0294677(10)^{-4}\,\hat{Q}^2\ln\left[\hat{R}\right] + \\ 4.7248503(10)^{-3}\,\hat{Q}\left(\ln\left[\hat{R}\right]\right)^2 \end{pmatrix}$$

$$= \begin{pmatrix} 1.5161198 - 0.4523099\,(3.4012) - 7.25919(10)^{-2}\,(12.2896) + \\ 5.0417213(10)^{-2}(3.4012)^2 + 9.2862457(10)^{-4}\,(12.2896)^2 - \\ 1.0999481(10)^{-2}\,(12.2896)\,(3.4012) - 2.7500406(10)^{-3}(3.4012)^3 - \\ 2.0566152(10)^{-5}\,(12.2896)^3 - 2.0294677(10)^{-4}\,(12.2896)^2\,(3.4012) + \\ 4.7248503(10)^{-3}\,(12.2896)\,(3.4012)^2 \end{pmatrix}$$

$$= -0.2296$$

$$s_o^r = K - \left|\bar{\sigma}_b^r\right| - \left|\bar{\sigma}_m^r\right| = 1.2 - 0.2296 - 0.30 = 0.6704$$

$$s_i^r = 0.25\,s_o^r = (0.25)\,(0.6704) = 0.1676$$

$$C = \arctan\left[\frac{5}{\pi}\left(\frac{s_o^r + s_i^r}{s_o^r - s_i^r}\right)\right] = \arctan\left[\frac{5}{\pi}\left(\frac{0.6704 + 0.1676}{0.6704 - 0.1676}\right)\right] = 1.2103$$

With $K = 1.2$ corresponding to residual stresses perpendicular to the weld

There is no indication that the crack-like flaw already existed in the pipe during the last field hydrotest performed as part of a rerate. Therefore the residual stress may not be reduced: $R_r = 1.0$

The values of the residual stress with respect to the depth $\varsigma = x/t$ ($\varsigma = 0$ on the inside surface and $\varsigma = 1$ on the outside surface) together with the intermediate coefficients in paragraph E.3.4.a are given in Table E9.6-1 where the column "Linear" corresponds to $\{\bar{\sigma}_m^r + \bar{\sigma}_b^r\left(2\zeta - 1\right)\}\sigma_{ys}^r R_r$ and the column "Auto-Eqlb" corresponds to the self-equilibrating part of the stress $\left\{A - B\right\}\sigma_{ys}^r\ R_r$.

Table E9.6-1 - Through-Thickness Distribution of Residual Stress per Annex E

ς	A	B	D	E	$\sigma^R(\varsigma)$	Linear	Auto-Eqlb
0.0	-0.2514	-0.4190	0.6972	0.6972	215.4324	163.6433	51.7892
0.1	-0.1287	-0.4318	0.7868	0.7868	243.1162	149.4546	93.6616
0.2	-0.0543	-0.2797	0.6632	0.6632	204.9168	135.2660	69.6509
0.3	-0.0161	-0.0208	0.3965	0.3965	122.5174	121.0773	1.4401
0.4	-0.0020	0.2461	0.0978	0.0978	30.2112	106.8887	-76.6774
0.5	0.0000	0.4190	-0.1190	-0.1190	-36.7730	92.7000	-129.4730
0.6	0.0020	0.4318	-0.1757	-0.1757	-54.3029	78.5113	-132.8142
0.7	0.0161	0.2797	-0.0555	-0.0555	-17.1361	64.3227	-81.4588
0.8	0.0543	0.0208	0.1958	0.1958	60.5019	50.1340	10.3678
0.9	0.1287	-0.2461	0.4912	0.4912	151.7754	35.9454	115.8300
1.0	0.2514	-0.4190	0.7408	0.7408	228.9135	21.7567	207.1567

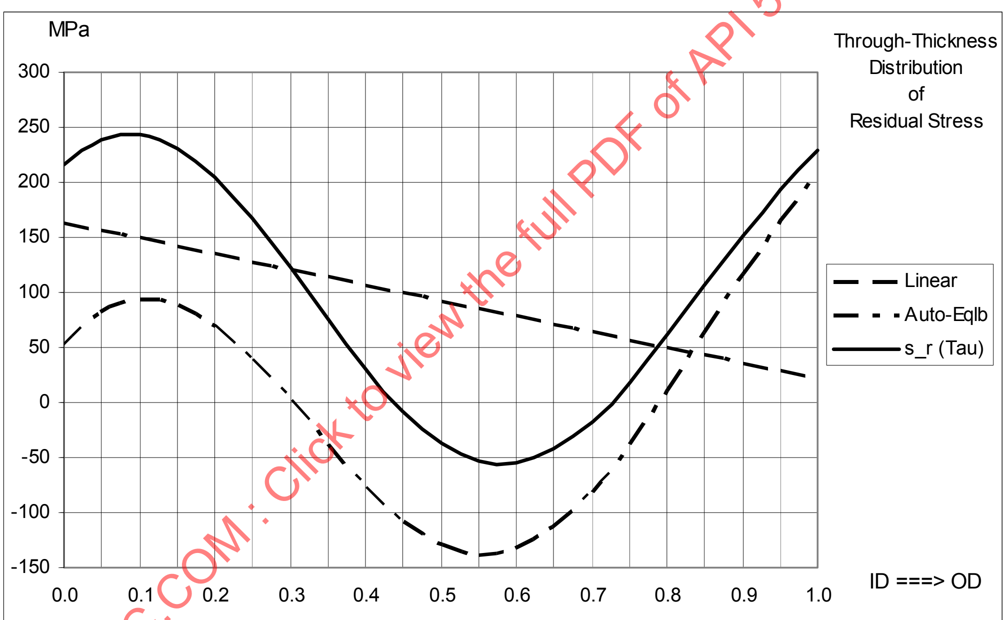


Figure E9.6-1 - Through-Thickness Distribution of Residual Stress per Annex E

In order to calculate the stress intensity factor and the reference stress, the through-thickness distribution will be represented by a polynomial function. From Annex C, Table C.1, the flaw geometry, component geometry, and loading condition correspond to KCSCCL2 and RCSCCL2, Cylinder - Surface Crack, Circumferential Direction - 360 Degrees, Through-Wall Fourth Order Polynomial Stress Distribution. The stress intensity factor solution for KCSCCL2 is provided in Annex C, paragraph C.5.8. The reference stress solution for RCSCCL2 is provided in Annex D, paragraph D.5.8.

A best-fit 4th order polynomial is determined by generating a graph of the through-thickness distribution versus ς in a Microsoft Excel spreadsheet and adding a trend curve to it. Since the flaw is on the outside surface, the variable ς of the polynomial is set to 0 on the outside surface and 1 on the inside surface. Values of $\sigma^R(\varsigma)$ are input data with a step $\Delta\zeta = 0.05$.

The residual stress for the calculation of the stress intensity factor is written as:

$$\sigma^R(x) = \sigma_0 + \sigma_1\left(\frac{x}{t}\right) + \sigma_2\left(\frac{x}{t}\right)^2 + \sigma_3\left(\frac{x}{t}\right)^3 + \sigma_4\left(\frac{x}{t}\right)^4$$

with:
$$\sigma_0 = 231.1584$$
$$\sigma_1 = -608.8177$$
$$\sigma_2 = -2806.8043$$
$$\sigma_3 = 8474.7480$$
$$\sigma_4 = -5084.2398$$

Figure E9.6-2 shows the through-wall residual stress distribution as determined per Annex E (s_r) and the best-fit polynomial curves of different degrees (deg 1 to 4). This figure validates the use of a 4th order polynomial for the representation of the residual stress.

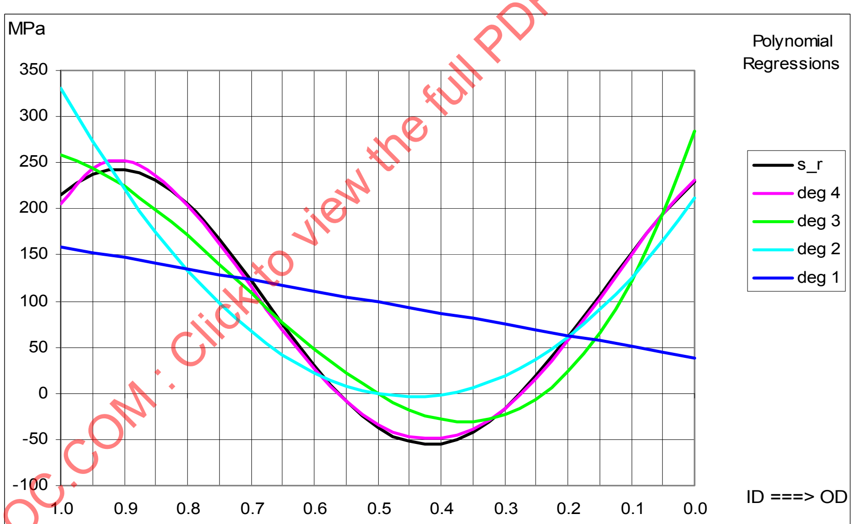


Figure E9.6-2 - Through-Thickness Distribution with Polynomial Trend Curves

The membrane and bending components of the residual stress for the calculation of the reference stress may be based on:

i) The linear part of the through-thickness distribution given in Annex E:

$$Q_m = \bar{\sigma}^r_m \, \sigma^r_{ys} \, R_r = (0.30)\,(309.00)\,(1.0) = 92.7000 \; MPa$$

$$Q_b = \bar{\sigma}^r_b \, \sigma^r_{ys} \, R_r = (-0.2296)\,(309.00)\,(1.0) = -70.9433 \; MPa$$

or

ii) Equivalent membrane and bending stresses for the 4th order polynomial stress distribution used for the stress intensity factor calculation, as described in Annex D, paragraph D.2.2.3:

$$\tilde{Q}_m = \sigma_0 + \frac{\sigma_1}{2} + \frac{\sigma_2}{3} + \frac{\sigma_3}{4} + \frac{\sigma_4}{5}$$

$$= (231.1584) + \left(\frac{-608.8177}{2}\right) + \left(\frac{-2806.8043}{3}\right) + \left(\frac{8474.7480}{4}\right) + \left(\frac{-5084.2398}{5}\right) = 92.9872\ MPa$$

$$\tilde{Q}_b = -\frac{\sigma_1}{2} - \frac{\sigma_2}{2} - \frac{9\,\sigma_3}{20} - \frac{6\,\sigma_4}{15}$$

$$= -\left(\frac{-608.8177}{2}\right) - \left(\frac{-2806.8043}{2}\right) - \left(\frac{9\,(8474.7480)}{20}\right) - \left(\frac{6\,(-5084.2398)}{15}\right) = -72.1296\ MPa$$

The 2 methods give similar values. Since the second set ($\tilde{Q}_m, \tilde{Q}_b$) is based on an approximate solution, the first set (Q_m, Q_b) will be retained for the calculation of the reference stress

c) STEP 3 – Determine the material properties; yield strength, tensile strength and fracture toughness. Material properties for the pipe containing the flaw are not available; therefore, the specified minimum specified yield and tensile strengths are used.

$$\sigma_{ys} = 240\ MPa$$

$$\sigma_{uts} = 415\ MPa$$

Based on the material specification and grade, the material fracture toughness is established using the lower-bound curve in Annex F, paragraph F.4.4.1

Determine the Reference Temperature – T_{ref} is established using Table 9.2. Inputs for this table are the exemption curve as per Table 3.2 in Part 3 and the minimum specified yield strength at ambient temperature based on the original construction code. ASTM A106 Grade B is a Curve B Carbon Steel with $\sigma_{ys} = 240\ MPa$, therefore:

$$\left\{\begin{matrix} Curve\ B\ Carbon\ \ Steel \\ \sigma_{ys} = 240\ MPa \end{matrix}\right\} \Rightarrow T_{ref} = 10°C$$

This leads to

$$K_{IC} = 36.5 + 3.084 \exp\left[0.036\left(T - T_{ref} + 56\right)\right]$$

$$= 36.5 + 3.084 \exp\left[0.036\left(20 - 10 + 56\right)\right] = 69.6893\ MPa\sqrt{m}$$

d) STEP 4 – Determine the crack-like flaw dimension from inspection data.

$$a = 3.0\ mm$$

e) STEP 5 – Modify the primary stress, material fracture toughness, and flaw size using Partial Safety Factors. Based on a risk assessment, it was decided that the most appropriate probability of failure to use in the FFS assessment would be $p_f = 10^{-3}$. The mean fracture toughness to specified minimum yield strength ratio, R_{ky}, is required to determine the Partial Safety Factors. Using the information in Notes 5 and 6 of Table 9.3 (Note that $sigma = 1$ is used in calculating the K_{mat}^{mean} / K_{IC} ratio per Table F.11 of Annex F):

$$\Delta T = T - T_{ref} = 20 - 10 = 10°C = 18°F$$

$$\left.\frac{K_{mat}^{mean}}{K_{IC}}\right|_{sigma=1} = \frac{1.0}{0.6252} = 1.5996$$

$$K_{mat}^{mean} = 1.5996\, K_{IC} = 1.5996\,(69.6893) = 111.4724\; MPa\sqrt{m}$$

$$R_{ky} = \frac{K_{mat}^{mean}}{\sigma_{ys}} C_u = \frac{111.4724}{240.0}(6.275) = 2.9145\,\sqrt{in}$$

From Table 9.3, with $(R_{ky} = 2.9145) > (R_c = 1.4)$, the Partial Safety Factors are:

$$\begin{Bmatrix} (a = 3.0\; mm) < 5\; mm \\ COV_s = 0.10 \\ R_c = 1.4 \end{Bmatrix} \Rightarrow \begin{Bmatrix} PSF_s = 1.50 \\ PSF_k = 1.00 \\ PSF_a = 1.00 \end{Bmatrix}$$

The primary stress, fracture toughness, and flaw size are factored by the Partial Safety Factors as follows:

$$P_m = P_m\; PSF_s = (37.7434)(1.5) = 56.6150\; MPa$$

$$P_{bg} = P_{bg}\; PSF_s = (20.1583)(1.5) = 30.2374\; MPa$$

$$\sigma_m^P = \sigma_m^P\; PSF_s = (57.5234)(1.5) = 86.2852\; MPa$$

$$\sigma_b^P = \sigma_b^P\; PSF_s = (0.3782)(1.5) = 0.5672\; MPa$$

$$K_{mat} = K_{mat} / PSF_k = (111.4724)/(1.0) = 111.4724\; MPa\sqrt{m}$$ (see Note STEP 5 of Example 9.5)

$$a = a\; PSF_a = (3.0)(1.0) = 3.0\; mm$$

f) STEP 6 – Compute the reference stress for the primary stress. The reference stress solution for RCSCCL1 is provided in Annex D, paragraph D.5.7.

$$R_o - a = 254.0 - 3.0 = 251.0\; mm$$

$$N_r = P_m \left\{(R_o)^2 - (R_i)^2\right\} / \left\{(R_o - a)^2 - (R_i)^2\right\}$$

$$= (56.6150)\left\{(254.0)^2 - (244.47)^2\right\} / \left\{(251.0)^2 - (244.47)^2\right\} = 83.1253\; MPa$$

$$M_r = P_{bg}\;(3\pi/16)\left\{(R_o)^4 - (R_i)^4\right\} / \left\{(R_o)\,(R_o - a)^3 - (R_i)^4\right\}$$

$$= (30.2374)\,(3\pi/16)\left\{(254.0)^4 - (244.47)^4\right\} / \left\{(254.0)\,(251.0)^3 - (244.47)^4\right\}$$

$$= 23.6496\; MPa$$

$$\sigma_{ref}^P = (M_r/2) + \left\{(N_r)^2 + (M_r/2)^2\right\}^{0.5}$$

$$= (23.6496/2) + \left\{(83.1253)^2 + (23.6496/2)^2\right\}^{0.5} = 95.7869\; MPa$$

Note: Usually the same primary and secondary stresses are used for the calculation of the stress intensity factor and for the calculation of the reference stress. This is not true for the type of crack under evaluation.

The calculation of σ^P_{ref} from σ^P_m and σ^P_b instead of P_m and P_{bg}, based on the formula given for a through-wall fourth order polynomial stress distribution (paragraph D.5.8) would have led to a very conservative value of the reference stress ($\sigma^P_{ref} = 126.9106\ MPa$) due to the facts that σ^P_m represents the mean stress on the cross section at the location of maximum global bending stress and that the distribution of this global bending stress would not have been taken into account.

g) STEP 7 – Compute the Load Ratio (L^P_r) or abscissa of the FAD.

$$\sigma_{ys} = 240.0\ MPa$$

$$L^P_r = \frac{\sigma^P_{ref}}{\sigma_{ys}} = \frac{95.7869}{240.0} = 0.3991$$

h) STEP 8 – Compute K^P_1 - The stress intensity factor solution for KCSCCL1 is provided in Annex C, paragraph C.5.7.
This solution is based on a through-wall first order polynomial stress distribution in which the constant coefficients are:

$$\sigma_0 = \sigma^P_m + \sigma^P_b = 86.2852 + 0.5672 = 86.8524\ MPa$$

$$\sigma_1 = -2\ \sigma^P_b = -2\ (0.5672) = -1.1345\ MPa$$

The parameters used to determine the G_0 and G_1 influence coefficients from Annex C Table C.11 are:

$$\frac{t}{R_i} = \frac{9.53}{244.47} = 0.03898$$

$$\frac{a}{t} = \frac{3.0}{9.53} = 0.3148$$

The influence coefficients required for the assessment are calculated by interpolation between values given in Table C11 for cracks on the outside surface (see Table E9.6-2):

Table E9.6-2 - Influence Coefficients used in the Assessment

t/R_i	a/t	G_0	G_1	G_2	G_3	G_4
0.025	0.2	1.316699	0.747945	0.549407	0.444194	0.392491
0.025	0.4	1.820527	0.938621	0.654343	0.512094	0.444266
0.025	0.3148	1.605885	0.857389	0.609638	0.483167	0.422209
0.05	0.2	1.301318	0.74179	0.545907	0.441883	0.390643
0.05	0.4	1.738126	0.906946	0.636767	0.500662	0.435407
0.05	0.3148	1.552036	0.836586	0.598059	0.475621	0.416337
0.03898	0.3148	1.575767	0.845754	0.603162	0.478946	0.418924

Note that coefficients G_0 and G_1 only are used to calculate K^P_I. Coefficients G_2, G_3 and G_4 will be needed to calculate K^{SR}_I in STEP 10.

Since the crack lies on the outside surface, the crack face pressure is nil ($p_c = 0$).

The stress intensity factor is:

$$K_I^P = \left[G_0 \left\{ \sigma_0 + p_c \right\} + G_1 \, \sigma_1 \left(\frac{a}{t} \right) \right] \sqrt{\pi \, a}$$

$$K_I^P = \left[(1.575767) \left\{ 86.8524 \right\} - (0.845754)\,(1.1345)\,(0.3148) \right] \sqrt{\pi \,(3.0)} = 419.2277 \; MPa\sqrt{mm}$$

$$K_I^P = 13.2571 \; MPa\sqrt{m}$$

i) STEP 9 – Compute the reference stress for secondary stresses. The reference stress solution for RCSCCL2 is provided in Annex D, paragraph D.5.8.

$$\alpha = \frac{a}{t} = \frac{3.0}{9.53} = 0.3148$$

$$\tau = \frac{t}{R_o} = \frac{9.53}{508.0} = 0.0375$$

$$Z = \left[1 - \alpha \left(\frac{2 - 2\tau + \alpha\tau}{2 - \tau} \right) \right]^{-1} = \left[1 - 0.3148 \left(\frac{2 - 2\,(0.0375) + 0.3148\,(0.0375)}{2 - 0.0375} \right) \right]^{-1}$$

$$= \frac{1}{0.6893} = 1.4507$$

$$\sigma_{ref}^{SR} = \frac{Q_b + \left\{ (Q_b)^2 + 9 \left[Z \, Q_m \, (1-\alpha)^2 \right]^2 \right\}^{0.5}}{3\,(1-\alpha)^2}$$

$$= \frac{(-70.9433) + \left\{ (-70.9433)^2 + 9 \left[(1.4507)\,(92.7000)\,(1-0.3148)^2 \right]^2 \right\}^{0.5}}{3\,(1-0.3148)^2}$$

$$= 93.2341 \; MPa$$

j) STEP 10 – Compute K_I^{SR}. The stress intensity factor solution for KCSCCL1 is provided in Annex C, paragraph C.5.8.

$$K_I^{SR} = \left[G_0 \left\{ \sigma_0 + p_c \right\} + G_1 \, \sigma_1 \left(\frac{a}{t} \right) + G_2 \, \sigma_2 \left(\frac{a}{t} \right)^2 + G_3 \, \sigma_3 \left(\frac{a}{t} \right)^3 + G_4 \, \sigma_4 \left(\frac{a}{t} \right)^4 \right] \sqrt{\pi \, a}$$

$$K_I^{SR} = \begin{bmatrix} (1.575767)\,(231.1584) \\ +(0.845754)\,(-608.8177)\,(0.3148) \\ +(0.603162)\,(-2806.8043)\,(0.3148)^2 \\ +(0.478946)\,(8474.7480)\,(0.3148)^3 \\ +(0.418924)\,(-5084.2398)\,(0.3148)^4 \end{bmatrix} \sqrt{\pi \,(3.0)} = 430.0992 \; MPa\sqrt{mm}$$

$$K_I^{SR} = 13.6009 \; MPa\sqrt{m}$$

k) STEP 11 – Compute the plasticity interaction factor, with L_r^P from STEP 7

$$L_r^{SR} = \frac{\sigma_{ref}^{SR}}{\sigma_{ys}} = \frac{93.2341}{240.0} = 0.3885$$

ψ and φ are calculated from Tables 9.3 and 9.5 respectively

$$\begin{Bmatrix} L_r^P = 0.3991 \\ L_r^{SR} = 0.3885 \end{Bmatrix} \Rightarrow \begin{Bmatrix} \psi = 0.0287 \\ \varphi = 0.4053 \end{Bmatrix}$$

and,

$$\frac{\Phi}{\Phi_0} = 1.0 + \frac{\psi}{\varphi} = 1.0 + \frac{0.0287}{0.4053} = 1.0709$$

Since $0 < \left(L_r^{SR} = 0.3885\right) \le 4.0$, then $\Phi_o = 1.0$ and $\Phi = 1.0709$

l) STEP 12 – Determine toughness ratio or ordinate of the FAD assessment point.

$$K_r = \frac{K_I^P + \Phi\, K_I^{SR}}{K_{mat}} = \frac{13.2571 + (1.0709)(13.6009)}{111.4724} = 0.2496$$

m) STEP 13 – Evaluate the results.

1) STEP 13.1 – Determine the cut-off for the L_r^P -axis of the FAD – Since the hardening characteristics of the material are not known, the following value can be used (see Figure 9.20, Note 2):

$$L_{r(\max)} = 1.0$$

2) STEP 13.2 – Plot the assessment point on the FAD shown in Figure 9.20.

$$(L_r^P, K_r) = (0.399, 0.250)$$

The point is inside the FAD (see Figure E9.6-3)

Note: Equation (9.33) under Figure 9.20 gives the maximum allowable K_r for $L_r^P = 0.399$:

$$K_{r,\max} = \left[1 - 0.14\left(L_r^P\right)^2\right]\left\{0.3 + 0.7\exp\left[-0.65\left(L_r^P\right)^6\right]\right\}$$

$$= \left[1 - 0.14\left(0.399\right)^2\right]\left\{0.3 + 0.7\exp\left[-0.65\left(0.399\right)^6\right]\right\} = 0.976$$

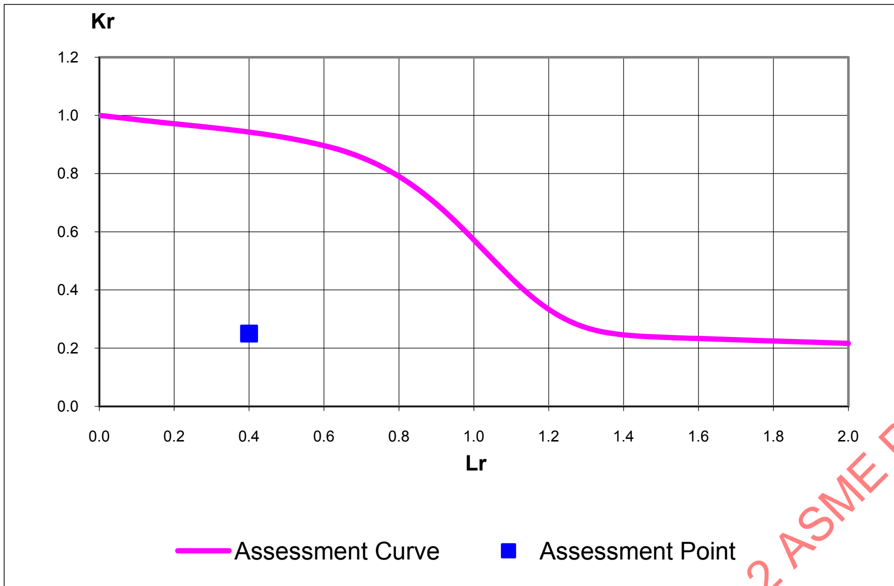


Figure E9.6-3 - FAD with the Assessment Point

The Level 2 Assessment Criteria are Satisfied. The pipe is acceptable for continued operation.

9.7 Example Problem 7

A crack-like flaw has been found in the circumferential seam on the outside surface of a pipe during a scheduled turnaround. The pipe and inspection data are provided below. The piping system was constructed to the ASME B31.3 Code, 2003 Edition. Determine if the pipe is acceptable for continued operation.

Pipe Data: Identical to those of Example 9.6

Operating Conditions: Identical to those of Example 9.6

Inspection Data

The flaw is located in a circumferential weld seam on the outside surface of the pipe on its lower part. The seam is a single V-groove weld. The flaw is parallel to the weld seam. The depth of the flaw was established by UT; consistent readings were noted and a final value for the flaw depth was established at 4.0 mm. The flaw length was established by MT and is 15.0 mm. The crack-like flaw is situated midway between 2 supports, the distance of which is 10.5 m.

Perform a Level 2 Assessment per paragraph 9.4.2.2 at the deepest point and at surface points of the crack (minimum required for a semi-elliptical surface crack) and at points at 45 degrees on the crack front of the flaw.

a) STEP 1 – Evaluate operating conditions and determine the pressure, temperature and supplemental loading combinations to be evaluated: See Example 9.6

$$T = 20°C$$

$$P = 3.0\ MPa$$

$$M_x = 36.8\ (10)^6\ N\text{–}mm$$

$$M_y = 0\ N\text{–}mm$$

b) STEP 2 – Determine the stress distribution at the location of the flaw - The primary stress distribution is based on the applied loads.

1) Primary Stress

The flaw is located away from all major structural discontinuities. From Annex C, Table C.1, the flaw geometry, component geometry, and loading condition correspond to KCSCCE2 and RCSCCE2, Cylinder - Surface Crack, Circumferential Direction - Semi-Elliptical Shape, Through-Wall Fourth Order Polynomial Stress Distribution with a Net Section Bending Stress. The stress intensity factor solution for KCSCCE2 is provided in Annex C, paragraph C.5.14. The reference stress solution for RCSCCE2 is provided in Annex D, paragraph D.5.14.

$$R_o = D/2 = 508/2 = 254.00\ mm$$

$$R_i = R_o - t = 254 - 9.53 = 244.47\ mm$$

$$R_m = (R_o + R_i)/2 = (254 + 244.47)/2 = 249.235\ mm$$

$$M_x / \pi (R_o^4 - R_i^4) = 36.8\ (10)^6 / \pi \left\{(254.00)^4 - (244.47)^4\right\} = 0.01984\ N/mm^3$$

The primary stress for the calculation of the stress intensity factor is written as:

$$\sigma^P(x) = (\sigma_0^P + p_c) + \sigma_1^P \left(\frac{x}{t}\right) + \sigma_2^P \left(\frac{x}{t}\right)^2 + \sigma_3^P \left(\frac{x}{t}\right)^3 + \sigma_4^P \left(\frac{x}{t}\right)^4 + (\sigma_5^P + \sigma_6^P)$$

With:

$$\sigma_0^P = P R_i^2 / (R_o^2 - R_i^2) = (3.0)\,(244.47)^2 / \left\{(254.00)^2 - (244.47)^2\right\} = 37.7434\ MPa$$

$$\sigma_5^P = 4 M_x R_o / \pi\,(R_o^4 - R_i^4) = 4(254.00)\,(0.01984) = 20.1583\ MPa$$

$$p_c = \sigma_1^P = \sigma_2^P = \sigma_3^P = \sigma_4^P = \sigma_6^P = 0$$

The membrane and bending components of the primary stress for the calculation of the reference stress are:

$$P_m = \sigma_0^P = 37.7434\ MPa$$

$$P_b = 0\ MPa$$

2) Secondary Stress: See Example 9.6

3) Residual Stress: See Example 9.6

The residual stress for the calculation of the stress intensity factor is written as:

$$\sigma^R(x) = \sigma_0^R + \sigma_1^R\left(\frac{x}{t}\right) + \sigma_2^R\left(\frac{x}{t}\right)^2 + \sigma_3^R\left(\frac{x}{t}\right)^3 + \sigma_4^R\left(\frac{x}{t}\right)^4$$

With:

$$\sigma_0^R = 231.1584 \qquad \sigma_1^R = -608.8177 \qquad \sigma_2^R = -2806.8043$$

$$\sigma_3^R = 8474.7480 \qquad \sigma_4^R = -5084.2398$$

The membrane and bending components of the residual stress for the calculation of the reference stress are:

$$Q_m = \overline{\sigma}_m^r\ \sigma_{ys}^r\ R_r = 92.7000\ MPa$$

$$Q_b = \overline{\sigma}_b^r\ \sigma_{ys}^r\ R_r = -70.9433\ MPa$$

c) STEP 3 – Determine the material properties; yield strength, tensile strength and fracture toughness. See Example 9.6

$$\sigma_{ys} = 240\ MPa$$

$$\sigma_{uts} = 415\ MPa$$

$$K_{IC} = 69.6893\ MPa\sqrt{m}$$

d) STEP 4 – Determine the crack-like flaw dimension from inspection data.

$$a = 4.0\ mm$$

$$2c = 15.0\ mm$$

e) STEP 5 – Modify the primary stress, material fracture toughness, and flaw size using Partial Safety Factors. See Example 9.6

$$P_m = P_m\ PSF_s = (37.7434)\ (1.5) = 56.6150\ MPa$$

$$P_b = P_b\ PSF_s = (0)\ (1.5) = 0\ MPa$$

$$\sigma_0^P = \sigma_0^P\ PSF_s = (37.7434)\ (1.5) = 56.6150\ MPa$$

$$\sigma_5^P = \sigma_5^P\ PSF_s = (20.1583)\ (1.5) = 30.2374\ MPa$$

$$M = M\ PSF_s = 36.8\ (10)^6\ (1.5) = 55.2\ (10)^6\ N\text{–}mm$$

$$K_{mat} = K_{mat}\ /\ PSF_k = (111.4724)/(1.0) = 111.4724\ MPa\sqrt{m}$$

$$a = a\ PSF_a = (4.0)\ (1.0) = 4.0\ mm$$

f) STEP 6 – Compute the reference stress for the primary stress. The reference stress solution for RCSCCE2 is provided in Annex D, paragraph D.5.14.

$$x = a/t = (4.00)/(9.53) = 0.41973$$

$$\tau = t/R_o = (9.53)/(254.0) = 0.03754$$

$$\theta = \pi c / 4R_o = \pi(7.5)/4(254.0) = 0.02319$$

$$\alpha = (a/t)/(1+t/c) = \{(4.00)/(9.53)\}/\{1+[(9.53)/(7.50)]\} = 0.18485$$

Intermediate coefficients for $\sigma_{ref}^{D.5.13}$ are:

$$A = x\left[\frac{(1-\tau)(2-2\tau+x\tau)+(1-\tau+x\tau)^2}{2\{1+(2-\tau)(1-\tau)\}}\right]$$

$$= (0.41973)\left[\frac{(1-0.03754)(2-2(0.03754)+(0.41973)(0.03754))+(1-0.03754+(0.41973)(0.03754))^2}{2\{1+(2-0.03754)(1-0.03754)\}}\right] = 0.2052$$

$$\psi = \arccos[A\sin\theta] = \arccos[0.2052\sin(0.02319)] = 1.5660$$

$$Z = \pi\Big/\left[2\psi - x\theta\left(\frac{2-2\tau+\alpha\tau}{2-\tau}\right)\right]$$

$$= \pi\Big/\left[2(1.5660)-(0.41973)(0.02319)\left(\frac{2-2(0.03754)+(0.41973)(0.03754)}{2-0.03754}\right)\right]$$

$$= 1.0061$$

Leading to:

$$\sigma_{ref}^{D.5.13} = \frac{P_b + \left\{(P_b)^2 + 9\left[Z\ P_m(1-\alpha)^2\right]^2\right\}^{0.5}}{3(1-\alpha)^2}$$

$$= \frac{(0)+\left\{(0)^2+9\left[(1.0061)(56.6150)(1-0.1848)^2\right]^2\right\}^{0.5}}{3(1-0.1848)^2} = 56.9621\ MPa$$

Intermediate coefficient for the bending moment part of the reference stress is:

$$\beta = \frac{\pi}{2}\left[1-\left(\frac{\theta}{\pi}\right)\left(\frac{a}{t}\right)-\frac{P_m}{\sigma_{ys}}\right] = \frac{\pi}{2}\left[1-\left(\frac{0.02319}{\pi}\right)\left(\frac{4.00}{9.53}\right)-\frac{56.6150}{240}\right] = 1.1954$$

Therefore: $\theta + \beta \le \pi$

Leading to:

$$\sigma_{ref}^{P} = \frac{M}{2R_m^2 t\left(2\sin\beta - \frac{a}{t}\sin\theta\right)} + \sigma_{ref}^{D.5.13}$$

$$= \frac{55.2(10)^6}{2(249.235)^2(9.53)\left(2\sin(1.1954)-\frac{4.00}{9.53}\sin(0.02319)\right)} + (56.9621)$$

$$= (25.1881) + (56.9621) = 82.1503\ MPa$$

g) STEP 7 – Compute the Load Ratio (L_r^P) or abscissa of the FAD.

$$\sigma_{ys} = 240.0\ MPa$$

$$L_r^P = \frac{\sigma_{ref}^P}{\sigma_{ys}} = \frac{82.1503}{240.0} = 0.3423$$

h) STEP 8 – Compute K_1^P - The stress intensity factor solution for KCSCCE2 is provided in Annex C, paragraph C.5.14. The influence coefficients required for the assessment are calculated by interpolation between values given in Table C15 for cracks on the outside surface with:

$$a/t = (4.00)/(9.53) = 0.4197$$

$$a/c = (4.00)/(7.50) = 0.5333$$

$$t/R_i = (9.53)/(244.47) = 0.03898$$

They are given in the Table E9.7-1 except coefficients for G_6 since $\sigma_6^P = 0$ and σ_6^R do not exist.

Influence coefficients G_i are calculated by:

$$G_i = A_{0,i} + A_{1,i}\,\beta + A_{2,i}\,\beta^2 + A_{3,i}\,\beta^3 + A_{4,i}\,\beta^4 + A_{5,i}\,\beta^5 + A_{6,i}\,\beta^6$$

With $\beta = 2\phi/\pi$

At the deepest point of the flaw: $\phi = \pi/2 \Rightarrow \beta = 1$: $\begin{Bmatrix} G_0 = 1.1907 \\ G_1 = 0.7396 \\ G_5 = 1.1697 \end{Bmatrix}$

At the surface points of the flaw: $\phi = 0 \Rightarrow \beta = 0$: $\begin{Bmatrix} G_0 = 1.0427 \\ G_1 = 0.1868 \\ G_5 = 1.0152 \end{Bmatrix}$

Table E9.7-1 - Coefficients $A_{i,j}$ used to calculate influence coefficients G_0, G_1 and G_5

t/Ri	a/c	a/t	A_0	A_1	A_2	A_3	A_4	A_5	A_6	G_i
0.01667	0.50000	0.40000	1.00743	-0.76277	3.29300	-2.77665	-2.09303	4.32357	-1.80347	G_0
			0.18103	0.28336	1.32187	-0.89224	-0.86010	1.04597	-0.34298	G_1
			0.98586	-0.61446	2.56591	-1.23971	-3.57874	4.85581	-1.80000	G_5
0.01667	0.50000	0.60000	1.18515	-1.10659	4.06043	-2.94805	-4.21099	7.28042	-2.97626	G_0
			0.23353	0.18294	1.47585	-0.82948	-1.28266	1.49070	-0.49922	G_1
			1.17250	-1.08329	4.02120	-3.32134	-2.84759	5.63241	-2.30435	G_5
0.01667	0.50000	0.41973	1.02496	-0.79668	3.36870	-2.79356	-2.30194	4.61522	-1.91915	G_0
			0.18621	0.27345	1.33706	-0.88605	-0.90178	1.08984	-0.35839	G_1
			1.00427	-0.66070	2.70946	-1.44503	-3.50662	4.93241	-1.84975	G_5
0.01667	1.00000	0.40000	1.30573	-1.00082	1.85727	-0.68080	-2.82315	4.07093	-1.64114	G_0
			0.22510	0.18701	3.10870	-8.69901	12.82733	-10.12680	3.20623	G_1
			1.26934	-0.66722	0.18054	3.06284	-6.83706	5.96279	-1.90000	G_5
0.01667	1.00000	0.60000	1.40975	-1.19587	2.11363	-1.17283	-1.92310	3.17223	-1.29280	G_0
			0.25281	0.49621	0.80298	-0.66098	-1.00590	1.40500	-0.52480	G_1
			1.38218	-0.99828	1.28265	0.07619	-2.24011	2.39070	-0.80000	G_5
0.01667	1.00000	0.41973	1.31599	-1.02006	1.88256	-0.72933	-2.73437	3.98229	-1.60678	G_0
			0.22783	0.21751	2.88127	-7.90617	11.46288	-8.98935	2.83822	G_1
			1.28047	-0.69987	0.28925	2.76825	-6.38364	5.61045	-1.79150	G_5
0.01667	0.53333	0.41973	1.04436	-0.81157	3.26962	-2.65594	-2.33077	4.57303	-1.89832	G_0
			0.18898	0.26972	1.44000	-1.35406	-0.07747	0.41789	-0.14528	G_1
			1.02268	-0.66331	2.54811	-1.16415	-3.69842	4.97762	-1.84586	G_5
0.05000	0.50000	0.40000	1.00499	-0.70402	2.93640	-1.71985	-3.74703	5.62052	-2.20244	G_0
			0.17760	0.32432	1.08515	-0.19893	-1.93119	1.87351	-0.59389	G_1
			0.97454	-0.50753	1.87406	0.82452	-6.83333	7.43256	-2.60000	G_5
0.05000	0.50000	0.60000	1.18168	-1.07416	3.99947	-2.98009	-3.98971	7.05478	-2.90510	G_0
			0.23036	0.19664	1.45258	-0.83048	-1.23276	1.43689	-0.48150	G_1
			1.15801	-0.99308	3.53422	-2.07390	-4.61459	6.94335	-2.69565	G_5
0.05000	0.50000	0.41973	1.02242	-0.74053	3.04126	-1.84415	-3.77097	5.76199	-2.27175	G_0
			0.18281	0.31173	1.12139	-0.26122	-1.86230	1.83044	-0.58280	G_1
			0.99264	-0.55542	2.03781	0.53863	-6.61448	7.38431	-2.60943	G_5
0.05000	1.00000	0.40000	1.30479	-0.99219	1.89257	-0.91007	-2.42228	3.76098	-1.54839	G_0
			0.22353	0.19657	3.03781	-8.49372	12.53922	-9.91357	3.13912	G_1
			1.26590	-0.74610	0.77026	1.03617	-3.50931	3.33954	-1.10000	G_5
0.05000	1.00000	0.60000	1.40401	-1.11885	1.75710	-0.21604	-3.43385	4.38762	-1.67230	G_0
			0.25167	0.49325	0.85599	-0.78686	-0.92838	1.42299	-0.54589	G_1
			1.36983	-0.98068	1.30308	-0.28596	-1.49111	1.75814	-0.60000	G_5
0.05000	1.00000	0.41973	1.31458	-1.00468	1.87921	-0.84161	-2.52206	3.82279	-1.56061	G_0
			0.22630	0.22583	2.82260	-7.73354	11.21083	-8.79537	2.77565	G_1
			1.27615	-0.76924	0.82281	0.90576	-3.31024	3.18355	-1.05068	G_5
0.05000	0.53333	0.41973	1.04190	-0.75814	2.96379	-1.77732	-3.68771	5.63271	-2.22434	G_0
			0.18571	0.30600	1.23481	-0.75938	-0.99076	1.12205	-0.35891	G_1
			1.01154	-0.56968	1.95681	0.56310	-6.39420	7.10425	-2.50552	G_5
0.03898	0.53333	0.41973	1.04271	-0.77580	3.06489	-2.06776	-3.23915	5.28242	-2.11657	G_0
			0.18679	0.29401	1.30264	-0.95596	-0.68886	0.88928	-0.28829	G_1
			1.01522	-0.60063	2.15228	-0.00787	-5.50307	6.40126	-2.28746	G_5

At 45 degrees on the crack front of the flaw: $\phi = \pi/4 \Rightarrow \beta = 0.5$: $\begin{Bmatrix} G_0 = 1.0921 \\ G_1 = 0.5202 \\ G_5 = 1.0723 \end{Bmatrix}$

Influence coefficients G_2, G_3 and G_4 will be needed for the stress intensity factor due to residual stresses. They are calculated per paragraphs C.14.2 and C.14.3 of Annex C for the surface points and the deepest point of the crack.

$$Q = 1.0 + 1.464\left(\frac{a}{c}\right)^{1.65} = 1.0 + 1.464\left(\frac{4.0}{7.5}\right)^{1.65} = 1.5189$$

At the deepest point of the flaw:

$$2\pi/\sqrt{2Q} = 2\pi/\sqrt{2(1.5189)} = 3.6050$$

$$M_1 = \left(2\pi/\sqrt{2Q}\right)\left(3G_1 - G_0\right) - 4.8 = (3.605)\{3(0.7396) - (1.1907)\} - 4.8 = -1.0937$$

$$M_2 = 3.0000$$

$$M_3 = 3\left(2\pi/\sqrt{2Q}\right)\left(G_0 - 2G_1\right) + 1.6 = 3(3.605)\{(1.1907) - 2(0.7396)\} + 1.6 = -1.5200$$

$$\sqrt{2Q}/\pi = \sqrt{2(1.5189)}/\pi = 0.5548$$

$$G_2 = \frac{\sqrt{2Q}}{\pi}\left(\frac{16}{15} + \frac{M_1}{3} + \frac{16M_2}{105} + \frac{M_3}{12}\right)$$

$$= (0.5548)\left(\frac{16}{15} + \frac{-1.0937}{3} + \frac{16(3.000)}{105} + \frac{-1.5200}{12}\right) = 0.5729$$

$$G_3 = \frac{\sqrt{2Q}}{\pi}\left(\frac{32}{35} + \frac{M_1}{4} + \frac{32M_2}{315} + \frac{M_3}{20}\right)$$

$$= (0.5548)\left(\frac{32}{35} + \frac{-1.0937}{4} + \frac{32(3.000)}{315} + \frac{-1.5200}{20}\right) = 0.4825$$

$$G_4 = \frac{\sqrt{2Q}}{\pi}\left(\frac{256}{315} + \frac{M_1}{5} + \frac{256M_2}{3465} + \frac{M_3}{30}\right)$$

$$= (0.5548)\left(\frac{256}{315} + \frac{-1.0937}{5} + \frac{256(3.000)}{3465} + \frac{-1.5200}{30}\right) = 0.4244$$

At the surface points of the flaw:

$$3\pi/\sqrt{Q} = 3\pi/\sqrt{1.5189} = 7.6473$$

$$N_1 = \left(3\pi/\sqrt{Q}\right)\left(2G_0 - 5G_1\right) - 8 = (7.6473)\{2(1.0427) - 5(0.1868)\} - 8 = 0.8057$$

$$N_2 = \left(3\pi/\sqrt{Q}\right)\left(3G_0 - G_1\right) + 15 = 5(7.6473)\{3(1.0427) - (0.1868)\} + 15 = -3.4431$$

$$N_3 = \left(3\pi/\sqrt{Q}\right)\left(3G_0 - 10G_1\right) - 8 = (7.6473)\{3(1.0427) - 10(0.1868)\} - 8 = 1.6374$$

$$\sqrt{Q}/\pi = \sqrt{1.5189}/\pi = 0.3923$$

$$G_2 = \frac{\sqrt{Q}}{\pi}\left(\frac{4}{5}+\frac{2N_1}{3}+\frac{4N_2}{7}+\frac{N_3}{2}\right)$$

$$= (0.3923)\left(\frac{4}{5}+\frac{2(0.8057)}{3}+\frac{4(-3.4431)}{7}+\frac{(1.6374)}{2}\right) = 0.07389$$

$$G_3 = \frac{\sqrt{Q}}{\pi}\left(\frac{4}{7}+\frac{N_1}{2}+\frac{4N_2}{9}+\frac{2N_3}{5}\right)$$

$$= (0.3923)\left(\frac{4}{7}+\frac{(0.8057)}{2}+\frac{4(-3.4431)}{9}+\frac{2(1.6374)}{5}\right) = 0.03883$$

$$G_4 = \frac{\sqrt{Q}}{\pi}\left(\frac{4}{9}+\frac{2N_1}{5}+\frac{4N_2}{11}+\frac{N_3}{3}\right)$$

$$= (0.3923)\left(\frac{4}{9}+\frac{2(0.8057)}{5}+\frac{4(-3.4431)}{11}+\frac{(1.6374)}{3}\right) = 0.02373$$

The influence coefficients G_2, G_3 and G_4 for points at 45 degrees on the crack front of the flaw are calculated per paragraph C.14.4 of Annex C with $\phi = \pi/4$

$$z = \sin\phi = \sin(\pi/4) = 0.7071 \qquad \sqrt{Q}/\pi = \sqrt{1.5189}/\pi = 0.3923$$

$$\delta = \sqrt{1+z} = \sqrt{1+0.7071} = 1.3066 \qquad \pi/\sqrt{Q} = \pi/\sqrt{1.5189} = 2.5491$$

$$\omega = \sqrt{1-z} = \sqrt{1-0.7071} = 0.5412$$

$$\eta = \sqrt{(1/z)-1} = \sqrt{(1/0.7071)-1} = 0.6436$$

$$M_1 = \left(\frac{\pi}{\sqrt{Q}}\right)\frac{\{-1050G_1+105G_0(3+7z)\}}{(168+152z)z^{0.5}\delta} - 4\frac{\{35-70z+35z^2+189\delta z^{0.5}+61\delta z^{1.5}\}}{(168+152z)z^{0.5}\delta}$$

$$= (\pi/\sqrt{Q})(365.4174/302.6658) - 4(258.0439/302.6658) = -0.3327$$

$$M_3 = \left(\frac{\pi}{\sqrt{Q}}\right)\frac{\{-210G_1+90G_0 z\}}{(-21+2z+19z^2)\eta} + 2\frac{\{28+24z-52z^2+44\delta z^{1.5}\}}{(-21+2z+19z^2)\eta}$$

$$= (\pi/\sqrt{Q})(-39.7381/-6.4912) + 2(53.1536/-6.4912) = -0.7720$$

$$G_{21} = 108+180z+576z^2-864z^3+(1056+128M_1)\delta z^{2.5}$$

$$= (217.8091)+(1056+128M_1)(0.5493) = 774.5205$$

$$G_{22} = M_3(45\eta+54\eta z+72\eta z^2-315\omega z^{2.5}+144\eta z^3)$$

$$= M_3(37.7958) = -29.1801$$

$$G_2 = (\sqrt{Q}/\pi)\left(G_{21}+G_{22}\right)/945 = 0.3094$$

$$G_{31} = 880 + 1232z + 2112z^2 + 7040z^3 - 11264z^4 + (13056 + 1280M_1)\delta z^{3.5}$$
$$= (2480.1714) + (13056 + 1280\,M_1)(0.3884) = 7386.2708$$
$$G_{32} = M_3(385\eta + 440\eta z + 528\eta z^2 + 704\eta z^3 - 3465\omega z^{3.5} + 1408\eta z^4)$$
$$= M_3(447.1555) = -345.2247$$
$$G_3 = (\sqrt{Q}/\pi)(G_{31} + G_{32})/13860 = 0.1993$$
$$G_{41} = 1820 + 2340z + 3328z^2 + 5824z^3 + 19968z^4 - 33280z^5 + (37376 + 3072M_1)\delta z^{4.5}$$
$$= (6306.5964) + (37376 + 3072\,M_1)(0.2747) = 16291.9755$$
$$G_{42} = M_3(819\eta + 909\eta z + 1040\eta z^2 + 1248\eta z^3 + 1664\eta z^4 - 9009\omega z^{4.5} + 3328\eta z^5)$$
$$= M_3(1180.8193) = -911.6469$$
$$G_4 = (\sqrt{Q}/\pi)(G_{41} + G_{42})/45045 = 0.1339$$

The stress intensity factors are:

At the deepest point of the flaw:

$$K_I^P = \left[G_0\sigma_0 + G_5\sigma_5\right]\sqrt{\pi a/Q} = \left[(1.1907)(56.6150) + (1.1697)(30.2374)\right]\sqrt{\pi(4.0)/1.5189}$$
$$= 295.6386\ MPa\sqrt{mm} = 9.3489\ MPa\sqrt{m}$$

At the surface points of the flaw:

$$K_I^P = \left[G_0\sigma_0 + G_5\sigma_5\right]\sqrt{\pi a/Q} = \left[(1.0427)(56.6150) + (1.0152)(30.2374)\right]\sqrt{\pi(4.0)/1.5189}$$
$$= 258.0960\ MPa\sqrt{mm} = 8.1617\ MPa\sqrt{m}$$

At 45 degrees on the crack front of the flaw:

$$K_I^P = \left[G_0\sigma_0 + G_5\sigma_5\right]\sqrt{\pi a/Q} = \left[(1.0921)(56.6150) + (1.0723)(30.2374)\right]\sqrt{\pi(4.0)/1.5189}$$
$$= 271.1101\ MPa\sqrt{mm} = 8.5733\ MPa\sqrt{m}$$

i) STEP 9 – Compute the reference stress for secondary stresses. Note that σ_{ref}^{SR} used in this calculation is based on the membrane and bending components of the residual stress (Q_m and Q_b) from STEP 2. Details regarding the calculation of the reference stress are provided in STEP 6 with σ_{ref}^{SR} restricted to its D.5.13 part.

$$\sigma_{ref}^{SR} = \frac{Q_b + \left\{(Q_b)^2 + 9\left[Z\,Q_m(1-\alpha)^2\right]^2\right\}^{0.5}}{3(1-\alpha)^2}$$
$$= \frac{(-70.9433) + \left\{(-70.9433)^2 + 9\left[(1.006)(92.7000)(1-0.1848)^2\right]^2\right\}^{0.5}}{3(1-0.1848)^2} = 64.2388\ MPa$$

j) STEP 10 – Compute K_1^{SR}. Details regarding the calculation of the stress intensity factor are provided in STEP 8.

$$K_I^{SR} = \left[G_0\sigma_0 + G_1\sigma_1\left(\frac{a}{t}\right) + G_2\sigma_2\left(\frac{a}{t}\right)^2 + G_3\sigma_3\left(\frac{a}{t}\right)^3 + G_4\sigma_4\left(\frac{a}{t}\right)^4\right]\sqrt{\pi a/Q}$$

The stress intensity factors are:

At the deepest point of the flaw:

$$K_I^{SR} = \begin{bmatrix} (1.1907)(231.1584) + (0.7396)(-608.8177)\left(\dfrac{4.0}{9.53}\right) \\ +(0.5729)(-2806.8043)\left(\dfrac{4.0}{9.53}\right)^2 + (0.4825)(8474.7480)\left(\dfrac{4.0}{9.53}\right)^3 \\ +(0.4244)(-5084.2398)\left(\dfrac{4.0}{9.53}\right)^4 \end{bmatrix} \sqrt{\pi(4.0)/1.5189}$$

$$= 110.3103\ MPa\sqrt{mm} = 3.4883\ MPa\sqrt{m}$$

At the surface points of the flaw:

$$K_I^{SR} = \begin{bmatrix} (1.0427)(231.1584) + (0.1868)(-608.8177)\left(\dfrac{4.0}{9.53}\right) \\ +(0.0739)(-2806.8043)\left(\dfrac{4.0}{9.53}\right)^2 + (0.0388)(8474.7480)\left(\dfrac{4.0}{9.53}\right)^3 \\ +(0.0237)(-5084.2398)\left(\dfrac{4.0}{9.53}\right)^4 \end{bmatrix} \sqrt{\pi(4.0)/1.5189}$$

$$= 510.1204\ MPa\sqrt{mm} = 16.1314\ MPa\sqrt{m}$$

At 45 degrees on the crack front of the flaw:

$$K_I^{SR} = \begin{bmatrix} (1.0921)(231.1584) + (0.5202)(-608.8177)\left(\dfrac{4.0}{9.53}\right) \\ +(0.3094)(-2806.8043)\left(\dfrac{4.0}{9.53}\right)^2 + (0.1993)(8474.7480)\left(\dfrac{4.0}{9.53}\right)^3 \\ +(0.1339)(-5084.2398)\left(\dfrac{4.0}{9.53}\right)^4 \end{bmatrix} \sqrt{\pi(4.0)/1.5189}$$

$$= 202.1419\ MPa\sqrt{mm} = 6.3923\ MPa\sqrt{m}$$

k) STEP 11 – Compute the plasticity interaction factor, with L_r^P from STEP 7

$$L_r^{SR} = \frac{\sigma_{ref}^{SR}}{\sigma_{ys}} = \frac{64.2388}{240.0} = 0.2677$$

ψ and φ are calculated from Tables 9.3 and 9.5 respectively

$$\begin{Bmatrix} L_r^P &= 0.3423 \\ L_r^{SR} &= 0.2677 \end{Bmatrix} \Rightarrow \begin{Bmatrix} \psi = 0.0186 \\ \varphi = 0.3021 \end{Bmatrix} \quad \Rightarrow \quad \frac{\Phi}{\Phi_0} = 1.0 + \frac{\psi}{\varphi} = 1.0 + \frac{0.0186}{0.3021} = 1.0615$$

Since $0 < \left(L_r^{SR} = 0.2677\right) \le 4.0$, then $\Phi_o = 1.0$ and $\Phi = 1.0615$

l) STEP 12 – Determine toughness ratio or ordinate of the FAD assessment point.

At the deepest point of the flaw: $$K_r = \frac{K_I^P + \Phi\, K_I^{SR}}{K_{mat}} = \frac{9.3489 + (1.0615)(3.4883)}{111.4724} = 0.1171$$

At the surface points of the flaw: $$K_r = \frac{K_I^P + \Phi\, K_I^{SR}}{K_{mat}} = \frac{8.1617 + (1.0615)(16.1314)}{111.4724} = 0.2268$$

At 45 degrees on the crack front: $$K_r = \frac{K_I^P + \Phi\, K_I^{SR}}{K_{mat}} = \frac{8.5733 + (1.0615)(6.3923)}{111.4724} = 0.1378$$

m) STEP 13 – Evaluate the results.

1) STEP 13.1 – Determine the cut-off for the L_r^P -axis of the FAD – See Example 9.6 – $L_{r(\max)}^P = 1.0$

2) STEP 13.2 – Plot the assessment point on the FAD shown in Figure 9.20.

At the deepest point of the flaw: $(L_r^P, K_r) = (0.342, 0.117)$; the point is inside the FAD

At the surface points of the flaw: $(L_r^P, K_r) = (0.342, 0.227)$; the point is inside the FAD

At 45 degrees on the crack front: $(L_r^P, K_r) = (0.342, 0.138)$; the point is inside the FAD

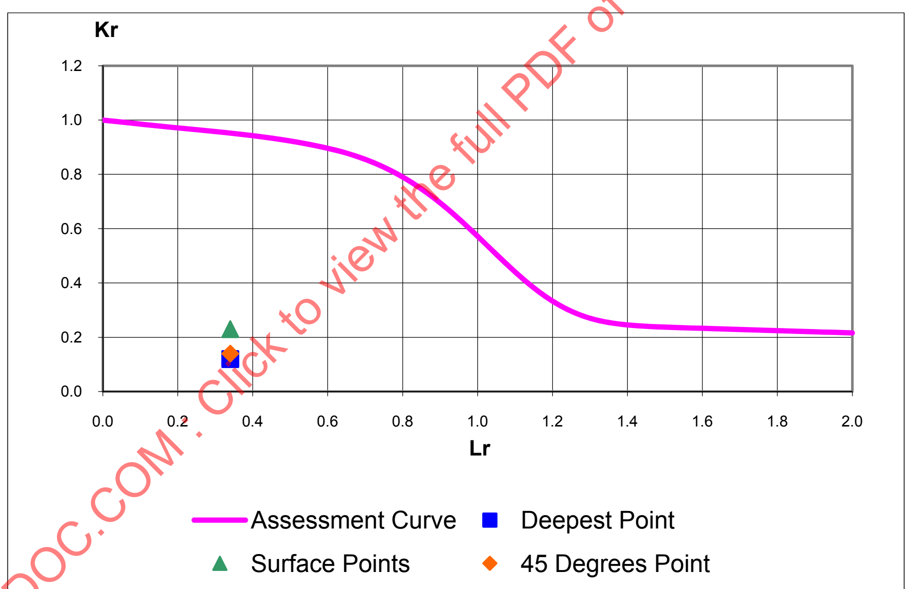


Figure E9.7-1 - FAD with Assessment Points

The Level 2 Assessment Criteria are Satisfied. The pipe is acceptable for continued operation.

9.8 Example Problem 8

A crack-like flaw has been found in the longitudinal seam on the inside surface of a cylindrical pressure vessel during a scheduled turnaround. The vessel and inspection data are provided below. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1, 1998 Edition. Determine if the vessel is acceptable for continued operation.

Vessel Data: Identical to those of Example 9.5 except the operating temperature which is 200°F

The fluid inside the vessel is non aggressive.

Operating Conditions

The vessel is not fully pressurized until the temperature is 40 °F. Below this temperature, the startup pressure remains under 100 psig. At shutdown, the pressure is decreased to 100 psig before letting the temperature drop below 40 °F. In service, the vessel is subject to cyclic loading between no pressure and full pressure.

Inspection Data: Identical to those of Example 9.5

Subcritical crack growth by fatigue is verified: Perform a Level 3 Assessment per paragraph 9.5.1.2 to determine the remaining life of the vessel

The methodology is the following:

a) Perform an assessment of the crack at maximum loading
b) If the assessment point is inside the FAD:
    1) Calculate the stress intensity factors at minimum loading (K_{min}) and at maximum loading (K_{max}), for the surface points and for the deepest point
    2) Calculate the variation of stress intensity factors between minimum and maximum loading ($\Delta K = K_{max} - K_{min}$)
    3) If ΔK is greater than the threshold then calculate the size increment on each dimension (Δa and Δc) by applying the fatigue propagation law with a given number of cycles, update the dimensions of the crack ($a + \Delta a$ and $c + \Delta c$) and the overall number of cycles before repeating the whole procedure.
    4) If ΔK is smaller than the threshold then the crack stops to propagate and the procedure ends
c) If the assessment point is outside the FAD, then the flaw is not acceptable and the procedure ends.
d) The remaining life is the overall number of cycles before the FAD boundary is reached

The overall procedure requires a Level 3 assessment. However, the acceptability of any current flaw can be based on a Level 2 Assessment.

a) STEP 1 – Evaluate operating conditions and determine the pressure, temperature and supplemental loading combinations to be evaluated: See Example 9.5

$$T = 40°F$$

$$P = 200\, psig$$

b) STEP 2 – Determine the stress distribution at the location of the flaw at maximum and at minimum loadings - The primary stress distribution at maximum loading is based on the applied loads. The primary stress distribution at maximum loading corresponds to the full pressure. The primary stress is nil at minimum loading

1) Primary Stress: See Example 9.5

$$P_{m,\max} = P_m = \sigma_m^C = 12000\ psi$$
$$P_{m,\min} = 0\ psi$$
$$P_{b,\max} = P_{m,\min} = P_b = 0\ psi$$

2) Secondary Stress: See Example 9.5: No secondary stresses.
3) Residual Stress: This stress is constant throughout the life of the vessel: See Example 9.5

$$Q_{m,\max} = Q_{m,\min} = Q_m = \sigma^r = 48000\ psi$$
$$Q_{b,\max} = Q_{b,\min} = 0\ psi$$

c) STEP 3 – Determine the material data – For yield strength, tensile strength and fracture toughness, see Example 9.5

$$\sigma_{ys} = 38\ ksi$$
$$\sigma_{uts} = 70\ ksi$$
$$T_{ref} = 43°F \quad (see\ Step\ 4\ of\ the\ Level\ 1\ Assessment\ of\ Example\ 9.5)$$
$$K_{IC} = 33.2 + 2.806\ \exp\left[0.02\left(T - T_{ref} + 100\right)\right]$$
$$= 33.2 + 2.806\ \exp\left[0.02\left(40 - 43 + 100\right)\right] = 52.7263\ ksi\sqrt{in}$$

The crack lies in a ferritic steel in a non aggressive environment. The fatigue crack growth law used in the assessment is given in Annex F paragraph F.5.3.2.a, with a threshold given in paragraph F.5.3.2.d.

$$\frac{da}{dN}(in/cycle) = 8.61\,(10)^{-10}\ (\Delta K\ ksi\sqrt{in})^{3.0} \text{ for } \Delta K > (\Delta K_{th} = 1.8\ ksi\sqrt{in})$$

The number of cycles for each increment must be small enough so as to consider the stress intensity factors as constant for the whole increment. This will be checked during the iterations. The retained value is:

$$\Delta N = 100\ cycles$$

Determine the cut-off for the L_r^P -axis of the FAD – See Example 9.5 - STEP 13.1

$$L_{r(\max)}^P = 1.0$$

d) STEP 4 – Determine the crack-like flaw dimensions from inspection data.

$$a = 0.20\ in$$
$$2c = 3.20\ in \quad \Rightarrow \quad c = 1.60\ in$$

e) STEP 5 – Modify the primary stress, pressure on the crack face, material fracture toughness, and flaw size using Partial Safety Factors. See Example 9.5

$$P_{m,\max} = P_{m,\max}\ PSF_s = (12000)(1.5) = 18000\ psi$$
$$P_{m,\min} = P_{m,\min}\ PSF_s = (0)(1.5) = 0\ psi$$
$$P_{b,\max} = P_{b,\min} = P_b\ PSF_s = (0)(1.5) = 0\ psi$$

$$p_{c,\max} = p_{c,\max}\ PSF_s = (200)(1.5) = 300\ psig$$
$$p_{c,\min} = p_{c,\min}\ PSF_s = (0)(1.5) = 0\ psig$$
$$K_{mat} = K_{mat}\ /\ PSF_k = (85.8720)/(1.0) = 85.8720\ ksi\sqrt{in}$$
$$a = a\ PSF_a = (0.20)(1.0) = 0.20\ \ in$$

ASSESSMENT OF THE CRACK

Note: Since the procedure for growing cracks is very similar but not identical to the procedure for non-growing cracks, the differences are emphasized by using bold characters.

f) STEP 6 – Compute the reference stress for the primary stress at maximum loading. See Example 9.5 The bending stress is nil, therefore the reference stress formula may be written as: $\sigma_{ref}^{P} = M_s^{NS}\ P_{m,\max}$

$$\lambda_a = \frac{1.818\,c}{\sqrt{R_i\ a}} = \frac{1.818(1.60)}{\sqrt{60\ (0.2)}} = 0.8397$$

$$M_t(\lambda_a) = \left[\frac{1.02 + 0.4411\,\lambda_a^{\ 2} + 0.006124\,\lambda_a^{\ 4}}{1.0 + 0.02642\,\lambda_a^{\ 2} + 1.533(10^{-6})\,\lambda_a^{\ 4}}\right]^{0.5}$$

$$= \left[\frac{1.02 + 0.4411(0.8397)^2 + 0.006124(0.8397)^4}{1.0 + 0.02642(0.8397)^2 + 1.533(10^{-6})(0.8397)^4}\right]^{0.5} = 1.1444$$

$$M_s^{NS} = \frac{1}{1 - \left(\dfrac{a}{t}\right) + \left(\dfrac{a}{t}\right)\left(\dfrac{1}{M_t(\lambda_a)}\right)} = \frac{1}{1 - \left(\dfrac{0.20}{1.00}\right) + \left(\dfrac{0.20}{1.00}\right)\left(\dfrac{1}{1.1444}\right)} = 1.0259$$

$$\sigma_{ref}^{P} = M_s^{NS}\ P_{m,\max} = (1.0259)(18000) = 18466.0216\ psi$$

g) STEP 7 – Compute the Load Ratio (L_r^P) or abscissa of the FAD assessment point at maximum loading.

$$\sigma_{ys} = 38\ ksi$$

$$L_r^P = \frac{\sigma_{ref}^{P}}{\sigma_{ys}} = \frac{18466.0216}{38000.0000} = 0.4859$$

h) STEP 8 – Compute K_1^P at maximum loading and at minimum loading for the 2 apex of the flaw. See Example 9.5

The influence coefficients required for the assessment are:

At the deepest point of the flaw $\varphi = 90^o$ $\Rightarrow$ $G_0 = A_{0,0} = 1.191824$

At the surface points of the flaw $\varphi = 0^o$ $\Rightarrow$ $G_0 = \sum_{i=0}^{6} A_{i,0} = 0.414198$

The stress intensity factors are:

At the deepest point of the flaw

$$K^P_{I,\max} = K^P_I = \frac{2\,p\,R_o^2\,G_0}{R_o^2 - R_i^2}\sqrt{\frac{\pi\,a}{Q}} = \frac{2(300)(61)^2(1.191824)}{(61)^2-(60)^2}\sqrt{\frac{\pi(0.20)}{1.0474}} = 17.0325\;ksi\sqrt{in}$$

$$K^P_{I,\min} = 0\;ksi\sqrt{in}$$

At the surface points of the flaw

$$K^P_{I,\max} = K^P_I = \frac{2\,p\,R_o^2\,G_0}{R_o^2 - R_i^2}\sqrt{\frac{\pi\,a}{Q}} = \frac{2(300)(61)^2(0.414198)}{(61)^2-(60)^2}\sqrt{\frac{\pi(0.20)}{1.0474}} = 5.9194\;ksi\sqrt{in}$$

$$K^P_{I,\min} = 0\;ksi\sqrt{in}$$

i) STEP 9 – Compute the reference stress for secondary stresses at maximum loading. See Example 9.5

There is no bending component, therefore: $\sigma^{SR}_{ref} = M_s^{NS}\,Q_{m,\max} = (1.0259)(48000) = 49242.7243\;psi$

j) STEP 10 – Compute K_1^{SR} at maximum loading and at minimum loading for the 2 apex of the flaw. See Example 9.5 – Since the secondary stresses are nil, K_1^{SR} is based only on the residual stresses which are constant with respect to time. The stress intensity factors are:

At the deepest point of the flaw:

$$K^{SR}_{I,\max} = K^{SR}_{I,\min} = K^{SR}_I = G_0\sigma_0\sqrt{\frac{\pi\,a}{Q}} = (1.191824)(48.0)\sqrt{\frac{\pi(0.2)}{1.0474}} = 44.3093\;ksi\sqrt{in}$$

At the surface points of the flaw:

$$K^{SR}_{I,\max} = K^{SR}_{I,\min} = K^{SR}_I = G_0\sigma_0\sqrt{\frac{\pi\,a}{Q}} = (0.414198)(48.0)\sqrt{\frac{\pi(0.2)}{1.0474}} = 15.3989\;ksi\sqrt{in}$$

k) STEP 11 – Compute the plasticity interaction factor at maximum loading. See Example 9.5

$$L_r^{SR} = \frac{\sigma^{SR}_{ref}}{\sigma_{ys}} = \frac{49242.7243}{38000.0000} = 1.2959$$

$$\begin{Bmatrix} L_r^P = 0.4859 \\ L_r^{SR} = 1.2959 \end{Bmatrix} \Rightarrow \begin{Bmatrix} \psi = 0.09086 \\ \varphi = 0.62739 \end{Bmatrix} \Rightarrow \frac{\Phi}{\Phi_0} = 1.0 + \frac{\psi}{\varphi} = 1.0 + \frac{0.09086}{0.62739} = 1.1448$$

Since $0 < \left(L_r^{SR} = 1.2959\right) \le 4.0$, then $\Phi_o = 1.0$ and $\Phi = 1.1448$

l) STEP 12 – Determine toughness ratio (K_r) or ordinate of the FAD assessment point at maximum loading.

At the deepest point of the flaw: $$K_r = \frac{K_I^P + \Phi\,K_I^{SR}}{K_{mat}} = \frac{17.0325 + (1.1448)\,44.3093}{85.8720} = 0.7891$$

At the surface points of the flaw: $$K_r = \frac{K_I^P + \Phi\,K_I^{SR}}{K_{mat}} = \frac{5.9194 + (1.1448)15.3989}{85.8720} = 0.2742$$

m) STEP 13 – Evaluate the results at maximum loading.

Determine the maximum allowable K_r for $L_r^P = 0.4859$:

$$K_{r,\max} = \left[1 - 0.14\left(L_r^P\right)^2\right]\left\{0.3 + 0.7\exp\left[-0.65\left(L_r^P\right)^6\right]\right\}$$

$$= \left[1 - 0.14\left(0.4859\right)^2\right]\left\{0.3 + 0.7\exp\left[-0.65\left(0.4859\right)^6\right]\right\} = 0.9612$$

Check that $K_r \le K_{r,\max}$ and that $L_r^P \le L_{r(\max)}^P$

At the deepest point of the flaw: $(L_r^P, K_r) = (0.4859, 0.7891)$; the point is inside the FAD

At the surface points of the flaw: $(L_r^P, K_r) = (0.4859, 0.2742)$; the point is inside the FAD

Both deepest point and surface points are acceptable, the propagation of the flaw by fatigue is then evaluated.

FATIGUE CRACK GROWTH

n) STEP 14 – Calculate the stress intensity factors at maximum loading and at minimum loading and their variation

At the deepest point of the flaw:

$$K_{\max} = K_{I,\max}^P + K_{I,\max}^{SR} = 17.0325 + 44.3093 = 61.3418\ ksi\sqrt{in}$$

$$K_{\min} = K_{I,\min}^P + K_{I,\min}^{SR} = 0 + 44.3093 = 44.3093\ ksi\sqrt{in}$$

$$\Delta K = K_{\max} - K_{\min} = 61.3418 - 44.3093 = 17.0325\ ksi\sqrt{in}$$

At the surface points of the flaw:

$$K_{\max} = K_{I,\max}^P + K_{I,\max}^{SR} = 5.9194 + 15.3989 = 21.3183\ ksi\sqrt{in}$$

$$K_{\min} = K_{I,\min}^P + K_{I,\min}^{SR} = 0 + 15.3989 = 15.3989\ ksi\sqrt{in}$$

$$\Delta K = K_{\max} - K_{\min} = 21.3183 - 15.3989 = 5.9194\ ksi\sqrt{in}$$

o) STEP 15 – Check that the crack is propagating

At the deepest point of the flaw: $\left(\Delta K = 17.0325\ ksi\sqrt{in}\right) \ge \left(\Delta K_{th} = 1.8\ ksi\sqrt{in}\right)$

At the surface points of the flaw: $\left(\Delta K = 5.9194\ ksi\sqrt{in}\right) \ge \left(\Delta K_{th} = 1.8\ ksi\sqrt{in}\right)$

The crack is propagating in the through thickness direction and in the surface direction

p) STEP 16 – Calculate the size increments in through thickness direction (Δa) and in surface direction (Δc) for the number of cycles in STEP 3.

At the deepest point of the flaw:

$$\Delta a = (\Delta N)\, 8.61\, (10)^{-10}\, (\Delta K)^{3.0} = (100)\, 8.61\, (10)^{-10}\, (17.0325)^{3.0} = 4.254\, (10)^{-4}\ in$$

At the surface points of the flaw:

$$\Delta c = (\Delta N)\, 8.61\, (10)^{-10}\, (\Delta K)^{3.0} = (100)\, 8.61\, (10)^{-10}\, (5.9194)^{3.0} = 1.786\, (10)^{-5}\ in$$

Table E9.8-1 - Fatigue Crack Propagation - Dimensions and Reference Stress Parameters

STEP	18	4 - 18	4 - 18	8	6 - 8	6	6	6
Increment	N	a	c	a/c	a/t	λ_a	M_t	M_s^{NS}
1	0	0.200000	1.600000	0.1250	0.2000	0.8397	1.1444	1.0259
2	100	0.200425	1.600018	0.1253	0.2004	0.8388	1.1441	1.0259
3	200	0.200853	1.600036	0.1255	0.2009	0.8379	1.1439	1.0259
4	300	0.201282	1.600054	0.1258	0.2013	0.8370	1.1436	1.0259
5	400	0.201713	1.600072	0.1261	0.2017	0.8362	1.1433	1.0259
6	500	0.202146	1.600091	0.1263	0.2021	0.8353	1.1431	1.0260
7	600	0.202580	1.600109	0.1266	0.2026	0.8344	1.1428	1.0260
8	700	0.203017	1.600128	0.1269	0.2030	0.8335	1.1426	1.0260
9	800	0.203456	1.600147	0.1271	0.2035	0.8326	1.1423	1.0260
10	900	0.203896	1.600166	0.1274	0.2039	0.8317	1.1420	1.0260
11	1000	0.204339	1.600185	0.1277	0.2043	0.8308	1.1418	1.0260
12	1100	0.204783	1.600204	0.1280	0.2048	0.8299	1.1415	1.0260
13	1200	0.205229	1.600223	0.1283	0.2052	0.8290	1.1412	1.0261
14	1300	0.205678	1.600243	0.1285	0.2057	0.8282	1.1410	1.0261
15	1400	0.206128	1.600263	0.1288	0.2061	0.8273	1.1407	1.0261
16	1500	0.206580	1.600282	0.1291	0.2066	0.8264	1.1404	1.0261
17	1600	0.207034	1.600302	0.1294	0.2070	0.8255	1.1402	1.0261
18	1700	0.207491	1.600323	0.1297	0.2075	0.8246	1.1399	1.0261
19	1800	0.207949	1.600343	0.1299	0.2079	0.8237	1.1396	1.0261
20	1900	0.208409	1.600363	0.1302	0.2084	0.8228	1.1394	1.0262
21	2000	0.208872	1.600384	0.1305	0.2089	0.8219	1.1391	1.0262
22	2100	0.209336	1.600405	0.1308	0.2093	0.8210	1.1389	1.0262
23	2200	0.209803	1.600426	0.1311	0.2098	0.8201	1.1386	1.0262
24	2300	0.210272	1.600447	0.1314	0.2103	0.8192	1.1383	1.0262
25	2400	0.210742	1.600468	0.1317	0.2107	0.8183	1.1381	1.0262
26	2500	0.211215	1.600490	0.1320	0.2112	0.8174	1.1378	1.0263
27	2600	0.211690	1.600511	0.1323	0.2117	0.8164	1.1375	1.0263
28	2700	0.212168	1.600533	0.1326	0.2122	0.8155	1.1373	1.0263
29	2800	0.212647	1.600555	0.1329	0.2126	0.8146	1.1370	1.0263
30	2900	0.213129	1.600577	0.1332	0.2131	0.8137	1.1367	1.0263
40	3900	0.218067	1.600809	0.1362	0.2181	0.8046	1.1341	1.0265
50	4900	0.223239	1.601061	0.1394	0.2232	0.7953	1.1314	1.0266
60	5900	0.228661	1.601335	0.1428	0.2287	0.7860	1.1287	1.0268
70	6900	0.234348	1.601634	0.1463	0.2343	0.7765	1.1261	1.0269
80	7900	0.240319	1.601961	0.1500	0.2403	0.7670	1.1234	1.0271
90	8900	0.246592	1.602319	0.1539	0.2466	0.7573	1.1207	1.0273
100	9900	0.253189	1.602714	0.1580	0.2532	0.7476	1.1180	1.0275
110	10900	0.260129	1.603149	0.1623	0.2601	0.7377	1.1153	1.0276
112	11100	0.261561	1.603242	0.1631	0.2616	0.7358	1.1148	1.0277
114	11300	0.263007	1.603336	0.1640	0.2630	0.7338	1.1143	1.0277
116	11500	0.264469	1.603433	0.1649	0.2645	0.7318	1.1137	1.0278
118	11700	0.265945	1.603531	0.1658	0.2659	0.7298	1.1132	1.0278
120	11900	0.267437	1.603631	0.1668	0.2674	0.7278	1.1127	1.0278
121	12000	0.268189	1.603682	0.1672	0.2682	0.7268	1.1124	1.0279
122	12100	0.268945	1.603734	0.1677	0.2689	0.7258	1.1121	1.0279
123	12200	0.269705	1.603786	0.1682	0.2697	0.7248	1.1119	1.0279
124	12300	0.270468	1.603838	0.1686	0.2705	0.7238	1.1116	1.0279

Table E9.8-2 - Fatigue Crack Propagation -Reference Stresses and Plasticity Interaction Factors

STEP	6	7	9	11	11	11	11
Increment	σ_{ref}^{P}	L_r^P	σ_{ref}^{SR}	L_r^{SR}	φ	ψ	Φ
1	18466.0	0.48595	49242.7	1.29586	0.627391	0.090855	1.14481
2	18466.3	0.48595	49243.4	1.29588	0.627389	0.090857	1.14482
3	18466.5	0.48596	49244.1	1.29590	0.627387	0.090859	1.14482
4	18466.8	0.48597	49244.7	1.29591	0.627385	0.090860	1.14482
5	18467.0	0.48597	49245.4	1.29593	0.627383	0.090862	1.14483
6	18467.3	0.48598	49246.1	1.29595	0.627381	0.090864	1.14483
7	18467.5	0.48599	49246.8	1.29597	0.627379	0.090866	1.14483
8	18467.8	0.48599	49247.5	1.29599	0.627376	0.090868	1.14484
9	18468.1	0.48600	49248.1	1.29600	0.627374	0.090870	1.14484
10	18468.3	0.48601	49248.8	1.29602	0.627372	0.090871	1.14484
11	18468.6	0.48601	49249.5	1.29604	0.627370	0.090873	1.14485
12	18468.8	0.48602	49250.2	1.29606	0.627368	0.090875	1.14485
13	18469.1	0.48603	49250.9	1.29608	0.627366	0.090877	1.14485
14	18469.3	0.48604	49251.6	1.29609	0.627363	0.090879	1.14486
15	18469.6	0.48604	49252.3	1.29611	0.627361	0.090881	1.14486
16	18469.9	0.48605	49253.0	1.29613	0.627359	0.090882	1.14487
17	18470.1	0.48606	49253.7	1.29615	0.627357	0.090884	1.14487
18	18470.4	0.48606	49254.4	1.29617	0.627355	0.090886	1.14487
19	18470.7	0.48607	49255.1	1.29619	0.627353	0.090888	1.14488
20	18470.9	0.48608	49255.8	1.29620	0.627350	0.090890	1.14488
21	18471.2	0.48608	49256.5	1.29622	0.627348	0.090892	1.14488
22	18471.4	0.48609	49257.2	1.29624	0.627346	0.090894	1.14489
23	18471.7	0.48610	49257.9	1.29626	0.627344	0.090896	1.14489
24	18472.0	0.48610	49258.6	1.29628	0.627342	0.090897	1.14489
25	18472.2	0.48611	49259.3	1.29630	0.627339	0.090899	1.14490
26	18472.5	0.48612	49260.0	1.29632	0.627337	0.090901	1.14490
27	18472.8	0.48613	49260.7	1.29633	0.627335	0.090903	1.14490
28	18473.0	0.48613	49261.4	1.29635	0.627333	0.090905	1.14491
29	18473.3	0.48614	49262.2	1.29637	0.627330	0.090907	1.14491
30	18473.6	0.48615	49262.9	1.29639	0.627328	0.090909	1.14491
40	18476.3	0.48622	49270.2	1.29658	0.627305	0.090928	1.14495
50	18479.1	0.48629	49277.6	1.29678	0.627282	0.090948	1.14499
60	18482.0	0.48637	49285.3	1.29698	0.627258	0.090969	1.14503
70	18484.9	0.48645	49293.1	1.29719	0.627234	0.090990	1.14507
80	18488.0	0.48653	49301.2	1.29740	0.627208	0.091011	1.14511
90	18491.1	0.48661	49309.6	1.29762	0.627182	0.091033	1.14515
100	18494.3	0.48669	49318.1	1.29785	0.627156	0.091056	1.14519
110	18497.6	0.48678	49327.0	1.29808	0.627128	0.091080	1.14523
112	18498.3	0.48680	49328.8	1.29813	0.627122	0.091085	1.14524
114	18499.0	0.48681	49330.6	1.29817	0.627117	0.091090	1.14525
116	18499.7	0.48683	49332.4	1.29822	0.627111	0.091094	1.14526
118	18500.3	0.48685	49334.2	1.29827	0.627105	0.091099	1.14527
120	18501.0	0.48687	49336.1	1.29832	0.627099	0.091104	1.14528
121	18501.4	0.48688	49337.0	1.29834	0.627097	0.091107	1.14528
122	18501.7	0.48689	49338.0	1.29837	0.627094	0.091109	1.14529
123	18502.1	0.48690	49338.9	1.29839	0.627091	0.091112	1.14529
124	18502.4	0.48691	49339.8	1.29842	0.627088	0.091114	1.14530

Table E9.8-3 - Fatigue Crack Propagation - Parameters and Stress Intensity Factors

STEP	8	8	8	8	8	10	10
Increment	Q	G_0 *deep*	G_0 *surf*	K_I^P *deep*	K_I^P *surf*	K_I^{SR} *deep*	K_I^{SR} *surf*
1	1.04736	1.19182	0.41420	17.0325	5.9194	44.3093	15.3989
2	1.04753	1.19237	0.41482	17.0570	5.9340	44.3731	15.4371
3	1.04770	1.19291	0.41544	17.0816	5.9488	44.4371	15.4755
4	1.04786	1.19346	0.41606	17.1063	5.9636	44.5013	15.5140
5	1.04803	1.19400	0.41669	17.1311	5.9785	44.5657	15.5528
6	1.04820	1.19455	0.41732	17.1559	5.9935	44.6303	15.5918
7	1.04837	1.19510	0.41795	17.1809	6.0086	44.6952	15.6310
8	1.04854	1.19565	0.41859	17.2059	6.0237	44.7603	15.6703
9	1.04871	1.19620	0.41923	17.2310	6.0389	44.8255	15.7099
10	1.04889	1.19675	0.41987	17.2562	6.0542	44.8910	15.7497
11	1.04906	1.19730	0.42052	17.2814	6.0696	44.9567	15.7897
12	1.04924	1.19786	0.42117	17.3068	6.0850	45.0227	15.8299
13	1.04941	1.19841	0.42182	17.3322	6.1006	45.0888	15.8704
14	1.04959	1.19897	0.42247	17.3577	6.1162	45.1552	15.9110
15	1.04977	1.19953	0.42313	17.3833	6.1319	45.2218	15.9519
16	1.04995	1.20008	0.42379	17.4090	6.1477	45.2886	15.9930
17	1.05013	1.20064	0.42446	17.4347	6.1636	45.3556	16.0342
18	1.05031	1.20121	0.42512	17.4606	6.1795	45.4229	16.0758
19	1.05049	1.20177	0.42579	17.4865	6.1956	45.4903	16.1175
20	1.05068	1.20233	0.42647	17.5125	6.2117	45.5580	16.1595
21	1.05086	1.20290	0.42714	17.5386	6.2279	45.6259	16.2016
22	1.05105	1.20346	0.42783	17.5648	6.2442	45.6941	16.2441
23	1.05123	1.20403	0.42851	17.5911	6.2606	45.7624	16.2867
24	1.05142	1.20460	0.42920	17.6175	6.2771	45.8310	16.3296
25	1.05161	1.20516	0.42989	17.6439	6.2937	45.8999	16.3727
26	1.05180	1.20573	0.43058	17.6705	6.3103	45.9689	16.4160
27	1.05199	1.20631	0.43128	17.6971	6.3271	46.0382	16.4596
28	1.05218	1.20688	0.43198	17.7238	6.3439	46.1077	16.5034
29	1.05238	1.20745	0.43268	17.7507	6.3608	46.1775	16.5474
30	1.05257	1.20803	0.43339	17.7775	6.3779	46.2474	16.5917
40	1.05458	1.21383	0.44067	18.0515	6.5534	46.9600	17.0483
50	1.05672	1.21974	0.44832	18.3346	6.7389	47.6966	17.5310
60	1.05899	1.22574	0.45637	18.6273	6.9353	48.4579	18.0420
70	1.06142	1.23184	0.46486	18.9296	7.1435	49.2445	18.5834
80	1.06400	1.23801	0.47381	19.2419	7.3643	50.0569	19.1579
90	1.06675	1.24425	0.48327	19.5643	7.5988	50.8957	19.7679
100	1.06970	1.25053	0.49326	19.8970	7.8481	51.7610	20.4165
110	1.07284	1.25684	0.50382	20.2398	8.1134	52.6530	21.1067
112	1.07350	1.25810	0.50601	20.3096	8.1685	52.8345	21.2500
114	1.07416	1.25937	0.50822	20.3798	8.2243	53.0171	21.3952
116	1.07484	1.26063	0.51046	20.4504	8.2809	53.2008	21.5422
118	1.07552	1.26189	0.51272	20.5214	8.3381	53.3855	21.6912
120	1.07621	1.26315	0.51501	20.5928	8.3961	53.5713	21.8420
121	1.07656	1.26378	0.51616	20.6287	8.4254	53.6645	21.9181
122	1.07692	1.26441	0.51732	20.6646	8.4548	53.7580	21.9948
123	1.07727	1.26503	0.51849	20.7007	8.4845	53.8518	22.0719
124	1.07763	1.26566	0.51967	20.7368	8.5143	53.9459	22.1496

Table E9.8-4 - Fatigue Crack Propagation - Evaluation of Result and Propagation

STEP	12	12	13	14	14	16	16	17	17
Incr.	K_r *deep*	K_r *surf*	K_r *allow*	ΔK *deep*	ΔK *surf*	Δa	Δc	Check Increment Size	
								deep	*surf*
1	0.78906	0.27423	0.96117	17.0325	5.9194	4.254E-04	1.786E-05	N.A	N.A
2	0.79020	0.27491	0.96117	17.0570	5.9340	4.273E-04	1.799E-05	0.146	0.045
3	0.79134	0.27559	0.96117	17.0816	5.9488	4.291E-04	1.813E-05	0.146	0.045
4	0.79249	0.27628	0.96117	17.1063	5.9636	4.310E-04	1.826E-05	0.146	0.045
5	0.79364	0.27697	0.96117	17.1311	5.9785	4.329E-04	1.840E-05	0.146	0.045
6	0.79479	0.27766	0.96116	17.1559	5.9935	4.348E-04	1.854E-05	0.146	0.045
7	0.79595	0.27836	0.96116	17.1809	6.0086	4.367E-04	1.868E-05	0.147	0.045
8	0.79711	0.27906	0.96116	17.2059	6.0237	4.386E-04	1.882E-05	0.147	0.045
9	0.79827	0.27977	0.96116	17.2310	6.0389	4.405E-04	1.896E-05	0.147	0.045
10	0.79944	0.28048	0.96116	17.2562	6.0542	4.424E-04	1.911E-05	0.147	0.045
11	0.80061	0.28119	0.96116	17.2814	6.0696	4.444E-04	1.925E-05	0.147	0.045
12	0.80179	0.28191	0.96116	17.3068	6.0850	4.463E-04	1.940E-05	0.147	0.045
13	0.80297	0.28263	0.96115	17.3322	6.1006	4.483E-04	1.955E-05	0.148	0.045
14	0.80415	0.28335	0.96115	17.3577	6.1162	4.503E-04	1.970E-05	0.148	0.045
15	0.80534	0.28408	0.96115	17.3833	6.1319	4.523E-04	1.985E-05	0.148	0.045
16	0.80653	0.28481	0.96115	17.4090	6.1477	4.543E-04	2.001E-05	0.148	0.046
17	0.80772	0.28555	0.96115	17.4347	6.1636	4.563E-04	2.016E-05	0.148	0.046
18	0.80892	0.28629	0.96115	17.4606	6.1795	4.583E-04	2.032E-05	0.148	0.046
19	0.81013	0.28703	0.96115	17.4865	6.1956	4.604E-04	2.048E-05	0.149	0.046
20	0.81133	0.28778	0.96114	17.5125	6.2117	4.624E-04	2.064E-05	0.149	0.046
21	0.81255	0.28853	0.96114	17.5386	6.2279	4.645E-04	2.080E-05	0.149	0.046
22	0.81376	0.28929	0.96114	17.5648	6.2442	4.666E-04	2.096E-05	0.149	0.046
23	0.81498	0.29005	0.96114	17.5911	6.2606	4.687E-04	2.113E-05	0.149	0.046
24	0.81620	0.29081	0.96114	17.6175	6.2771	4.708E-04	2.130E-05	0.150	0.046
25	0.81743	0.29158	0.96114	17.6439	6.2937	4.729E-04	2.146E-05	0.150	0.046
26	0.81866	0.29235	0.96114	17.6705	6.3103	4.751E-04	2.164E-05	0.150	0.046
27	0.81990	0.29313	0.96113	17.6971	6.3271	4.772E-04	2.181E-05	0.150	0.046
28	0.82114	0.29391	0.96113	17.7238	6.3439	4.794E-04	2.198E-05	0.150	0.046
29	0.82238	0.29470	0.96113	17.7507	6.3608	4.816E-04	2.216E-05	0.150	0.047
30	0.82363	0.29549	0.96113	17.7775	6.3779	4.837E-04	2.234E-05	0.151	0.047
40	0.83634	0.30362	0.96111	18.0515	6.5534	5.065E-04	2.423E-05	0.152	0.047
50	0.84948	0.31223	0.96110	18.3346	6.7389	5.307E-04	2.635E-05	0.154	0.048
60	0.86306	0.32134	0.96108	18.6273	6.9353	5.565E-04	2.872E-05	0.156	0.049
70	0.87709	0.33099	0.96107	18.9296	7.1435	5.840E-04	3.139E-05	0.158	0.050
80	0.89159	0.34123	0.96105	19.2419	7.3643	6.134E-04	3.439E-05	0.160	0.051
90	0.90655	0.35210	0.96103	19.5643	7.5988	6.448E-04	3.778E-05	0.163	0.052
100	0.92199	0.36367	0.96102	19.8970	7.8481	6.782E-04	4.162E-05	0.165	0.053
110	0.93790	0.37597	0.96100	20.2398	8.1134	7.139E-04	4.599E-05	0.167	0.054
112	0.94114	0.37853	0.96100	20.3096	8.1685	7.213E-04	4.693E-05	0.168	0.054
114	0.94440	0.38112	0.96099	20.3798	8.2243	7.288E-04	4.790E-05	0.168	0.054
116	0.94768	0.38374	0.96099	20.4504	8.2809	7.364E-04	4.889E-05	0.169	0.054
118	0.95098	0.38639	0.96098	20.5214	8.3381	7.441E-04	4.991E-05	0.169	0.054
120	0.95429	0.38908	0.96098	20.5928	8.3961	7.519E-04	5.096E-05	0.170	0.055
121	0.95596	0.39044	0.96098	20.6287	8.4254	7.558E-04	5.150E-05	0.170	0.055
122	0.95762	0.39181	0.96098	20.6646	8.4548	7.598E-04	5.204E-05	0.170	0.055
123	0.95930	0.39318	0.96097	20.7007	8.4845	7.638E-04	5.259E-05	0.171	0.055
124	0.96098	0.39457	0.96097	20.7368	8.5143	7.678E-04	5.314E-05	0.171	0.055

q) STEP 17 – Check that the number of cycles is small enough for the stress intensity factors to be considered as constant during the increment.

1) Check on crack dimensions:

$$\Delta a \leq 0.5\,\%\,(a)\,? \Rightarrow 4.254\,(10)^{-4} \leq 0.005\,(0.2\,)\,? \Rightarrow 4.254\,(10)^{-4}\,in \leq 10.0\,(10)^{-4}\,in\ \ ? \Rightarrow True$$

$$\Delta c \leq 0.5\,\%\,(a)\,? \Rightarrow 1.786\,(10)^{-5} \leq 0.005\,(0.2\,)\,? \Rightarrow 1.786\,(10)^{-5}\,in \leq 10.0\,(10)^{-4}\,in\ \ ? \Rightarrow True$$

2) Check on stress intensity factors: (This does not apply to the 1st increment)

ΔK (at increment k+1) - ΔK (at increment k) $\leq$ 1% ΔK (at increment k) ?

For the second increment (see Tables E9.8-1 to E9.8-4 with detailed results of all increments):

At the deepest point of the flaw: $\left(17.0570 - 17.0325 = 0.0245\right) \leq \left(1\%\,17.0325 = 0.1703\right) \Rightarrow True$

At the surface points of the flaw: $\left(5.9340 - 5.9194 = 0.0146\right) \leq \left(1\%\ \ 5.9194 = 0.0592\right) \Rightarrow True$

r) STEP 18 – Increment crack dimensions and total number of cycles

$$a_{k+1} = a_k + (\Delta a)_k = 0.20 + 4.254\,(10)^{-4} = 0.200425\ in$$

$$c_{k+1} = c_k + (\Delta c)_k = 1.60 + 1.786\,(10)^{-5} = 1.600018\ in$$

$$N_{k+1} = N_k + (\Delta N) = 0 + 100 = 100\,cycles$$

s) Repeat STEPs 6 to 18 until the FAD boundary is reached.

The detailed results obtained with Microsoft Excel are given in Tables E9.8-1 to E9.8-4.

The check on stress intensity factors is written as:

$(1.01)\,\Delta K$ (at increment k) - ΔK (at increment k+1) ≥ 0

Note: Due to crack size increments used in the crack propagation analysis, double precision is needed to ensure accuracy

Table E9.8-4 shows that the assessment point is outside the FAD at increment number 124. Therefore the allowable number of cycles is given by increment number 123, leading to:

The remaining life of the vessel corresponds to 12200 cycles between no pressure and full pressure. An additional safety factor on this number of cycles is recommended for actual vessel operation.

9.9 Example Problem 9

A crack-like flaw has been found in the base metal of a vessel. In order to take advantage of the actual properties of the material it is decided to perform a Level 3 Method B Assessment.

Determine the material-specific FAD used in the Level 3 Method B Assessment per paragraph 9.4.4.1 for the material of the vessel

a) STEP 1 – Obtain the engineering stress-strain curve data for the material of the vessel and determine the 0.2% offset yield strength, tensile strength and modulus of elasticity.

These data are obtained from test. The engineering stresses (σ_e) and engineering strains (ε_e) are smoothened. They are given in columns 2 and 3 of Table E9.9-1 and are represented by the curve in Figure E9.9-1. Not all necessary values are output by the test. Missing values are obtained by interpolation; they are printed in bold characters.

The other material properties are:

- 0.2% offset yield strength: $\sigma_{ys} = 33.9\ ksi$
- tensile strength: $\sigma_{uts} = 80.0\ ksi$
- modulus of elasticity: $E_y = 29350\ ksi$

b) STEP 2 – Convert the engineering stress-strain curve into a true stress strain curve as shown in Annex F, paragraph F.2.3.2. The true stresses (σ_t) and true strains (ε_t) are given in columns 4 and 5 of Table E9.9-1.

For $\sigma_e / \sigma_{ys} = 0.9$:

$$\sigma_t = (1+\varepsilon_e)\,\sigma_e = (1+0.001566)\,(30.510) = 30.5578\ ksi$$

$$\varepsilon_t = \ln\left[1+\varepsilon_e\right] = \ln\left[1+0.001566\right] = 0.001564 = 0.1564\ \%$$

c) STEP 3 – Determine the material-specific FAD - $K_r(0.0000) = 1.000$

For $\sigma_e / \sigma_{ys} = 0.9$:

$$L_r = \sigma_t / \sigma_{ys} = 30.5578 / 33.90 = 0.9014$$

$$K_r = \left(\frac{E_y\,\varepsilon_{ref}}{L_r\,\sigma_{ys}} + \frac{L_r^3\,\sigma_{ys}}{2\,E_y\,\varepsilon_{ref}}\right)^{-0.5} = \left(\frac{29350\,(0.001564)}{(0.9014)\,(33.90)} + \frac{(0.9014)^3\,(33.90)}{2\,(29350)\,(0.001564)}\right)^{-0.5} = 0.7510$$

The values for the other σ_e / σ_{ys} ratios are given in columns 6 and 7 of Table E9.9-1. Column 8 gives the value of K_r for the Level 2 FAD as given in Figure 9.20.

The resulting FAD is shown in Figure E9.9-2.

For $\sigma_e / \sigma_{ys} = 0.9$:

$$K_{r,\max} = \left[1-0.14\left(L_r\right)^2\right]\left\{0.3+0.7\exp\left[-0.65\left(L_r\right)^6\right]\right\}$$

$$= \left[1-0.14\left(0.9014\right)^2\right]\left\{0.3+0.7\exp\left[-0.65\left(0.9014\right)^6\right]\right\} = 0.6937$$

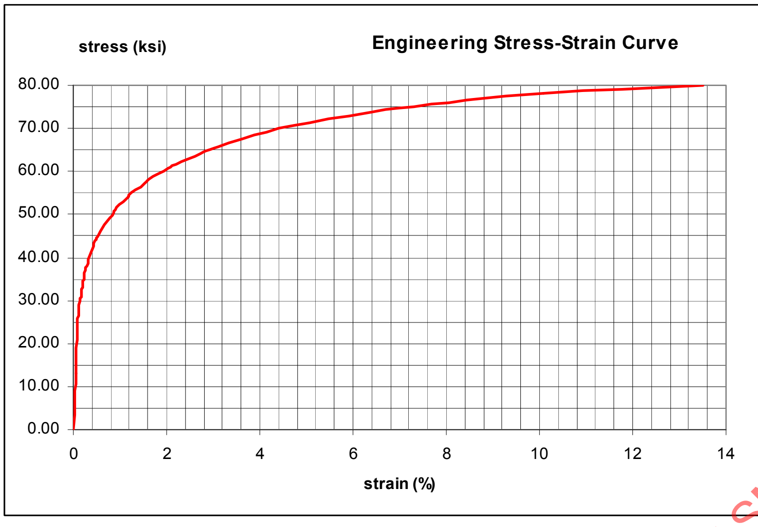


Figure E9.9-1 - Engineering Stress-Strain Curve of the Material of the Vessel

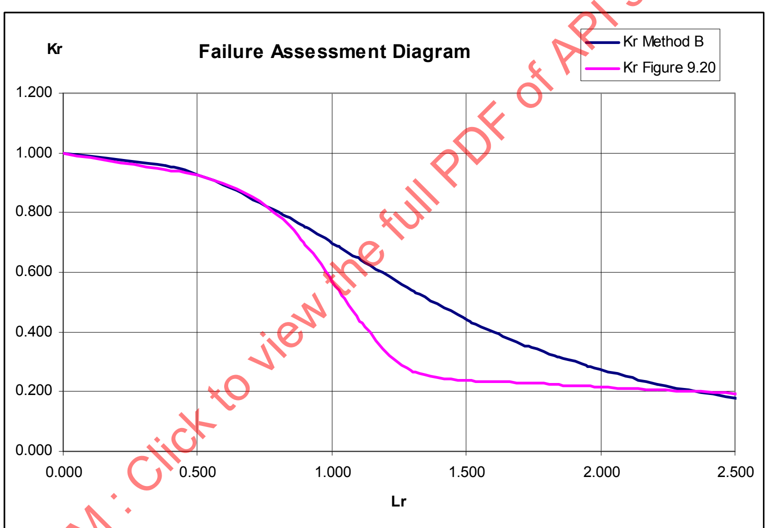


Figure E9.9-2 - Material Dependent of the FAD used in the Level 3 Method B Assessment of the Vessel

Table E9.9-1 - Stress-Strain Curves and Failure Assessment Diagram Parameters

σ_e / σ_{ys}	σ_e (ksi)	ε_e (%)	σ_t (ksi)	ε_t (%)	$L_r = \sigma_t / \sigma_{ys}$	K_r Method B	K_r Figure 9.20
0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	1.0000	1.0000
0.3833	12.9941	0.0450	13.0000	0.0450	0.3835	0.9584	0.9449
0.4128	13.9932	0.0488	14.0000	0.0487	0.4130	0.9512	0.9401
0.5012	16.9897	0.0607	17.0000	0.0607	0.5015	0.9254	0.9231
0.6190	20.9833	0.0795	21.0000	0.0795	0.6195	0.8825	0.8902
0.7073	23.9767	0.0974	24.0000	0.0973	0.7080	0.8449	0.8513
0.8000	**27.1200**	**0.1215**	27.1530	0.1214	0.8010	0.8014	0.7898
0.8249	27.9639	0.1292	28.0000	0.1291	0.8260	0.7893	0.7689
0.8836	29.9551	0.1499	30.0000	0.1498	0.8850	0.7597	0.7116
0.9000	**30.5100**	**0.1566**	30.5578	0.1564	0.9014	0.7510	0.6937
0.9130	30.9499	0.1618	31.0000	0.1617	0.9145	0.7445	0.6790
0.9423	31.9441	0.1749	32.0000	0.1748	0.9440	0.7291	0.6439
0.9716	32.9376	0.1893	33.0000	0.1892	0.9735	0.7136	0.6069
1.0000	33.9000	0.2051	33.9695	0.2049	1.0021	0.6977	0.5696
1.0200	**34.5780**	**0.2167**	34.6529	0.2164	1.0222	0.6871	0.5428
1.0302	34.9223	0.2225	35.0000	0.2223	1.0324	0.6820	0.5292
1.0594	35.9132	0.2416	36.0000	0.2413	1.0619	0.6661	0.4900
1.0886	36.9031	0.2625	37.0000	0.2622	1.0914	0.6501	0.4518
1.1000	**37.2900**	**0.2715**	37.3912	0.2711	1.1030	0.6436	0.4373
1.1178	37.8918	0.2854	38.0000	0.2850	1.1209	0.6341	0.4155
1.2094	41.0000	0.3680	41.1509	0.3673	1.2139	0.5871	0.3216
1.2918	43.7918	0.4754	44.0000	0.4742	1.2979	0.5400	0.2711
1.3000	**44.0700**	**0.4874**	44.2848	0.4862	1.3063	0.5355	0.2678
1.3206	44.7683	0.5176	45.0000	0.5163	1.3274	0.5249	0.2605
1.4065	47.6818	0.6673	48.0000	0.6651	1.4159	0.4815	0.2435
1.4916	50.5666	0.8570	51.0000	0.8534	1.5044	0.4410	0.2371
1.5000	**50.8500**	**0.8789**	51.2969	0.8750	1.5132	0.4371	0.2367
1.5198	51.5206	0.9305	52.0000	0.9262	1.5339	0.4282	0.2357
1.6000	**54.2400**	**1.1762**	54.8779	1.1693	1.6188	0.3933	0.2320
1.6034	54.3551	1.1865	55.0000	1.1796	1.6224	0.3921	0.2319
1.6814	57.0000	1.5035	57.8570	1.4923	1.7067	0.3589	0.2283
1.7000	**57.6300**	**1.5757**	58.5381	1.5634	1.7268	0.3529	0.2275
1.7126	58.0568	1.6246	59.0000	1.6115	1.7404	0.3491	0.2269
1.7923	60.7603	2.0402	62.0000	2.0197	1.8289	0.3205	0.2232
1.8000	**61.0200**	**2.0865**	62.2932	2.0650	1.8376	0.3178	0.2228
1.8184	61.6451	2.1979	63.0000	2.1741	1.8584	0.3116	0.2219
1.8951	64.2427	2.7355	66.0000	2.6987	1.9469	0.2868	0.2182
1.9000	**64.4100**	**2.7756**	66.1978	2.7378	1.9527	0.2852	0.2180
1.9200	65.0877	2.9381	67.0000	2.8958	1.9764	0.2791	0.2170
2.0161	68.3466	3.8823	71.0000	3.8089	2.0944	0.2509	0.2120
2.1055	71.3780	5.0745	75.0000	4.9499	2.2124	0.2265	0.2071
2.3044	78.1176	10.0904	86.0000	9.6132	2.5369	0.1743	0.1935
2.3599	80.0000	13.5204	90.8163	12.6812	2.6789	0.1560	0.1875

9.10 Example Problem 10

A crack-like flaw has been found in a forged nozzle of a cylindrical pressure vessel on its inside surface during a scheduled turnaround. The vessel and inspection data are provided below. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1, 2001 Edition. Determine if the vessel is acceptable for continued operation.

Vessel Data

- Material = $SA\text{-}182\ Grade\ F304\ Year\ 2001$
- Design Conditions = $6.0\ MPa\ (60\ bar)\ @\ 20°C$
- Shell Mean Diameter = $1000\ mm$
- Shell Fabricated Thickness = $25\ mm$
- Nozzle Mean Diameter = $500\ mm$
- Nozzle Fabricated Thickness = $20\ mm$
- Angle between Shell and Nozzle = 90 degrees
- Fillet Radius between Shell and Nozzle = $10\ mm$ (outside surface)
- Fillet Radius between Shell and Nozzle = $5\ mm$ (inside surface)
- Uniform Metal Loss = $0.0\ mm$
- Future Corrosion Allowance = $0.0\ mm$
- Weld Joint Efficiency = 1.0
- PWHT = No

Inspection Data

The flaw is a corner crack located in the longitudinal plane of the nozzle. Its shape is quarter-elliptical. Its dimensions were established by MT leading to a small axis of 10 mm on the shell side and 20 mm on the nozzle side with a center at the intersection of the inside surfaces of the shell and nozzle without fillet radius (see Figure E9.10-1). The distance of the crack-like flaw to the nearest weld seam is large enough to neglect the residual stresses due to welding.

It is decided to perform a Level 3 Method C Assessment per paragraph 9.4.4.1

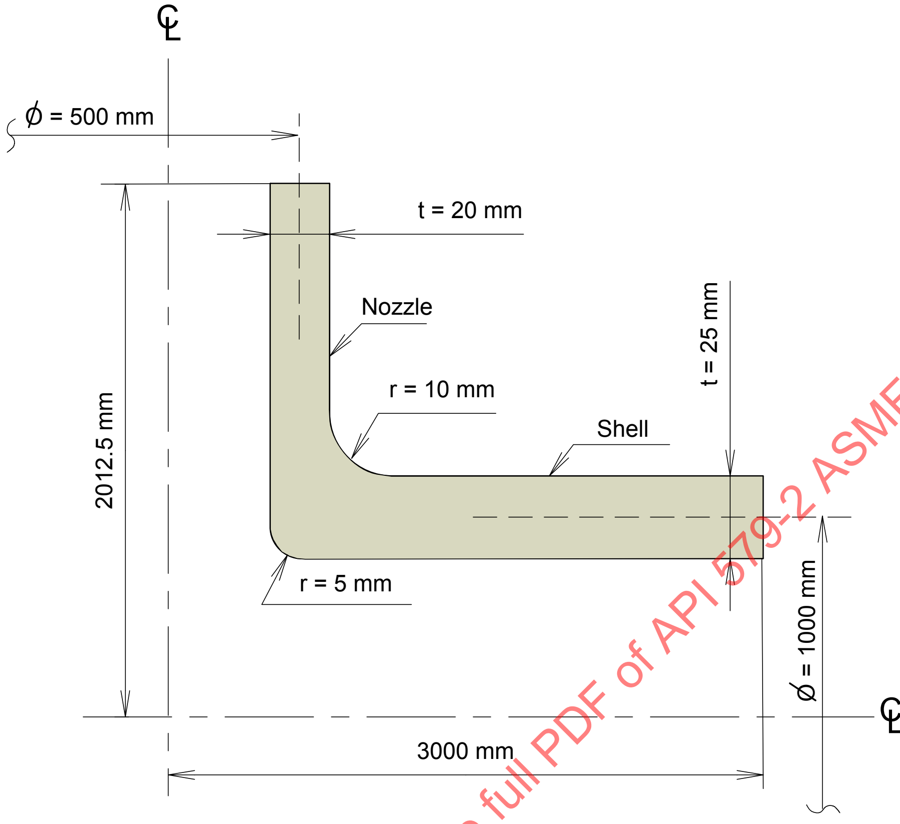
In 3D, the values of K_I and σ_{ref} vary along the crack front. It is decided to divide the crack front into 3 parts of equal length and to perform assessments at division points and at points close to the shell and nozzle surfaces. The first assessment is performed at the division point on the shell side (see Figure E9.10-4.a)

Level 3 Method C involves elastic-plastic Finite Element analyses. The computations are performed with ANSYS, following the rules of Annex B1 paragraphs B1.7.3 and B1.7.4.

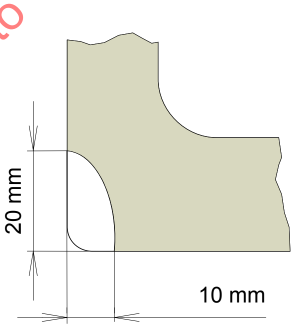
The units are mm for the lengths and MPa for the stresses and pressures.

Since a crack is to be meshed in a large 3D structure in an elastic-plastic analysis, the mesh refinement around the crack front and the size of the load steps are first validated on a 2D model with a similar crack size. The material is the one of the nozzle. The specific commands to be added for the computation of the J-integral are validated at the same time.

A through-wall crack 40 mm long is considered at the center of a plate 400 mm wide and 600 mm long. Due to the symmetries only one quarter of the plate is modeled with nil normal displacements on the surfaces of symmetry. The maximum tension applied on the plate is chosen as twice the yield strength. This phase shows that the elements near the crack tip on the lip side are so distorted at high loading that it is necessary to use the "large displacement" option of the elements in order to obtain results near the cut-off for the L_r^P of the FAD.



(a) Overall Geometry of Nozzle



(b) Detail of the cracked region

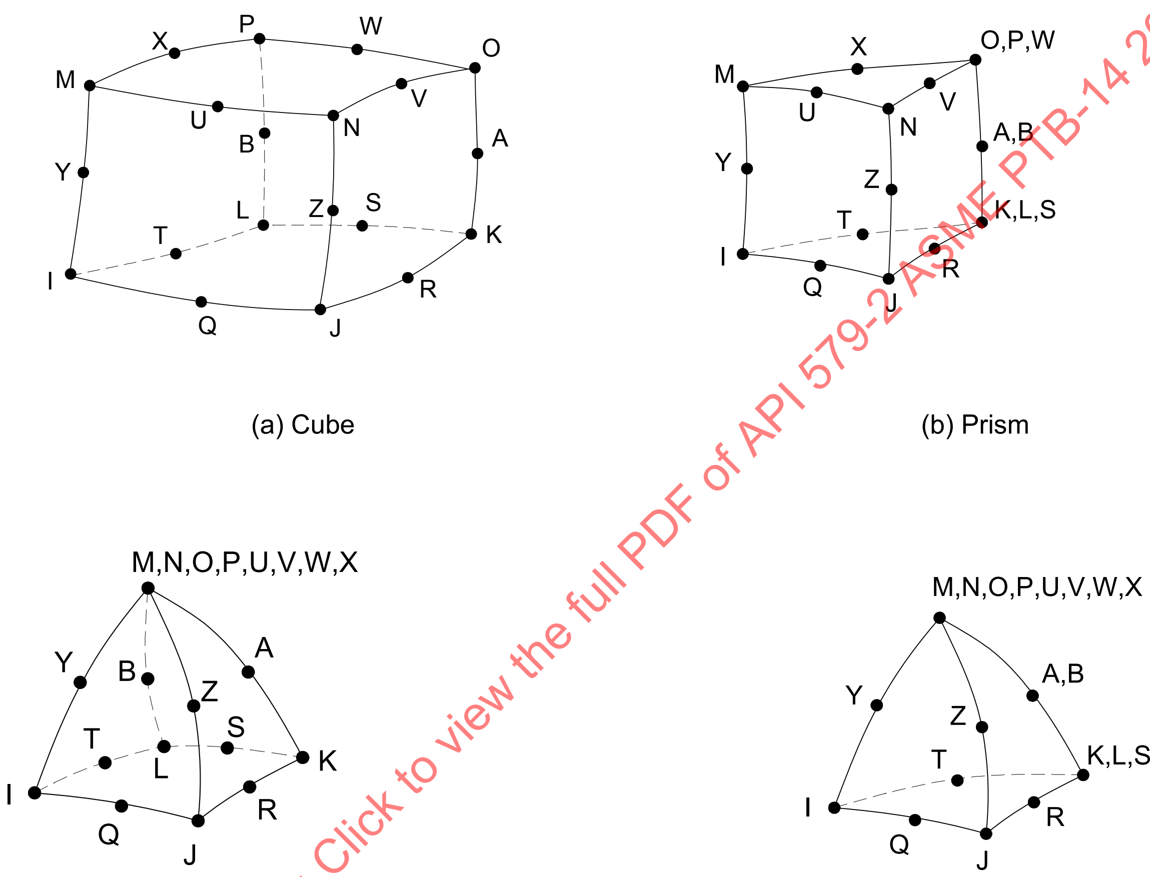
Figure E9.10-1 - Cracked Nozzle

a) STEP 1 - Categorize loads as primary and secondary.

   The only load is the pressure which is considered as primary. There is no other mechanical or thermal load, therefore there is no secondary load

b) STEP 2 - Construct an elastic-plastic finite element model.

Due to the 2 symmetries, only one quarter of the nozzle is modeled with SOLID186 elements. This is a 20-node brick element that degenerates into prism, pyramid or tetrahedron by merging nodes (see Figure E9.10-2). The length of modeled shell is 3000 mm, the length of nozzle is 1500 mm. The crack front itself is embedded in a torical region in order to ensure a regular spider mesh around it (see Figure E9.10-3). The size of the triangular faces next to the crack front is 0.5 mm.



(a) Cube

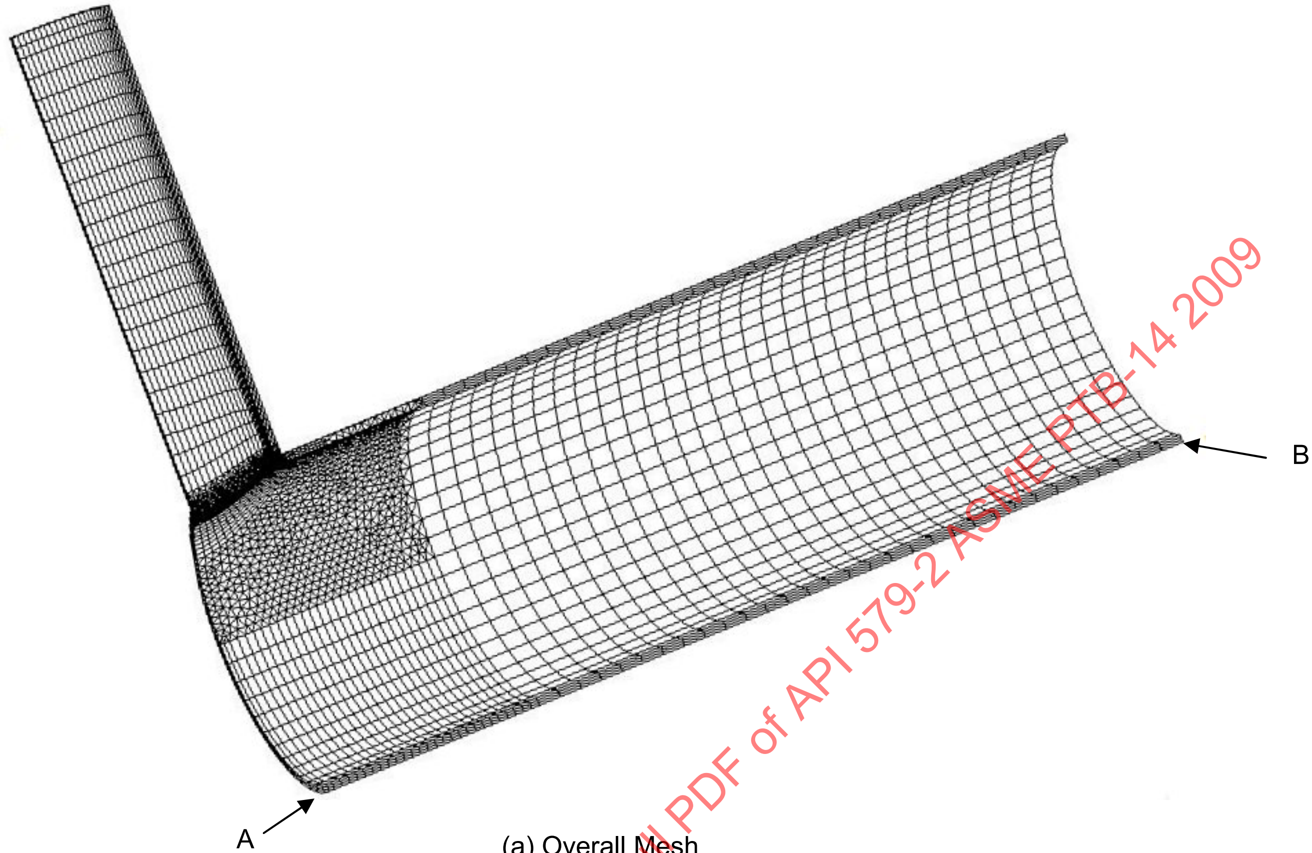
(b) Prism

(c) Pyramid

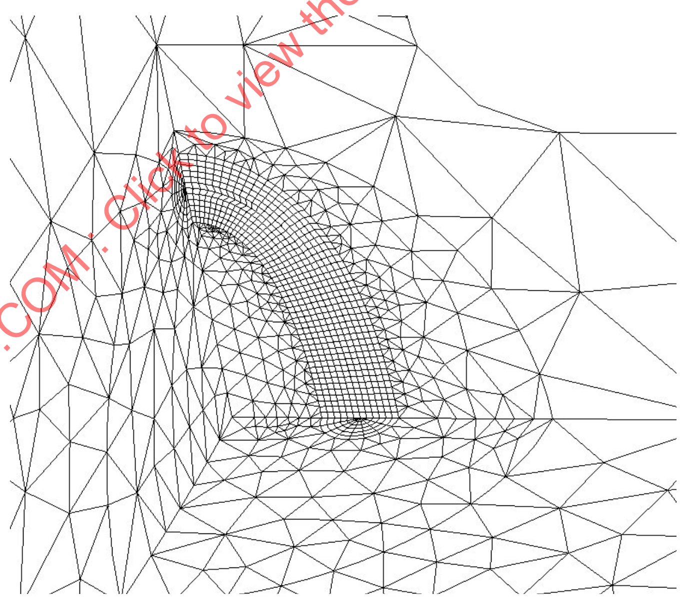
(d) Tetrahedron

Figure E9.10-2 - 3D 20-Node Solid Elements used for Elastic-Plastic Analysis

A plane perpendicular to the crack front is also defined in order to enter the nodes that will be used by the software to describe the contour on which the J-integral will be performed (see Figure E9.10-4), the first of these nodes being on the crack lip.

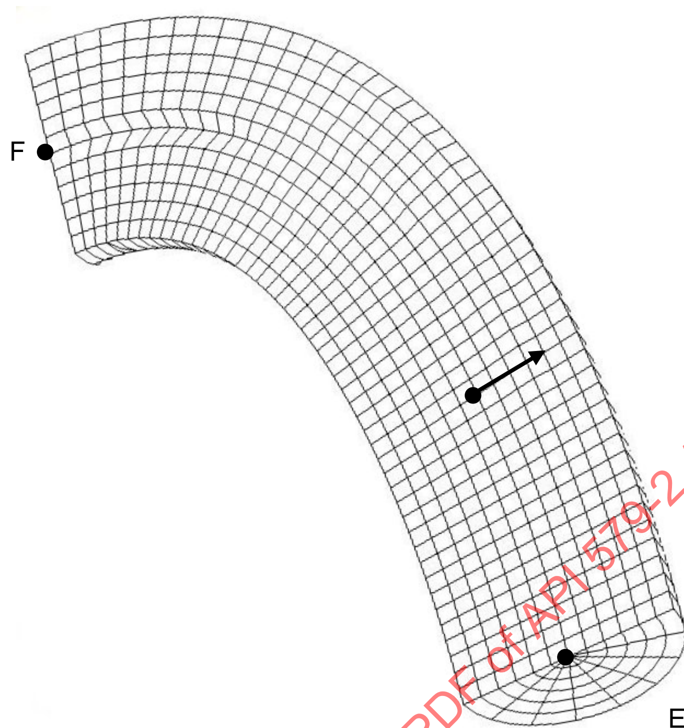


(a) Overall Mesh

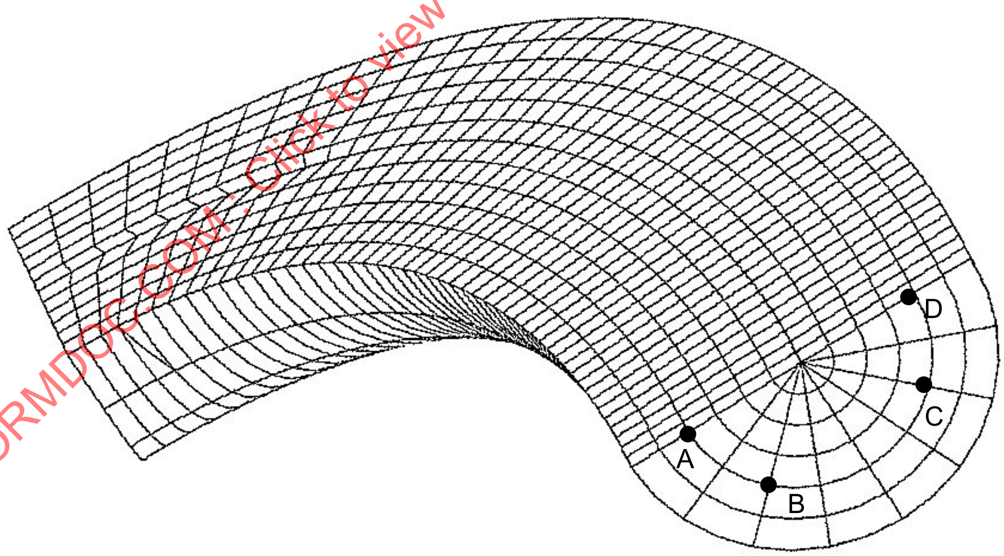


(b) Mesh in the Vicinity of the Crack-Front

Figure E9.10-3 - 3D Mesh of the Cracked Nozzle



(a) Assessment Node and Local Axis of Crack Extension



(b) Nodes Defining the Contour for the J-Integral Projected on the Shell Surface

Figure E9.10-4 - Nodes used in Fracture Mechanics Computations

For the boundary conditions, zero normal displacements are applied on surfaces of symmetry except on the crack face. The nodes on the line from point A to point B (see Figure E9.10-3) are assigned a nil displacement in the z-direction (nozzle axis) where the resultant of the forces is equal to zero.

For the loading, the applied pressure is a little bit above the upper limit that must be reached by the elastic-plastic analysis. This pressure corresponds to a membrane circumferential stress equal to the yield strength (205 MPa for SA-182 Grade F304) in the shell, calculated from the MAWP formula in paragraph A.3.4.a of Annex A. This leads to $P = 10.20\ MPa$. It is thus decided to specify a pressure equal to $12.0\ MPa$ on the internal surfaces of the shell and of the nozzle, and on the face of the crack

End effects are applied on the radial surfaces of the shell (tension = $114.07\ MPa$) and of the nozzle (tension = $69.12\ MPa$) calculated as $P\,r_i^2 / (r_o^2 - r_i^2)$.

For the material, the stress-strain relationship is based on the MPC Model as described in paragraph F.2.3.1 of Annex F for stainless steels with the basic properties E_y, ν, σ_{ys} and σ_{uts} from ASME Section II Part D. These data, expressed as a function of engineering stress and strain, are given in Table E9.10-1:

- Young modulus $E_y = 195000\ MPa$
- Poisson ratio $\nu = 0.3$
- Yield strength $\sigma_{ys} = 205\ MPa$
- Tensile strength $\sigma_{uts} = 515\ MPa$
- The stress-strain curve above the yield strength is piecewise linear.

The inputs are the stress versus the plastic strain.

Table E9.10-1 - Data for the non-linear part of the stress-strain curve

ε_p	σ - MPa
0.00	205.
0.05	305.
0.10	365.
0.15	412.
0.20	447.
0.25	468.
0.30	485.
0.35	496.
0.40	504.
0.45	508.
0.50	511.

c) STEP 3 - The elastic-plastic analysis is performed with an increasing load.
   The size of each step is regulated by the software. The default value is 0.833% of the prescribed loading in order to generate load steps equal to $0.1\ MPa$; the maximum and minimal values are respectively 1% and 0.1 % of the prescribed loading.

   At each step the software outputs (columns 1-2-3-4 of Table E9.10-2):

   - the percentage of the total load reached
   - the corresponding pressure
   - the J-integral calculated by formula $J = \oint_\Gamma \left(\sigma_{ij}\, \varepsilon_{ij}\, dy - \sigma_{ij}\, n_j \frac{\partial u_i}{\partial x} ds \right)$ on the contour Γ defined by the user with the local axes x and y such that x lies in the crack plane and is normal to the crack-front toward the inside of the material and y is perpendicular to the crack lips (opening direction) toward the inside of the material if only one side of the crack is modelled due to symmetry considerations

d) STEP 4 - Calculate K_J defined as $K_J = \sqrt{J.E_y / (1-\nu^2)}$ based on the J integral calculated in STEP 3.

Table E9.10-2 - Fracture Mechanics Parameters used to Define the FAD Curve

% Total Load	Pressure MPa	J-Integral $MPa\text{–}mm$	K_J $MPa\sqrt{mm}$	K_I^P $MPa\sqrt{mm}$	K_r	L_r
0.000	0.000	0.000	0.000	0.000	1.000	0.000
0.833	0.100	0.006	35.041	35.041	1.000	0.012
2.500	0.300	0.053	105.000	105.123	1.001	0.035
4.167	0.500	0.147	174.924	175.205	1.002	0.059
5.833	0.700	0.289	245.099	245.287	1.001	0.083
7.500	0.900	0.482	316.395	315.369	0.997	0.106
8.333	1.000	0.598	352.323	350.410	0.995	0.118
12.500	1.500	1.402	539.598	525.615	0.974	0.177
16.667	2.000	2.566	729.962	700.820	0.960	0.236
20.833	2.500	4.117	924.702	876.025	0.947	0.295
25.000	3.000	6.041	1120.092	1051.230	0.939	0.354
33.333	4.000	10.843	1500.652	1401.640	0.934	0.472
41.667	5.000	18.394	1954.551	1752.050	0.896	0.590
50.000	6.000	32.729	2607.198	2102.460	0.806	0.708
54.167	6.500	43.668	3011.550	2277.665	0.756	0.767
58.333	7.000	58.003	3470.851	2452.870	0.707	0.826
62.500	7.500	76.063	3974.644	2628.075	0.661	0.885
66.667	8.000	99.569	4547.496	2803.280	0.616	0.944
69.167	8.300	118.016	4950.855	2908.403	0.587	0.979
70.000	8.400	125.028	5095.817	2943.444	0.578	0.991
70.833	8.500	132.523	5246.333	2978.485	0.568	1.003
71.667	8.600	140.579	5403.438	3013.526	0.558	1.015
75.000	9.000	178.993	6097.175	3153.690	0.517	1.062
79.167	9.500	243.807	7115.959	3328.895	0.468	1.121
83.333	10.000	329.073	8267.161	3504.100	0.424	1.180
91.667	11.000	554.994	10736.293	3854.510	0.359	1.298
100.000	12.000	799.788	12888.362	4204.920	0.326	1.416

e) STEP 5 - Infer the elastic solution K_I^P for each step.

From columns 2 and 4 of Table E9.10-2 the curve $K_J = f(pressure)$ is drawn (Figure E9.10-5). In this figure, or from the values of $(K_J / pressure)$, the linear part of the curve is identified, leading to $K_I^P = 350.4\ P$. The values are given in column 5 of Table E9.10-2.

f) STEP 6 - Compute the vertical coordinate of the FAD, $K_r = \dfrac{K_I^P}{K_J}$

K_J - Elastic-Plastic Equivalent Stress Intensity Factor - is represented by the Solid Line in Figure E9.10-5.

K_I^P - Elastic Stress Intensity Factor - is represented by the Dotted Line in Figure E9.10-5.

The values of K_r are given in column 6 of Table E9.10-2.

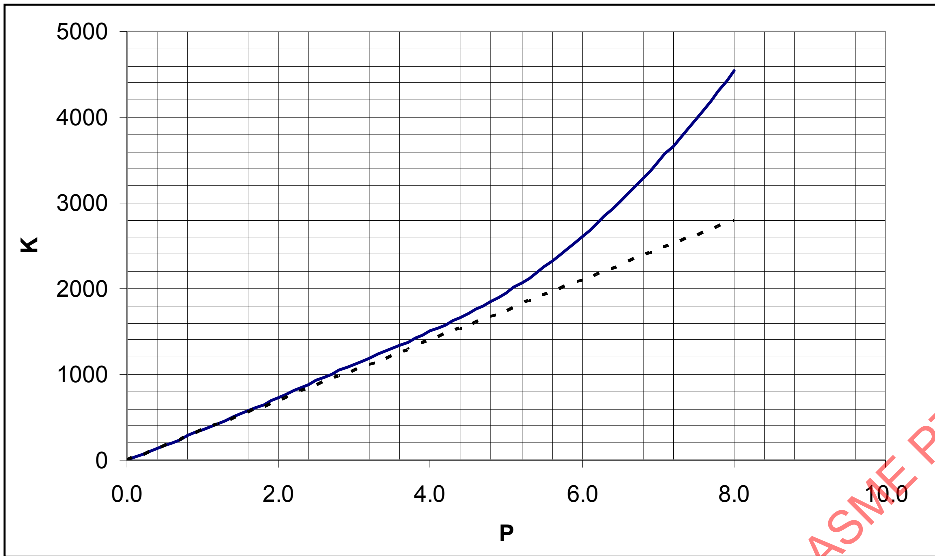


Figure E9.10-5 - Stress Intensity Factors versus Pressure

g) STEP 7 - Compute the horizontal coordinate of the FAD, $L_r = \sigma_{ref} / \sigma_{ys}$

Calculate the value of K_r corresponding to $L_r = 1$

$$K_r(L_r = 1) = \left[1 + \left(0.002\, E_y\right) / \sigma_{ys} + \frac{1}{2}\left(1 + \left(0.002\, E_y\right) / \sigma_{ys}\right)^{-1} \right]^{-0.5}$$

$$= \left[1 + \frac{(0.002)\,(195000)}{205} + \frac{1}{2}\left(1 + \frac{(0.002)\,(195000)}{205}\right)^{-1} \right]^{-0.5} = 0.5703$$

This corresponds to $P = 8.477\ MPa = 70.64\ \%$ max loading in Table E9.10-2 enabling to situate the value $L_r = 1$ in column 7 of Table E9.10-2 and then deduce the other values of this column.

h) STEP 8 - Plot the FAD curve K_r versus L_r - See Figure E9.10-6

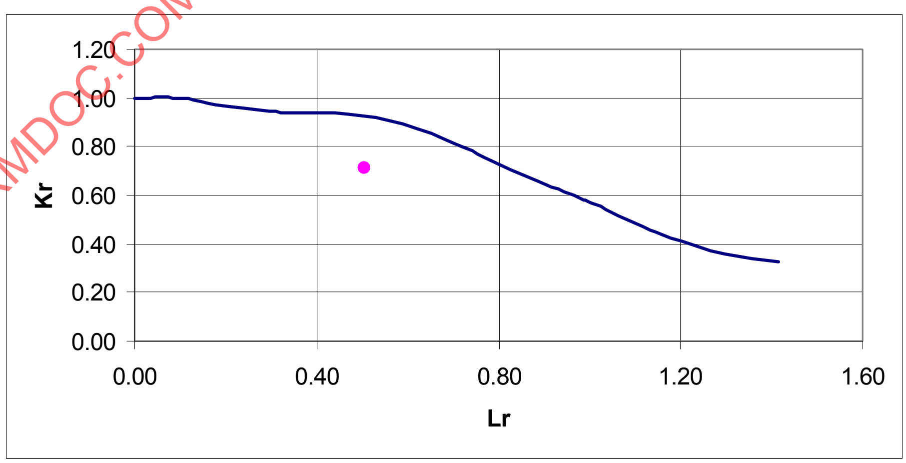


Figure E9.10-6 - FAD with Assessment Point

i) STEP 9 - Compute L_r for the operating load

The applied primary stress at $L_r = 1$ is calculated per Annex A paragraph A.3.4 in the shell:

$$\sigma^P(L_r = 1) = \frac{P(L_r = 1)}{E}\left(\frac{R}{t_c} + 0.6\right) = \frac{(8.477)}{(1.0)}\left(\frac{500 - 12.5}{25} + 0.6\right) = 170.4\ MPa$$

Leading to a reference stress geometry factor

$$F_{ref} = \sigma_{ys} / \sigma^P(L_r = 1) = (205.00)/(170.4) = 1.203$$

The MAWP is $6.0\ MPa$. It generates an applied primary stress in the shell equal to

$$\sigma^P = \frac{P}{E}\left(\frac{R}{t_c} + 0.6\right) = \frac{(6.0)}{(1.0)}\left(\frac{500 - 12.5}{25} + 0.6\right) = 120.6\ MPa$$

and a reference stress equal to

$$\sigma_{ref} = F_{ref}.\sigma^P = (1.203)\ (120.6) = 145.1\ MPa$$

Therefore $L_r = \sigma_{ref} / \sigma_{ys} = (145.1)/(205.0) = 0.7077$

Note: Since there is only one primary load, L_r could also have been calculated as the ratio between the MAWP and the pressure corresponding to $L_r = 1$ i.e $L_r = (6.0)/(8.477) = 0.7078$

j) STEP 10 - Compute the elastic K_I^P for the operating load using formula in STEP 5 $K_I^P = 350.4\ P$

$$K_I^P = (350.4)\ (6.0) = 2102.\ MPa\sqrt{mm} = 66.49\ MPa\sqrt{m}$$

k) STEP 11 - Compute the toughness ratio
The toughness of this material, austenitic stainless steel, is taken from paragraph F.4.8.2 in Annex F. A conservative value equal to $132\ MPa\sqrt{m}$ is selected (value for weld material)

Therefore $K_r = K_I^P / K_{mat} = (66.49)/(132.0) = 0.5037$

l) STEP 12 - Plot the assessment point $(L_r, K_r) = (0.708, 0.504)$ on the FAD of STEP 8 - See Figure E9.10-6

m) STEP 13 - Evaluate the result
The assessment point lies in the Acceptable Region of the FAD. A very conservative value of toughness is taken into account and other data are known with sufficient accuracy, therefore

The Level 3 Method C Assessment Criteria are Satisfied for the Assessment Point

The assessment is repeated for other points on the crack-front. For point E of Figure E9.10-4(a) it is not possible to define a plane perpendicular to the crack-front because this plane would be tangent to the shell interior surface. Therefore the assessment at the apex of the small axis is performed at the next point on the crack-front. The same comment applies to point F (long axis) of Figure E9.10-4(a) on the nozzle side.

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PART 10

ASSESSMENT OF COMPONENTS OPERATING IN THE CREEP RANGE

EXAMPLE PROBLEMS

10.1 Example Problem 1

A liquid knock-out vessel that is part of a pressure relief system typically operates at temperatures below the creep range. During a recent upset condition, high temperature liquid was relieved in the vessel for a period of time, subjecting the vessel to temperatures in the creep range. Details regarding the vessel and the upset condition are given below. The shell contains a weld seam which was exposed to the excursion conditions. The vessel was constructed to the ASME B&PV Code, Section VIII, Division 1. Estimate the level of creep damage sustained by the vessel shell during the upset condition.

Vessel Data

- Material = $SA-516\,Grade\,60\;Year\;1998$
- Design Conditions = $50\,psig\,@\,450\,^{\circ}F$
- Inside Diameter = $60\;in$
- Fabricated Thickness = $0.375\;in$
- Future Corrosion Allowance (FCA) = $0.10\;in$
- Weld Joint Efficiency = 1.0
- Unsupported Length = $144\,in$
- Cylindrical Shell with 2:1 Elliptical Heads $(R_{ell}=2)$
- PWHT = Yes, Original Fabrication Requirement

Temperature Excursion Data

- Excursion Pressure: = $82.6\;psig$
- Excursion Temperature: = $950\;^{\circ}F$
- Excursion Duration: = $20\;hours$

Inspection Data

There are no visual signs of damage to the vessel, no bulging, metal loss, or excessive scale was noted. UT thickness readings indicated light general metal loss within the original corrosion allowance. Looking through the inspection records, this is the first operational excursion into the creep range for this component.

Perform a Level 1 Assessment for the component in creep service per paragraph 10.4.2.1

Each component of the vessel must be analyzed separately. In this example, the cylindrical shell is analyzed first, followed by the elliptical heads. Nozzles and supplemental loadings are ignored for the purposes of this example.

Level 1 Assessment for the cylindrical shell

a) STEP 1 – Determine the maximum operating temperature, pressure, and service time the component was exposed to. Since the component contains a weld seam exposed to the excursion conditions, 25°F shall be added to the maximum operating temperature.

$$T\max = 950 + 25 = 975°F$$

$$P\max = 82.6\,psig$$

$$time = 20\ hours$$

b) STEP 2 – Determine the operating stress of the component for the operating condition defined in STEP 1 using Annex A. The computed nominal stress shall include the effects of service-induced wall thinning.

Definition of common variables:

$$R = \frac{ID + 2(FCA)}{2} = \frac{60 + 2(0.1)}{2} = 30.1\ in$$

$$t_c = t_{nom} - FCA = 0.375 - 0.1 = 0.275\ in$$

Supplemental loadings are not considered in this example.

Cylindrical shell circumferential membrane stress (A.11)

$$\sigma_m^C = \frac{P}{E}\left(\frac{R}{t_c} + 0.6\right)$$

$$\sigma_m^C = \frac{82.6}{1.0}\left(\frac{30.1}{0.275} + 0.6\right)$$

$$\sigma_m^C = 9091\ psi$$

Cylindrical shell longitudinal membrane stress (A.17)

$$\sigma_m^L = \frac{P}{2E}\left(\frac{R}{t_c} - 0.4\right)$$

$$\sigma_m^L = \frac{82.6}{2(1.0)}\left(\frac{30.1}{0.275} - 0.4\right)$$

$$\sigma_m^L = 4{,}504\ psi$$

$$\sigma_{\max} = \max\left(\sigma_m^C, \sigma_m^L\right)$$

$$\sigma_{\max} = \max(9091, 4504)$$

$$\sigma_{\max} = 9091\ psi$$

c) STEP 3 – Determine the material of construction for the component and find the figure with the screening and damage curves to be used for the Level 1 assessment from Figures 10.3 through 10.25.

The cylindrical shell is constructed of SA-516 Grade 60, carbon steel; therefore, Figure 10.3 shall be used for the analysis.

d) STEP 4 – Determine the maximum permissible time for operation based on the screening curve obtained from STEP 3, the nominal stress from STEP 2, and the assessment temperature from STEP 1. If the time determined from the screening curve exceeds the service time for the component from STEP 1, then the component is acceptable per the Level 1 Assessment procedure.

From Figure 10.3, the acceptable creep life of the cylindrical shell at 10 ksi and 975°F is over 25 hours. Since the component was only exposed to these conditions for 20 hours, and has no history of prior temperature excursions on record, the component is fit for service without further evaluation. However, it is important to note the temperature excursion in the vessel's files so that future analyses can accurately take into account all past temperature excursions.

Level 1 Assessment for the 2:1 elliptical heads

a) STEP 1 – Determine the maximum operating temperature, pressure, and service time the component was exposed to. Since the component contains a weld seam exposed to the excursion conditions, 25°F shall be added to the maximum operating temperature.

$$T\max = 950 + 25 = 975°F$$

$$P\max = 82.6\ psig$$

$$time = 20\ hours$$

b) STEP 2 – Determine the operating stress of the component for the operating condition defined in STEP 1 using Annex A. The computed nominal stress shall include the effects of service-induced wall thinning.

Definition of common variables:

$$D = ID + 2(FCA) = 60 + 2(0.1) = 60.2\ in$$

$$t_c = t_{nom} - FCA = 0.375 - 0.1 = 0.275\ in$$

Elliptical head membrane stress (A.33 and A.32)

$$K = \frac{1}{6}\left(2.0 + (R_{ell})^2\right)$$

$$K = \frac{1}{6}\left(2.0 + 2.0^2\right)$$

$$K = 1.0$$

$$\sigma_m = \frac{P}{2(E)}\left(\frac{DK}{t_c} + 0.2\right) = \frac{82.6}{2(1.0)}\left(\frac{60.2(1.0)}{0.275} + 0.2\right) = 9049\ psi$$

c) STEP 3 – Determine the material of construction for the component and find the figure with the screening and damage curves to be used for the Level 1 assessment from Figures 10.3 through 10.25.

The heads are constructed of SA-516 Grade 60, carbon steel; therefore, Figure 10.3 shall be used for the analysis.

d) STEP 4 – Determine the maximum permissible time for operation based on the screening curve obtained from STEP 3, the nominal stress from STEP 2, and the assessment temperature from STEP 1. If the time determined from the screening curve exceeds the service time for the component from STEP 1, then the component is acceptable per the Level 1 Assessment procedure.

From Figure 10.3, the acceptable creep life of the cylindrical shell at 10 ksi and 975°F is over 25 hours. Since the component was only exposed to these conditions for 20 hours, and has no history of prior temperature excursions on record, the component is fit for service without further evaluation. However, it is important to note the temperature excursion in the vessel's files so that future analyses can accurately take into account all past temperature excursions.

10.2 Example Problem 2

A fired crude heater experienced a temperature excursion for a short duration. The refinery needs to know how much additional damage occurred to the tubes to understand how the excursion impacts the remaining tube life. This information will be used to help determine if the heater will need to be re-tubed at an upcoming scheduled turn-around, or if the tubes are likely to last for another run. Evaluate the tube remaining life (typical past history plus known temperature excursion) and determine if they are fit for service for another run.

Heater Tube Data

- Material = $SA-335\ Grade\ P22\ Year\ 1998$
- Typical Conditions (j=1) = $210\ psig @ 1115\ °F$
- Outside Diameter = $8.625\ in$
- Fabricated Thickness = $0.322\ in$
- Future Corrosion Allowance (FCA) = $0.10\ in$
- Weld Joint Efficiency = 1.0
- Unsupported Length = $144\ in$
- Cylindrical Shell
- Past Operating Time (j=1) = $131400\ hours$
- Past Operating Time (j=2) = $336\ hours$
- Future Expected Time (j=1) = $43800\ hours$

Temperature Excursion Data

- Excursion Pressure: = $210\ psig$
- Excursion Temperature: = $1220\ °F$
- Excursion Duration: = $336\ hours$

Inspection Data

There are no visual signs of damage to the tube, no bulging, metal loss, or excessive scale was noted. UT thickness readings indicated light general metal loss within the original corrosion allowance. Looking through the inspection records, this is the first operational excursion into the creep range for this component. There are no weld seems in the fire box.

Perform a multiple condition Level 1 Assessment for the component in creep service per paragraph 10.4.2.2

Each component of the vessel must be analyzed separately. In this example, the tube bends are located outside the firebox, so only the cylindrical portion of the tubes will be analyzed. For the purposes of this example, assume the tubes are adequately supported and that circumferential pressure stress is the limiting design condition.

Level 1 Assessment for the heater tube

a) STEP 1 – Determine the maximum operating temperature, pressure, and service time the component was exposed to. The component does not contain any weld seams exposed to the excursion conditions; therefore, it is not necessary to add the 25°F to the maximum operating temperature. The superscript j, indicates either 1 for the typical operating conditions (design) or 2 for the temperature excursion.

$$T^1_{\max} = 1115°F$$

$$P^1_{\max} = 210\ psig$$

$$time^1_{total} = 131400 + 43800 = 175200\ hours$$

$$T^2_{\max} = 1220°F$$

$$P^2_{\max} = 210\ psig$$

$$time^2_{total} = 336\ hours$$

b) STEP 2 – Determine the nominal stress of the component for each of the operating conditions defined in STEP 1 using Annex A. The computed nominal stress shall include the effects of service-induced wall thinning.

Definition of common variables:

$$R = \frac{OD}{2} - t_{nom} + FCA = \frac{8.625}{2} - 0.322 + 0.1 = 4.0905\ in$$

$$t_c = t_{nom} - FCA = 0.375 - 0.1 = 0.275\ in$$

Supplemental loadings are not considered in this example.

Cylindrical shell circumferential membrane stress (A.11)

$$\sigma^C_m = \frac{P}{E}\left(\frac{R}{t_c} + 0.6\right)$$

$$\sigma^C_m = \frac{210}{1.0}\left(\frac{4.0905}{0.222} + 0.6\right)$$

$$\sigma^C_m = 3995\ psi$$

Cylindrical shell longitudinal membrane stress (A.17)

$$\sigma^L_m = \frac{P}{2E}\left(\frac{R}{t_c} - 0.4\right)$$

$$\sigma^L_m = \frac{210}{2(1.0)}\left(\frac{4.0905}{0.222} - 0.4\right)$$

$$\sigma^L_m = 1893\ psi$$

$$\sigma_{\max} = \max\left(\sigma^C_m, \sigma^L_m\right)$$

$$\sigma_{\max} = \max\left(3995, 1893\right)$$

$$\sigma_{\max} = 3995\ psi$$

c) STEP 3 – Determine the material of construction for the component and find the figure with the damage curves to be used for the Level 1 assessment from Figures 10.3 through 10.25.

The cylindrical shell is constructed of SA-335 P22, 2.25Cr-1.0Mo annealed steel; therefore, Figure 10.9 shall be used for the analysis.

d) STEP 4 – Determine the creep damage rate, R_c^j and associated creep damage, D_c^j for each of the j operating conditions defined in STEP 1 using the damage curve obtained from STEP 3, the nominal stress from STEP 2, and the assessment temperature from STEP 1. The creep damage for each operating condition, j, can be computed using Equation (10.6) where the service exposure time is determined from STEP 1.

$$D_c^j = R_c^j \left(t_{se}^j\right)$$

The creep damage rate, R_c^j and the associated creep damage, D_c^j for the typical operating condition ($j=1$) are:

$$R_c^1 = 1.75\times10^{-6} \ 1/Hr$$
$$D_c^1 = R_c^1\left(t_{se}^1\right)$$
$$D_c^1 = 1.75\times10^{-6}\left(175200\right)$$
$$D_c^1 = 0.3066$$

The creep damage rate, R_c^j and the associated creep damage, D_c^j for the temperature excursion condition (j = 2) are:

$$R_c^2 = 6.5\times10^{-5} \ 1/Hr$$
$$D_c^2 = R_c^2\left(t_{se}^2\right)$$
$$D_c^2 = 6.5\times10^{-5}\left(336\right)$$
$$D_c^2 = 0.0218$$

e) STEP 5 – Determine the creep damage for the total number of operating conditions, J, using Equation (10.7).

$$D_c^{total} = \sum_{j=1}^{J} D_c^j$$

The creep damage for the total number of operating conditions, J, is determined as follows:

$$D_c^{total} = \sum_{j=1}^{J} D_c^j$$
$$D_c^{total} = \sum_{j=1}^{2} D_c^j$$
$$D_c^{total} = \left(D_c^1 + D_c^2\right)$$
$$D_c^{total} = \left(0.3066 + 0.0218\right)$$
$$D_c^{total} = 0.3284$$

f) STEP 6 – If the total creep damage determined from STEP 5 satisfies Equation (10.8), then the component is acceptable per the Level 1 Assessment procedure. Otherwise, the component is not acceptable and the requirements of paragraph 10.4.2.3 shall be followed.

$$D_c^{total} \le 0.25$$

In this case, the total creep damage determined in STEP 5, $D_c^{total} = 0.3284$ exceeds the allowable per Equation (10.8).

Therefore, the Level 1 assessment criteria are not satisfied.

This same problem is examined further with a Level 2 assessment in Example Problem 3.

10.3 Example Problem 3

A fired crude heater experienced a temperature excursion for a short duration. The refinery needs to know how much additional damage occurred to the tubes to understand how the excursion impacts the remaining tube life. This information will be used to help determine if the heater will need to be re-tubed at an upcoming scheduled turn-around, or if the tubes are likely to last for another run. The tubes have already failed a Level 1 assessment (Example Problem 2). Evaluate the remaining life of the tubes, using the Level 2 assessment procedures, and determine if they are fit for service for another run.

Heater Tube Data

- Material = $SA-335\ Grade\ P22\ Year\ 1998$
- Typical Conditions (j=1) = $210\ psig@1115\ °F$
- Outside Diameter = $8.625\ in$
- Fabricated Thickness = $0.322\ in$
- Future Corrosion Allowance (FCA) = $0.10\ in$
- Weld Joint Efficiency = 1.0
- Unsupported Length = $144\ in$
- Cylindrical Shell
- Past Operating Time (j=1) = $131400\ hours$
- Past Operating Time (j=2) = $336\ hours$
- Future Expected Time (j=1) = $43800\ hours$

Temperature Excursion Data

- Excursion Pressure: = $210\ psig$
- Excursion Temperature: = $1220\ °F$
- Excursion Duration: = $336\ hours$

Inspection Data

There are no visual signs of damage to the tube, no bulging, metal loss, or excessive scale was noted. UT thickness readings indicated light general metal loss within the original corrosion allowance. Looking through the inspection records, this is the first operational excursion into the creep range for this component. There are no circumferential weld seams in the fire box.

Perform a multiple condition Level 2 Assessment for the component in creep service per paragraph 10.4.3

Each component of the vessel must be analyzed separately. In this example, the tube bends are located outside the firebox, so only the cylindrical portion of the tubes will be analyzed. For the purposes of this example, assume the tubes are adequately supported and that circumferential pressure stress is the limiting design condition.

Level 2 Assessment for the heater tube

a) STEP 1 – Determine a load history based on past operation and future planned operation. The load history for this example includes three operating conditions as listed below:

Table E10.3-1

	Past (m = 1)	Excursion (m= 2)	Future (m = 3)
Design Pressure (P)	210 psig	210 psig	210 psig
Design Temperature (T)	1115°F	1220°F	1115°F
Service Time (hours)	131400	336	43800

b) STEP 2 – For the current operating cycle m, determine the total cycle time, ${}^{m}t$, and divide the cycle into a number of time increments, ${}^{n}t$ as shown in Figure 10.27. Define N as the total number of time increments in operating cycle m.

For this illustration, N is set to 2 even though the condition for each sub-cycle is the same. In general, N should be set to match any change in pressure, temperature, or tube thickness. Each of the operating cycles in the load history is split into its respective sub-increments below:

Table E10.3-2

Operating Cycle	Past (m = 1)		Excursion (m = 2)		Future (m = 3)	
Sub-Increment	n = 1	n = 2	n = 1	n = 2	n = 1	n = 2
Design Pressure (P)	210	210	210	210	210	210
Service Time (hours)	65700	65700	168	168	21900	21900

c) STEP 3 – Determine the assessment temperature, ${}^{n}T$, for the time increment ${}^{n}t$.

Table E10.3-3

Operating Cycle	Past (m = 1)		Excursion (m = 2)		Future (m = 3)	
Sub-Increment	n = 1	n = 2	n = 1	n = 2	n = 1	n = 2
Design Pressure (P)	210	210	210	210	210	210
Service Time (hours)	65700	65700	168	168	21900	21900
Design Temperature (T)	1115	1115	1220	1220	1115	1115

d) STEP 4 – Determine the stress components, ${}^{n}\sigma_{ij}$, for the time increment ${}^{n}t$.

First, the tube dimensions are checked to insure the tubes are considered to be thin-walled per the definition given in paragraph 10.5.2.5.

$$\frac{OD}{t_{nom}} > 6$$

$$\frac{8.625}{0.322} > 6$$

$$26.8 > 6$$

Since the thin-walled criterion is met, the mean diameter stress equations per Table 10.2 are applicable. For this example a fully-corroded thickness is used for simplicity. A more realistic approach is to calculate the stress as a function of the thickness according to the past and predicted corrosion rates. An example of this calculation is worked out below for the first sub-increment of the first operating cycle. The subsequent increments are calculated similarly.

$${}^{n}\sigma_1 = {}^{n}\sigma_{mean} = \frac{P(D_{mean})}{2(t_{corr})}$$

$${}^{1}\sigma_1 = \frac{P(OD - t_{nom} + FCA)}{2(t_{nom} - FCA)}$$

$${}^{1}\sigma_1 = \frac{210(8.625 - 0.322 + 0.1)}{2(0.322 - 0.1)}$$

$${}^{1}\sigma_1 = 3974 \ psi$$

$${}^{n}\sigma_2 = 0.5({}^{n}\sigma_{mean})$$

$${}^{1}\sigma_2 = 0.5({}^{1}\sigma_1)$$

$${}^{1}\sigma_2 = 0.5(3974)$$

$${}^{1}\sigma_2 = 1987 \ psi$$

$${}^{n}\sigma_3 = 0.0 \ psi$$

$${}^{n}\sigma_e = 0.866({}^{n}\sigma_{mean})$$

$${}^{1}\sigma_e = 0.866({}^{1}\sigma_1)$$

$${}^{1}\sigma_e = 0.866(3974)$$

$${}^{1}\sigma_e = 3442 \ psi$$

Each of the stress components are included in the table shown below:

Table E10.3-4

Operating Cycle	Past (m = 1)		Excursion (m = 2)		Future (m = 3)	
Sub-Increment	n = 1	n = 2	n = 1	n = 2	n = 1	n = 2
Design Pressure (P)	210	210	210	210	210	210
Service Time (hours)	65700	65700	168	168	21900	21900
Design Temperature (T)	1115	1115	1220	1220	1115	1115
$^n\sigma_{xx} = {}^n\sigma_1$ (psi)	3974	3974	3974	3974	3974	3974
$^n\sigma_{yy} = {}^n\sigma_2$ (psi)	1987	1987	1987	1987	1987	1987
$^n\sigma_{zz} = {}^n\sigma_3$ (psi)	0.0	0.0	0.0	0.0	0.0	0.0
$^n\tau_{xy}$ (psi)	0.0	0.0	0.0	0.0	0.0	0.0
$^n\sigma_e$ (psi)	3442	3442	3442	3442	3442	3442

e) STEP 5 – Determine if the component has adequate protection against plastic collapse.

Since the primary load reference stress, $^n\sigma^p_{ref}$, is less than 75% of the minimum yield strength, the plastic collapse criteria are satisfied. The stress in the component is constant in this example, therefore the results below are valid for all operating cycles and sub-increments.

$$^n\sigma^p_{ref} = \frac{^nP_b + \left(^nP_b^2 + 9\left(^nP_L^2 \right) \right)^{0.5}}{3}$$

$$^n\sigma^p_{ref} = \frac{0 + \left(0^2 + 9\left(3974^2 \right) \right)^{0.5}}{3}$$

$$^n\sigma^p_{ref} = 3974 \ psi$$

$$\sigma_{ys}\left(1115\right) = 19851 \ psi$$

$$\sigma_{ys}\left(1220\right) = 15034 \ psi$$

$$^n\sigma^p_{ref} \le \min\left[0.75\left(\sigma_{ys}\left(1115\right)\right), 0.75\left(\sigma_{ys}\left(1220\right)\right)\right]$$

$$^n\sigma^p_{ref} \le \min\left[0.75\left(19851\right), 0.75\left(15034\right)\right]$$

$$3974 \ psi \le 11276 \ psi$$

f) STEP 6 – Determine the principal stresses, $^n\sigma_1, {}^n\sigma_2, {}^n\sigma_3$ and the effective stress, $^n\sigma_e$.

Thin-walled tubes experience a bi-axial stress state and the shear stress is zero; therefore, the principal stresses are given by the stress components calculated in STEP 4 ($^n\sigma_{xx} = {}^n\sigma_1$, $^n\sigma_{yy} = {}^n\sigma_2$, $^n\sigma_{zz} = {}^n\sigma_3$). The table given at the end of STEP 4 includes the principal stresses.

g) STEP 7 – Determine the remaining life at the stress level $^n\sigma_e$ and temperature ^nT for time increment ^nt by utilizing creep rupture data for the material and designate this value as ^nL. All stresses are in ksi and all temperatures are in °F, the corresponding time to rupture is in hours.

Material constants for the Omega method creep remaining life calculation, see Annex F, Table F.30 for 2.25Cr-1Mo annealed.

$$A_o = -21.86$$
$$A_1 = 50205$$
$$A_2 = -5436$$
$$A_3 = 500$$
$$A_4 = -3400$$

$$B_o = -1.85$$
$$B_1 = 7205$$
$$B_2 = -2436$$
$$B_3 = 0.0$$
$$B_4 = 0.0$$

For a cylinder or cone $\alpha_\Omega = 2$. The MPC Project Omega parameter is defined as $\beta_\Omega = \frac{1}{3}$. An example calculation for the remaining life at the stress level ${}^n\sigma_e$ and temperature ${}^nT$ for time increment ${}^nt$ is shown below. For this example, the adjustment factors for creep ductility Δ_Ω^{cd} and creep strain Δ_Ω^{sr} are set to 0.0

$$S_l = \log_{10}\left({}^n\sigma_e\right)$$
$$S_l = \log_{10}(3.442)$$
$$S_l = 0.5368$$

$$\log_{10}\dot{\varepsilon}_{co} = -\left\{\left(A_o + \Delta_\Omega^{sr}\right) + \left[\frac{1}{460 + {}^nT}\right]\left[A_1 + A_2S_l + A_3S_l^2 + A_4S_l^3\right]\right\}$$
$$\log_{10}\dot{\varepsilon}_{co} = -\left\{(-21.86 + 0.0) + \left[\frac{1}{460 + 1115}\right]\left[50205 + -5436(0.5368) + 500(0.5368)^2 + -3400(0.5368)^3\right]\right\}$$
$$\log_{10}\dot{\varepsilon}_{co} = -7.921$$
$$\dot{\varepsilon}_{co} = 1.199 \times 10^{-8} \ 1/Hr$$

$$\log_{10}\Omega = \left(B_o + \Delta_\Omega^{cd}\right) + \left[\frac{1}{460 + {}^nT}\right]\left[B_1 + B_2S_l + B_3S_l^2 + B_4S_l^3\right]$$
$$\log_{10}\Omega = (-1.85 + 0.0) + \left[\frac{1}{460 + 1115}\right]\left[7205 + -2436(0.537) + 0.0(0.537)^2 + 0.0(0.537)^3\right]$$
$$\log_{10}\Omega = 1.894$$
$$\Omega = 78.406$$

$$n_{BN} = -\left\{\left[\frac{1}{460 + {}^{n}T}\right]\left[A_2 + 2A_3S_l + 3A_4S_l^2\right]\right\}$$

$$n_{BN} = -\left\{\left[\frac{1}{460 + 1115}\right]\left[-5436 + 2(500)(0.537) + 3(-3400)(0.537)^2\right]\right\}$$

$$n_{BN} = 4.977$$

$$\Omega_n = \max\left[(\Omega - n_{BN}),\ 3.0\right]$$

$$\Omega_n = \max\left[(78.406 - 4.977),\ 3.0\right]$$

$$\Omega_n = 73.429$$

$$\delta_\Omega = \beta_\Omega\left(\frac{{}^{n}\sigma_1 + {}^{n}\sigma_2 + {}^{n}\sigma_3}{{}^{n}\sigma_e} - 1.0\right)$$

$$\delta_\Omega = \frac{1}{3}\left(\frac{3974 + 1987 + 0.0}{3442} - 1.0\right)$$

$$\delta_\Omega = 0.244$$

$$\Omega_m = \Omega_n^{\delta_\Omega + 1} + \alpha_\Omega \cdot n_{BN}$$

$$\Omega_m = 73.429^{0.244+1} + 2(4.977)$$

$$\Omega_m = 219.43$$

$${}^{n}L = \frac{1}{\dot{\varepsilon}_{co}\Omega_m}$$

$${}^{1}L = \frac{1}{1.199\times 10^{-8}(219.43)}$$

$${}^{1}L = 380090\ hours$$

The remaining life for each other increment is calculated similarly.

h) STEP 8 – Repeat STEP 3 through STEP 7 for each time increment ${}^{n}t$ in the mth operating cycle to determine the rupture time, ${}^{n}L$, for each increment.
The results for each time period are included in the table below.

Table E10.3-5

Operating Cycle	Past (m = 1)		Excursion (m = 2)		Future (m = 3)	
Sub-Increment	n = 1	n = 2	n = 1	n = 2	n = 1	n = 2
Design Pressure (P)	210	210	210	210	210	210
Service Time (hours)	65700	65700	168	168	21900	21900
Design Temperature (T)	1115	1115	1220	1220	1115	1115
${}^{n}\sigma_{xx} = {}^{n}\sigma_1$ (psi)	3974	3974	3974	3974	3974	3974
${}^{n}\sigma_{yy} = {}^{n}\sigma_2$ (psi)	1987	1987	1987	1987	1987	1987
${}^{n}\sigma_{zz} = {}^{n}\sigma_3$ (psi)	0.0	0.0	0.0	0.0	0.0	0.0
${}^{n}\tau_{xy}$ (psi)	0.0	0.0	0.0	0.0	0.0	0.0
${}^{n}\sigma_e$ (psi)	3442	3442	3442	3442	3442	3442
Remaining Life = ${}^{n}L$ (hrs)	380090	380090	10330	10330	380090	380090

i) STEP 9 – Compute the accumulated creep damage for all points in the mth cycle using Equation (10.25).

$${}^{m}D_c = \sum_{n=1}^{N} \frac{{}^{n}t}{{}^{n}L}$$

$${}^{1}D_c = \sum_{n=1}^{2} \frac{{}^{n}t}{{}^{n}L}$$

$${}^{1}D_c = \frac{{}^{1}t}{{}^{1}L} + \frac{{}^{2}t}{{}^{2}L} = \frac{65700}{380090} + \frac{65700}{380090} = 0.346$$

j) STEP 10 – Repeat STEP 2 through STEP 9 for each of the operating cycles defined in STEP 1.
The results for each operating cycle are included in the table below.

Table E10.3-6

Operating Cycle	Past (m = 1)		Excursion (m = 2)		Future (m = 3)	
Sub-Increment	n = 1	n = 2	n = 1	n = 2	n = 1	n = 2
Design Pressure (P)	210	210	210	210	210	210
Service Time (hours)	65700	65700	168	168	21900	21900
Design Temperature (T)	1115	1115	1220	1220	1115	1115
${}^{n}\sigma_{xx} = {}^{n}\sigma_1$ (psi)	3974	3974	3974	3974	3974	3974
${}^{n}\sigma_{yy} = {}^{n}\sigma_2$ (psi)	1987	1987	1987	1987	1987	1987
${}^{n}\sigma_{zz} = {}^{n}\sigma_3$ (psi)	0.0	0.0	0.0	0.0	0.0	0.0
${}^{n}\tau_{xy}$ (psi)	0.0	0.0	0.0	0.0	0.0	0.0
${}^{n}\sigma_e$ (psi)	3442	3442	3442	3442	3442	3442
Remaining Life = ${}^{n}L$ (hrs)	380090	380090	10330	10330	380090	380090
Damage = ${}^{m}D_c$	0.346		0.033		0.115	

k) STEP 11 – Compute the total creep damage for all cycles of operation.

$$D_c^{total} = \sum_{m=1}^{M} {}^{m}D_c \le D_c^{allow}$$

$$D_c^{total} = \sum_{m=1}^{3} {}^{m}D_c \le D_c^{allow}$$

$$D_c^{total} = {}^{1}D_c + {}^{2}D_c + {}^{3}D_c \le D_c^{allow} = 0.346 + 0.033 + 0.115 \le 0.80$$

$$D_c^{total} = 0.494 \le 0.80$$

l) STEP 12 – The creep damage prediction is complete for this location in the component. Follow the requirements of Part 10 to determine the recommended actions.

For this example, since the total damage, $D_c^{total} = 0.494$, is less than the allowable damage, $D_c^{allow} = 0.80$, the component is acceptable for continued operation, including a future run of five years (operating condition m = 3). The remaining life for operation could be determined by repeating this exercise and determining the time when $D_c^{total} = D_c^{allow}$.

Larson Miller Parameter Approach

g) Alternative STEP 7 - Determine the remaining life at the stress level using the Larson-Miller parameter data per Annex F, Table F.31. For SA335 Grade P22 material (2.25 Cr-1Mo)

Table E10.3-7

Parameters	Minimum Larson-Miller Parameter - LMP_m	Average Larson-Miller Parameter - LMP_a
A_0	4.3981719E+01	4.3494159E+01
A_1	-8.4656117E-01	-6.0165638E-01
A_2	-4.0483005E+01	-2.8040471E+01
A_3	2.6236081E-01	2.0644229E-01
A_4	1.5373650E+01	1.0982290E+01
A_5	4.9673781E-02	2.8393767E-02
A_6	6.6049429E-01	3.6067024E-01
C_{LMP}	20.0	20.0

Where Larson-Miller parameter is given by $\sigma \ in \ ksi$

$$LMP_{m,a} = \frac{A_o + A_2\sqrt{\sigma} + A_4\sigma + A_6\sigma^{1.5}}{1 + A_1\sqrt{\sigma} + A_3\sigma + A_5\sigma^{1.5}}$$

Rupture Life L is evaluated using Equation (10.21) to (10.24)

$$\log_{10}{}^{n}\left[L\right] = \frac{1000 \cdot LMP\left({}^{n}S_{eff}\right)}{\left({}^{n}T + 460\right)} - C_{LMP}$$

Where

$$^{n}S_{eff} = {}^{n}\sigma_e \exp\left[0.24\left(\frac{J_1}{S_s} - 1\right)\right]$$

$$J_1 = {}^{n}\sigma_1 + {}^{n}\sigma_2 + {}^{n}\sigma_3$$

$$S_s = \left({}^{n}\sigma_1^2 + {}^{n}\sigma_2^2 + {}^{n}\sigma_3^2\right)^{0.5}$$

$$J_1 = (3974 + 1987 + 0) = 5961$$

$$S_s = \sqrt{3974^2 + 1987^2 + 0^2} = 4443$$

$$^{n}S_{eff} = 3442\exp\left[0.24\left(\frac{5961}{4443} - 1\right)\right] = 3736$$

Calculate the rupture life using the minimum Larson-Miller parameter data

$$LMP_{\min} = \frac{A_o + A_2\sqrt{S_{eff}} + A_4 S_{eff} + A_6 S_{eff}^{\;1.5}}{1 + A_1\sqrt{S_{eff}} + A_3 S_{eff} + A_5 S_{eff}^{\;1.5}}$$

$$= \frac{43.981719 + (-40.483005\sqrt{3.736}) + (15.37365\cdot 3.736) + (0.66049429\cdot 3.736^{1.5})}{1 + (-0.84656117\sqrt{3.736}) + (0.26236081\cdot 3.736) + (0.049673781\cdot 3.736^{1.5})}$$

$$= 39.765$$

$$\log_{10} L = \left[\frac{1000\cdot LMP_{\min}}{(T+460)} - C_{LMP}\right] = \left[\frac{1000\cdot 39.765}{(1115+460)} - 20\right] = 5.2476$$

$$^{1}L = 10^{5.2476} = 176{,}850\ hours$$

$$^{1}t = 65{,}700\ hours$$

Life Fraction used for first sub-increment $= \left(\frac{65700}{176{,}850}\right) = 0.3715$

Similarly it can be shown that for the other 5 sub-increments, the life fractions are: 0.3715, 0.0359, 0.0359, 0.1238, 0.1238, therefore

$$D_c^{total} = \left[0.3715 + 0.3715 + 0.0359 + 0.0359 + 0.1238 + 0.1238\right] = 1.06 > 0.80$$

Therefore, the component is not acceptable per Level 2 analysis using the minimum Larson-Miller parameter data

Calculate the rupture life using the average Larson-Miller parameter data.

$$LMP_{avg} = \frac{A_o + A_2\sqrt{S_{eff}} + A_4 S_{eff} + A_6 S_{eff}^{\ 1.5}}{1 + A_1\sqrt{S_{eff}} + A_3 S_{eff} + A_5 S_{eff}^{\ 1.5}}$$

$$= \frac{43.494159 + (-28.040471\sqrt{3.736}) + (10.982229 \cdot 3.736) + (0.36067024 \cdot 3.736^{1.5})}{1 + (-0.60165638\sqrt{3.736}) + (0.20644229 \cdot 3.736) + (0.028393767 \cdot 3.736^{1.5})}$$

$$= 40.485$$

$$\log_{10} L = \left[\frac{1000 \cdot LMP_{\min}}{(T+460)} - C_{LMP}\right] = \left[\frac{1000 \cdot 40.485}{(1115+460)} - 20\right] = 5.70476$$

$$^{1}L = 10^{5.7048} = 506,710 \ hours$$

$$^{1}t = 65,700 \ hours$$

Life Fraction used for first sub-increment $= \left(\frac{65700}{506,710}\right) = 0.1297$

Similarly it can be shown that for the other 5 sub-increments, the life fractions are: 0.1297, 0.0134, 0.0134, 0.0432, 0.0432, therefore

$$D_c^{total} = \left[0.1297 + 0.1297 + 0.0134 + 0.0134 + 0.0432 + 0.0432\right] = 0.373 < 0.80$$

Therefore, the component is acceptable per Level 2 analysis using the average Larson-Miller parameter data

Comparison with API 530 Method

If the same data were to be analyzed using the API 530 method, the Huddleston uniaxial stress $S_{eff} = 3.736 \ ksi$ is replaced by the mean diameter hoop stress $\sigma_{mean} = 3.974 \ ksi$ in Equation 10.21. Since S_{eff} is 0.94 times σ_{mean}, the corresponding life fractions consumed using API 530 become higher.

a) Using minimum LMP data:

Life fractions consumed are: 0.5068, 0.5068, 0.0481, 0.0481, 0.1689, 0.1689. Total life fraction $D_c^{total} = 1.448$ compared with $D_c^{total} = 1.063$ using S_{eff} and $D_c^{total} = 0.494$ using Omega data with both adjustment factors for creep strain and creep ductility set to zero.

b) Using average LMP data:

Life fractions consumed are: 0.1685, 0.1685, 0.0171, 0.0171, 0.0562, 0.0562. Total life fraction $D_c^{total} = 0.484$ compared with $D_c^{total} = 0.373$ using S_{eff} and $D_c^{total} = 0.494$ using Omega data with both adjustment factors for creep strain and creep ductility set to zero.

c) Analysis using Actual Corroded Tube Wall Thickness

Assuming accurate and reliable historical tube wall corrosion rates are available, actual tube wall thickness can be used to obtain a more accurate estimate of rupture life and life fraction.

For this example, assuming the tubes were corroding at 0.005 inch per year from the inside surface, the load history corresponding to the tube dimension during each of the operating cycles and sub-increments can be derived. Rupture life and damage results based on various methods are summarized in Table E10.3-8. Note that with this approach, all cumulative damages are below 0.80.

Table E10.3-8

Operating Cycle		Past (m = 1)		Excursion (m = 2)		Future (m = 3)	
Sub-Increment		n = 1	n = 2	n = 1	n = 2	n = 1	n = 2
Service Time in Hours	L_hours	65,700	65,700	168	168	21,900	21,900
Operating Pressure, psig	P_avg	210	210	210	210	210	210
Tube Wall Temperature, ° F	T_avg	1115	1115	1220	1220	1115	1115
ID Corrosion Rate, 0.001 inch / year		5.0	5.0	5.0	5.0	5.0	5.0
Beginning Tube OD, inch	Do_begin	8.625	8.625	8.625	8.625	8.625	8.625
Ending Tube OD, inch	Do_end	8.625	8.625	8.625	8.625	8.625	8.625
Beginning Tube ID, inch	Di_begin	7.981	8.056	8.131	8.131	8.131	8.156
Ending Tube ID, inch	Di_end	8.056	8.131	8.131	8.131	8.156	8.181
Beginning Tube Thickness, inch	t_begin	0.322	0.285	0.247	0.247	0.247	0.234
Ending Tube Thickness, inch	t_end	0.285	0.247	0.247	0.247	0.234	0.222
Average Outside Diameter, inch	Do_avg	8.625	8.625	8.625	8.625	8.625	8.625
Average Inside Diameter, inch	Di_avg	8.019	8.094	8.131	8.131	8.144	8.169
Average Tube Wall, inch	t_avg	0.303	0.266	0.247	0.247	0.241	0.228
Omega Method							
Principal Stress 1, psi	$\sigma 1$	2881	3303	3562	3564	3660	3866
Principal Stress 2, psi	$\sigma 2$	1441	1651	1781	1782	1830	1933
Principal Stress 3, psi	$\sigma 3$	0	0	0	0	0	0
Effective Stress, psi	σe	2495	2860	3085	3086	3169	3348
Ω Rupture Life, hrs	$L\Omega$	879,235	633,665	13,839	13,825	482,208	412,347
Ω Life Used (This Period)	$L / L\Omega$	0.075	0.104	0.012	0.012	0.045	0.053
Damage (Cumulative)	$\Sigma (L / L\Omega)$	0.075	0.178	0.191	0.203	0.248	0.301
LMP Using Huddleston Unaxial Stress Approach							
$J1 = (\sigma 1 + \sigma 2 + \sigma 3)$	J1	4322	4954	5343	5345	5490	5799
$S_S = (\sigma_1{}^2 + \sigma_2{}^2 + \sigma_3{}^2)^{0.5}$	S_S	3222	3693	3983	3984	4092	4322
Huddleston Uniaxial Stress	S_{EFF}	2709	3105	3349	3350	3440	3634
Minimum LMP at S_{EFF}	LMP_{min} (S_{EFF})	40.721	40.350	40.122	40.120	40.036	39.858
Rupture Life, hours	L_{EFF}	715,601	416,094	7,620	7,607	263,013	202,581
Life Used (This Period)	L / L_{EFF}	0.092	0.158	0.022	0.022	0.083	0.108
Damage (Cumulative)	$\Sigma (L / L_{EFF})$	0.092	0.250	0.272	0.294	0.377	0.485
Average LMP at S_{5EFF}	LMP_{avg} (S_{EFF})	41.263	40.965	40.780	40.779	40.710	40.562
Rupture Life, hours	L_{EFF}	1,579,314	1,022,363	18,775	18,748	703,860	567,314
Life Used (This Period)	L / L_{EFF}	0.042	0.064	0.009	0.009	0.031	0.039
Damage (Cumulative)	$\Sigma (L / L_{EFF})$	0.042	0.106	0.115	0.124	0.155	0.193
API STD 530 Approach							
API 530 Mean Diameter Stress, psi	σ_{mean}	2881	3303	3562	3564	3660	3866
API 530 Minimum LMP at σ_{mean}	LMPmin (σ_{mean})	40.560	40.164	39.924	39.923	39.835	39.649
Rupture Life, hours	L_{530}	565,463	317,115	5,810	5,800	195,805	149,182
Life Used (This Period)	L / L_{530}	0.116	0.207	0.029	0.029	0.112	0.147
Damage (Cumulative)	$\Sigma (L / L_{530})$	0.116	0.323	0.352	0.381	0.493	0.640
API 530 Average LMP at σ_{mean}	LMP_{avg} (σ_{mean})	41.134	40.814	40.617	40.616	40.543	40.387
Rupture Life, hours	L_{530}	1,308,211	820,247	15,023	15,000	551,484	439,088
Life Used (This Period)	L / L_{530}	0.050	0.080	0.011	0.011	0.040	0.050
Damage (Cumulative)	$\Sigma (L / L_{530})$	0.050	0.130	0.142	0.153	0.192	0.242

Therefore the heater tubes now pass Level 2 analysis regardless of the approach used.