API 579-1/ASME FFS-1 FAD Level 2 Assessment Method is Conservative for Cases of Pipelines with SCC and Seam Weld Toe Cracking

Samarth Tandon, Sergio Limon, Ravi Krishnamurthy, Shaikh Rahman
Blade Energy Partners

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Abstract

Accurately predicting limiting pressures in fitness-for-service evaluations is essential for ensuring pipeline integrity, determining appropriate mitigation measures, and scheduling subsequent assessment intervals. Historically, the API 579-1/ASME FFS-1 FAD Level 2 methodology has been employed for evaluating the fitness for service concerning limiting pressure predictions. However, the degree of conservatism in this approach has not been thoroughly quantified, particularly for pipelines affected by stress corrosion cracking and seam weld toe cracks. This lack of quantification has prompted operators to introduce additional safety factors, often leading to overly conservative limiting pressure predictions. This paper aims to assess the inherent conservatism of the API-579 FAD Level 2 method concerning pipeline rupture failures by analyzing burst test results of pipelines exhibiting natural stress corrosion cracking and toe weld cracks. The implications of these findings are discussed in detail

Introduction

Stress corrosion cracking (SCC) is a prevalent defect in aging pipeline systems worldwide. As a time-dependent threat, its assessment is a critical component of pipeline integrity management. Overly conservative assessments can lead to unnecessary pipeline excavations, while non-conservative evaluations may result in unintended leaks or catastrophic ruptures. Therefore, selecting an appropriate assessment method for predicting limiting pressure is essential for ensuring the safe operation of pipelines.

The pipeline industry continues to have an increased focus on evaluating the accuracy and degree of conservatism in fracture mechanics-based failure predictions of pipelines with cracks and crack-like defects [1-6]. This is driven mainly by an increased number of in-line inspections assessing for cracking and seam weld anomalies and recently published gas pipeline regulations for addressing pipelines cracking and crack-like anomalies in the USA under 49CFR 192.933 and 192.712. The response to ILI reported and NDE confirmed cracks or crack-like anomalies can be safely established by means of a fracture mechanics-based model. The industry utilizes various models to evaluate axial planar defects in pipelines subjected to internal pressure (NG-18 ln-sec, CorLAS and MAT-8) and those that were created for a broad pipeline, piping and pressure vessels applications (Newman-Raju, BS 7910, and API 579-1/ASME FFS-1). Each of these models is based on fracture mechanics principles to some degree, dependent on the knowledge available at the time of the model development, assumptions on material fracture behavior, description of the crack driving force, and calibration with empirical data.

In this paper, the limiting pressure prediction from API 579-1/ASME FFS-1 Failure Assessment Diagram (API 579 FAD) Level 2 is compared to eighteen full-size pipeline burst test results with cracks to ascertain the conservativeness of API 579 FAD Level 2 assessment of pipelines with cracks. Actual pipe tensile properties and fracture toughness, and measured crack dimensions from post-fracture surfaces were available for analysis. The cracks included SCC colonies in the base material

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and Toe cracks on the seam weld. Further, the end cap influence on the burst test is accounted for in the evaluation of the API 579 Level 2 model. .

Background

The API 579-1/ASME FFS-1 Failure Assessment Diagram (API 579 FAD) is a widely utilized fitness-for-service procedure for evaluating the acceptability of crack-like features in various structures and components [7]. The concept of the failure assessment diagram was first introduced in the R6 procedure, a flaw assessment methodology developed in 1976 for the British electric power industry [8-10]. The R6 procedure was subsequently incorporated into the second edition of PD6493, "Guidance on Methods for Assessing the Acceptability of Flaws in Fusion Welded Structures," published in 1991. In 1999, the British Standard Institution elevated PD6493 to a British Standard, releasing it as BS 7910, "Guide on Methods for Assessing the Acceptability of Flaws in Metallic Structures" [11]. API 579 fitness-for-service practice was first published in 2000, and a revised edition was released jointly with ASME in 2007. The latest edition is published in 2021. Since its inception, the Failure Assessment Diagram has been an integral part of this fitness-for-service practice.

While the failure assessment diagram in API 579 shares several similarities with the BS 7910 guide, API 579 offers a more comprehensive library of stress intensity factor (K) solutions compared to both R6 and BS 7910. This expanded capability has made API 579 one of the most widely adopted approaches for elastic-plastic fracture mechanics analysis of structural components.

The FAD approach is two failure criteria where cracking or fracture and plastic collapse are assessed together. Non-linear stress equations are integrated to predict failure through the combined failure modes, which govern the two key assessment parameters fracture ratio Kr and load ratio Lr [7]. The FAD methodology enables one to assess brittle and ductile fractures, and a ductile overload failure in the same assessment. A typical FAD is shown in **Figure** *1*.

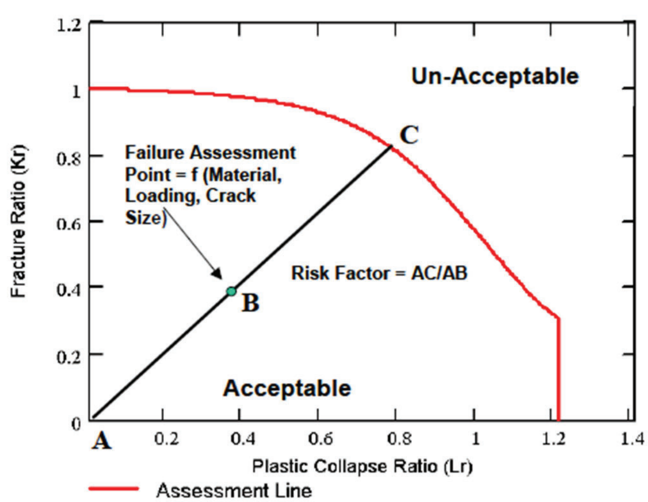

Figure 1. Typical failure assessment diagram, $K_r = K_I / K_{mat}$, $Lr = \sigma_{ref} / \sigma_y$

To determine the significance of a flaw, the Kr and Lr values for the flaw are calculated and plotted on the diagram. If the assessment point lies on or outside the area bounded by the axes and the assessment curve, the flaw is unacceptable. Conversely, if the point lies inside within the curve, the flaw is acceptable. To account for localized plastic collapse, a cut-off limit is incorporated on the horizontal axis. The closer the assessment point lies to the FAD curve, the lower the safety factor. The intersection of the line that is generated with the failure curve provides a critical/limiting crack dimension, for either a fixed load and varying crack dimensions, or fixed crack dimensions increasing load.

API-579 defines three levels of assessment:

- Level 1 – a simplified, conservative assessment method.
- Level 2 – a standard assessment method with more detailed analysis.
- Level 3 – an advanced method that includes a material-specific FAD and ductile tearing instability analysis, particularly suitable for predicting burst pressure and leak/rupture in high-toughness ductile materials.

For Fitness-for-Service (FFS) evaluations, FAD Levels 1 and 2 are commonly used to assess crack and crack-type flaws in structural components. FAD Level 3 is intended to predict burst failure pressure [5] and can be used for least conservatism and requires detailed tensile and fracture toughness material property data. The focus of this study is API FAD Level 2, which is increasingly used to assess fitness for purpose and estimates limiting pressure for cracks in pipeline systems [7]. The conservatism of API-579 FAD Level 2 has not been comprehensively quantified, particularly from a usability standpoint where data availability for measured material properties and actual wall thickness is limited. The present study quantifies the degree of conservatism for axial external SCC defects in pipe body and seam.

Burst test data

A total of 18 pipe samples with SCC were removed from service and burst tested. Among them, seven were in 16-inch outside diameter (OD) pipeline, four were 20-inch OD., two were 34-inch O., and five were 36-inch OD, as shown in **Table *1*.** The actual failure pressures were in the range of 95-144 %SMYS. It is important to note that all the failure pressures far exceeded the pipelines' normal operating or maximum operating pressure. Pipe #11 cracks were mechanically fatigued to increase the crack depth and was then burst tested. All the other pipes were subjected to burst testing with monotonically increasing pressure with the original SCC cracks.

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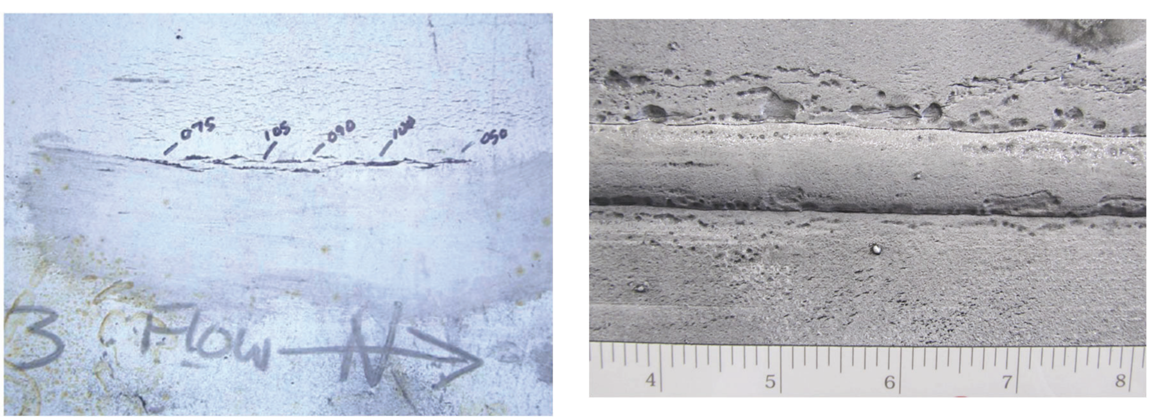
Table 1. Main characteristics of the pipeline samples burst tested

#	OD (in)	Nominal Wall Thickness (NWT), in	Grade	Cracking Type	Burst Pressure (P_B), psi	P_B as %SMYS
1	20	0.25	X52	SCC on Body Material	1,672	129.0%
2	16	0.25	X52		1,757	108.1%
3	16	0.25	X52		1,625	100.0%
4	16	0.25	X52		1,910	117.5%
5	16	0.25	X52		1,812	111.5%
6	16	0.25	X52		1,786	109.9%
7	16	0.25	X52		1,738	107.0%
8	20	0.25	X52		1,433	110.0%
9	20	0.25	X52		1,584	122.0%
10	20	0.25	X52		1,403	108.0%
11	26	0.281	X52		1,067	95.0%
12	34	0.36	X52		1,585	144.0%
13	34	0.36	X52		1,474	134.0%
14	36	0.36	X65		1,525	117.4%
15	36	0.358	X65	Toe Crack on Seam Weld / Heat Affected Zone (SCC)	1,418	109.1%
16	36	0.358	X65		1,392	107.1%
17	36	0.358	X65		1,455	112.0%
18	36	0.358	X65		1,644	126.50%

Figure 2 shows an example of pipe body cracking and weld toe cracking.



(a) (b)

Figure 2. (a) SCC colony on the body material (b) toe crack at the DSAW

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Figure *3* shows the preparation for the burst test. The pipes were capped and pressurized using the hydraulic system. A pressure transducer was installed on each pipe sample, and the crack was monitored using the clip and strain gages. The information determined through the burst test included failure pressure and crack initiation size.

(a) (b)

(c)

Figure 3. (a) Samples end capped, (b) set up for the burst test (c) clip gage for monitoring crack opening

The initial crack size that caused the rupture was determined from the high-speed video, which captured stable tearing, crack coalescence, and unstable crack tearing. **Figure *4*** shows the sequence of events leading to a burst test.

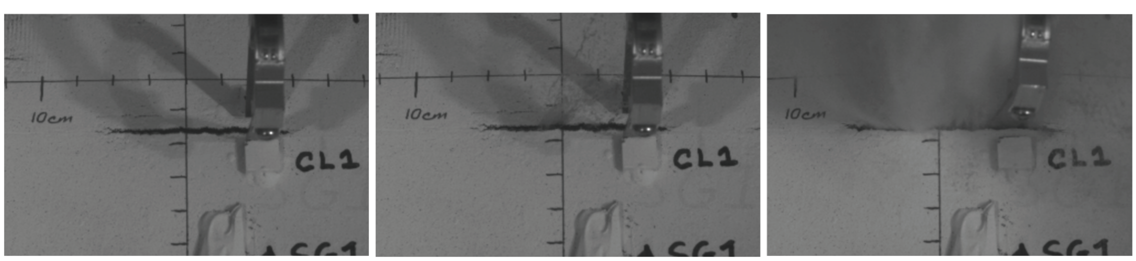

Figure 4. Sequence of events leading to the burst test

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Table *2* reports the length and maximum depth of the crack or cracks that initiated the failure.

Table 2. Dimensions of cracks tested

#	Length (in.)	Maximum Depth (in.)	Max depth as % nominal wt
1	2.2	0.087	34.0%
2	4.3	0.126	50.4%
3	3.0	0.150	60.0%
4	3.0	0.118	47.2%
5	3.0	0.157	62.8%
6	4.5	0.118	47.2%
7	3.8	0.124	49.6%
8	2.2	0.106	43.0%
9	1.2	0.150	61.0%
10	2.3	0.165	69.0%
11	3.0	0.261	93.0%
12	1.6	0.122	33.9%
13	1.3	0.122	33.9%
14	2.8	0.201	55.9%
15	85.9	0.157	44.0%
16	99.2	0.157	44.0%
17	7.6	0.161	45.1%
18	5.6	0.150	41.8%

Material tests were conducted for all the pipes, and they included yield, tensile and fracture toughness. Tensile properties were measured in transverse orientation and for toughness testing, J-integral tests in C-L orientation were performed to measure fracture toughness, and it was converted to K_J. For the samples with crack in the seam weld toe area, stress-strain microprobe technology was utilized to measure the yield and tensile strength of the heat-affected zone (HAZ). J-integral tests were also performed from the material in the HAZ area, that is, at the Seam Weld/Base material interface and 2 mm away from the interface towards the base material.

API-579 FAD Level 2 – Model Prediction

The API-579 FAD Level 2 limiting pressure was estimated, and then the Failure Pressure Ratio (FPR). The term FPR is commonly used in the pipeline industry and is defined as the ratio of the actual measured failure pressure to the predicted pressure obtained from the API-579 FAD Level 2 analysis.

Traditionally the application of Level 2, the nominal material properties should be utilized. This predicts limiting pressure that has an inherent safety factor. However, if actual material properties

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are used, then the conservatism is reduced, and the predictions provide a more realistic assessment and impact of the defect on pipeline integrity.

In this work, the pressure prediction was made under different scenarios to assess the conservatism of Level 2. The pressure prediction here is carried out for external, axial, and an assumed semi-elliptical crack shape under the following scenarios:

- Case A: all measured properties and dimensions (yield strength, tensile strength, toughness, and wall thickness) are utilized.
- Case B: specified minimum tensile properties (SMYS and SMTS), measured toughness, and nominal wall thickness (NWT).
- Case C: using SMYS, SMTS, assumed CVN toughness value of 20 ft-lb, and NWT.

Case A: *Table 3* provides Case A FPR for the SCC body material burst tests. The average FPR was 1.18 with a standard deviation of 0.15. The FPR was in the range of 1.07 to 1.63.

Table 3. Results of Case A limiting pressure and FPR for body material SCC

#	MWT (in)	Measured YS, ksi	Measured TS, ksi	K_{JC} (ksi $in^{1/2}$)	Actual Failure Pressure, psi	Case A: Level 2 Predicted Pressure, psi	FPR
1	0.272	52.6	76	120	1,672	1,536	1.09
2	0.250	67	81.8	109	1,757	1,571	1.12
3	0.250	67	81.8	109	1,625	1,537	1.06
4	0.250	67	81.8	109	1,910	1,736	1.10
5	0.250	67	81.8	109	1,812	1,490	1.22
6	0.250	67	81.8	109	1,786	1,623	1.10
7	0.250	67	81.8	109	1,738	1,622	1.07
8	0.256	49.5	70.6	89	1,433	1,203	1.19
9	0.257	50.7	72.1	96	1,584	1,303	1.22
10	0.251	51.9	75.7	102	1,403	1,073	1.31
11	0.281	58.0	89.5	116	1,067	656	1.63
12	0.374	60.2	77.9	95	1,585	1,346	1.18
13	0.374	52.6	72.6	95	1,474	1,246	1.18
14	0.377	69.7	89.0	178	1,525	1,387	1.10

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Table 4 provides Case A FPR for seam weld toe cracks burst tests. The average FPR was 1.25, with a standard deviation of 0.02. The FPR was in the range of 1.23 to 1.27.

Table 4. Results of Case A limiting pressure and FPR for seam weld toe cracks

#	MWT (in)	Measured YS, ksi	Measured TS, ksi	K_{JC} (ksi $in^{1/2}$)	Actual Failure Pressure, psi	Case A: Level 2 Predicted Pressure, psi	FPR
15	0.362	68.8	90.4	259	1,418	1,125	1.26
16	0.362	68.8	90.4	259	1,392	1,122	1.24
17	0.370	74.6	95.1	132	1,455	1,186	1.23
18	0.370	74.6	95.1	132	1,644	1,294	1.27

Case B: *Table 5* provides the Case B FPRs for SCC body material burst tests. The average FPR was 1.32, with a standard deviation of 0.13. The FPR was in the range of 1.18 to 1.69.

Table 5. Results of Case B limiting pressure and FPR body material SCC

#	NWT (in)	Grade	K_{JC} (ksi $in^{1/2}$)	Actual Failure Pressure, psi	Case B: Level 2 Predicted Pressure, psi	FPR
1	0.250	X52	120	1,672	1,376	1.22
2	0.250	X52	109	1,757	1,316	1.34
3	0.250	X52	109	1,625	1,302	1.25
4	0.250	X52	109	1,910	1,445	1.32
5	0.250	X52	109	1,812	1,269	1.43
6	0.250	X52	109	1,786	1,353	1.32
7	0.250	X52	109	1,738	1,356	1.28
8	0.250	X52	89	1,433	1,214	1.18
9	0.250	X52	96	1,584	1,281	1.24
10	0.250	X52	102	1,403	1,068	1.31
11	0.281	X52	116	1,067	631	1.69
12	0.360	X52	95	1,585	1,155	1.37
13	0.360	X52	95	1,474	1,179	1.25
14	0.360	X65	178	1,525	1,241	1.23

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Table 6 provides the Case B FPR's for seam weld toe cracks burst tests. The average FPR was 1.44, with a standard deviation of 0.02. The FPR ranges from 1.42 to 1.47.

Table 6. Results of Case B limiting pressure and FPR calculated for seam weld toe cracks

#	NWT (in)	Grade	K_{JC} (ksi in$^{1/2}$)	Weld Type	Actual Failure Pressure, psi	Case B: Level 2 Predicted Pressure, psi	FPR
15	0.358	X65	259	DSAW	1,418	975	1.45
16	0.358	X65	259	DSAW	1,392	972	1.43
17	0.358	X65	132	DSAW	1,455	1,026	1.42
18	0.358	X65	132	DSAW	1,644	1,115	1.47

Case C: Case C used the specified minimum tensile properties, NWT, and a CVN of 20 ft-ln. Rolfe Novak correlation [12] was used to convert the CVN to toughness value (K_{mat}). *Table 7* provides the Case C FPR for SCC body material burst test, where the average FPR was 1.60, with a standard deviation of 0.32. The FPR was in the range of 1.29 to 2.6.

Table 7. Results of Case C limiting pressure and FPR for body material SCC

#	NWT (in)	Grade	CVN (ft-lb)	K_{mat} (ksi in1/2)	Actual Failure Pressure, psi	Case C: Level 2 Predicted Pressure, psi	FPR
1	0.250	X52	20	66.7	1,672	1,191	1.40
2	0.25	X52	20	66.7	1,757	1,113	1.58
3	0.25	X52	20	66.7	1,625	1,071	1.52
4	0.25	X52	20	66.7	1,910	1,241	1.54
5	0.25	X52	20	66.7	1,812	1,031	1.76
6	0.25	X52	20	66.7	1,786	1,158	1.54
7	0.25	X52	20	66.7	1,738	1,152	1.51
8	0.250	X52	20	66.7	1,433	1,109	1.29
9	0.250	X52	20	66.7	1,584	1,145	1.38
10	0.250	X52	20	66.7	1,403	890	1.58
11	0.281	X52	20	66.7	1,067	411	2.60
12	0.360	X52	20	66.7	1,585	1,047	1.51
13	0.360	X52	20	66.7	1,474	1,076	1.37
14	0.360	X65	20	73.1	1,525	860	1.77

Table 8 provides the Case C FPR for seam weld toe crack burst test. The average FPR was 1.89 with standard deviation of 0.09. The FPR was in the range of 1.81 to 1.98.

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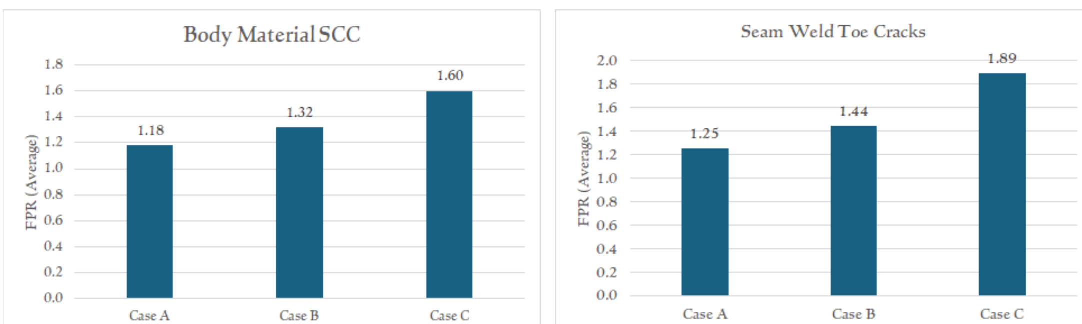
Table 8. Results of Case C limiting pressure and FPR for seam weld toe cracks

#	NWT (in)	Grade	CVN (ft-lb)	K_{JC} (ksi in$^{1/2}$)	Weld Type	Actual Failure Pressure, psi	Case C: Level 2 Predicted Pressure, psi	FPR
15	0.358	X65	20	73.1	DSAW	1,418	717	1.98
16	0.358	X65	20	73.1	DSAW	1,392	716	1.95
17	0.358	X65	20	73.1	DSAW	1,455	805	1.81
18	0.358	X65	20	73.1	DSAW	1,644	902	1.82

All Cases

Figure 5 shows the average FPR for the evaluated cases. For the SCC in the body material, the average FPR values are 1.18, 1.32, and 1.60 for cases A, B, and C, respectively. For toe cracks along the Seam Weld, the average FPR values are 1.25, 1.44, and 1.89 for cases A, B, and C, respectively.



(a) (b)

Figure 5. FPR for three cases evaluated (a) SCC/Cracks in the body material (b) Toe Cracks along the Seam Weld

Discussion

The API-579 FAD Level 2 methodology is applicable for calculating the limiting pressure of crack features. The Level 2 methodology predicts limiting pressure, not failure pressure. This approach is easy to apply and typically uses nominal properties of the material for assessment of limiting pressure.

In this analysis, the true crack length and depth that resulted in the failure, measured through laboratory examination, was utilized for the analysis. For all cases the true crack dimensions were utilized.

Case B results are reflective of the analysis that would be conducted for pipelines. The FPR or safety factor ranges from 1.18 to 1.69 for body SCC and 1.42 to 1.47 for DSAW weld SCC using measured toughness data. This important observation reveals that inherent in Level 2, with true critical crack dimensions, results fit for service SCC pipe. As one uses actual wall thickness and material properties,

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Case A, the FPR drops to a range of 1.07 to 1.63 for pipe body SCC and 1.23 to 1.27 for DSAW SCC.

Level 2 FAD analysis often uses ILI or NDE crack dimension data, and that is often conservative whilst accounting for tool tolerance on depth and possibly utilizing colony length. Level 2 FAD will provide significant safety factor and should be adequate. The FPR estimated using actual material properties, actual wall thicknesses and actual dimensions, Level 2 still exhibits significant conservatism.

API-579 FAD Level 2 is most suitable for axial cracks under internal pressure in an open-ended cylinder condition (i.e., uniaxial stress). However, burst tests are typically performed on end-capped cylinders, which produce a different stress state. Based on finite element analysis (FEA) results [5] and stress analysis studies [12] previously completed, a correction factor of 0.85 can be applied to the FPR for open-ended conditions. This factor accounts for the lower failure pressures expected in the non-end-capped condition. By applying the 0.85 correction factor, the adjusted average FPRs for SCC in the body material for Cases A, B, and C become 1.0, 1.12, and 1.36, respectively. For toe cracks in the weld material, the adjusted FPRs are 1.06, 1.23, and 1.60, respectively.

Summary

API 579 Level 2 assessment provides adequate safety factors for SCC cracks (body and DSAW weld) and does not require any additional safety factors during crack evaluation.

Eighteen burst test data were analyzed to estimate the conservatism of API-579 FAD Level 2. Conservatism is measured for three cases for each body material: SCC cracks and weld toe cracks. The dimensions of the crack that initiated the failure were captured using a high-speed camera. Measured tensile and toughness properties and thickness were utilized for calculation.

- Case A: measured material properties: YS, TS, and toughness, and MWT were used for prediction
- Case B: measured toughness, and SMYS, SMTS, and NWT were used for prediction
- Case C: SMYS, SMTS, assumed CVN of 20 ft-lbs, and NWT were used for prediction

Table 9. Average FPR for body material SCC and toe cracks on seam weld with no adjustment factor

	FPR		
	Case A	Case B	Case C
Body Material SCC	1.18	1.32	1.60
Toe Cracks on Seam (SCC)	1.25	1.44	1.89

With the application of the 0.85 correction factor, the resulting FPR values are as follows: Case A yields an FPR of approximately 1.0 for SCC in the body material and 1.06 for toe cracks in the seam weld. Case C exhibits the highest FPR, with values of 1.36 for SCC in the body material and 1.60 for toe cracks in the seam weld.

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Assuming Charpy V-notch (CVN) toughness values lower than 20 ft-lb would result in FPR values higher than those presented for these cases.

Table 10. Average FPR for body material SCC and toe crack on seam weld with an adjustment factor of 0.85

	FPR		
	Case A	Case B	Case C
Body Material SCC	1.0	1.12	1.36
Toe Cracks on Seam (SCC)	1.06	1.23	1.60

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