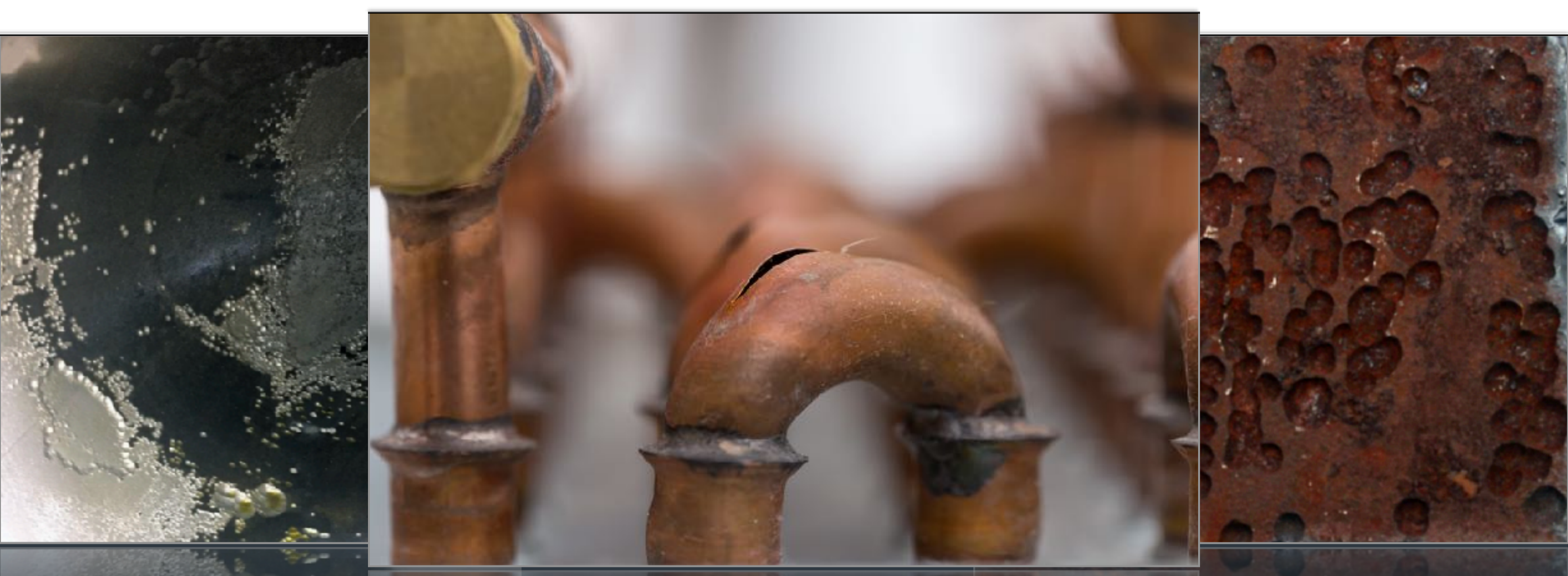
Inspectioneering

FITNESS-FOR-SERVICE

The User's Guide to API 579-1/ASME FFS-1



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Inspectioneering, LLC
701 Sawdust Road, Suite 4
The Woodlands, TX 77380 USA
www.inspectioneering.com

Written by Greg Garic

Inspectioneering would like to thank all of those that contributed to the development of this work.

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Introduction - Setting the Stage

During inspection...

- A 3.00" long X 0.06" deep crack is found in the long seam of a 30-year old reactor vessel,
- Severe pitting is discovered in the skirt of a vessel after insulation removal,
- Visible warpage is found in the shell of a condensate drum as the result of high temperature exposure in a refinery fire.

None of these defects are allowable by the construction Code. How does a plant engineer deal with these defects? Repair? Replace? Use as-is?

The answers to these, and many similar questions, are in the realm of Fitness-For-Service (FFS). Most plant engineers and inspectors have come to understand the general concept of FFS assessment to help deal with the difficult realities of equipment degradation over time. But let's step back for a bit and look at the big picture. What is FFS assessment and where does it fit into the overall scheme of plant integrity management?

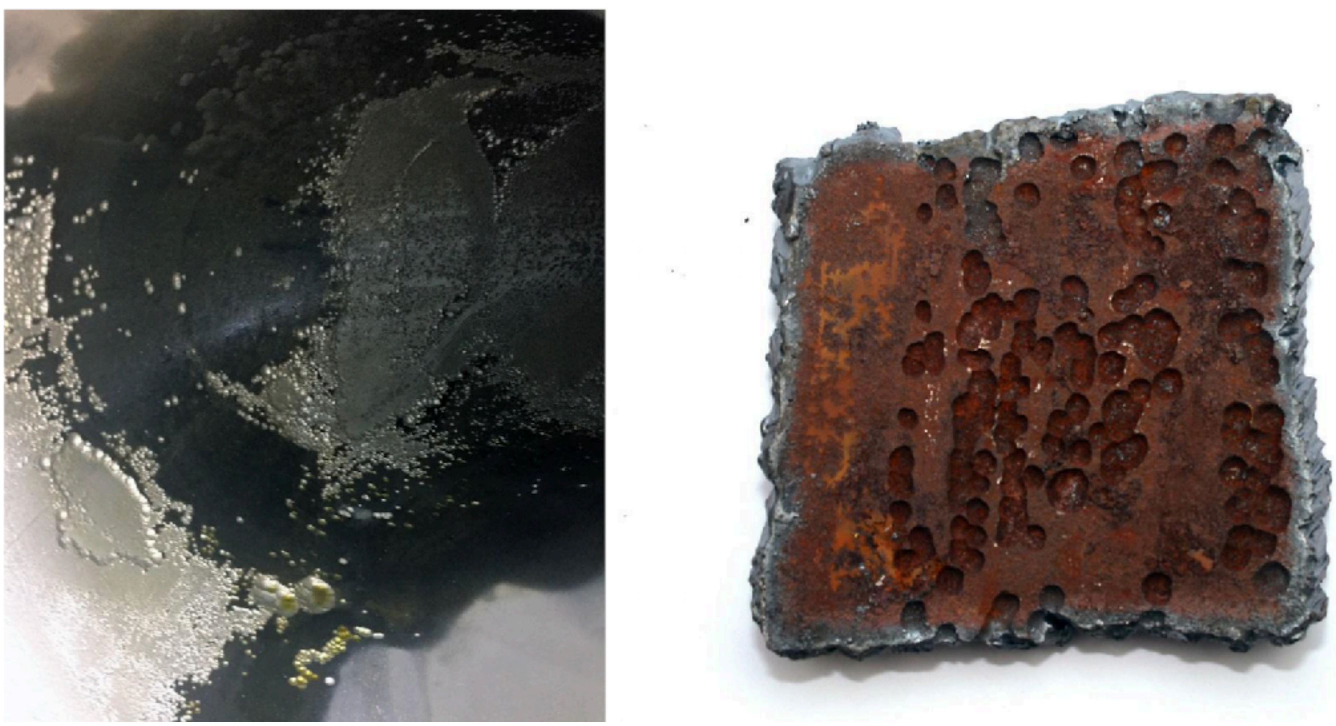

Figure 1: The left image shows a pitted and cratered pipe surface. The right image shows a material that has corroded since being removed from service, contaminating the surface, and making analysis of the original cause of pitting difficult.

What is "Fitness-For-Service"?

Let's start with a formal definition of "Fitness-For-Service." According to the 2016 edition of API 579-1/ ASME FFS-1 (API 579), Fitness-For-Service assessments are defined as:

> "... quantitative 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 a specific condition that might cause a failure."

Dissecting this definition reveals the key features of FFS evaluations. They are:

- Quantitative,
- Applicable to in-service components (i.e., NOT original design), and
- Applied to a defect or degradation or some condition that may cause failure.

FFS is a very powerful tool for the plant engineer. In the "olden days" (that's pre-1990), if a pressure vessel was found to have one small area of localized corrosion, the engineer's only options were to repair, replace, or derate the entire vessel based on the thinnest spot. This was often extremely conservative, but there was no generally accepted alternative method for dealing with the issue. As technology improved through the 1970s, 80s, and 90s, methods for dealing with older pressure systems began to emerge.

Today, the plant engineer has a toolbox full of techniques to evaluate the effect of in-service degradation. These tools allow more intelligent cradle-to-grave management of equipment and can prevent or postpone costly equipment replacement or unscheduled shutdowns.

In practice, the three most common FFS questions posed by plant engineers are:

1. Is it safe to continue operation?
2. How long can I continue operation?
3. Can I keep running until the next scheduled shutdown in X months or years?

It's probably fair to say that the primary goal of the **vast** majority of all FFS assessments is to answer at least one of these three questions.

The principal "tools" at our disposal to address these questions are embodied in the API 579-1/ASME FFS-1 Standard, Fitness-For-Service (API 579). This ANSI accredited "American National Standard" has achieved acceptance in the United States – and across much of the world – and is focused on FFS assessments of pressure equipment in the refining and petrochemical industries.

Although this Standard was developed specifically with regard to pressure equipment, many of the techniques and methods can be applied to non-pressure equipment as well. Similarly, although it was developed by and for the refining and petrochemical industry, it can be effectively used in a broader range of industries too.

The principal issue with using API 579 in other industries is related to damage mechanisms and regulatory acceptance. A certain set of damage mechanisms have been addressed in API 579 because they represent the major issues of concern in the target industries. If you are from another industry, there may be technical issues unique to your industry that are not considered in API 579. This might include different types of chemical and environmental damage, different materials, different loading and stress sources, different codes or laws. Many local and national governments require that FFS assessments be documented as part of a facility's mechanical integrity procedure. In some of these cases, documentation must be submitted to the jurisdictional authority. There are also jurisdictions where pre-approval must be granted by the regulatory authority for more complex levels of analysis (i.e., Levels 2 or 3).

One assumption inherent in FFS assessments is that the underlying design is adequate. API 579 requires that components were originally designed in compliance with a nationally recognized Code or Standard, equivalent international standards, or corporate standards.

"It Takes a Village..."

You've probably heard the African proverb "It takes a village to raise a child." You may wonder what that has to do with pressure system management... but bear with me.

Pressure system integrity is not the result of one design Code, or one inspection Code, or one FFS Code. It is the cumulative result of all the Codes, Practices, and Standards working together to achieve safety in design, inspection, operation, repair, and maintenance.

Pressure system failures usually involve multiple things that have gone wrong. Author and researcher James Reason used a Swiss cheese model to describe how systems fail when all layers of protection are breached. He proposes that a system is like many slices of Swiss cheese stacked up, as layers of protection, with all of their holes in random locations. In order to have a failure, a single series of holes in all the slices have to line up such that there is a path through all the slices (**Figure 2**). If a hole in even one layer doesn't line up, there is no failure path.

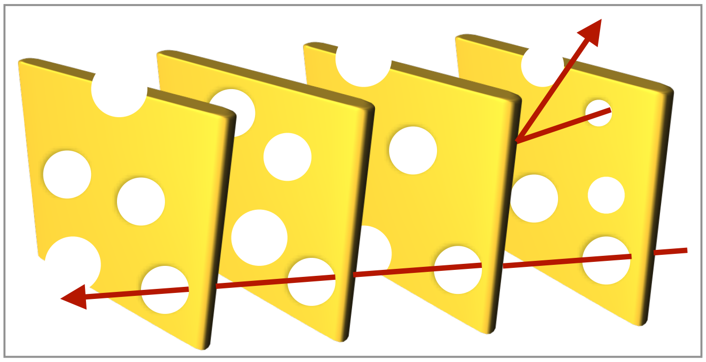

Figure 2: Swiss Cheese Model

Analogously, pressure system integrity is achieved by a combination of strong design Codes, quality fabrication, careful inspection, responsible operation, diligent maintenance, rigorous FFS assessment, and when necessary, quality repair. Just like the Swiss cheese model, it's a system... each layer contributes to the overall system safety. Or, to say it another way... it takes a village.

Roles of Different Codes and Standards

Many different Codes, Practices, Standards, and procedures play a role in pressure system integrity management. Some of these are listed in **Table 1**.

Collectively, these Codes, Practices and Standards address the many different stages of equipment life and contribute to the overall safety of the pressure system.

Three Assessment Levels

One of the cornerstones of the API 579 Standard is the three-level assessment approach. This is the simple acknowledgement that it's not always necessary to perform extremely detailed and rigorous calculations. Sometimes the back-of-the-envelope calculation is all that's needed.

Of course, all levels of calculation must result in safe and conservative decisions. So, a simple "back-of-the-envelope" approximation would have to be based on a set of assumptions that are demonstratively conservative. On the other hand, a more accurate calculation may use more accurate, but less conservative, data.

For example, consider a simple hoop stress calculation, $\sigma=pr/t$. Solving for the minimum required thickness (t_{min}), one would typically use the Code allowable stress at temperature. The Code allowable is derived from the specified minimum tensile and yield strengths and is, therefore, innately conservative. On the other hand, if a more accurate solution was desired, the engineer could perform tensile tests on a sample of the material and obtain actual tensile and yield values for the material in question. For a typical SA-516-70 pressure vessel material, the SMTS = 70 ksi; whereas the actual tensile test might yield 80 ksi – a significant difference.

Table 1: Examples of Codes & Standards in Stages of Pressure System Life

Stage	Documents
Design	BPVC Section VIII, Divisions 1/2/3
	Piping Design Codes , B31 Codes
Fabrication	BPVC Section VIII, Division 1/2/3
Operation	Company operating procedures
	PPC-1, Bolted Flange Joint Assembly
Inspection	Company inspection procedures
	Pressure Vessel Inspection Code, API 510
	Piping Inspection Code, API 570
	BPVC Section V, Nondestructive Examination
	National Board Inspection Code
Maintenance	Company maintenance procedures
Alteration & Repair	National Board Inspection Code
	PCC-2, Repair of Pressure Equipment & Piping
	BPVC, Section VIII, Division 1
	Pressure Vessel Inspection Code, API 510
Fitness-For-Service	API 579-1/ASME FFS-1, Fitness-For-Service
Pressure Relieving Systems	API 510, API RP 576, API Standards 520 & 521
Integrity Operating Windows	API RP 584
Damage Mechanisms Affecting Fixed Equipment in the Refining Industry	API RP 571

With the application of equal safety factors, both the SMTS and tensile test approaches would yield safe and conservative results. The difference is that for the cost of some additional engineering rigor (i.e., the tensile test), a more accurate and less conservative result would be achieved. This balance of trading more work and engineering rigor for a more accurate and less conservative answer is the foundation of the three-level analysis.

The three levels of analysis in API 579 are as follows:

Level 1

- Simplest, quickest, and cheapest assessment level
- Highly prescriptive
- Typically requires use of charts or graphs, or simple calculations
- Intended to be performed by inspection or plant engineering personnel

Level 2

- More complicated, time consuming, and expensive than Level 1
- Highly prescriptive
- Typically requires solving algebraic equations; sometime a significant number of equations
- Intended to be performed by plant engineering personnel or engineering specialists

Level 3

- Most complex assessment
- Requires significant judgement and technical knowledge on the part of the engineer performing the assessment
- May involve advanced numerical methods, such as finite element analysis (FEA).
- Intended to be performed by engineering specialists with in-depth knowledge of the subject.

In principle, a FFS assessment would begin with a Level 1 assessment. If the Level 1 assessment failed, the Level 2 assessment would be undertaken. Then, if Level 2 failed, a Level 3 assessment would be undertaken. But in actual practice, assessments often do not proceed in that orderly sequence.

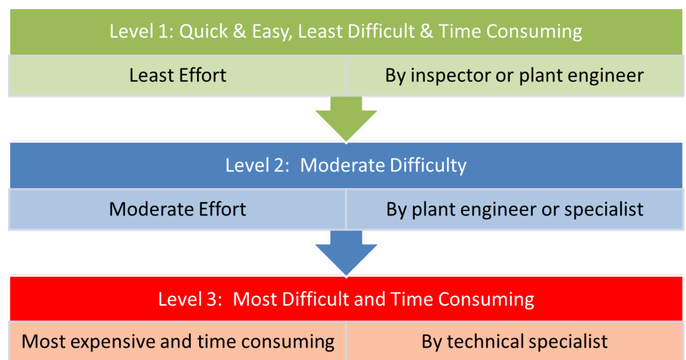

Figure 3: Levels of Assessment

There are several reasons why an assessment might begin with a Level 2 or Level 3, such as:

- Concern over wasted time & money – In the engineer's judgement, a fairly severe defect may have a minimal chance of passing a simple assessment and the engineer chooses to begin at a higher Level.
- Lower levels not applicable – Level 1 and 2 assessments are not available for all types of defects. For example, there is no Level 1 or Level 2 approach for general shell distortions.
- Geometric complexity – The geometry in the region of the defect is more complicated than can be handled by simple methods and a higher level of assessment is required.

Current Integrity vs. Remaining Life

In many FFS assessments there are two separate questions to be answered:

1. What is the current state of integrity?
2. What is the remaining life?

These are not the same. In the simplest case, consider active corrosion. If corrosion has decreased the wall thickness to half the Code-required thickness in a local area, we can do a stress analysis and decide if the corroded region is safe to use today. But this tells us nothing about how much longer the component will remain safe.

To calculate the remaining life, we would first have to calculate the minimum acceptable wall thickness in the local area. Then, if we could identify a corrosion rate, we could calculate how long it would be before the corrosion reached the minimum thickness. This would be the calculated remaining life.

The point is, these are usually two different calculations. API 579 provides guidance on obtaining both the current FFS (integrity) and the remaining life.

This also raises the important point that operating practices should be monitored after the FFS and remaining life estimate. For example, the FFS calculation may say it is safe to continue operating for another 3 years if the damage rate is no more severe than anticipated. If damage rates increase, a new assessment may be required.

Importance of Damage Mechanisms

A damage mechanism is something that causes damaging micro and/or macro changes to the material condition or mechanical properties.

A few examples of damage mechanisms would include: cracks, dents, corrosion and erosion. Damage mechanisms are usually incremental, cumulative, and unrecoverable.

Identification and understanding of the relevant damage mechanisms is absolutely fundamental to any FFS assessment. If you don't identify the relevant damage mechanisms, you can't possibly evaluate if the damage is acceptable or how it might propagate. You can't predict the rate of growth if you can't identify what is causing it. And remember, there may be more than one damage mechanism in play.

Damage mechanisms are somewhat like failure modes. If you have a long slender column with a weight on the top and want to calculate its structural sufficiency, you might do a simple Force/Area calculation to calculate the stress in the column. If the stress is well below yield, you might conclude that the column is adequate for the load. Of course, the problem would be that you forgot about buckling. Buckling is an entirely different failure mode that you didn't evaluate. Similarly, if you perform a FFS assessment on a pressure vessel to evaluate local corrosion but miss the fact that it was in a service that causes stress corrosion cracking, you could well miss the primary failure mode related to failure of crack-like flaws.

This discussion of damage mechanisms provides a segue into a discussion of the API 579 Standard itself. API 579 is organized by damage mechanism. One *Part* of the document is devoted to each of the covered damage mechanisms. Damage mechanisms can act singly or in conjunction with other damage mechanisms.

Now, let's jump into a discussion of different damage mechanisms and how they can be approached in a FFS assessment. This is just a primer, so we won't be able to go into too much detail, but this should provide you with enough detail to get started.

Assessment Techniques

API 579 *Parts 3* through *14* address twelve different damage mechanisms (**Table 2**).

Table 2: Damage Mechanisms in API 579 (2016)

Part	Damage Mechanism
3	Brittle Fracture
4	General Metal Loss
5	Local Metal Loss
6	Pitting
7	Hydrogen Blisters, HIC, SOHIC
8	Weld Misalignment & Shell Distortion
9	Crack-Like Flaws
10	Creep
11	Fire Damage
12	Dents and Gouges
13	Laminations
14	Fatigue

Each *Part* is presented in a highly structured format including sections on "Applicability and Limitations", "Data Requirements", "Assessment Techniques", "Remaining Life Assessment", and others. Although all of the sections are important, the "Applicability and Limitations" section deserves special attention. There are many limits on the applicability of individual techniques and levels of assessment. For example, certain sections may only be applicable to cylindrical shells, while others may be limited to particular material types. It's very important to carefully review the limitations of an analysis before you get started.

Now we'll discuss each of the assessment techniques in turn.

Part 3 – Brittle Fracture

Issue

Ferritic steels undergo a decrease in toughness at decreasing temperatures. Some steels are more susceptible than others. Low toughness can result in a catastrophic brittle fracture.

Assessment Approach

Level 1 – Level 1 provides for evaluation against the industry standard "Exemption Curves."

Level 2 – Obtain lower "adjusted" minimum allowable temperatures (MAT) by taking credit for stress levels below the design stress.

Level 3 – Perform fracture mechanics assessment under the rules of *Part 9, Crack-Like Flaws*.

Comments on Part 3

- Toughness rules appeared in most major pressure system codes around 1987. Systems designed before 1987 would benefit from brittle fracture screening.
- Many companies have initiated systematic brittle fracture reviews of older piping and pressure vessels.

Parts 4, 5, and 6 provide methods for dealing with corrosion. Corrosion is an extremely pervasive and costly damage mechanism. These are the most frequently used sections of this Standard.

Part 4 – General Metal Loss

Issue

Part 4 is applicable to metal loss from corrosion or erosion. It is most applicable to metal loss that reduces the wall thickness evenly over a relatively large area.

Assessment Approach

Level 1 – Level 1 is a thickness averaging approach. It allows averages from either point readings or profile readings (i.e., a grid). Generally, to pass the assessment, the average thickness at the time of inspection (t_{avg}) must be greater than or equal to the minimum required design thickness (t_{min}). This is how it would be expressed as a formula:

$$t_{avg} \geq t_{min\ (Design)}$$

Level 2 – Level 2 used the same thickness averaging approach as Level 1, but it includes a knock-down factor called an "RSF" which effectively reduces the required minimum thickness (the RSF is discussed in more detail later). Level 2 also allows either point or profile readings. Generally, to pass the assessment requires:

$$t_{avg} \geq RSF \cdot t_{min\ (Design)}$$

Level 3 – *Part 2* describes options for detailed stress analysis that may involve advanced numerical methods, such as FEA. Detailed measurements of the corrosion profile, tensile testing, and measurement of loads may be included in a Level 3 assessment.

Comments on Part 4

- There is no hard and fast definition as to what defines "General" vs. "Local" metal loss. Generally, try the "General" approach first. If that fails, try the "Local" approach. Assessment of highly localized metal loss will be conservative using the "General" approach (*Part* 4).
- Typically, software is used to perform Level 2 assessments, and sometimes Level 1 assessments.
- General metal loss allows, in some situations, the use of "Point" measurements as an alternative to a fully developed inspection grid of wall thickness. To use point readings, the data must pass a check to establish that the thickness is relatively even.
- The assessment applies to metal loss on the inside or outside of the component.

Part 5 – Local Metal Loss

Issue

Part 5 is applicable to metal loss from erosion, corrosion, or mechanical damage, which reduces the material available to react pressure and mechanical loads. This *Part* is most applicable to loss that is generally more localized or more uneven than that addressed by the general metal loss assessment.

Assessment Approach

Level 1 – A thickness averaging approach in which the user calculates several parameters and evaluates the results on a simple graph.

Level 2 – A more complicated thickness averaging approach which does a better job of managing variations in thickness. The calculations are fairly involved and software is typically used to perform Level 2 assessments.

Level 3 – *Part 2* describes options for detailed stress analysis that may involve advanced numerical methods, such as FEA. Detailed measurements of the corrosion profile, tensile testing, and measurement of loads may be included in a Level 3 assessment.

Comments on Part 5

- Local metal loss evaluation requires a full inspection grid of wall thickness measurements. A "point measurement" option is not available.
- *Part 5* can be used to address metal loss in the form of local thin areas (LTAs) or grooves.
- Criteria are provided to determine if grooves are crack-like. If so, the evaluation is performed by *Part 9*, Crack-Like flaws.

Part 6 – Pitting

Issue

Metal loss from pitting can be evaluated using this *Part*. The pitting can be widely scattered, localized, or in combination with an LTA.

Assessment Approach

Level 1 – "Pit Charts" are provided for comparison to the pitted region. With minimal field measurements, simple tables provide conservative evaluation.

Level 2 – More detailed field measurements involve measurement of numerous "pit couples". Moderately complicated spreadsheet calculations can be performed to evaluate the pitting.

Level 3 – *Part 2* describes options for detailed stress analysis that may involve advanced numerical methods, such as finite element analysis. Detailed measurements of the corrosion profile, tensile testing, and measurement of loads may be included in a Level 3 assessment. Alternately, arrays of pits may be evaluated by the effective stiffness method, as used for tube sheets in ASME Boiler and Pressure Vessel Code (BPVC) Section VIII, Division 1, Part UHX.

Comments on Part 6

- Level 1 pitting assessment is very easy to perform. It's an excellent first pass screening technique.
- Level 2 field measurements require measurement of a sample of pits, with measurements including pit depth and diameter and pit couple separation and orientation.
- Pitting assessment techniques can also be used to evaluate a field of hydrogen blisters.

Part 7 – Hydrogen Blisters, HIC, & SOHIC

Issue

This *Part* provides techniques to assess hydrogen blisters, hydrogen induced cracking (HIC), and stress-oriented hydrogen induced cracking (SOHIC). It specifically excludes: high temperature hydrogen attack (HTHA), sulfide stress cracking (SSC), and hydrogen embrittlement.

Assessment Approach

Level 1

- HIC & Hydrogen Blisters – Assessment methods are based on evaluation of length, width, and through-thickness dimensions, and other dimensional parameters.
- SOHIC – There is no Level 1 assessment method for SOHIC.

Level 2

- Hydrogen Blisters – Assessment is based on *Part 5, Local Metal Loss* assessment.
- HIC – Calculations are performed to evaluate the circumferential and longitudinal extent of the HIC. Fracture mechanics assessment per *Part 9* is performed, if required.
- SOHIC – There is no Level 2 assessment method for SOHIC.

Level 3

- Hydrogen Blisters – Evaluation is based on elastic-plastic assessment methods, as described in *Part 2*. Arrays of blisters may be evaluated under pitting rules from *Part 6*.
- HIC – Assessment should address: loss of load carrying ability by RSF methods, fracture, future flaw growth, and inspection requirements.
- SOHIC – Assessment is based on *Part 9*, crack-like flaws. There is currently no methodology to evaluate future crack growth associated with SOHIC.

Comments on Part 7

- Effective evaluation of extensive HIC & SOHIC are perhaps two of the most difficult tasks in FFS.
- Blisters near welds present special considerations in API 579.

Part 8 – Weld Misalignment & Shell Distortions

Issue

Part 8 provides techniques for evaluation of weld misalignment and shell distortions in: flat plates; cylinders, spherical, or conical shells; and formed heads. Weld misalignment includes the problems of peaking and mismatch. Shell distortion is a broader category of geometric distortions that can include out-of-round, bulges, and more generalized shell distortions. All of these create high stresses due primarily to local bending and significant instability when subjected to external pressure or local mechanical loads.

Assessment Approach

Level 1 – Level 1 assessment is based on the fabrication tolerances in the original code of construction.

Level 2

- Weld misalignment and out-of-round assessments are based on a stress approach. The assessment involves a significant amount of algebra used to calculate the moments and forces related to bending from the non-uniform geometry.
- Bulges – No Level 2 assessment is available for bulges.

Level 3 – *Part 2* describes options for detailed stress analysis that may involve advanced numerical methods such as FEA.

Comments on Part 8

- Several terms in *Part 8* may require definition and elaboration.
  - General Shell Distortions are deviations from ideal shell geometry:
    - In the longitudinal and/or circumferential directions, and
    - May be characterized by multiple local curvatures

    Note: A flat spot is a form of general shell distortion.
  - Out-of-roundness is a deviation from ideal shell geometry that is:
    - Constant in longitudinal direction
    - Either global (i.e., oval) or of arbitrary shape in circumferential direction

- A bulge is an outward deviation characterized by a local radius & angular extent.
- Dents – Not included in *Part 8* – now in *Part 12*. A dent is "An inward or outward deviation... characterized by a small local radius or notch."

If the component is in cyclic service, a fatigue analysis should be performed.

Examples of distortion (e.g., peaking), measurement tools and techniques are provided in API 579.

Part 9 – Crack-Like Flaws

Issue

Cracks or crack-like features can fail catastrophically if the crack tip stress intensity exceeds a certain critical value. Analysis can be performed to identify both the critical flaw size and the expected flaw growth rate.

Assessment Approach

Level 1 – In a few situations, a simplified screening curve can be used to quickly and easily evaluate the acceptable flaw size.

Level 2 – This requires evaluation of the failure assessment diagram (FAD). The FAD is discussed in more detail later. The engineer should have good familiarity with fracture mechanics principles.

Level 3 – Five options are available for Level 3 flaw assessment. Each of the options requires specialized knowledge in fracture mechanics and some may require explicit crack modeling by the finite element method.

Comments on Part 9

- Typically commercial software is used to perform Level 2 & 3 fracture mechanics analysis.
- Examples of crack-like flaws include: lack of fusion, lack of penetration in welds, sharp groove-like local corrosion, and branch-type cracks associated with environmental cracking.
- Volumetric flaws may be treated as crack-like if they are likely to contain micro-cracks at the root.
- Rules and guidance are provided for flaws not oriented normal to principal stress fields, closely spaced flaws, networks of cracks, and deep surface flaws that approach the opposite surface.
- A failure assessment diagram approach my prove helpful to guide inspection planning for critical equipment as an indication of maximum tolerable flaw depth and length. This can have a bearing on the NDE methods chosen for detection (i.e., is the method suited to find the damage before a leak or failure?). This is sometimes referred to proactive FFS.

Part 10 – Creep

Issue

High temperature (above about 35% to 40% of the absolute melting temperature of the material) can result in progressive, time-dependent deformation of the material, which is called "Creep". Creep can eventually lead to rupture of the material. Evaluation of the time to creep rupture is covered in this *Part*.

Assessment Approach

Level 1 – Two sets of screening curves are provided to allow quick and easy (but very conservative) evaluation of creep life.

Levels 2 & 3 – Both Level 2 and Level 3 assessments use the same creep damage models to assess creep damage and creep life. The Omega model has become widely associated with API 579, but Larson-Miller and other methods are also allowed.

Comments on Part 10

- Some materials exhibit high creep ductility; others exhibit low creep ductility. Visible dilation of the material is typically not apparent in materials with low creep ductility.
- Metallographic examination is not a reliable indicator of creep damage in most materials.
- Table 4.1 (in API 579) provides a list giving the beginning (i.e., lower end) of the creep range for a variety of materials.

Part 11 – Fire Damage

Issue

Vessels, tanks, and piping exposed to the extreme heat of a fire can experience deformation, material degradation, and other damage. This *Part* provides techniques for:

- Evaluating the extent to which components have been affected, and
- Performing FFS evaluation of the affected components

Assessment Approach

Level 1 – Level 1 is a simple screening to determine if the material may have experienced a sufficiently high temperature to have been adversely affected by the fire.

Levels 2 & 3 – Components that have experienced sufficient heat to fail a Level 1 assessment may be evaluated dimensionally or metallurgically to determine if they have been damaged. If damage or material degradation is discovered, evaluation techniques of other *Parts* are typically invoked to evaluate the damage or degradation.

Comments on Part 11

- A significant portion of *Part 11* is focused on providing information that is useful in determining the maximum temperature that a material may have experienced. It includes multiple tables with information such as the melting point of different materials, from which one can deduce the temperature in an area of the affected unit.
- Heat Exposure Zones (HEZ) are a fundamental step in fire damage assessment. They indicate the maximum temperature experienced in an area and guide subsequent evaluations.

Part 12 – Dents & Gouges

Issue

Part 12 provides for FFS assessment of dents, gouges, or dent-gouge combinations.

Assessment Approach

Level 1

- Dent – Level 1 dent assessment is a simple screening criterion which only requires checking certain dimensional limitations (e.g., proximity to welds and dent depression). It is limited to carbon steel cylindrical shells located away from major structural discontinuities.
- Gouge – Level 1 gouge assessment refers to the *Part 5*, Level 1 procedure where the gouge is treated as an LTA. There is also a minimum toughness requirement for gouged material.

Level 2

- Dent – Same as Level 1 procedure, but also includes a fatigue analysis.
- Gouge – Same as Level 1 procedure, but references the *Part 5*, Level 2 procedure.

Level 3 – *Part 2* describes options for detailed stress analysis that may involve advanced numerical methods, such as FEA.

Comments on Part 12

- The damage may be on the inner diameter (ID) or outer diameter (OD).
- A "dent" is an inward or outward deviation of a cross-section of a shell member, characterized by a small local radius or notch.
- A gouge is an elongated local removal and/or relocation in wall thickness. It is similar to a groove but can be caused by mechanical damage, often having a work hardened layer of material as a result of the gouging process.
- Gouges are frequently associated with dents.
- A very common example of dent-gouge combinations occurs during pipeline excavation when a backhoe bucket strikes a pipe and drags along the pipe as it is retracted. In these cases, a dent with a gouge often results.
- Grooves and gouges can be very similar, but a groove is typically caused by corrosion or erosion, while a gouge results from mechanical removal of material.

Part 13 – Laminations

Issue

This *Part* addresses the FFS of components with laminations. It excludes laminations associated with HIC and SOHIC.

Assessment Approach

Level 1 – A simple screening criteria is provided. It is based on size, orientation, and proximity to welds and major structural discontinuities (MSDs). If the lamination has a significant through-thickness component, it is evaluated as crack-like, using *Part 9*.

Level 2 – Same as Level 1 assessment criteria. But if the lamination requires assessment of crack-like behavior, the user is referred to Level 2 of *Part 9*.

Level 3 – *Part 2* describes options for detailed stress analysis that may involve advanced numerical methods, such as FEA.

Comments on Part 13

- Laminations are a plane of non-fusion in the interior of a steel plate that result from the steel manufacturing process. They are usually discovered through ultrasonic examination.
- Laminations are likely of little consequence if:
  - They are parallel to the plate surface,
  - The component is subject only to tensile stress from internal pressure, and
  - They are away from structural discontinuities.

Part 14 – Fatigue

Issue

This *Part* provides procedures for evaluating the fatigue life of components in cyclic service. It does **not** include procedures for evaluation of components in the creep range, containing crack-like flaws, HIC, step-wise indications, and SOHIC.

Assessment Approach

Level 1 – Level 1 includes screening methods used to determine if a fatigue assessment is necessary. It includes 3 options: prior experience, cycle counting, and simplified fatigue curves.

Level 2 – This level provides for detailed fatigue assessment based on fatigue curves included in the standard. Three options are available, allowing for elastic or elastic-plastic analysis with smooth bar fatigue curves and welded joint fatigue curves. Significant algebraic computations are involved in the Level 2 fatigue assessment.

Level 3 – Level 3 analysis is similar to Level 2 but it is more prescriptive and somewhat more computationally intensive.

Comments on Part 14

- Procedures are included for several different types of fatigue evaluations, including: smooth bar curves, welded joint fatigue curves, stress-based fatigue, and strain-based fatigue.
- This *Part* does **not** include procedures applicable to ultra-high cycle fatigue, such as damage that might result from vibratory fatigue. It does not include fatigue methodologies which include an endurance limit or a non-propagating limit. However, these procedures will likely be added to future editions.
- Mean stress effects are already included in the smooth bar curves. The welded joint curves require application of correction factors to account for non-zero mean stress effects.

Acceptance Criteria

When an engineer performs an analysis, there comes a point when the calculations are done and you have the answer. At that point, you have to decide if the answer is acceptable or unacceptable. That's where the "acceptance criteria" comes to center stage. In the FFS assessments of API 579, there are basically 3 different types of assessment criteria:

- Remaining Strength Factor (RSF) approach
- Failure Assessment Diagram (FAD) approach
- Other miscellaneous approaches

Remaining Strength Factor (RSF)

The remaining strength factor is the ratio of the limit or plastic collapse load (i.e., the load at failure) in the damaged component to the undamaged component. In equation form:

$$RSF = \frac{L_{DC}}{L_{UC}}$$

Where: L_{DC} = Limit or collapse load in the damaged component

L_{UC} = Limit or collapse load in undamaged component

For example, if an undamaged pressurized cylinder would burst at 1000 psi, and the same cylinder with a corroded area would burst at 800 psi, then the RSF = 0.8.

API 579 recommends using an allowable remaining strength factor of RSF_a = 0.9, but other values can be used, if justified.

Six *Parts* of API 579 are assessed based on the RSF:

- Corrosion – *Parts* 4, 5, & 6
- HIC, Blisters, SOHIC – *Part 7*
- Weld Misalignment & Shell Distortion – *Part 8*
- Dents and Gouges – *Part 12*

Failure Assessment Diagram (FAD)

Fracture mechanics analysis of crack-like flaws is based on the FAD for Levels 1 & 2, and some parts of Level 3.

In fracture mechanics, there has always been a problem with the degree of plasticity surrounding the crack tip. Classical linear elastic fracture mechanics (LEFM) is based on very brittle materials (think "glass") and assumes a very small plastic zone around the crack tip. Most real world applications with steel involve much more plasticity. Many

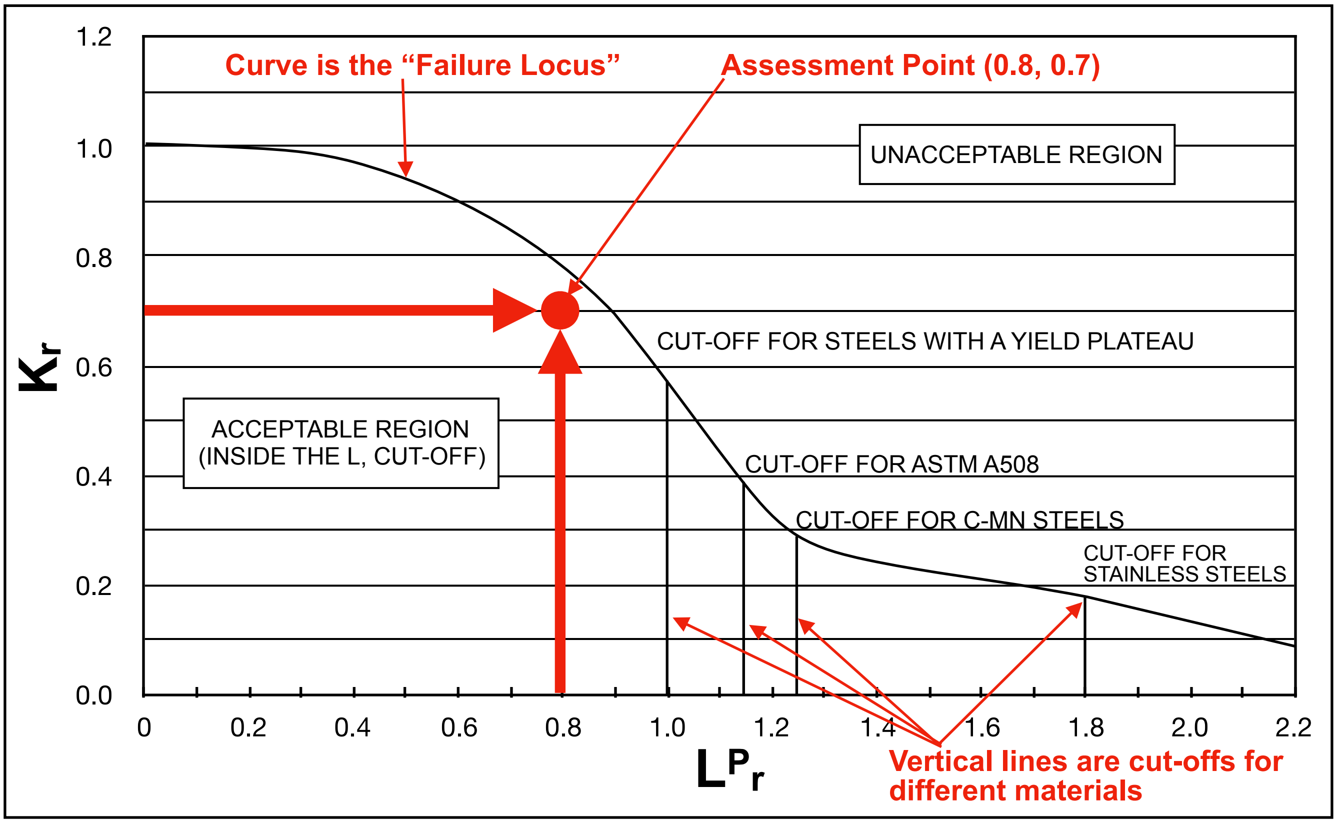

Figure 4: Failure Assessment Diagram

complex elastic-plastic fracture mechanics (EPFM) approaches have been developed, but the relatively easy to implement FAD has increasingly become the method of choice for most FFS assessments. A typical FAD is shown in **Figure 4**.

There are multiple complexities and nuances to a FAD, and a primer can't cover each of them in sufficient detail. There are, however, 5 general elements that are worthy of note:

1. The vertical axis is the fracture axis, where K_r is the ratio of the calculated to allowable fracture toughness. K_r is referred to as the "toughness ratio" and is dependent on both primary and secondary stresses.
2. The horizontal axis is the stress axis, where L^P_r is the ratio of the reference stress due to primary load to the yield stress.
3. The curved line is the "failure locus".
4. The vertical lines below the curve are the cut-offs for different materials.
5. To use the FAD, calculate the L^P_r and K_r values for your operating case and plot the point on the graph (as shown with the red dot in **Figure 4**. If the dot is below the curve (and left of the cut-off) you pass; if it's above the curve (or right of the cut-off), you fail.

In the example of **Figure 4**, the case analyzed passes the assessment because the red dot is below the failure locus. Keep in mind that only *Part 9*, Crack-Like Flaws, uses the FAD approach as the acceptance criteria.

Other Miscellaneous Criteria

The remaining 5 Parts use a variety of acceptance criteria, as follows:

- *Part 3, Brittle Fracture* – Uses the ASME UCS exemption curves
- *Part 10, Creep* – Uses creep damage models
- *Part 11, Fire Damage* – Uses "heat zones" and references other applicable sections
- *Part 13, Laminations* – This *Part* is rule based
- *Part 14, Fatigue* – Uses fatigue curves and linear damage accumulation models

Failing an Assessment vs. Failing a Component

There is occasionally some confusion on what it means to "Fail" a FFS assessment. The question often arises when a component which has long been in service fails a FFS assessment. In this situation one occasionally hears the seemingly common sense argument that...

> *"[FFS] analysis can't be right, because we know the component has been in service for years with no problem."*

This goes to the crux of the difference between be failing a FFS assessment and failing a component.

Consider a Level 3 FFS assessment of a locally corroded region of a vessel in which a detailed FEA is used to evaluate the LTA. If the vessel was fabricated pre-1999, the design safety factor was 4. If the recommended RSF of 0.9 is used in the FFS assessment, then the FEA must demonstrate that the LTA can withstand 4 X 0.9 = 3.6 times the operating pressure in order for the assessment to "Pass".

However, if the FEA could only demonstrate that the LTA would withstand only 3 times the operating load, it would fail the assessment. But the actual component would still be operating at only 1/3 of the predicted failure load. Thus, this component would not meet the API 579 acceptance criteria because it has an insufficient margin of safety. But we wouldn't expect it to rupture.

Conclusion

This primer is intended to give the uninitiated user a good general overview of the concepts and approach to FFS that represent the current "Best Practice." Those who perform FFS assessment should carefully follow the guidance of API 579.

Lastly, API 579 is a living document. It is constantly being expanded and improved. For example, three significant changes likely to be included in upcoming editions include:

- Addition of two new *Parts* on:
  - (1) Vibration of Fixed Equipment, and
  - (2) High Temperature Hydrogen Attack (HTHA)
- (3) Expansion of *Part 14, Fatigue*, to add methodology to handle ultra-high cycle fatigue problems, such as will be needed by the new vibration *Part*.

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