1 Executive Summary

Fitness-for-service (FFS) assessment is a multi-disciplinary approach to determine, as the name suggests, whether a structural component is fit for continued service. In 2000, the American Petroleum Institute (API) published API 579, a Recommended Practice for FFS assessment. Although this document was intended primarily for refining and petrochemical assets, it has seen widespread use in a wide range of industries that utilize pressure vessels, piping, and storage tanks. In 2007, API joined forces with the American Society for Mechanical Engineers (ASME) to produce an updated document with the designation API 579-1/ASME FFS-1. This document, which is a Standard rather than a Recommended Practice, contains numerous improvements and explicitly addresses industries outside of refining and petrochemical.

This paper summarizes the key features of the new API/ASME fitness-for-service standard. Case histories in FFS assessment are also presented.

2 Introduction

2.1 What is Fitness-for-Service Assessment?

Fitness-for-service (FFS) assessment is a multi-disciplinary approach to determine, as the name suggests, whether equipment is fit for continued service. The equipment or system in question may contain flaws or other damage, or may be subjected to more severe operating conditions than anticipated by the original design. The outcome of a fitness-for-service assessment is a decision to run as is, repair, re-rate, alter, or retire the equipment. A remaining life analysis may also be performed as part of the assessment, which can be used to set future inspection intervals and to budget for capital expenditures when existing equipment is to be retired.

A typical FFS assessment may involve several engineering disciplines, and it requires collecting data from a number of sources. Although one person may take a lead role in performing the assessment, he/she must rely on others to provide crucial data and expertise. Some of the areas of expertise that may be part of an FFS assessment are outlined below.
• **Stress Analysis.** An accurate estimate of stresses acting on the component of interest is essential to assessing structural integrity and remaining life.

• **Metallurgy/Materials Engineering.** An understanding of the performance of various materials subject to specific environments, temperatures, and stress levels is essential for ensuring safe and reliable operation.

• **Nondestructive Examination (NDE).** Flaws must be detected and sized before they can be assessed. The most suitable inspection technology depends on a variety of factors, including type of the flaws or damage present and the accessibility of the region of interest.

• **Corrosion.** An understanding of environmental degradation mechanism(s) that led to the observed damage is a prerequisite for FFS assessments. Moreover, expertise in corrosion is useful for prescribing suitable remediation measures.

• **Plant Operations.** Interaction with plant personnel is usually necessary to understand the operating parameters for the equipment of interest. Information such as operating temperature & pressure, process environment, and startup/shutdown procedures are key inputs to a FFS assessment.

• **Fracture Mechanics.** This discipline is used to analyze cracks and other planar flaws.

• **Probability and Statistics.** This discipline is useful for data analysis and for probabilistic risk assessments.

Fitness-for-service assessments can range in complexity from simple screening evaluations to highly sophisticated computer simulations, including finite element analysis (FEA) and computational fluid dynamics (CFD). The necessary level of complexity varies from one situation to the next. In some cases, an advanced analysis is performed when a simple screening assessment is unable to demonstrate that the equipment in question is fit for continued service. Standardized FFS procedures typically include a range of assessment options that cover the full spectrum of complexity.

The leading fitness-for-service standard for pressure equipment (pressure vessels, storage tanks and piping) has been published by American Petroleum Institute (API) and the American Society for Mechanical Engineers (ASME). The original version of this method, API 579, was published in 2000 by API. Both organizations collaborated in the creation of the revised edition, API 579-1/ASME FFS-1, which was published in 2007. The original API 579 document pertained primarily to refiery equipment, although the procedure was widely used outside of the petroleum industry. With the addition of the ASME brand name in the new version, there is an explicit recognition that this standard is suitable to a broad range of industries that rely on pressure equipment, including electric power, chemical, pipeline, and pulp & paper. The contents of the standard have been updated to reflect technological advances and the broader industry coverage. The API/ASME fitness-for-service standard is discussed in more detail in Section 3 below.
2.2 Advantages of Fitness-for-Service Assessment

It goes without saying that safety is an important goal of any ethical company. Although there is an inherent risk in processing, transporting, and storing liquids & gases under pressure, it is important to reduce this risk to minimal levels. Design codes and standards are intended to ensure reliable operation of newly-constructed vessels, tanks and piping. Fitness-for-service standards such as API 579-1/ASME FFS-1, can be used to assess whether or not it is safe to operate aging equipment that may have degraded in service.

While improved safety is an obvious benefit of fitness-for-service assessment, there are substantial economic benefits to this technology that may be less apparent. For example, unplanned shutdowns are extremely costly in terms of lost production. Fitness-for-service assessments performed on key assets during a scheduled shutdown can greatly reduce the likelihood of unplanned outages.

When flaws or other damage are detected, the decisions on how to deal with such imperfections have enormous economic implications. If flaws are discovered during normal operation, a fitness-for-service assessment can determine whether or not it is safe to operate the equipment until the next planned outage. If the outcome of the FFS assessment is favorable in such a case, then the operator can avoid a costly unplanned shutdown. Even during an outage, whether planned or not, it is desirable to avoid or postpone repairs, provided the FFS assessment indicates that the equipment can be safely operated until the next planned shutdown. Unscheduled retirement of components can be particularly costly, as long lead times for delivery of replacement components can result in extensive delays in production. Fitness-for-service assessments provide a rational basis to determine whether or not a damaged component can continue to operate until a replacement can be delivered.

A lesser-known but significant economic benefit of FFS technology is that it can lead to improved yields. If the rate of life consumption of equipment can be accurately quantified through FFS assessment, a plant can be run more aggressively between shutdowns. Even if components are replaced more frequently due to accelerated life consumption, the increased output may generate significantly larger net profits for the plant.

3 The New API/ASME Fitness-for-Service Standard

The API 579-1/ASME FFS-1 standard, which was published in 2007, covers a wide range of flaw types and degradation mechanisms. A brief history of this standard is presented below, followed by an overview of the most recent release.
3.1 **Historical Background**

In 1990, a joint-industry project was organized by the Materials Properties Council (MPC) to develop fitness-for-service guidelines for the refining industry. Most of the major multi-national oil companies were part of the initial sponsor group, including Exxon, Shell, BP, Amoco, Mobil, Chevron, Texaco, Pennzoil and Arco.\(^1\) Some of these companies had developed in-house FFS procedures, but they recognized that an industry standard was needed. One of the driving forces behind this effort was that improvements in NDE technology led to the detection of more flaws. In-service inspections were often more rigorous and sensitive than the initial inspections that had been performed at the time of fabrication, so many previously undetected fabrication flaws were found in refinery equipment during turnarounds. When significant flaws are detected in pressure equipment, the onus is on the owner/user to address these flaws, even if the equipment had been operating successfully for many years before the flaws were detected.

The MPC project assembled several consultants, including the author of this 4MENDT paper, to develop FFS guidelines and prepare a detailed report that outlined the procedures. A total of four versions of this report were circulated to the MPC sponsor group over the next several years. The final draft of the MPC consultants’ report was turned over to a newly-formed API committee on fitness-for-service. The initial committee membership consisted primarily of the same individuals who had been involved in the MPC FFS project. The MPC consultants’ report evolved very quickly into what became known as API 579, which was ultimately published in early 2000. API 579 immediately received widespread acceptance, both within and outside of the refining industry.

In the meantime, the Post-Construction Committee of the ASME Boiler and Pressure Vessel Code Main Committee formed the Task Group on Flaw Evaluation, which was charged with developing an FFS standard for pressure equipment in non-refinery applications. This task group made very little progress, however, and was disbanded shortly after the publication of API 579. Rather than duplicating efforts, ASME decided it would be beneficial to join forces with API to develop a unified FFS standard. For its part, API welcomed the alliance with ASME because of the latter’s positive reputation among regulatory bodies and the public at large.

A joint API/ASME committee was formed to revise API 579 to make it applicable to broader range of industries. This broader base was reflected in the committee membership. The document was also edited to conform to ISO guidelines for standards, and recent advances in technology were adopted. The joint standard was published in the summer of 2007. The joint committee will continue to maintain and update the FFS standard in the years to come.

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\(^1\) Of course, most of these companies have since undergone mergers, so Amoco, Mobil, Texaco, and Arco no longer exist as separate entities.
3.2 Levels of Assessment

The API/ASME fitness-for-service standard provides three levels of assessment:

- **Level 1.** This is a basic assessment that can be performed by properly trained inspectors or plant engineers. A Level 1 assessment may involve simple hand calculations.

- **Level 2.** This assessment level is more complex than Level 1, and should be performed only by engineers trained in the API/ASME FFS standard. Most Level 2 calculations can be performed with a spreadsheet.

- **Level 3.** This is the most advanced assessment level, which should be performed only by engineers with a high level of expertise and experience. A Level 3 assessment may include computer simulation, such as finite element analysis (FEA) or computational fluid dynamics (CFD).

These three assessment levels represent a trade-off between simplicity and accuracy. The simplified assessment procedures are necessarily more conservative than more sophisticated engineering analyses. In some cases, the component being evaluated may fail a Level 1 assessment but pass a Level 2 or Level 3 component because of the conservative simplifying assumptions in the former. In certain situations, the API/ASME standard does not permit a Level 1 assessment. For example, Level 1 assessments are not applicable to pressure equipment subject to significant supplemental loads, such as dead loads, wind loads, thermal expansion loads, and seismic loads.

With Level 1 assessments, the specified procedures must be followed exactly, and there is little or no room for interpretation. Level 2 procedures provide some latitude to exercise sound engineering judgment. For Level 3 assessments, the API/ASME standard provides a few overall guidelines, but the details of the assessment are left to the user. The lack of specificity in Level 3 is by design. There is no practical way to codify step-by-step procedures for advanced engineering analyses because every situation is different, and there a wide range of approaches that may be suitable for a given situation.

As one might expect, the cost of a fitness-for-service assessment tends to increase with complexity. Sophisticated computer modeling that is performed as part of a Level 3 assessment is obviously more expensive than a simple hand calculation. Moreover, Level 1 assessments may have less onerous inspection requirements than higher-level evaluations. When compared with the potential savings, however, the cost of an assessment, even at Level 3, is often insignificant. If a complex engineering analysis allows a plant to avoid a catastrophic failure or an unplanned shutdown, then it is certainly a good investment.
3.3 Remaining Strength Factor

The API/ASME standard uses the remaining strength factor (RSF) concept in a number of assessment procedures. The RSF is defined by the following ratio:

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

(1)

where $L_{DC}$ is the limit load or burst pressure of the damaged component (i.e., the component with a flaw) and $L_{UC}$ is the corresponding load or pressure for the undamaged component. For example, consider a pressure vessel in which corrosion has caused wall thinning over a localized region of the shell. If an RSF of 0.85 is computed for this vessel, it means that the burst pressure has been reduced to 85% of the original value as a result of the corrosion. The RSF can be computed from Level 1 or Level 2 equations, or from a finite element analysis in a Level 3 assessment.

The calculated RSF is compared with an allowable value, $RSF_a$. If $RSF < RSF_a$, then a pressure vessel or pipe can be re-rated using the following expression:

$$ MAWP_r = MAWP \left( \frac{RSF}{RSF_a} \right) $$

(2a)

Where $MAWP$ is the original maximum allowable working pressure and $MAWP_r$ is the re-rated value. For atmospheric storage tanks, a similar re-rating of maximum fill height (MFH) can be performed:

$$ MFH_r = MFH \left( \frac{RSF}{RSF_a} \right) $$

(2b)

The API/ASME standard recommends an $RSF_a$ value of 0.9 for most situations.

3.4 Corrosion Assessment

There are three sections (or Parts, as defined in the standard) that address corrosion:

- Part 4 – Assessment of General Metal Loss.
- Part 5 – Assessment of Local Metal Loss.
- Part 6 – Assessment of Pitting Corrosion.

There is no quantitative demarcation between general and local metal loss in the API/ASME standard. The qualitative definition is that Part 4 pertains to metal loss over most or all of the component, while Part 5 is applicable to metal loss over a confined
Either or both assessments can be applied to a given instance of wall thinning. Part 5 is usually less conservative than Part 4 because the former accounts for the finite extent of the metal loss, while the assessment in Part 4 assumes that the metal loss is over the entire component. The two assessments give similar answers when the metal loss extends over long distances. Both the Part 4 and Part 5 assessments use the RSF concept to evaluate wall thinning. Inspection data for local and general metal loss assessments typically consists of wall thickness readings in a grid pattern.

The pitting corrosion assessment entails computing an RSF that depends on the diameter, depth, and spacing of pits. In the Level 1 assessment, the RSF is estimated by visually comparing pitting charts with the observed pitting. The Level 2 assessment requires measurement of pit dimensions and spacing and includes a series of calculations to estimate the RSF.

### 3.5 Assessment of Crack-Like Flaws and Brittle Fracture

There are two parts that pertain to brittle fracture and cracks:

- Part 3 – Assessment of Existing Equipment for Brittle Fracture.
- Part 9 – Assessment of Crack-Like Flaws.

Part 3 does not assess specific flaws and their effect on the risk of brittle fracture. Rather, this assessment procedure evaluates the material of construction relative to the temperatures at which it is subject to significant applied stress. The Part 3 assessment is based on the toughness rules and exemption curves in Section VIII of the ASME Boiler and Pressure Vessel Code.

When cracks or other planar flaws are detected, Part 9 of the API/ASME fitness-for-service standard provides suitable assessment procedures. The failure assessment diagram (FAD) approach is used for Level 2 crack evaluation. Engineers who apply this assessment procedure should have at least a basic understanding of fracture mechanics. A simple screening assessment is provided at Level 1, which can be applied without having a background in fracture mechanics.

### 3.6 Assessment of Blisters and Hydrogen-Induced Cracking

Part 7 of the API/ASME standard, which is entitled Assessment of Hydrogen Blisters and Hydrogen Damage Associated with HIC and SOHIC, has been extensively revised since the 2000 edition of API 579 was released. A new assessment procedure for hydrogen-induced cracking (HIC) damage has been added. This methodology relies on the remaining strength factor (RSF) concept to account for loss of load-carrying capacity in HIC-damaged steel. Although the title of Part 7 mentions stress-oriented hydrogen-induced cracking (SOHIC), it does not include a Level 1 or 2 assessment procedure for SOHIC. When SOHIC is present, a Level 3 assessment using Part 9 is recommended.
3.7 Assessment of Creep Damage

Part 10, entitled Assessment of Components Operating in the Creep Range, is a new addition to the FFS standard. Creep damage is assessed using the Omega method, which was developed in a joint-industry project in the 1990s. The Omega model has a number of advantages over the traditional Larson-Miller approach. It can be used to estimate creep rate, creep damage, and time to rupture in components operating at elevated temperatures. In a Level 3 assessment, creep deformation can be modeled with finite element analysis. The API/ASME standard lists material constants for the Omega model for a wide range of alloys.

3.8 Additional Assessments

The API/ASME fitness-for-service standard contains a number of other assessment methods, which are listed below.

- Part 8 – Assessment of Weld Misalignment and Shell Distortions.
- Part 11 – Assessment of Fire Damage.
- Part 12 – Assessment of Dents, Gouges and Dent-Gouge Combinations.
- Part 13 – Assessment of Laminations.

4 Application of Fitness-for-Service Technology

Four examples of fitness-for-service applications are given below. Two of the examples pertain to crack-like flaws and brittle fracture, and the other two involve corrosion assessment. Space limitations preclude an exhaustive description of potential applications of the API/ASME fitness-for-service standard. The examples below represent only small sample.

4.1 Hydrotest Exemption in Aboveground Storage Tanks

API 653 is a standard that covers inspection, repair, alteration, and reconstruction of aboveground storage tanks. When a major repair or alteration is performed on a storage tank, API 653 normally requires that a hydrostatic test be conducted afterwards. However, Paragraph 12.3.2.6 of API 653 permits using a fitness-for-service assessment to justify a hydrotest exemption.

Hydrostatic testing of aboveground storage tanks is very costly and inconvenient. A very large volume is water is needed for the test, and this water must be safely disposed of after the test. Depending on the contents of the tank, the hydrotest water may need to be
cleaned prior to disposal. Consequently, performing a fitness-for-service assessment to justify a hydrotest exemption can result in tremendous cost savings.

Quest Reliability routinely performs FFS assessments on aboveground storage tanks for the purpose of exempting the tank from hydrostatic testing. In a typical case, we are provided with original construction drawings for the tank, along with an additional set of drawings for the repair or alteration. We then construct a finite element model of the tank to infer stresses in the area of the repair or alteration. Figure 1 shows a typical finite element model. In this case, a set of 4 nozzles with a reinforcing pad was added to the tank, as the close-up view illustrates. Figure 2 is a false color plot of stresses in the vicinity of the alteration. The highest computed stresses from the finite element analysis are used in the FFS assessment.

A Level 2 assessment of crack-like flaws, in accordance with Part 9 of the API/ASME standard, is performed to justify the hydrotest exemption. The limiting crack size computed from this analysis is compared with a reference crack size that corresponds to a flaw that can easily be detected with magnetic particle inspection. If the limiting flaw size (i.e. flaw tolerance) is greater than the reference size, and the inspection does not reveal significant linear indications, then the tank is deemed to be exempt from hydrostatic testing.

The stresses obtained from the finite element analysis are input into the crack assessment, along with the fracture toughness of the material. The latter is inferred from testing of samples removed from the tank. Figure 3 shows typical results from a crack analysis. The curve corresponds to the limiting flaw dimensions for this particular case. The data point is the reference flaw size, which is a surface flaw $\frac{3}{16}$ inch (4.8 mm) long by $\frac{1}{16}$ inch (1.6 mm) deep. Flaws of this size or greater should be readily detectable by magnetic particle inspection. In this particular analysis, the reference flaw is well below the limiting flaw curve, so this tank can be exempted from hydrostatic testing provided that no significant planar flaws are detected in the inspection.

### 4.2 Corrosion and Creep Damage in Fired Heater Coils

Fired heaters are an integral part of a refinery as well as other types of process plants. The process fluid is heated by passing it through a serpentine coil inside a furnace. The piping that makes up the coil can degrade over time through corrosion and creep. An unexpected failure of a heater tube could result in a prolonged shutdown of the plant, so it is crucial to avoid such events.

Manual inspection of the heater coil is difficult and time-consuming, and it is not practical to attain 100% coverage. Quest TruTec, which is part of the Quest Integrity Group along with Quest Reliability, deploys its Furnace Tube Inspection System (FTIS™) to address the need to assess the condition of fired heater coils. FTIS is an intelligent pigging system that provides 100% coverage. It measures both wall thinning
due to corrosion and diameter swelling due to creep with compression wave ultrasonic technology.

Quest Reliability has developed the LifeQuest-Heater™ software to perform fitness-for-service assessments on heater coils. This software imports the FTIS inspection data and evaluates both metal loss and creep damage in accordance with the API/ASME standard. Remaining life is computed at 1 ft (305 mm) long segments. Figure 4 is a 3D plot of wall thickness obtained from a typical FTIS dataset. Figure 5 is a corresponding plot of remaining life.

4.3 Pipeline Corrosion

Pipelines experience various degradation mechanisms, including corrosion, cracking, dents, and gouges. The API/ASME fitness-for-service assessment can be applied to each of these damage mechanisms. Most pipelines are examined periodically with in-line inspection (ILI). A variety of ILI inspection technologies are commercially available. The most suitable technology depends on the contents of the pipeline and the type of damage one wishes to detect.

ILI technology that measures wall thickness is similar to FTIS, but on a different scale in terms of pipe diameter and length of pipe to be inspected. Quest Reliability is currently developing software called LifeQuest Pipe™, which has been adapted from the fired heater software described above. Figure 6 is a color plot of thickness data obtained from a pipeline inspection. The LifeQuest Pipe software analyzes these data with a Level 2 assessment of local metal loss. The remaining strength factor (RSF) is computed for short segments of pipe, usually on the order of 1 m in length. The RSF values are used to rank individual pipe segments for corrosion damage. The segments with the lowest RSF values correspond to the most highly corroded areas. Using proprietary corrosion rate models, the LifeQuest Pipe software can also estimate the remaining life for each segment.

4.4 Brittle Fracture of a Pressure Vessel in an Ammonia Plant.

This last example is a cautionary tale of what can go wrong if proper procedures are not followed. The incident described below would not have occurred if plant personnel were conversant with fitness-for-service concepts. Given that the catastrophic event did occur, however, fitness-for-service methodology was used after the fact to reconstruct the accident. Obviously, it is better to use FFS assessment to avoid catastrophic failures, but this technology is also a useful tool in failure analysis.

Figure 7 is a photograph of the bottom head of a molecular sieve pressure vessel from an ammonia plant. This vessel sustained a catastrophic brittle fracture that resulted in a number of fatalities and serious injuries. The root cause of the accident was a weld repair that was done incorrectly. The incident occurred approximately 12 hours after the repair.
was completed. The brittle fracture initiated from a hydrogen crack that formed in the heat-affected zone (HAZ) at the toe of the repair weld.

Figure 8 is a macrograph of the repair weld. The collector plate, which holds the wire mesh structure shown in Figure 7 (i.e., the “elephant stool”), became detached from the bottom head due to low-cycle fatigue failure. During a shutdown, the collector plate was re-welded to the head. Note the high hardness values in the HAZ. Figure 9 is a scanning electron microscope (SEM) photograph of the hydrogen cracking at the fracture origin.

The molecular sieve vessel operated at elevated temperatures with high-pressure hydrogen gas. During normal operation, the steel would have become charged with atomic hydrogen. When the vessel is shut down and cooled to ambient temperature, the hydrogen will gradually diffuse out of the steel. However, it would take on the order of several weeks at ambient temperature for the hydrogen concentration to decrease to negligible levels. An outgassing treatment, where the vessel is heated to a sufficiently high temperature to promote rapid hydrogen diffusion, can remove the hydrogen in a few hours.

The molecular sieve vessel was not subject to an outgassing treatment prior to repair welding, so there was a large reservoir of dissolved hydrogen in the steel, which migrated to the HAZ after welding. Moreover, the HAZ was very hard because the head was made from a Mn-Mo alloy steel. The material in the HAZ was very brittle, and had high residual welding stresses. The combination of these factors led to the brittle failure.

The repair region was not subject to a post-weld heat treatment (PWHT). The head material was misidentified, which led to the fatal decision not to perform a PWHT. Had the repair region been subject to a PWHT immediately following welding, the failure would not have happened, because such a heat treatment would have removed all of the factors that caused the accident:

- The PWHT would have served the purpose of an outgassing treatment by removing dissolved hydrogen from the steel in the vicinity of the weld.
- The PWHT would have softened the HAZ and made it much tougher.
- The PWHT would have removed the high residual stresses that were a major contributor to the event.

Moreover, the repair itself was completely unnecessary. Recall Section 2.2 above, where avoiding unnecessary repairs was mentioned as an advantage of FFS methodology. The collector plate was attached to the bottom nozzle neck, so it did not need to be attached to the head as well. When the collector plate attached to both the nozzle and the head, it was over-constrained, and the low-cycle fatigue failure of the attachment weld on the head was probably due to thermal expansion loads during startup and shutdown of the vessel. This attachment weld had actually failed twice during the life of the vessel, so the catastrophic failure of the pressure boundary was triggered by the second repair at this location. Had this structural detail been evaluated by a competent stress analyst or pressure vessel designer, the ill-fated repair would not have been made.
As part of the accident investigation, a highly detailed Level 3 assessment of the mole sieve vessel was performed. This assessment included a series of finite element simulations of the repair weld in order to estimate residual stresses. Figure 10 shows a finite element model of the repair region. The finite element weld simulation consisted of two parts. First, a heat transfer analysis of welding was performed, where the weld passes were applied sequentially and the heat conduction through the steel was computed. Next, an elastic-plastic stress analysis, which accounted for the temperature dependence of the tensile properties, was performed. Figure 11 is a color map of calculated weld residual stresses. The HAZ has the highest residual stress because of its very high yield strength.

5 CONCLUDING REMARKS

Since the publication of the original API 579 procedure in 2000, fitness-for-service assessment has seen widespread application in a range of industries that rely on pressure equipment. This technology has enormous advantages, both in terms of safety and profitability. The recently published API/ASME standard represents the state of the art in fitness-for-service methodology. The joint API/ASME committee that maintains this standard is committed to expanding and improving the document in the coming years.