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Table of contents

Evolution of Fitness-For-Service: From safety margins to advanced engineering analysis

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The concept of Fitness-For-Service (FFS) has a rich historical progression that is intricately linked to the advancement of engineering principles and standards. It has evolved from essential safety factors in design codes to advanced engineering analyses that consider the real-time condition of equipment in operation. This evolution, a worldwide development, impacts the work of engineers and researchers across the globe. By exploring the historical progression of FFS principles, we can link our past to our future, strengthening our shared commitment to safety and excellence.

Before the 1950s, industrial equipment like boilers, pressure vessels, and pipelines were designed with high safety margins to prevent failure. This approach, significantly influenced by key organizations such as the American Society of Mechanical Engineers (ASME) and the American Petroleum Institute (API), developed design codes based on material strength properties and over-engineering. However, there was minimal consideration for assessing equipment degradation during service. The ASME Boiler and Pressure Vessel Code (ASME BPVC), first published in 1914[1], was one of the earliest comprehensive standards for pressure equipment. Still, it primarily focused on design and fabrication rather than addressing the integrity of in-service components with defects or damage.

The 1950s and 1960s saw the emergence of fracture mechanics as a pivotal scientific field, particularly in the development of modern FFS principles. The work of A.A. Griffith in 1921[2] on brittle fracture and G.R. Irwin's development of Linear Elastic Fracture Mechanics (LEFM)[3] in the 1950s laid the foundation for understanding how cracks initiate and propagate in materials, a crucial aspect in predicting equipment failure.

During this time, significant advancements occurred in the nuclear industry, where ensuring the safety of reactor pressure vessels under thermal stress became paramount. Applying fracture mechanics and FFS principles allowed engineers to predict the growth of cracks in reactor vessels, particularly under cyclic loading, leading to more precise assessments of component safety beyond traditional design factors. This work, particularly in the nuclear industry, underscores the gravity and importance of the FFS principles.[4]

In the 1970s and 1980s, formal flaw assessment guidelines began to take shape, with the British Standards Institution's PD 6493[5] being a key early document published in 1980. PD 6493 provided guidance on evaluating flaws in metallic structures, particularly crack-like defects in welds, pressure vessels, pipelines, and other structural components. During this time, the nuclear industry's focus on component integrity led to the development of methods for assessing fracture toughness, crack growth rates, and fatigue life, particularly for ensuring the safety of nuclear reactors. The Nuclear Regulatory Commission (NRC) in the U.S. and British Nuclear Fuels (BNFL) in the U.K. made significant contributions to developing methodologies for FFS assessments in nuclear applications.[6]

In the 1990s, the oil and gas industry faced significant challenges due to aging infrastructure, particularly in refineries and chemical plants. API recognized the need for a comprehensive approach to assess the fitness of damaged equipment, leading to the development of FFS standards. The initial edition, released in 1996, provided engineers with a structured methodology to evaluate damaged components for continued service[7]. This standard allowed for assessing various damage mechanisms, such as brittle fracture, plastic collapse, localized corrosion, pitting, creep, fatigue, and crack-like flaws. FFS quickly gained widespread adoption in the oil, gas, and petrochemical industries, serving as a critical tool for extending the life of aging assets while ensuring safety.

The API and ASME collaborated to create a joint standard, API 579-1/ASME FFS-1 Fitness For Service, first published in 2007. This standard unified FFS procedures and expanded the scope to include a broader range of industries, such as power generation, chemical processing, and aerospace. It became the dominant FFS standard in North America and beyond, incorporating advancements in fracture mechanics, material science, and damage evaluation techniques[8]. The standard provided detailed procedures for evaluating equipment under various damage mechanisms and environmental conditions, making it one of FFS's most comprehensive global standards.

FFS methodologies have been widely embraced across various industries globally due to their ability to assess the integrity of existing infrastructure and potentially save costs compared to opting for expensive replacements. Some essential global standards for FFS include:

– BS 7910 (UK)
This British Standard evolved from PD 6493. It offers comprehensive procedures for evaluating the acceptability of flaws in metallic structures. The standard covers fracture mechanics, fatigue, corrosion, and creep and is widely utilized in Europe and other regions.[6,9]

– JIS Z 2300 (Japan)
Japan's Industrial Standards (JIS) developed their FFS approach for assessing pressure vessels and other critical components, incorporating fracture mechanics and NDT methods in industries like shipbuilding and petrochemicals.[10]

– AS/NZS 3788 (Australia/New Zealand)
This standard provides guidelines for conducting in-service pressure equipment inspections, incorporating FFS principles to ensure safety and reliability in power generation and chemical processing industries.[11]

– ISO 24817 (International)
The following ISO standard is dedicated to assessing and repairing pipeline systems, specifically emphasizing those affected by corrosion or damage. It offers guidelines for evaluating the structural soundness of pipelines and is commonly utilized alongside other Fitness-For-Service (FFS) approaches.[12]

Nondestructive Testing (NDT) has significantly progressed in the last 20 years, greatly improving its FFS assessment capabilities. Traditional techniques such as ultrasonic testing (UT), magnetic particle inspection (MPI), and radiography have been enhanced by advanced technologies like Phased Array Ultrasonics (PAUT) and Digital Radiography (DR), enabling more accurate detection of defects and degradation in components.[13]

Additionally, integrating 3D modeling and finite element analysis (FEA) has allowed engineers to create virtual equipment models and predict how defects will evolve under operational conditions. This development has revolutionized FFS, enabling real-time evaluations and more precise decision-making regarding equipment use, repair, or retirement.

The National Board Inspection Code (NBIC) includes FFS principles in its guidelines for inspecting, maintaining, and repairing boilers and pressure vessels.[14] By using NDT, damage evaluation, and engineering assessments, the NBIC ensures that equipment can continue operating safely or requires repair. This approach closely aligns with formal FFS methodologies and helps determine industrial assets' remaining life and safe inspection intervals.

Moreover, FFS is essential in the energy transition context, as aging infrastructure in the oil, gas, and power sectors requires safe maintenance while transitioning to new energy sources like hydrogen and renewable power.

Over time, FFS has advanced from simple safety factors to a complex engineering discipline based on fracture mechanics, material science, and sophisticated damage assessment methods. Today, global standards such as API 579-1/ASME FFS-1, BS 7910, and ISO 24817 are integral to FFS assessments in various industries, ensuring the safe operation of equipment even when damaged and reducing the need for costly repairs or replacements. The future of FFS is expected to involve greater integration of real-time monitoring, computational simulations, and advanced materials technology to enhance the safety and reliability of critical infrastructure worldwide.

Last year, HSB, the largest Authorized Inspection Agency in the world, partnered with ATC, a leading provider of boiler/HRSG FFS, condition assessment, and technical consulting services. This partnership brought together two industry leaders to provide enhanced solutions to the power generation industry. Together, HSB and ATC provide a full range of services from inspections and assessments to repairs and outage management.

Through this strategic partnership, HSB and ATC have united their strengths to broaden service offerings, integrate expertise, and enhance market reach. Together, they ensure trusted, reliable service by upholding fair business practices, adhering to established guidelines, and meeting all legal and regulatory requirements. HSB's value lies in their people, their deep technical expertise, and their 150-year legacy as an industry leader. ATC brings extensive experience in delivering customer-focused, cost-effective solutions designed for reliability and flexibility. With their combined resources, HSB and ATC are well-equipped to address industry challenges, offering innovative solutions that meet the evolving needs of the market.

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References

1. ASME Boiler and Pressure Vessel Code, Section I: Rules for Construction of Power Boilers. American Society of Mechanical Engineers, 1915.
2. Griffith, A. A. (1921). "The Phenomena of Rupture and Flow in Solids". Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 221 (582–593): 163–198.
3. Irwin G (1957), Analysis of stresses and strains near the end of a crack traversing a plate, Journal of Applied Mechanics 24, 361–364.
4. Barsom, John M., and Stanley T. Rolfe. Fracture and Fatigue Control in Structures: Applications of Fracture Mechanics. 3rd ed., ASTM International, 1999.
5. "PD 6493 becomes BS 7910; what's new in fracture and fatigue assessment?". twi-global.com. Retrieved 7 October 2024.
6. "BS 7910: History and future developments". twi-global.com. Retrieved 7 October 2024.
7. API 579-1: Fitness-for-Service. American Petroleum Institute, 1996.
8. ASME API 579-1/ASME FFS-1-2021 Fitness-For-Service. December 2021.
9. BS 7910:2019: Guide to Methods for Assessing the Acceptability of Flaws in Metallic Structures. British Standards Institution, 2019.
10. JIS Z 2300:2020: Terms and Definitions of Nondestructive Testing. Japanese Standards Association, 2020.
11. AS/NZS 3788:2024: Pressure Equipment – In-Service Inspection. Standards Australia, 2024.
12. ISO 24817:2017: Petroleum, Petrochemical and Natural Gas Industries — Composite Repairs for Pipework — Qualification and Design, Installation, Testing and Inspection. 2nd ed., International Organization for Standardization, 2017.
13. Hellier, Charles J. Handbook of Nondestructive Evaluation. 2nd ed., McGraw-Hill Education, 2013.
14. National Board Inspection Code. National Board of Boiler and Pressure Vessel Inspectors, 2023.

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Michael Crichton joined the HSB Codes & Standards team in 2023. He holds a B.S. in welding engineering from the Ohio State University and is a Registered Professional Engineer. Before joining HSB, he spent 19 years in the utility industry as a quality assurance engineer and welding program owner. Michael has worked to maintain utility generation equipment through weld repairs and fitness for service. In his current role with Codes & Standards, he provides technical assistance for all non-nuclear ASME Boiler and Pressure Vessel Codes and the National Board Inspection Code (NBIC). Michael's technical expertise is in condition assessment, life management, and welding.

Michael currently serves as vice chair of the AWS D10 Committee on Piping & Tubing, is a member of AWS D10.10 Practices for Local PWHT, and chair of AWS D10.8 Welding of Chromium Moly Steel Piping and Tubing.

Managing risk and inspection strategies for damage-intolerant materials in pressure equipment

Author: Jay Cameron, Principal Engineer, Codes & Standards

For materials in pressure equipment, there is an expectation of "a margin for deterioration in service to give a reasonably long, safe period of usefulness." (ASME Boiler Pressure Vessel Code, Section II, Part D, 2023) This is managed by the Code rules and data values that have sufficient conservatism to fulfill this expectation. Therefore, as designed, the equipment can be expected to perform well in service.

However, sometimes there are unexpected circumstances that can cause the equipment to be in a situation beyond the design requirements. For

example, there could be pressures or temperatures that the material experiences beyond the design inputs or there could be undetected fabrication differences that can weaken the material. In addition, there can be external or internal degradation conditions, such as corrosion or metallurgical changes, which can make the equipment more susceptible to damage.

For most pressure equipment materials, these unexpected circumstances can be managed due to the forgiveness of the material. The material can show dimensional changes that can be seen on a periodic visual examination. Even surface cracks can be detected by visual or simple surface examination methods, but most critically, these dimensional changes or cracking are an exceedingly early indicator of a potential significant problem. Once the initial indications are observed, an informal or formal fitness-for-service evaluation or condition assessment can be performed that can predict the continuation of this damage to some set criteria (maximum component dimension, crack size, leak, etc.) within a calculated period. Once this total period (time, cycles, etc.) to a rejection criterion is determined, a reexamination schedule can be set, or the immediate decision to repair or replace the component can be made.

The newer materials, such as Grade 92, are designed to possess exceptional mechanical properties. For example, a new material may exhibit minimal deformation over time (creep) or show remarkably high resistance to surface cracking, even after prolonged use. This allows pressure equipment to operate at increasingly higher stresses, temperatures, and durations. However, unseen damage can still accumulate — damage that may be undetectable even by advanced surface or volumetric nondestructive examination techniques. This hidden strain is similar to a fault line beneath the earth's surface, building tension without visible signs until a sudden release occurs, similar to an earthquake. In metals, this phenomenon is known as damage intolerance, where accumulated stress is unleashed abruptly and without warning.

This means that prudent inspection schedules may not be enough to prevent a catastrophic event — the material can fail suddenly. Another consequence of the use of these materials is that a conservative inspection frequency may not be economically favorable. For a damage-tolerant material, it may be possible to set a reexamination period once damage is detected to several years, which may fall readily within normal planned examination schedules. Although, with a damage-intolerant material, the reexamination period may be much less than the planned schedule and even as short as a year or less — this is very disruptive and costly to business.

To address this behavior for damage-intolerant materials, one can increase the examination frequency and the sophistication of the technology used for those examinations or decrease the probability of such damage occurring. There were three actions to address the latter concern:

Action 1

The first action was by the Section I Committee who developed Code Case 3048 to provide an analytical assessment of damage intolerance with a λ (lambda) value. For damage-intolerant materials, there are two options — either or both of which may help minimize risk. The first option is to lower the allowable stress — this may lower the average or membrane stresses, and also the concentrated stresses. A more precise method is to use Design By Analysis (DBA) to lower the concentrated stresses only. Note that Grade 91 Type 1 and Grade 92 were identified as generally damage-intolerant materials — both of which had laboratory samples with single-digit (down to essentially zero) reduction of area in creep tests. Grade 91 Type 2 was identified as generally creep tolerant and is explicitly addressed in Code Case 3048 that includes a statement that this material is exempt from the Code Case. Specifically, for the boiler tees issue identified as of late, it is accepted that the key issue with the premature failures was not only a damage-intolerant material, but also geometries with stress concentrators.

Action 2

The second action was to add the following note to several Code Cases:

"This material is a Creep Strength-Enhanced Ferritic (CSEF) steel, whose creep temperature strength is enhanced by the creation of a precise condition of microstructure, specifically martensite, which is stabilized during tempering by controlled precipitation of temper-resistant carbides, carbo-nitrides, or other stable and/or meta-stable phases. Refer to PW-10 of Section I for additional cautionary information. CSEF alloys may demonstrate a susceptibility to creep-intolerant behavior, which manifests as limited amount of plastic deformation at the time of creep-rupture." (ASME, Boiler Pressure Vessel Code Cases, Supplement No. 6, 2023)

The Code Cases with this note added are 2179 (Grade 92), 2199 (Grade 23), 2540 (T24), 2781 ("VM12"), 2890 (Grade 115), and 3001 ("Super VM12"). It is also in process with the Code Committees to add this same cautionary note to Code Cases 2180 (Grade 122) and 2327 (Grade 911). The addition of this note will encourage the use of Code Case 3048.

Action 3

The third action may be published in the 2025 Edition of Section II, Part D, Appendix 5. These revisions to this Appendix will significantly strengthen the data requirements for the requests for new materials to capture the data during the laboratory testing that can demonstrate or at least potentially influence the damage tolerance. The additional data requirements address the following: chemistry; grain size; heat treatment; method of manufacture; reduction of area; metallographic evaluation; and test stress, time, frequency, and number of specimens.

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References

American Society of Mechanical Engineers. (2023). ASME BPV Supplement No. 6. American Society of Mechanical Engineers.
American Society of Mechanical Engineers. (2023). ASME BPV Section II, Part D. American Society of Mechanical Engineers.

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Jay joined Hartford Steam Boiler in 1992. He holds a B.S. in mechanical engineering, engineering mechanics from Worcester Polytechnic Institute and an M.S. in metallurgy from Rensselaer Polytechnic Institute, and is a Registered Professional Engineer. Since joining Hartford Steam Boiler, Jay has worked in the Home Office and at Mechanical & Materials Engineering (Austin, TX). Jay provides technical assistance for all non-nuclear ASME Boiler and Pressure Vessel Codes and the National Board Inspection Code (NBIC), and supports clients with design reviews. His technical expertise is in the areas of pressure vessel design and repair, stress analysis, and materials.

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Ask the engineer

Author: Paul Coco, Principal Engineer, Codes & Standards

Q: I just received a calibration certificate for a digital pressure gauge. It mentions "Allowed Value." What does this term mean, and where can I find the percentage error?

A: To determine if your digital pressure gauge meets the accuracy requirements of your construction code (such as Section III), the Allowed Value (or permissible error) on the calibration certificate should be no more than 1% of the test pressure. The Allowed Value represents the maximum permissible error or tolerance for the gauge's accuracy. Essentially, it's the range within which measurement errors are acceptable.

Error is the specific deviation observed in a measurement, and it is compared against this Allowed Value to confirm compliance with the tolerance.

For some construction codes, like ASME Section VIII, similar accuracy standards are required for digital gauges as with analog ones. Accuracy here refers to how close a measurement is to the true or reference pressure. For digital gauges, accuracy within the 1% range ensures that the gauge's readings reliably represent the actual pressure.

If you're looking for the percentage error, review the calibration certificate for the Allowed Value or tolerance and compare it to the test pressure to see if it meets the 1% requirement.

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Paul joined HSB in January 2014. Paul is a graduate of the United States Naval Academy where he earned a Bachelor of Science in aeronautical engineering. Paul also holds a Master of Engineering Management and a Master of Science in Mechanical Engineering. Paul served in the U.S. Navy from 2002 through 2010. During this time, one of his many responsibilities included the role of Reactor Mechanical Division Officer and Training Officer, where Paul was responsible for the safe operation of a nuclear power plant onboard a Nuclear Powered Aircraft Carrier. From 2007 through 2010, Paul joined the Mechanical Engineering Department at the U.S. Naval Academy, where he taught Applied Engineering Thermodynamics for Naval Applications as a Military Professor. After Military Service, Paul then joined the U.S. Nuclear Regulatory Commission (NRC) as a reactor operations engineer, where he conducted detailed technical reviews of nuclear licenses in accordance with federal codes and standards, and performed quality assurance inspections on domestic and international nuclear vendors for nuclear safety related components. Within the HSB Codes and Standards group, Paul is responsible for providing code technical support to internal and external clients with a focus on nuclear construction to ASME Section III and the associated nuclear conformity assessment programs. He is responsible for the development, maintenance, and delivery of technical training related to nuclear construction, as well as supporting the HSB NQA Services Program. Paul is also responsible for the development of HSB's remote inspection program and is the technical lead on emerging renewable technologies. He holds a Professional Engineer License in the state of Maryland, National Board Endorsements as an AI and ANI, and is a member of various ASME Section III committees.

Events calendar

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March 4-6	ASME Section I and B31.1 - Power Boilers and Components (E23)
March 18-20	ASME Section VIII, Division 1 - Boilers & Pressure Vessels (E23)

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April 1-3	ASME Section IX Welding Requirements with WPS and PQR (E23)	Euclid, OH
September 16-18	ASME Section IX Welding Requirements with WPS and PQR (E25)	Euclid, OH

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