Evaluation of Thinning in Continuous Digesters with Fitness-for-Service Methods

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1. ABSTRACT

The pulp and paper industry has devoted significant resources to understanding the damage mechanisms affecting continuous digesters in the Kraft pulping process. The detection and monitoring of these damage mechanisms are addressed in industry guidelines such as TAPPI TIP 0402-27 "Guidelines for Inspection of Continuous Digesters and Impregnation Vessels". This TIP advises that to assess the continuing "fitness for service" of a digester vessel, it can be done as described in API 579-1/ASME FFS-1.

However, once damage is detected, industry practice is generally to perform "in-kind" repairs once varying conservative thresholds are met. Important steps are omitted by taking this approach, namely, fitness-for-service (FFS) evaluations and consideration to the rate of degradation addressed in various post-construction codes (PCC).

This paper serves to give the reader an overview of the options available when evaluating thinning-related damage in continuous digesters. The FFS methods outlined in API 579-1/AMSE FFS-1 for general thinning, local thinning, and pitting are addressed with regard to damage in continuous digesters. Also, consideration of the rate of damage and its effect on an FFS evaluation is discussed.

2. BACKGROUND

Numerous corrosion mechanisms are present in continuous digesters, all found in various locations with a diverse range of visual appearance. Damage can present as general wall thinning, local thin areas (LTA's), pitting, or any combination of the three. Repair activities, such as flaw excavation, can also result in LTA's requiring evaluation. Note that cracking is a predominant damage mechanism in continuous digesters, but is not discussed specifically in this paper.

Industry typical practice involves routine inspection and monitoring of identified thinning and/or defects. Various damage thresholds, often conservative in nature, are identified, and when met, a decision is made to repair in kind or leave as is and mitigate future damage. For example, major digester components, such as each shell course, have specified minimum thicknesses; however, these values give no consideration to the size and exact location of the damaged area, which is an important variable in the ability of the component to resist rupture.

The paper industry has catalogued pertinent damage mechanisms, specified inspection practices, and developed repair procedures and corrosion mitigation techniques. Owner/users of digesters often do not have a defined fitness-for-service program of record. The use of FFS is especially important in equipment where unplanned and rushed repairs can, and often do, accelerate thinning and cracking mechanisms or simply relocate them. When evaluating the need for repairs, utilizing FFS frequently allows the owner/user to defer repairs in order to more carefully plan repair procedures or prevent future repairs with the addition of other corrosion mitigating techniques.

3. Overview of API 579/AMSE FFS-1

API 579 was published for the petroleum industry in 2000. Additionally, API 579-1/ASME FFS-1 (hereafter referred to as "API 579") was published in 2007, consisting of the known best practices for evaluating damage in fixed equipment applicable to all industries. Subsequent editions in 2016 and 2021 have further refined the subject practices in order to remain consistent with both current practices and other fixed equipment codes.

API 579 was produced to provide users with standardized methods to evaluate flaws located in in-service equipment. New construction codes, such as ASME Sect. VIII and API 650, do not provide rules that govern in-service damage to fixed equipment components. While the various post-construction codes (API 510, API 653, NB-23, etc.) do address damage located during inspection of in-service equipment, they often provide overly conservative estimates of remaining life. API 579 serves to supplement the various post-construction codes, often providing a more accurate picture of the relative severity of damage found in fixed equipment.

The user should take care to refer to the inspection code of record when performing a FFS evaluation. API 510 and API 570 reference API 579 in Section 1.3, while API 653 references API 579 in Section 1.1.6. NB-23 (NBIC) addresses the use of API 579 in Part 2 Section 4.4, and the user should note that NB-23 requires the acceptance of form NB-403 by the inspector to document the evaluation, if required by the jurisdiction.

Organization of API 579

API 579 is organized into separate parts based on flaw type and damage mechanism. Parts of particular relevance to continuous digesters are listed below. Bolded Parts indicate the sections addressed in the scope of this paper.

- Part 3 – Brittle Fracture
- **Part 4 – General Metal Loss**
- **Part 5 – Local Metal Loss**
- **Part 6 – Pitting Corrosion**
- Part 8 – Weld Misalignment and Shell Distortions
- Part 9 – Crack Like Flaws
- Part 12 – Dent, Gouge, and Dent Gouge Combinations
- Part 13 – Laminations

Part 2 also provides a general overview of the FFS process, including applicability, limitations, data requirements, and remaining life assessment. Several annexes to Part 2 address damage mechanisms, design rules, stress analysis, and alternative methods for establishing remaining life.

Assessment Levels

Each Part is separated into three levels of analysis, referred to in API 579 as Level 1 to Level 3. The levels are meant to provide the user with varying levels of conservativeness, offset by corresponding levels of complexity. Level 1 assessments provide the most conservative results with minimal evaluation effort, while Level 3 assessments provide the least conservative results with an equivalent complex evaluation.

Data Collection

The collection of data is an integral part of the FFS process. API 579 outlines two methods for collecting thickness data, namely point thickness readings and critical thickness profiles.

Point thickness readings (PTRs) can be utilized where thinning is confirmed to be uniform wall loss and are only valid for Part 4 evaluations. Point readings can be scattered or ordered, with a minimum of 15 readings in general.

Critical thickness profiles (CTPs) can be utilized for uniform or localized thinning and are valid for both Part 4 and Part 5 evaluations. CTPs are developed by taking ordered thickness readings in both the circumferential and meridional directions of the component. The CTP is then found by projecting the minimum remaining thickness along parallel inspection planes onto a common plane. API 579 prefers the use of CTPs where possible.

Remaining Strength Factor

API 579 uses the Remaining Strength Factor (RSF) to determine the acceptability of a flaw for continued service. The RSF is defined in API 579 as the ratio of the limit or plastic collapse load of the damaged component to the limit or plastic collapse load of the undamaged component. The method of determining the RSF is dependent on the damage mode and described in detail in each Part of API 579

The Allowable Remaining Strength Factor (RSF_a) is a limit on the determined RSF. API 579 recommends using a value of 0.90 for RSF, unless other values can be proven by other means. The factor of 0.90 is based on multiple burst tests to determine plastic collapse loads. Comparison of the RSF to the RSF_a provides a means for calculating a reduced MAWP for pressure equipment and a reduced fill height for storage tanks.

Future Corrosion Allowance

Future Corrosion Allowance (FCA) is defined by API 579 as the anticipated metal loss over the next period of operation. Correct assignment of an FCA is integral to an FFS evaluation, as the evaluation must not only determine current ability of the component to operate, but must also assess the component at a future date.

Consultation with an engineer familiar with material science, corrosion mechanisms, and the process environment of a continuous digester is essential to the accurate assessment of condition in damaged components. Tracking historical corrosion rates can lead to good estimates of future corrosion rates for use in FFS evaluations. Typically, uniform thinning is observed in the wash zone and liquor corrosion (pitting) is observed in the impregnation zone. Determining corrosion rates at areas of erosion/corrosion or other local thinning phenomena can prove more difficult, and often requires conservative assumptions.

4. Evaluation of General Thinning (Part 4)

Part 4 of API 579 addresses the evaluation of general or uniform thinning. The Part 4 methodology is based on thickness averaging, which is similar to the approach taken by the various post-construction codes. The user should be aware that the presence of local thin areas can produce conservative results with these methods, therefore Part 5 should be consulted for more accurate results. A Part 4 evaluation should be completed prior to the decision to move to a Part 5 evaluation in most cases. It is worth noting that Part 4 evaluation allows evaluating thickness loss near a structural discontinuity, while Part 5 does not.

Part 4 Application and Limitations

Part 4.2 should be addressed prior to conducting the evaluation to ensure all related requirements are met. Limitations that apply to continuous digesters in Part 4 include:

- The design criteria must be in accordance with a recognized construction code.
- The damaged regions shall be free of sharp contours and notches which may lead to high local stresses.
- The damaged region must not be in cyclic service per the screening procedures of Part 14.
- Level 1 assessments are limited to Type A components subject to internal or external pressure. Level 2 assessments are limited to Type A and B components subject to internal pressure, external pressure, and supplemental loads.
- A Level 1 and Level 2 assessment includes limitations on the minimum measured thickness.

Level 1 Evaluation

The Level 1 evaluation based on PTRs is addressed in Part 4.4.2.1. The involved steps include the collection of data and calculation of average thickness and minimum thickness. Equation 4.1 must be satisfied to ensure uniform thinning. Assuming equation 4.1 is satisfied, the acceptance criteria of Tables 4.4 - 4.7 must then be evaluated using the calculated average thickness values.

The Level 1 evaluation based on CTPs is addressed in Part 4.4.2.2. After collecting the required data and associated minimum thickness, the remaining thickness ratio, R_t, is calculated. Using the calculated value R_t, Table 4.8 should be consulted to determine the value Q. The value of Q can be utilized to calculate the length of thickness averaging, L. Using the value L, the CTP can be constructed such that the average thickness is minimized. Using the average measured thickness, t_{am}, Tables 4.4 – 4.7 should be consulted for acceptability criteria.

Level 2 Evaluation

The Level 2 evaluation of general thinning can be utilized on Type A and B Class 1 components including internal pressure, external pressure, and supplemental loads. The procedure for determining acceptability is identical to the Level 1 procedure, except that Tables 4.4 – 4.7 must be referenced for the Level 2 acceptability criteria. The Level 2 acceptability criteria incorporate RSF_a, which is commonly taken to be 0.90, unless other values can be supported.

The Level 2 procedure also allows for the evaluation of thinning at structural discontinuities, which include nozzles/branch connections, axisymmetric structural discontinuities, and piping systems. This procedure involves calculating the reduced MAWP using t_{am} (minus FCA) of the component using the equations of the original code of construction. The calculated reduced MAWP should exceed the original MAWP of the component. The method of determining the area of averaging for each of the various types of discontinuities is addressed in 4.4.3.3.a). Additionally, the minimum measured thickness must meet the criteria of Tables 4.4 – 4.7.

5. Evaluation of Local Thin Areas (Part 5)

Part 5 of API 579 can be utilized to evaluate local thin areas (LTAs) for acceptability. LTAs in continuous digesters can arise from multiple damage mechanisms including erosion/corrosion, preferential weld corrosion, and excavation of cracks. The user must also classify the nature of the LTA as a local thin area, groove, or gouge. Note that Part 5 evaluations require the use of CTPs to accurately characterize the dimensions of the flaw.

Part 5 Application and Limitations

Part 5.2 should be addressed prior to conducting the evaluation to ensure all related requirements are met. Limitations that apply to continuous digesters in this section include:

- The design criteria must be in accordance with a recognized construction code.
- The material is assumed to have sufficient toughness. Consideration should be given to a Part 3 evaluation.
- The damaged region must not be in cyclic service per the screening procedures of Part 14.
- Level 1 assessments are limited to Type A components subject to internal pressure. Level 2 assessments are limited to Type A and B Class 1 components subject to internal pressure, external pressure, and supplemental loads.
- A Level 1 and Level 2 assessment includes limitations on the minimum measured thickness.

Level 1 Evaluation

The Level 1 evaluation for Type A components begins with the determination of the CTP and the future corroded wall thickness away from the damaged area, t_c. Additionally, the longitudinal and circumferential extents of the thin area, s and c, must be measured. The minimum measured thickness within the flaw must also be recorded. Using this information, the remaining thickness ratio, R_t, can be calculated, along with the longitudinal flaw length parameter, λ. The flaw must also meet geometric criteria related to remaining minimum thickness and distance from nearby structural discontinuities. Additionally, the flaw must be classified as a local thin area or groove.

The MAWP of the component using the future corroded wall thickness is then calculated. Entering Fig. 5.6 and 5.7 it can then be determined if the flaw is acceptable for continued operation. Points falling above the curve in the figure are acceptable for continued use. If the point falls below the curve, the RSF must be calculated and compared to RSF_a. If the RSF is less than RSF_a, the component is acceptable for continued use at a reduced MAWP. Additional criteria are provided to evaluate the circumferential extent of the flaw for cylinders, conical shells, and elbows.

Level 2 Evaluation

The evaluation procedure for Type A components subject to internal pressure is similar to the Level 1 analysis, up to the point of entering Fig. 5.6 and 5.7. In lieu of referencing these figures, the RSF is more accurately calculated by subdividing the thickness profile into a series of subsections. The RSF is calculated for all possible subsection combinations, with the resultant lowest value being the RSF used in further calculation. It should be noted that the Level 2 evaluation offers guidance for components operating under external pressure and supplemental loadings; however, these conditions rarely exist in a continuous digester.

6. Evaluation of Pitting (Part 6)

Part 6 of API 579 provides evaluation procedures for determining the acceptability of pitting-type corrosion. Pitting corrosion is generally found in the impregnation zone of the digester, or areas subject to erosion/corrosion. API 579 defines pitting as local regions of metal loss that can be characterized by a pit diameter on the order of the plate thickness, with pit depth being less than the plate thickness. Part 6 covers four types of pitting:

- Widely scattered pitting that occurs over a significant region of the component.
- An LTA located in a region of widely scattered pitting.
- Localized regions of pitting.
- Pitting confined within an LTA.

Part 6 Application and Limitations

Part 6.2 should be addressed prior to conducting the evaluation to ensure all related requirements are met. Of particular importance to continuous digesters in this section:

- The design criteria must be in accordance with a recognized construction code.
- The material is assumed to have sufficient toughness. Consideration should be given to a Part 3 evaluation.
- The damaged region must not be in cyclic service per the screening procedures of Part 14.
- Level 1 assessments are limited to Type A components subject to internal pressure. Level 2 assessments are limited to Type A and B Class 1 components subject to internal pressure and supplemental loads.
- A Level 1 and Level 2 assessment includes limitations on the minimum measured thickness.

- Pitting must be arrested for a Level 1 assessment.

Level 1 Evaluation

The Level 1 evaluation uses visual assessment criteria for estimating conservative values of RSF. The user should collect photographic evidence of the pit density, ideally including a scale for reference. The maximum pit depth should be determined by the use of a pit gauge, or other suitable means. The user must also verify that minimum remaining wall thickness values are met and the screening criteria for a local thin area are met.

The MAWP of the component is calculated based on the future corroded thickness of the wall away from the damaged area. Utilizing the pit comparison charts of Fig. 6.6 – 6.13, the user can estimate the RSF for evaluation.

Level 2 Evaluation

The Level 2 evaluation utilizes the concept of the pit-couple to determine acceptability of thinning due to pitting. As several pitting types of damage are addressed, the user is encouraged to consult Fig. 6.2 for a flowchart relating the type of damage to the correct analysis procedure.

Widespread and localized pitting can be evaluated with paragraph 6.4.3.2. Once the necessary data covering the geometry of the pitting has been documented, the RSF for each pit-couple can be calculated. The average RSF is then calculated with the RSF for all pit-couples. The acceptance criteria for widespread pitting is whether the averaged RSF_{pit} is greater than RSF_a, and if this is not true, the reduced MAWP can be calculated. Localized pitting is evaluated as an LTA, with a calculated equivalent thickness based on RSF_{pit}.

Pitting confined within a region of local metal loss can be evaluated per paragraph 6.4.3.3. Additionally, a region of local metal loss located in an area of widespread pitting can be evaluated per paragraph 6.4.3.4. It should be noted that the analysis assumes the depth of both the pits and the LTA will be similar to the defined FCA. The evaluation develops a combined RSF, RSF_{comb}, which is calculated from determining the RSF of the LTA with Part 5 and determining the RSF of the pitting using paragraph 6.4.3.2. The acceptance criteria requires that RSF_{comb} be greater than RSF_a; otherwise, the reduced MAWP is calculated.

7. Level 3 Evaluations

A Level 3 analysis is required when the Level 1 and Level 2 analysis produce unacceptable results. A Level 3 analysis is addressed for each individual damage mechanism, but generally refers to Annex 2D for detailed guidance on performing the required stress analysis. Level 3 analysis commonly requires the use of numerical methods to obtain a solution, which in practice is some form of finite element analysis. The stress analysis techniques highlighted in Annex 2D are based on the Design by Analysis rules of ASME Sect. VIII, Div. 2 Part 5. Evaluation of general metal loss, local thin areas, and pitting typically follow the same procedure, with minor differences, for each emphasized in their respective Parts of API 579. The concept of RSF is included through the API 579 use of ASME Sect. VIII, Div. 2 Part 5.

Protection from Failure Modes

The Design by Analysis rules require the evaluation of five failure modes. The specific failure modes are listed below with modes of concern for continuous digesters bolded.

- **Plastic Collapse** – Unrestrained or excessive plastic deformation, i.e., rupture.
- Local Failure – Rupture with minimal plastic deformation and is related to triaxial stress states.

- Buckling – The collapse of a structure related to axial compression or external pressure. Note that this often can apply to digester support skirts.
- Ratcheting – Failure from the accumulation of strain and deformation from repeated application and removal of a load.
- Fatigue – Failure from repeated cyclic loading.

Plastic collapse is typically the failure mode of concern when evaluating continuous digesters for thinning. API 579 requires the consideration of all failure modes when performing an analysis, but note this may only require analytical methods to prove a failure mode is not of concern.

Protection from Plastic Collapse

API 579 allows the use of three methods when evaluating a component for susceptibility to plastic collapse. Each of the methods is described below:

- Elastic Stress Analysis – In this method, the material behavior is assumed to be a linear relation of stress and strain. This method is assumed to be the most conservative of the three options. Use of the elastic stress method requires minimal pre-processing, but extensive post-processing of the results is required. To evaluate the results of an elastic analysis, the user must be trained to identify and categorize stresses determined by the analysis. Stresses must be linearized through the thickness of the component, separating out membrane, bending, and peak stresses. These stresses are then compared to allowable limits for each stress combination.
- Limit Load Analysis – Limit load analysis modifies the material properties to be elastic-perfectly plastic. The material is assumed to behave elastically up to a point defining a plastic limit, taken to be 1.5*S,S_y in API 579, and strain-displacement relations utilize small displacement theory. The loads are factored as outlined in ASME Sect. VIII, Div. 2 Part 5. If convergence is achieved, the component is acceptable.
- Elastic-Plastic Analysis – Elastic-plastic analysis is considered to be the most accurate evaluation available for thinning damage. In this method, the material model accurately represents the full stress-strain curve up to the point of ultimate failure. This method also allows for consideration to non-linear geometry and loading. This method also has the added benefit of concurrently evaluating for local failure and buckling. The loads are factored as outlined in ASME Sect. VIII, Div. 2 Part 5. The acceptance criteria for elastic plastic analysis are convergence of the solution and the acceptability of the calculated deformations.

8. Example Evaluations

Uniform Thinning in the Wash Zone

Inspection in the current year reveals an area of thinning in the wash zone of the digester, with several readings below the minimum thickness requirements of ASME Sect. VIII, Div. 1. Extensive mitigation work is planned for the following year; therefore, the owner would prefer to defer these repairs if possible. The following point thickness readings (in.) were obtained:

1.15	1.18	1.175	1.052
1.077	1.05	1.181	1.18
1.18	1.15	1.102	1.13
1.12	1.07	1.24	1.11

Average Thickness = 1.134 in.

Minimum Thickness = 1.050 in.

The following values are obtained:

- T_{min}^c = 1.141in.
- FCA = 0.015in. The FCA was based on calculated annual corrosion rates. 0.015in. was chosen in order to safely operate the digester for another year.
- t_{am} = 1.134in.
- t_{mm} = 1.050in.

A Part 4 Level 1 assessment of the thinning is performed. Step 1 is completed by gathering the required PTRs and determining t_{mm} and t_{am}. It is determined that $t_{mm} > 0.9*t_{am}$; therefore, the use of PTRs is valid. Step 3 requires using the Level 1 acceptance criteria of Table 4.4, and it is shown that t_{am} – FCA is not greater than T_{min}^c, resulting in a failure of the Level 1 assessment. The Level 2 acceptance criteria are applied with the appropriate allowable remaining strength factor. A new T_{min}^c is calculated equal to 1.026in. The minimum measured thickness is verified to meet the lower limit thickness requirements. The average measured thickness, t_{am}, is found to be greater than the recalculated T_{min}^c, resulting in a pass of the Level 2 acceptance criteria. Therefore, the digester is safe to operate at the original MAWP until the next year.

Excavation of Cracking in Weld Seam

Stress corrosion cracking was located in weld seams of the impregnation zone of the digester. The flaws are excavated to a depth of approximately 490 mils. The final excavation was determined to be 4in. wide x 2in. tall.

- D = 120in
- T_{nom} = 1.25in.
- T_{min}^c = 1.01in.
- T_{mm} = 0.76in.
- FCA = 0.05in.
- FCA_{ml} = 0.05in.
- s = 2in.
- c = 4in.

The following thickness data was obtained, along with the corresponding CTPs.

Longitudinal Inspection Planes	Circumferential Inspection Plane						Circumferential CTP
	C1	C2	C3	C4	C5	C6	
M1	1.25	1.23	1.22	1.26	1.25	1.24	**1.22**
M2	1.21	1.17	1.24	1.25	1.25	1.23	**1.17**
M3	1.24	0.92	0.85	0.82	0.87	1.23	**0.82**
M4	1.24	0.88	0.76	0.82	0.86	1.23	**0.76**
M5	1.18	1.21	1.25	1.25	1.19	1.23	**1.18**
M6	1.21	1.22	1.24	1.23	1.25	1.25	**1.21**
Longitudinal CTP	**1.18**	**0.88**	**0.76**	**0.82**	**0.86**	**1.23**	

A Part 5 Level 1 assessment of the LTA is performed. Per Step 4, the remaining thickness ratio, R_t, is determined to be 0.592 and the longitudinal flaw length parameter, λ, is found to be 0.214. The limiting flaw size criteria of Step 5 are met. Per Step 7, the MAWP of the shell course at the future corroded thickness is 345psi. Using Fig. 5.6, and corresponding values of R_t and λ, we see that the longitudinal flaw is acceptable at the MAWP calculated in Step 7. Being that the component is a cylindrical shell, Step 9 must be utilized to evaluate the circumferential extent of the flaw. Equation 5.13 is satisfied; therefore, the circumferential flaw size is also acceptable. The excavation is found to be acceptable per a Level 1 evaluation. Therefore, the digester is safe to operate at the original MAWP for another inspection cycle.

9. References

[1] API 579-1/ASME FFS-1, December 2021 ed., American Petroleum Institute

[2] Janelle, J.A. and Osage, D.A., An Overview and Validation of the Fitness-For-Service Assessment Procedures for Local Thin Areas in API 579, WRC Bulletin 505, Welding Research Council, Inc., New York, NY, 2005.