Advanced integrity assessments based on inspection results can demonstrate that tanks and their components are fit for continued service. This allows tank operators to postpone repairs until the next shutdown, eliminate the need for repairs or be exempt from hydrostatic testing.

Improvements in inspection and computing technologies, coupled with the emergence of fitness for service standards, have advanced tank integrity assessments. Advanced inspection technologies including ultrasonic testing (UT) and laser scanning provide detailed mappings of corrosion, settlement, bulging and denting of tank shells and floors. Quest Integrity Group assesses fitness for service and determines remaining useful life of tanks using finite element analysis (FEA) simulations incorporating the measured condition of the tank. Simulations include crack stability and propagation, shell buckling and floor settlement. The following three examples demonstrate the benefits of advanced structural integrity assessments:

**Hydrostatic test exemption**

The purpose of a hydrostatic test exemption analysis is to establish that the repaired tank is fit for continued service, without the need for a hydrostatic test, by application of detailed stress analysis and fracture mechanics technology per API 653, Section 1. Quest Integrity routinely performs hydrostatic test exemptions for floor replacement, shell repairs for removing nozzles and new nozzle installations.

A hydrostatic test exemption analysis has many benefits. It eliminates the cost and time of the hydrostatic test itself, as well as treatment and disposal costs of the water used for the test. The exemption is particularly well suited for tanks repaired during the winter, when cold temperatures make hydrostatic testing extremely difficult. Furthermore, eliminating a hydrostatic test allows an operator to return the tank to service earlier.

To determine if the repaired tank is fit for service without the need for a hydrostatic test, a fracture mechanics analysis is performed to establish the critical sizes of surface connected defects located in the repaired regions. The tank is considered safe if all flaws are reliably detected and eliminated before the flaws grow to critical size. Additionally, inspection technologies are limited because flaws below a certain size cannot be detected. This is referred to as the detectability limit. For conservatism, the repaired region is always assumed to contain flaws sized at the detectability limit and these flaws must be...
smaller than the critical size for the tank to be considered safe. Otherwise, flaws may grow to critical size and cause catastrophic failure prior to being detectable.

In order to perform a fracture mechanics analysis (FMA), the stresses imposed on the region of interest must be established. A simple finite element analysis model can be used to simulate the storage tank hydrostatic test when the tank is filled with water. An example of an FEA model is shown in Figure 1. Shell thicknesses obtained from inspection data can be incorporated in the finite element model.

For FEA incorporating shell elements, the resulting stress can be portrayed at the inside and outside surfaces of the element. Figure 2 shows an example of hoop stress results. The locations of maximum hoop stress on both the outside and inside are easily identified in the first course of the tank shell. At these locations, the corresponding stresses on the opposite side of the shell thickness were then identified, thereby establishing a linear, through thickness stress profile. Figure 3 illustrates another example, showing that the bending stress at the bottom fillet weld connecting the tank wall to the tank bottom is of concern.

The material fracture toughness is required to perform an accurate fracture mechanics analysis. Often, no material samples are available for testing, and the material toughness is determined from lower bound estimates described in API 579/ASME FFS-1.

Once the applied stress and material toughness are established, critical defect sizes for regions of interest can be calculated using the Signal™ Fitness for Service software package. The software is a Windows® based program that implements methodologies described in the British Standards BS-7910 as well as API 579/ASME FFS-1 Part 9 Level 3. For this work, the flaw is assumed to be a semi elliptical surface crack in a flat plate with a surface length, \(2c\) and a depth, \(a\). For a semi elliptical flaw, there is no unique critical flaw size \(2c\) and \(a\). Instead, combinations of \(2c\) and \(a\) resulting in critical flaws are plotted as a line on a graph of surface crack length \(2c\) versus crack depth \(a\).

Figure 4 shows an example critical flaw size curve, shown in blue. In the modified tank, the new welds will be inspected visually and by magnetic particle testing. Assuming that ASME standard procedures and acceptance limits are used, linear indications are only considered relevant if the length is greater than three times the width. Relevant rounded indications greater than 0.1875 in. are cause for rejection. A rounded indication is one of circular or elliptical shape with a length equal to or less than three times the width. For this example, using these criteria for acceptance, it is observed that the critical defect size curves established by fracture mechanics analysis methods lie entirely above the relevant rounded indication size. The finite element analysis and fracture mechanics calculations have shown for this example that the repairs made to the tank do not require a hydrostatic test. The tank is considered fit for service so long as no defects of the critical size or larger exist in the region of the new repairs. This statement can be made since the critical defect sizes exceed the defect sizes that would be cause for rejection during inspection.

The weld residual stress is also incorporated into the analysis for a more accurate assessment. Weld residual stress profiles are calculated using Signal™ Fitness for Service, which implements profiles described in Annex E of API 579/ASME FFS-1.

A hydrostatic test exemption does not waive the inspection of welds. New vertical and horizontal shell butt welds should have complete penetration and fusion and finished welds should be fully radiographed to ensure that this is the case.

**Tank settlement**

Tank bottoms and shells can settle for various reasons. API 653-2009 suggests periodically measuring settlement. Figure 5 shows an example of elevation measurements for a tank bottom. For edge settlement exceeding permissible values, API 653-2009 stipulates all shell to bottom welds and bottom welds should be inspected visually and with magnetic particle examination or liquid penetrant examination.
All indications should be repaired or evaluated for risk of brittle fracture and/or fatigue failure prior to returning the tank to service. Often, assessments demonstrate that the repairs are unnecessary, thereby allowing the operator to return the tank to service sooner than would have been possible with repair. The fitness for service assessments for tank settlement follow procedures that are nearly identical to the aforementioned procedures for the hydrostatic test exemptions.

Stresses in the bottom and shell are computed using a finite element model (FEM) incorporating an axisymmetric profile of the tank, settled soil and ring wall (if present). Modelling the contact and separation between the tank bottom and soil as well as the yielding of steel is necessary for an accurate analysis. Several fill cycles are simulated to assess if the tank is susceptible to fatigue or plastic ratcheting. Through thickness stress profiles for key locations are obtained from the FEM. This stress profile is used to establish critical defect sizes of varying dimensions. The data is plotted on a graph of surface crack length (2c) versus crack depth (a). The dimensions for measured flaws and the minimum detectable flaws are plotted on the same graph to determine if these flaws are stable. Appropriate factors of safety should be incorporated to ensure a conservative assessment.

### Thinning assessment

The objective of a thinning assessment is to determine if the corroded tank is fit for service per API 579/ASME FFS-1, Part 4 (Assessment of General Metal Loss) or Part 5 (Assessment of Local Metal Loss). A common, rudimentary approach is to compare the minimum measured thickness against a code specified minimum required thickness, such as in ASME Section VIII. This is a rapid but overly conservative assessment that leads to many unnecessary repairs because the tank can still safely contain fluids.

API 579/ASME FFS-1 describes three assessment methods with increasing levels of analysis sophistication. These methods calculate the pressure carrying capacity of the material with localised thinned areas. Portions within the thinned areas may yield, thus redistributing stresses to adjacent parts. The methods in API 579/ASME FFS-1 incorporate this phenomenon leading to higher allowable internal pressures compared to simple calculations based on minimum thickness. Both Level 1 and 2 assessment methods were developed based on large databases of experiments and FEA simulation results of thinned areas. The two methods differ in the idealisations of the thickness profiles of thinned areas. The Level 1 assessment method assumes a rectangular area circumscribing the thinned area with a ‘bathtub’ depth profile, while the Level 2 assessment method incorporates the profile measured on a grid resulting in a ‘river bottom’ profile.

For Level 3 assessments, stress redistribution is simulated using finite element models. The model is constructed using measured shell wall thicknesses in the corroded area. Figure 6 shows examples of FEA models incorporating wall thinning. For this type of assessment, Quest Integrity generates the mesh using proprietary mesh generation software that incorporates nozzles, heads, repads and corroded wall thickness profiles. The simulated strains are compared to strain limits stipulated in API 579/ASME FFS-1 to assess if the tank wall has sufficient capacity to resist hydrostatic, gravity, thermal and other loads.

If the tank does not satisfy Level 3 fitness for service requirements, rerated fill height required to satisfy the acceptance criteria can be calculated. Alternatively, if the assessment was based on assumed material strengths, the tank may be reassessed using material strengths measured on the actual vessel material, using in field positive material identification techniques or cut out samples. This typically results in higher yield and ultimate strengths and reduces conservative assumptions inherent in ASTM specified minimum property values.

### Conclusion

The significant benefits of advanced integrity assessment are evident in the three given examples. Yet these methods are not limited only to tanks: they are often used to demonstrate fitness for service of other structures such as pressure vessels, piping, furnaces, heat exchangers, coke drums and rotating equipment. Ultimately, the use of more advanced integrity assessments allows operators to more efficiently and cost effectively allocate their integrity management budget, concentrating resources as needed across their asset portfolios.

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**Figure 4.** Critical flaw size curve.

**Figure 5.** Elevation measurements for a tank bottom.

**Figure 6.** FEA models incorporating measured and predicted future wall thicknesses.