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Determining Inspection Strategies for Anhydrous Ammonia Storage Tanks – A Joint RBI and FFS Approach

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Introduction

When developing and implementing an inspection strategy for any equipment, it is crucial to identify and evaluate all credible damage mechanisms thoroughly. When using RBI for ammonia storage, the inspection strategy strikes a balance between assessing the tank's condition and managing the associated risks, including those related to decommissioning and recommissioning the equipment. Ammonia stress corrosion cracking (SCC) can develop in carbon steel material when exposed to anhydrous ammonia in the presence of tensile stress and oxygen. Ammonia SCC has led to failures of pressurized, slightly refrigerated, and ambient ammonia storage vessels, particularly in areas with significant residual stress, such as cold-formed heads and welds. Several factors affect susceptibility to ammonia SCC, with oxygen contamination playing a key role in both initiating and accelerating damage.

In determining the optimal inspection strategy for an ammonia storage tank, it is important to consider the potential for oxygen ingress during preparations for an internal inspection. Industry experience suggests that the risks of SCC and other safety hazards inherent in emptying and the subsequent warming of a refrigerated ammonia storage tank for out-of-service inspection may outweigh the risks of continued service with less frequent internal inspections. A formal risk assessment can help address these challenges, enabling the development of optimal inspection strategies and intervals, often focused on nonintrusive inspection methods.

Combining risk-based inspection (RBI) with fitness-for-service (FFS) can be a powerful solution for optimizing inspection planning for ammonia storage tanks. Fertilizers Europe's RBI guidelines provide a qualitative risk assessment developed specifically for anhydrous ammonia storage tanks [1]. A pro-active FFS analysis plays a crucial role in assessing the tolerance levels for crack-like flaws and predicting the potential growth of ammonia SCC using the design and operating parameters unique to the subject tank. In addition, the FFS analysis provides valuable information for the inspection strategy including inspection location guidance and acceptance criteria when indications are found. The definition of acceptable versus unacceptable flaw sizes affects the selection of appropriate NDE methods and their sensitivities. By integrating the results from both the RBI and FFS assessments, a well-rounded, data-driven recommendation can be developed to optimize safety, reliability, and costs.

Methodology

Risk-based Inspection Assessment

Fertilizers Europe's Guidance for Inspection of Atmospheric, Refrigerated Ammonia Storage Tanks provides a qualitative RBI assessment that was developed through a Fertilizers Europe member survey of 48 tanks and focused on factors that affect both the probability and consequence of failure. The Fertilizers Europe approach involves a series of questions regarding operating history, commissioning procedures, tank secondary containment design, fracture susceptibility, and oxygen and water content in the ammonia to determine a POF and COF for the tank. The resulting POF and COF can then be used with the Fertilizers Europe risk matrix to determine the tank's risk level and corresponding recommended inspection interval. The risk matrix categorizes risk from very low to high, with recommended inspection intervals ranging from 20-25 years to immediate action recommended, respectively.

For ammonia storage tanks, a thorough review of operating procedures and historical data is crucial to assess the tank's vulnerability to ammonia SCC. The review should consider historical water content measurements, potential for oxygen ingress, and systems designed to keep these parameters within guidelines.

Fitness-for-Service Assessment

Ammonia SCC is a non-linear damage mechanism, making it difficult to predict outside the context of a fracture mechanics framework. Cracks in carbon steel equipment exposed to anhydrous ammonia often begin from very small, undetectable defects that exist from the time of construction. These defects or imperfections are common in welded components but typically do not pose a threat because the steel generally has sufficient toughness to prevent these flaws from propagating, thus avoiding sudden brittle failure. Steel has an inherent tolerance to crack-like flaws up to a certain flaw size; however, when exposed to a combination of liquid ammonia, oxygen, temperature, and stress, these small flaws can grow over time and eventually reach a critical size, leading to failure of the storage tank pressure boundary.

To assess a tank's fracture susceptibility, an FFS assessment is performed. This FFS assessment includes an elastic stress analysis—typically using finite element analysis (FEA)—to identify areas with elevated tensile stress where SCC is more likely to occur and tolerance for cracking is lowest. While all welded joints are potentially vulnerable to brittle fracture due to residual stresses, the most critical areas for ammonia storage tanks are welds at the shell-to-bottom corner, shell-to-roof corner, and nozzles. These locations experience high tensile stresses from both structural discontinuities and residual stresses from the welding process. It is important to note that only the ammonia-wetted surface should be analyzed for tensile stresses, as ammonia SCC will not initiate on the exterior of the tank.

The stress results can be used in elastic-plastic fracture mechanics calculations to determine the stress intensity at the crack tip for a given flaw size under the tank's load conditions. API 579-1/ASME FFS-1, Part 9, "Assessment of Crack-Like Flaws," provides a framework for the assessment methods. A flaw is considered critical when the stress intensity at the crack tip exceeds the material's toughness. The fracture mechanics analysis should also include crack growth modeling due to ammonia exposure. Nyborg and Lunde's research on crack growth in steel exposed to anhydrous ammonia under stress, published in ASTM STP 1194, provides a model for predicting crack progression over time [2]. By assuming an initial undetectable flaw size, the model can be used to calculate the crack growth until it reaches a critical size. Variations in these factors can be used to generate a POF curve, which, when combined with a COF model, helps determine the risk from ammonia SCC and informs the tank inspection strategy.

While ammonia does not directly impact the toughness of the carbon steels used in refrigerated ammonia storage tanks, the cold temperatures of refrigerated ammonia operation can reduce the toughness of steels characterized by a ductile-to-brittle transition. Conversely, the low temperatures of refrigerated ammonia were observed to inhibit initiation of cracking from ammonia SCC. Researchers from the Nyborg study had to warm the test specimens to ambient temperature before sharp cracks initiated at the machined notches. Once the cracks were initiated, the specimens were returned to refrigerated ammonia, at which point limited flaw growth was measured. This finding suggests that while cold temperatures can reduce steel's resistance to brittle fracture, refrigeration has a greater benefit to ammonia tank operation in terms of slowing or even inhibiting ammonia SCC. Therefore, caution is advised when conducting intrusive internal inspections for ammonia SCC, as the inspection process itself could trigger cracking if the tank is brought to ambient temperatures and oxygen is introduced.

Case Study

An owner-operator in the fertilizer industry aimed to optimize an inspection plan for a refrigerated ammonia storage tank with consideration for mechanical integrity, equipment availability, and economics. The tank in question was a low-pressure, welded aboveground storage tank constructed of A516 Grade 60N carbon steel and had been in service for less than 10 years. The tank was approaching the initial internal inspection due date per API 653, "Tank Inspection, Repair, Alteration, and Reconstruction," and the tank owner was interested in alternative solutions to intrusive inspection.

A joint RBI-FFS study was performed for the storage tank. After a thorough review of the design drawings and operating procedures provided, it was determined that the tank had a low susceptibility to ammonia SCC. The tank's low operating temperature was expected to limit ammonia SCC propagation, the water content of the tank was well-monitored and consistently above minimum thresholds, and the tank had not been subject to oxygen ingress. The Fertilizers Europe RBI assessment categorized the tank as "Medium Risk," with a recommended inspection interval of 10-15 years.

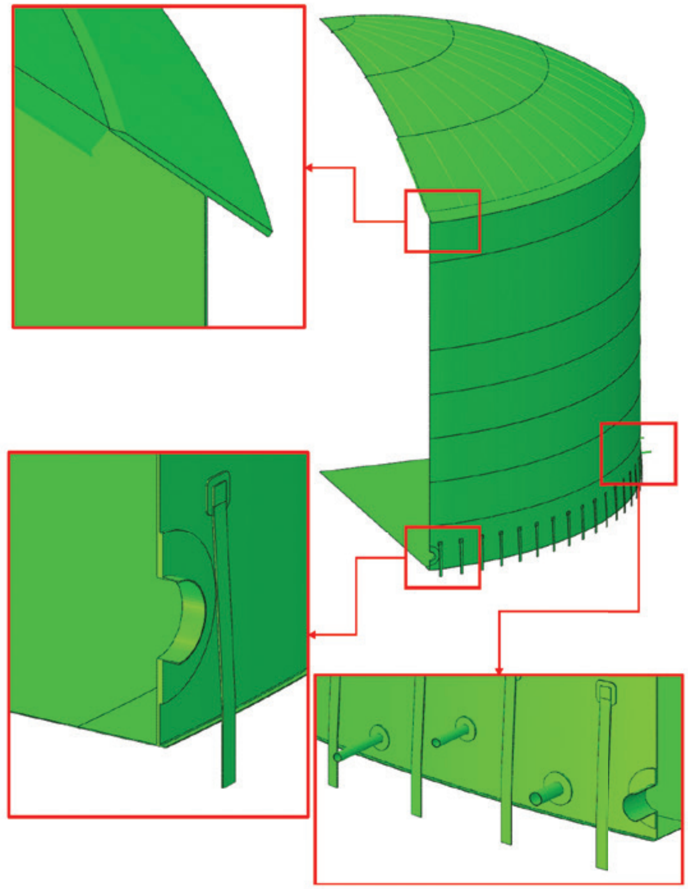

Figure 1. Overview of Finite Element Model.

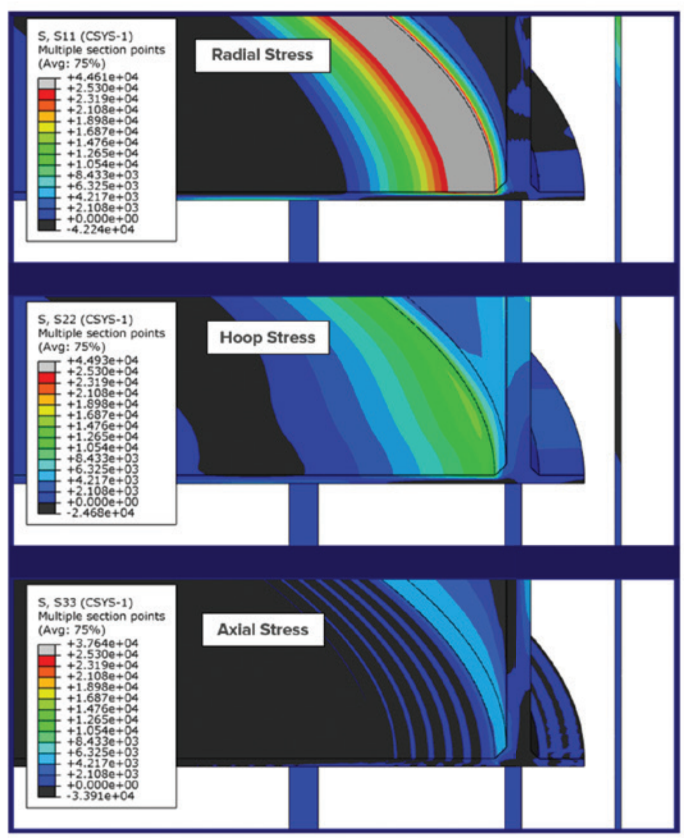

Figure 2. Plot of Stress Components, Bottom Corner Joint

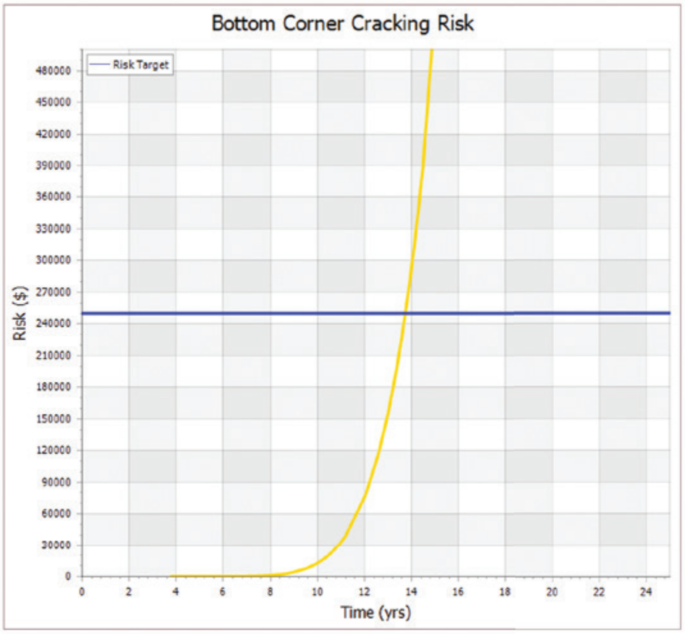

Figure 3. Risk of Bottom Corner Joint Cracking Failure.

A supporting FFS evaluation, including critical flaw sizing and a crack growth study, was conducted to assess the susceptibility of tank components to SCC and refine inspection requirements. Elastic stress analysis using FEA was conducted to determine the through-wall stress distributions at critical tank locations. An overview of the model geometry is shown in **Figure 1**. The focus of the analysis was on the highest stresses on the tank's inner wetted surfaces. A fracture assessment in accordance with Part 9 of API 579 identified the annular plate at the bottom corner joint as the most critical location for ammonia SCC (see **Figure 2**). Additionally, a probabilistic crack growth analysis was performed to guide the required inspection interval. The results of a Monte Carlo analysis with 20,000 simulations indicated that the risk of failure at the tank's bottom corner joint, assuming an initial flaw based on original NDE detection capabilities, reaches the risk target after 13.4 years (see **Figure 3**).

As the results of the FFS analysis demonstrated acceptable risk for over 13 years, a 10-year initial inspection date was set per the Fertilizers Europe RBI assessment. Furthermore, a nonintrusive inspection using acoustic emission (AE) testing was recommended in lieu of an internal inspection to eliminate the risks of opening and warming an ammonia storage tank. Detailed guidance on critical tank locations, such as the bottom corner joint, was provided for focus during the inspection efforts. Ultimately, the tank was inspected using AE testing and no significant AE signals were detected. Future operation was supported for another 10 years (at which point re-evaluation or inspection is required) by applying the RBI-FFS solution.

Standards Development

Currently, tank inspections are typically managed through individual corporate procedures, through reference to API 653 (i.e., prescriptive or RBI), disparate industry guidelines or due to the need to meet local jurisdiction or regulatory compliance. Industry standards for refrigerated storage tanks cover design requirements through API 620 and API 625, leaving an unfortunate gap when it comes to the in-service inspection and assessment protocols for refrigerated tanks.

Members of the API Subcommittee on Aboveground Storage Tanks (SCAST) identified this gap and created a task group to charter a new standard, API RP 626, “Refrigerated and Cryogenic Tank Inspection and Assessment.” While still in the development stages, this anticipated standard is expected to support the development of inspection strategies that address the damage unique to refrigerated and cryogenic storage tanks. RBI and fracture-based considerations are areas of emphasis for the new inspection standard.

Conclusion

Industry experiences with ammonia storage tanks suggest that the risks associated with traditional out-of-service inspection, requiring emptying and warming a refrigerated ammonia tank for entry, often justifies inspection strategies using alternative nonintrusive methods. When developing an inspection plan to effectively minimize the lifetime risk of a tank, it is crucial to consider the tank's history and vulnerability to damage.

Utilizing a combined Fertilizers Europe RBI and pro-active FFS analysis can offer deeper insights into the likelihood of failure, which make possible the development of an appropriate, better-focused inspection strategy and interval for a refrigerated ammonia tank while optimizing reliability and cost. A comprehensive solution where the value of a fracture-based FFS assessment is seamlessly integrated with RBI results through probabilistic analysis can provide significant safety and reliability benefits over the traditional prescriptive approach. ■

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For more information on this subject or the author, please email us at inquiries@inspectioneering.com.

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Maria Rennillo, Engineering Solutions Lead at CorrSolutions, supports clients with risk-based inspection assessments, insulation practices, and tube rupture credibility. Maria has been actively involved in the systemization and circuitization of numerous facilities from initial systemization to final internal review. She has performed risk-based inspection assessments for assets in the oil & gas and fertilizer industries, with a particular focus on ammonia storage tanks. Prior to CorrSolutions, Maria led a team of machine operators to meet daily production schedules and efficiency targets at a beverage production facility. Maria also worked in new equipment start-up, creating procedures and documentation used to minimize operator response time and line downtime.

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