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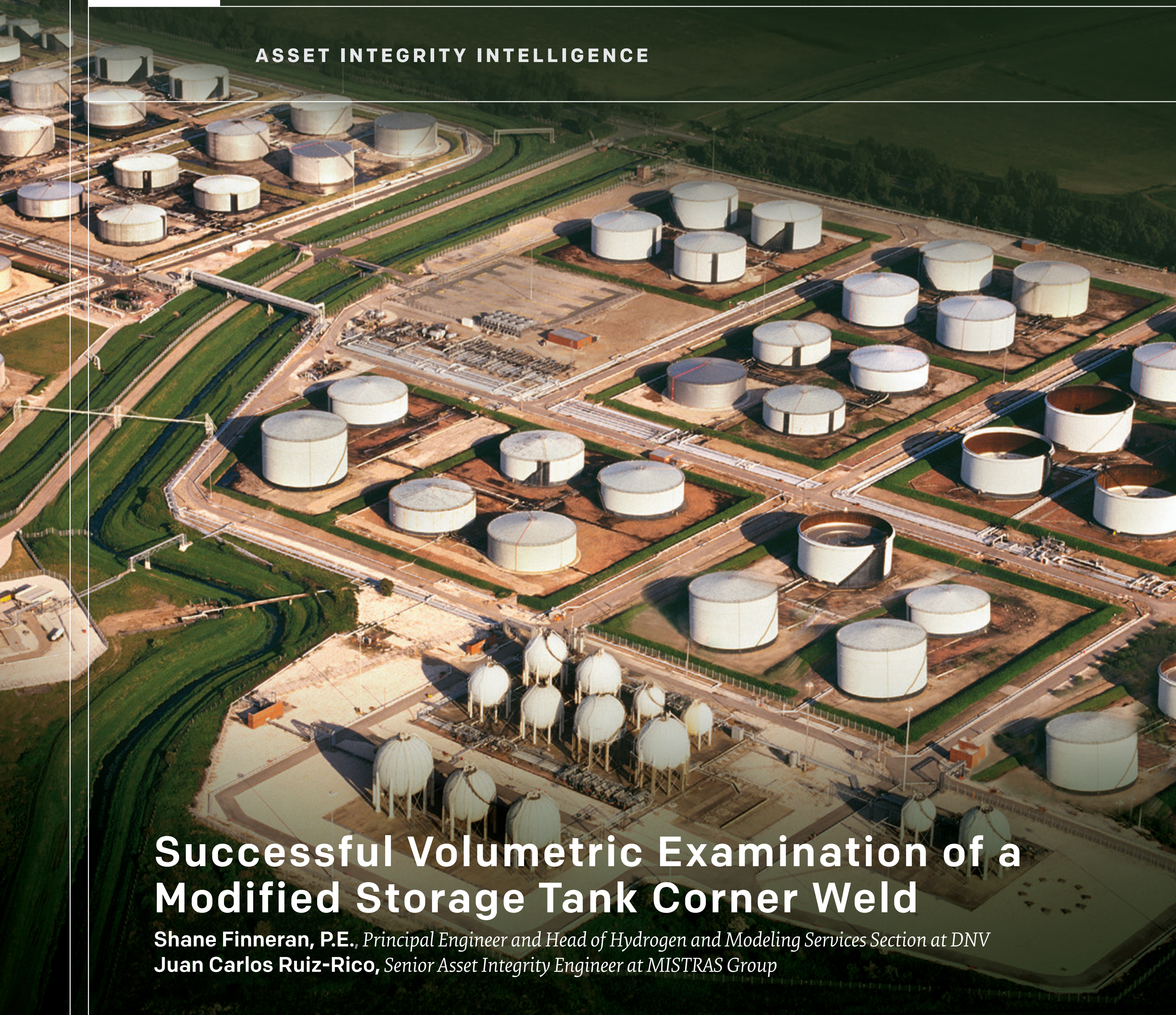

Successful Volumetric Examination of a Modified Storage Tank Corner Weld

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Introduction

In this article, a successful experience is presented using a volumetric examination on a modified storage tank shell-to-bottom weld, known in the industry as corner-weld. The experience resulted from developing a 20-year nonintrusive inspection strategy for a new ammonia storage tank designed and being constructed to API Standard 620, with the goals of improving reliability and extending the internal inspection interval [1].

In-service anhydrous ammonia storage tanks must periodically be inspected internally to assess their integrity. For instance, API Standard 653 requires a formal complete inspection that is supervised by an authorized inspector and is conducted at an interval from the initial service date not to exceed 10 years [2]. However, intrusive inspections of ammonia tanks bring multiple technical and integrity considerations, as well as operational and economic impacts. An intrusive inspection involves tank decommissioning, long downtime, high costs, hazards from tank entry, as well as the potential for off-service material damage. In ammonia tanks, internal surfaces exposed to atmospheric oxygen may increase the threat of stress corrosion cracking (SCC). Consequently, internal inspection of ammonia tanks is a complex task which requires an appropriate level of competence and expertise in tank design, operations, maintenance, and mechanical integrity. Some owners may only have one single ammonia tank without a spare tank, which implies additional considerations of project management to reduce downtime to compensate for the financial impact of production loss.

This case presents the design, construction, and inspection considerations for an ammonia storage tank, targeting a 20-year nonintrusive inspection strategy to minimize tank decommissioning. Several design, construction, quality verification, and operating considerations were implemented in an effort to improve reliability and achieve the desired inspection interval. The lower corner weld was considered a critical weld and was therefore modified to increase tank reliability, exceeding design code requirements. A conservative novel design used a double-sided full penetration butt weld instead of the code required dual fillet weld. Nondestructive testing (NDT) was used prior to commissioning to inspect the modified corner weld. One method consisted of a thorough volumetric examination conducted during tank construction to confirm full weld penetration, while the entire weld volume was examined for the nonintrusive inspection strategy. While both weld design and weld examination schedule exceed tank design minimum requirements for weld sizing and examination, the design code does not specify acceptance criteria for volumetric examination of double-sided full penetration butt-type tank corner-welds. Finite element analysis (FEA) and fracture mechanics were used to determine appropriate acceptance criteria and confirm the successful application of the modified corner-weld volumetric examination.

Tank Description

The tank is a double-wall carbon steel structure comprised of two concentric containers to make up a full containment cryogenic storage tank, with a nominal capacity of 8 million US gallons (30,000 cubic meters) of liquid anhydrous ammonia. The inner container is an open cup design, which is not considered gas-tight, with a diameter of 125 ft (38 m) and a height of 92 ft (28 m). The outer container has a diameter of 131 ft (40 m) and a shell height of 97 ft (29.5 m). The outer container is specified as a full containment, and as such is designed to contain product vapors in normal operation and full volume in case of inner container leakage. The material of construction is ASTM A516 Gr. 70, normalized carbon steel plate impact tested. The design stress was limited to 18 ksi (124 MPa) to improve resistance to ammonia SCC. The tank design lifetime is 25 years.

Corner-weld Sizing Requirements

API Standard 620 requires the attachment between the lowest course plate and the bottom to be a continuous fillet weld laid on each side. For half-inch or less bottom plates, the size of each fillet weld shall not be greater than half-inch, not less than the nominal thickness of the thinner plate, and not less than the values shown in **Table 1**. For bottom plates greater than half-inch, the fillet welds shall be sized so that either leg or the groove depth plus the leg for a combined weld are of a size equivalent to the bottom thickness (**Figure 1**).

Table 1. Shell-to-Bottom Fillet Weld Sizing (Source: API Standard 620, Table 5-4) [1].

Maxiumum Thickness of Shell Plate (in.)	Minimum Size of Fillet Weld (in.)
0.1875	3/16
> 0.1875 to 0.75	1/4
>0.75 to 1.25	5/16
> 1.25 to 1.50	3/8

Corner-weld Examination Requirements

In API Standard 620, Annex P (*NDE and Testing Requirements Summary*) and Annex R (*Low-pressure Storage Tanks Operating Between +40°F and -60°F*) elaborate the weld examination requirements.

Annex P indicates magnetic particle testing (MT) for the corner-weld of carbon steel tanks. Annex P is informative and as such is considered not mandatory. The experience of the authors

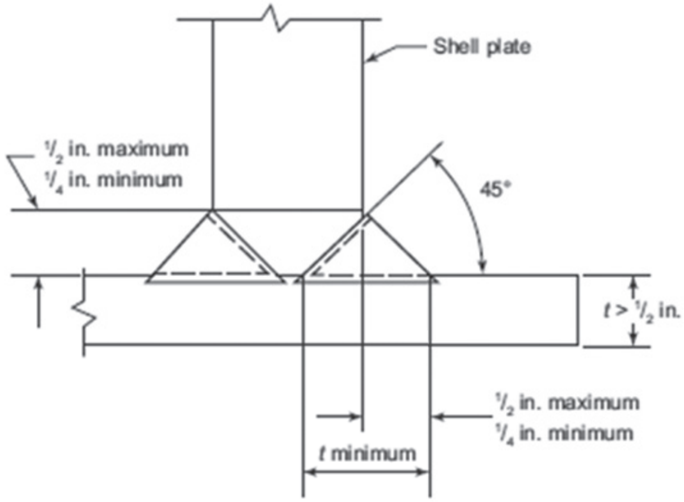

Figure 1. Double Fillet-groove Weld for Bottoms Greater than Half-inch (Source: API Standard 620, **Figure 5-3**) [1].

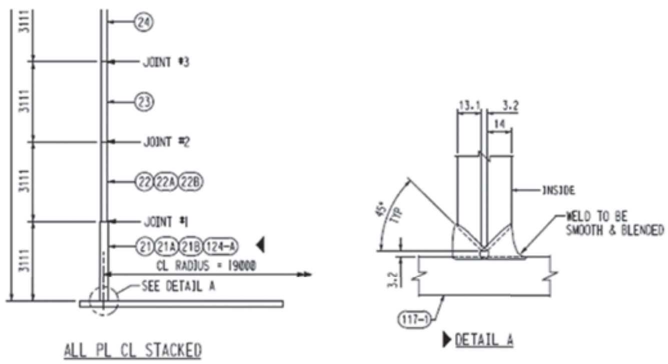

Figure 2. Corner-weld Conceptual Design [3].

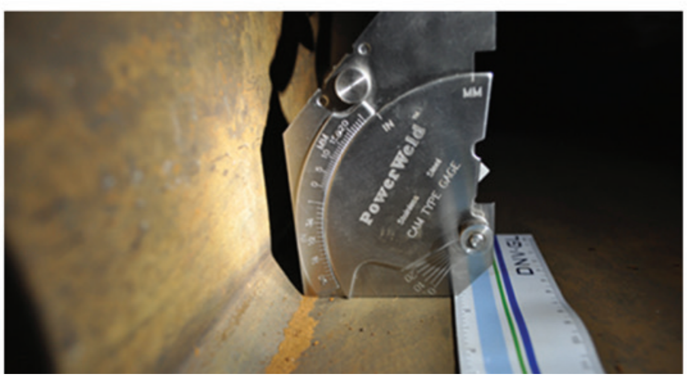

Figure 3. Corner-weld as-built view [4].

is that MT is normally conducted on the final weld pass of the corner weld. Annex R is normative and states that primary and secondary liquid container welds shall be examined using MT for carbon steel and liquid penetrant testing (PT) for stainless steel. It also states butt-type welds of the primary and secondary container shall be examined by either radiographic testing (RT) or ultrasonic testing (UT).

UT is not listed in Annex P, but it is mentioned in Annex R along with RT for butt-type welds. Though, RT and UT are specified for butt welds in API Standard 620 for complete mandatory examination [1]. However, UT is proposed in lieu of RT under an agreement between tank owner and manufacturer.

Corner-Weld Modification

In an effort to improve reliability and achieve the desired inspection interval, the tank designers specified a modified lower corner weld, exceeding design code requirements. The corner-weld modification comprises a conservative novel design of a double-sided full penetration and complete fusion butt weld completed from both sides of the shell plate without leaving a groove in between (**Figure 2**, Detail A). The design concept was a weld option to the required traditional double fillet weld (i.e., inner and outer fillet welds with a groove in between—refer to **Figure 1**). This groove is generated because a complete penetration is not required by code.

The tank owner specified and included this weld design in the 20-year nonintrusive inspection strategy to increase tank reliability, exceeding code requirements related to weld sizing and nondestructive examination. The as-built weld final dimensions were as per code with full penetration and a nondestructive volumetric weld examination, in addition to the code surface examination. The conceptual weld design is presented in **Figure 2**, and a view of the as-built weld is presented in **Figure 3**.

NDT Plan

An NDT plan was developed for the 20-year nonintrusive inspection strategy which included visual testing (VT), MT, and UT. NDT procedures were prepared and approved by an ASNT NDT Level III certified examiner, endorsed by the engineering organization in charge of the development, and witness of the inspection strategy.

VT using direct visual examination technique was performed during fit-up of the corner-weld, and after root and final welding passes. As-built weld dimensions were taken and recorded for future traceability and "banding" of findings collected with the other NDT methods. For MT, alternate current portable yoke magnetization, with wet fluorescent particles (WFMT), was used and applied on root and final welding passes. Findings found were assessed per ASME Section VIII Appendix 6 [5].

Volumetric Examination

Even though it is not a code-mandatory NDT unless specified in lieu of RT for butt-type welds, a UT examination was requested by the tank owner to confirm complete penetration of the modified corner weld and assess its entire volume. This examination was

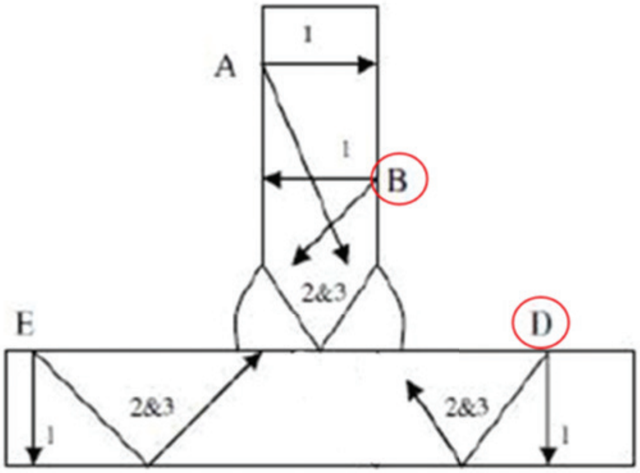

Figure 4. Transducer Position for PAUT Scan Plan [4].

Figure 5. As-built mock-up for PAUT scan plan and calibration [4].

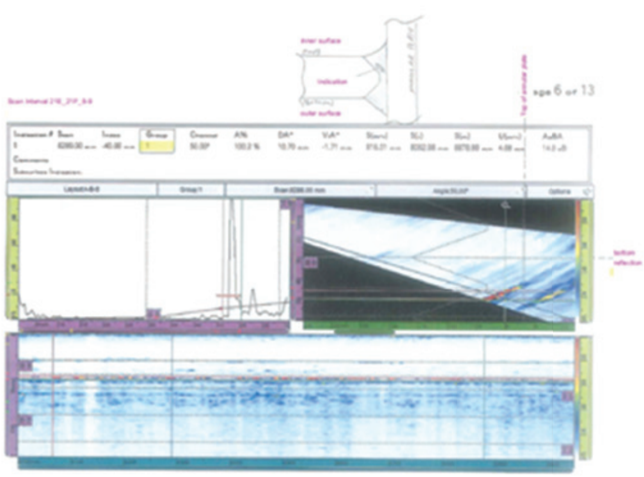

Figure 6. Example of PAUT Unit Screen and Data Analysis [6].

within the 20-year nonintrusive inspection strategy to confirm weld quality and increase tank reliability.

Considering the novel design of a double-sided full penetration butt weld, a manual phased array ultrasonic examination (PAUT) procedure was developed and completed during tank commissioning, conducted on the final welding pass covering 100% of the corner-weld volume and length. As an advanced UT technique, PAUT offers the following advantages for the inspection strategy:

- Availability of permanent records
- Auditability of recorded data
- High degree of repeatability (PAUT record can be used as a baseline for future in-service inspections)
- Ability to use findings with fitness-for-service acceptance criteria

An Olympus OmniScan® Phased-array Flaw Detector MX2 with software version MX2 4.1 was used, producing angular range S-scans and fixed angle E-scans, as well as conventional A-scans and B-scans; with 64-element transducer with scanning angle range 48°-73° and frequency 5 MHz. To determine the best examination strategy, a scan plan considering weld geometry, base material thickness, and refracted angles was developed rehearsing several transducer positions as shown in **Figure 4**. Scans B and D from the tank's internal surface were finally selected. The scan plan comprised transducer placement, movement, weld coverage, ultrasonic beam angle, and beam directions, providing a standardized and repeatable weld examination methodology.

The developed PAUT procedure and system were verified using the requirements of ASME Section V Article 4 and the applicable guidelines of DNVGL-RP-F118, *Pipe Girth Weld Automated Ultrasonic Testing System Qualification and Project Specific Procedure Validation* [9,7]. The intention was to provide a uniform qualification of the UT system, documenting system performance in terms of inherent functionality related to hardware, software, calibration philosophy, and personnel qualification; to produce a reliable, repeatable, and auditable ultrasonic examination. This verification included the following:

- Review of technical procedure background, operating methodology, data quality checks, and system performance: detection ability and sizing accuracy of indications
- Evaluation of significant UT parameters and their variability
- Confirmation of personnel experience, training, and certifications
- Consideration of the following variables:
  - Welding procedure
  - Corner-weld geometry
  - Base materials
  - Actual wall thickness
  - Root and final weld set-up
  - PAUT channel set-up
  - Calibration blocks and as-built mock-up (**Figure 5**)
  - Reference reflectors
  - Temperature effects
  - Data acquisition and processing

PAUT examination data were recorded, including unprocessed data. A data set with no gating filtering or threshold for ultrasonic examination responses were included. The extent of recorded data, processed or unprocessed, was sufficient for subsequent review and further repeatable examinations. Therefore, the data was assessed to ensure full execution of the scan plan over 100% of

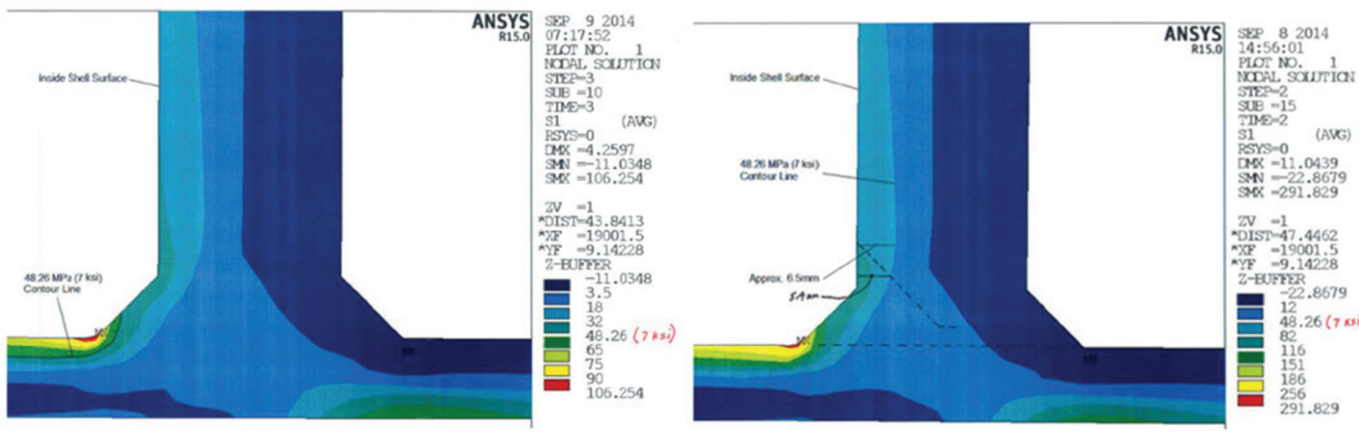

Figure 7. Stress States at Corner-weld. Values reported in MPa. Left: Normal Operating Liquid Level. Right: Design Liquid Level [6].

corner-weld volume and length. The assessment was done using predetermined gates to identify the source, location, and nature of all PAUT indications. Signals and images were investigated in detail, for weld root and weld crown geometries, and indication size. Any indication warranting further evaluation was analyzed for anomaly severity and acceptability. Finally, reporting of indications included location, peak amplitude, depth below the surface, volumetric sizing, and relative position for length. **Figure 6** shows an example of a PAUT unit screen and weld sketches for data analysis.

Findings

The volumetric examination did not report indications related to lack of penetration, confirming achievement of full weld penetration. Nevertheless, PAUT reported a total of 203 indications of other kinds. When analyzed, most of the indications exhibited similar heights and locations almost exclusively along the top-level face near the final to middle welds passes. Weld sketch of **Figure 6** shows an approximate indication of location. Detailed sizing and individual analysis indicated that indication lengths and spacings showed a repeating pattern of discontinuous indications separated by short lengths of reflector-free corner-weld. Joint detail and indication patterns are shown in S-scans and A-scans, suggesting that PAUT indications are due to the presence of inter-pass trapped slag lines. An anomaly interaction analysis was also performed to evaluate the maximum length reported. Interaction and combined length resulted in an indication length shorter than the maximum reported.

Assessment

Since UT is not a code mandatory NDT and API Standard 620 does not specify acceptance criteria for a volumetric examination of a double-sided full penetration butt-type corner-weld; findings were assessed using finite element analysis (FEA) and fracture mechanics, to calculate and evaluate high localized stresses at any reported indication chosen for evaluation and determine allowable indication size [1].

An FEA model was developed comprising the as-built corner-weld geometry, including measured sizes of the fillet portions. Regarding stress levels, tensile stresses less than 10% of the minimum allowable ultimate tensile strength of the construction material are not considered to cause crack-like indication growth, even in low toughness materials. This is consistent with API Standard 620 and ASME Section VIII [1,5]. Therefore, plots were set with a stress contour line equal to 10% of the material minimum allowable ultimate strength, equal to 7 ksi (48.26MPa). Indications located in areas with this level of tensile stress were not considered for further evaluation.

The stress states at the corner-weld were analyzed for normal operating liquid level and design liquid level. The stress plots can be observed in **Figure 7**. For normal operating liquid levels, the stress levels above the contour line were localized in the toe of the inside fillet portion and along the annular plate top surface. For the design liquid level, the stress levels of interest were restricted to near the corner-weld inside surface. The contour line intersected the weld bevel at a depth of about 0.212 inches (5.4 mm). Consequently, PAUT indications nearer to the surface than this depth were identified for further detailed evaluation.

Acceptance criteria for the volumetric examination indications were determined through a Level 3 fracture mechanics assessment to determine critical indication size. API 579-1/ASME FFS-1 Part 9, *Assessment of Crack-like Flaws* was used to establish flaw acceptance limits [8].

All reported PAUT indications were assessed for stresses generated at the tank design liquid level. As a conservative approach, if all indications were acceptable for these stresses, no further analysis is required. The results are shown in **Figure 8**. The plot consists of symbols representing the analysis of hypothetical flaws as a function of height and length. Green circles represent flaw sizes considered acceptable, while red triangles represent unacceptable flaw sizes. Considering a hypothetical flaw height "*a*" of 0.2 inches (5mm), the maximum acceptable flaw length was 6.7 inches (170 mm). No indications were identified by the PAUT data with individual sizes greater than the acceptable dimensions. Therefore, the indications were considered acceptable per the completed assessment.

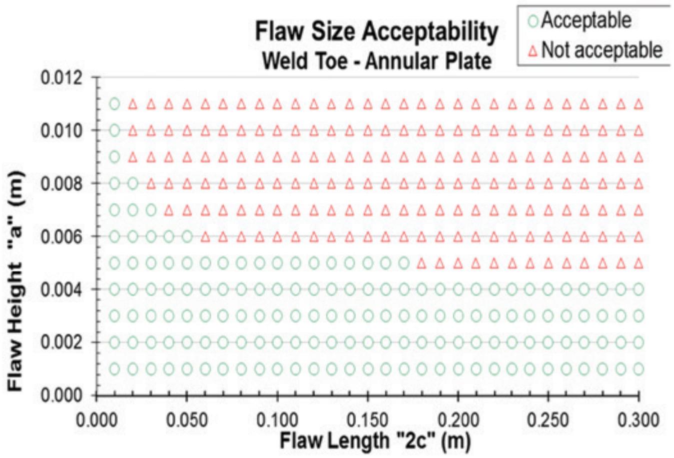

Figure 8. Flaw size acceptability plot as function of hypothetical indication height "a" and length "2c" [6].

Conclusions

A nondestructive volumetric examination using PAUT was successfully developed and applied to a novel design of a corner weld of an ammonia storage tank under construction. The weld modification and its examination were part of a non-intrusive inspection strategy. An internal inspection requires tank decommissioning, which can potentially allow atmospheric oxygen exposure to internal surfaces leading to an increased susceptibility to SCC, the main integrity threat of ammonia storage tanks. For this reason, a target internal inspection interval of 20 years or greater was being pursued to avoid hazards associated with an internal inspection.

The executed NDT during commissioning provided confidence that no surface breaking indications were evident and ensured that construction procedures in place minimized residual stresses that could induce SCC. An assessment of findings was defined and successfully conducted using FEA and fracture mechanics, to calculate relevant stresses for indication severity and allowable indication size.

Development of tank long-term nonintrusive inspection strategies that include the mentioned modification of the corner-weld with a corresponding volumetric examination, would contribute to improved design and corner-weld quality, increasing tank reliability with extended internal inspection intervals, minimizing the risks associated with SCC damage in ammonia storage tanks. ■

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

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