# Testing and Recommended Practices to Improve Nurse Tank Safety: Phase IV

U.S. Department of Transportation
**Federal Motor Carrier Safety Administration**

**June 2022**

# FOREWORD

Since 2008, the Federal Motor Carrier Safety Administration (FMCSA) has sponsored research to improve the safety of anhydrous ammonia nurse tanks. In Phase IV, advanced non-destructive testing (NDT) techniques were employed to explore recommendations from previous studies—using both phased array (PA) ultrasonic examination and acoustic emission (AE) monitoring to locate cracks and determine the effects of hydro testing. In summary, the Phase IV study found:

- PA ultrasonic devices are a considerable improvement over the handheld single-beam angle ultrasonic units used in previous phases, providing better discrimination capabilities between weld geometry effects and true crack indications, although at a higher cost.
- AE monitoring could detect changes in the tank during hydro testing, but could not definitively tell if a recorded AE event was associated with the formation or growth of a crack. Also, the changes detected were not large enough to render the tank even marginally less safe, or decrease the tank life.

The results of this study may be of interest to agribusinesses, fertilizer companies, government regulators, and the manufacturers of anhydrous ammonia nurse tanks.

# NOTICE

# QUALITY ASSURANCE STATEMENT

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16. Abstract

**A selection of agricultural anhydrous ammonia nurse tanks was examined using phased array (PA) ultrasonic technology and acoustic emission (AE) monitoring to determine what effect is produced in the tanks during hydrostatic pressure testing ("hydro testing"). Tanks were selected to cover a variety of manufacturing ages and conditions, included those that received post weld heat treatment (PWHT) and those that did not; pre-1999 tanks with thicker steel; post-1999 tanks with thinner steel; and a new tank. Before hydro testing, tanks were examined using PA to locate existing cracks. This included re-testing 20 previously studied tanks, and 1 new tank. (An older tank was also included for testing to failure.) Next, the tanks were monitored for AE during the hydro test. The majority of tanks (16) showed no change at all due to the hydro test. Seven tanks did show slight differences and were re-examined using PA. These differences could be attributed to a variety of reasons including formation of new cracks, growth of existing cracks, better detectability of existing cracks due to the increased sensitivity of the PA equipment, or enhanced detection of an existing crack due to expansion/cleaning of the crack during the hydro test. A single crack was strongly suspected as having been initiated due to the hydro test, and it was at a probe minimum (PM) value in length, far below what calculations show is dangerous. The limited changes seen indicate that hydro testing does little or no harm to the tanks.**

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# SI* (MODERN METRIC) CONVERSION FACTORS

## Approximate Conversions to SI Units

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| **Length** | | | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| **Area** | | | | |
| in$^2$ | square inches | 645.2 | square millimeters | mm$^2$ |
| ft$^2$ | square feet | 0.093 | square meters | m$^2$ |
| yd$^2$ | square yards | 0.836 | square meters | m$^2$ |
| ac | Acres | 0.405 | hectares | ha |
| mi$^2$ | square miles | 2.59 | square kilometers | km$^2$ |
| **Volume (volumes greater than 1,000L shall be shown in m$^3$)** | | | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| ft$^3$ | cubic feet | 0.028 | cubic meters | m$^3$ |
| yd$^3$ | cubic yards | 0.765 | cubic meters | m$^3$ |
| **Mass** | | | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2,000 lb) | 0.907 | megagrams (or “metric ton”) | Mg (or “t”) |
| **Temperature (exact degrees)** | | | | |
| °F | Fahrenheit | 5(F-32)/9 or (F-32)/1.8 | Celsius | °C |
| **Illumination** | | | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/m$^2$ | cd/m$^2$ |
| **Force and Pressure or Stress** | | | | |
| lbf | pound-force | 4.45 | newtons | N |
| lbf/in$^2$ | pound-force per square inch | 6.89 | kilopascals | kPa |

## Approximate Conversions from SI Units

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| **Length** | | | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| **Area** | | | | |
| mm$^2$ | square millimeters | 0.0016 | square inches | in$^2$ |
| m$^2$ | square meters | 10.764 | square feet | ft$^2$ |
| m$^2$ | square meters | 1.195 | square yards | yd$^2$ |
| Ha | hectares | 2.47 | acres | ac |
| km$^2$ | square kilometers | 0.386 | square miles | mi$^2$ |
| **Volume** | | | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| m$^3$ | cubic meters | 35.314 | cubic feet | ft$^3$ |
| m$^3$ | cubic meters | 1.307 | cubic yards | yd$^3$ |
| **Mass** | | | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or “t”) | megagrams (or “metric ton”) | 1.103 | short tons (2,000 lb) | T |
| **Temperature (exact degrees)** | | | | |
| °C | Celsius | 1.8c+32 | Fahrenheit | °F |
| **Illumination** | | | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/m$^2$ | candela/m$^2$ | 0.2919 | foot-lamberts | fl |
| **Force and Pressure or Stress** | | | | |
| N | newtons | 0.225 | pound-force | lbf |
| kPa | kilopascals | 0.145 | pound-force per square inch | lbf/in$^2$ |

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003, Section 508-accessible version September 2009.)

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# LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

| **Acronym** | **Definition** |
|---|---|
| AE | acoustic emission |
| ASME | American Society of Mechanical Engineers |
| de1, de2, etc. | distance of event to transducer 1, distance of event to transducer 2, etc. |
| FMCSA | Federal Motor Carrier Safety Administration |
| HAZ | heat affected zone |
| kHz | kilohertz |
| MAWP | maximum allowable working pressure |
| NDT | non-destructive testing |
| $NH_3$ | chemical formula for ammonia |
| MHz | megahertz |
| MP | magnetic particle |
| MPA | megapascal |
| P | pressure in a tank |
| PA | phased array |
| PHMSA | Pipeline and Hazardous Materials Safety Administration |
| PM | probe minimum (0.5 inch) |
| PSI | pound-force per square inch |
| PWHT | post weld heat treatment |
| QSC | Quality Steel Corporation |
| r | tank radius |
| SCC | stress corrosion cracking |
| $\sigma$ (sigma) | stress |
| t | thickness |
| T1, T2, etc. | transducer location 1, transducer location 2, etc. |

| **Acronym** | **Definition** |
|---|---|
| $T_1$, $T_2$, etc. | time 1, time 2, etc. |
| USDOT | U.S. Department of Transportation |
| UT | ultrasonic testing |
| V | velocity of sound in steel |

# EXECUTIVE SUMMARY

## PURPOSE

This study is a continuation of efforts funded by the Federal Motor Carrier Safety Administration (FMCSA) and the U.S. Department of Transportation (USDOT) aimed at improving the reliability and safety of steel nurse tanks used to transport agricultural anhydrous ammonia ($NH_3$). The study focused on answering two questions which arose from previous research into the likelihood of tanks failing suddenly due to stress corrosion cracking (SCC) of the steel over extended periods of time. These questions were:

1. Does a hydrostatic pressure test ("hydro test") (used to judge the safety of a tank) cause undetected crack growth in existing SCC cracks, turning a safe tank into a potentially hazardous one?
2. Does the lower resolution of single-beam ultrasonic methods miss (or misdiagnose) SCC cracks that could be found using a nondestructive testing (NDT) technique with advanced capabilities, such as phased array (PA) ultrasonic examination?

These questions have been examined and answered during the course of this research by employing a combination of PA examination and acoustic emission (AE) monitoring of tanks.

## PROCESS

In the Phase IV study, 20 tanks were included that had previously been surveyed in 2012 and 2015 using a lower precision single-beam ultrasonic device to detect and monitor cracks present within the tanks. Phase IV also included one relatively new tank (2017 manufacture) and one older tank (age undetermined) that was tested to failure.

### Pre-Hydro PA Testing

The first step of the process involved a re-examination of each of the 20 tanks previously studied to determine whether any new cracks had initiated since 2015, or whether existing cracks had grown. This examination established a baseline for comparing future results, and allowed a determination of the effectiveness of PA examination. This survey revealed that many prior crack indications found in 2012 and 2015 using the less expensive handheld ultrasonic model were due to false echoes generated from the geometry of the weld itself (i.e., false positives). However, the examination also revealed numerous additional cracks had appeared since the 2015 survey, and in some cases, slight crack growth in existing cracks. These additional detections could be due to a combination of greater sensitivity and precision of the PA unit, or the additional formation of cracks due to SCC. The initial survey revealed additional cracks in 11 tanks, no change in the number of cracks in 2 tanks, and fewer cracks in 7 tanks, as compared to the 2015 data. No indications were found in the one new tank tested.

### AE Monitoring During Hydrostatic Pressure Testing (“Hydro Testing”)

The second step of the process involved instrumenting each tank to monitor AE during a standard hydro test. Whenever a new crack is nucleated (i.e., created where no crack existed before), or an existing crack grows, it does so to release internal stress. This release of stress is accompanied by a release of energy in the form of an acoustic signal. By placing sensors around a tank at various locations, AE events detected can be triangulated using the sensors that detect signals, thereby revealing the approximate location of the event, and whether that is a new crack or growth of an existing one. The acoustic monitors measured recordable events in 16 of the 21 tanks tested (not including the tank tested to failure).

### Post-Hydro PA Testing

The third and final step of the process was to re-examine each of these 16 tanks at the locations indicated by the AE results. This examination was simpler than the initial survey because 1) it was known that any cracking took place at the weld seams; 2) AE could determine the location to within a few inches, meaning the entire weld seam did not have to be re-examined; and 3) the number of AE events was limited. PA testing confirmed cracks in 7 of the 16 tanks. All but one crack were at probe minimum (PM) level.

## RATIONALE AND BACKGROUND

This study is based on the results of Testing and Recommended Practices to Improve Nurse Tank Safety: Phases I–III. The Phase I study conducted in 2012 found that SCC was likely in anhydrous nurse tanks, especially those which had not undergone post weld heat treatment (PWHT).(1) This was due to the high residual stresses present after welding, especially in the end caps. Twenty in-service tanks were surveyed. Cracks were discovered in almost every tank examined. Phase II determined a growth rate for the cracks and investigated the effect of the additive N-Serve on crack formation and growth.(2) During Phase III (2015), the tanks surveyed in 2012 were examined again to compare real crack growth rates to calculated ones (Phase II), and to measure whether new cracks had nucleated.(3) It was found that the inexpensive units used for crack measurement were largely dependent upon operator expertise for distinguishing small cracks from weld geometry effects. Throughout all phases, over 400 in-service tanks have been studied.

The objective for Phase IV was two-fold. First, to see whether more accurate results could be obtained using PA ultrasonic detection, resolving the discrepancies between 2012 and 2015 data. Second, agribusinesses have questioned the requirement to hydro test tanks bearing illegible data plates. Their concern is that the hydro test, in which the tank is raised to a much higher pressure than normal operating conditions, could damage the tank. By instrumenting a tank for AE monitoring during the test, any changes to the tank due to the test itself could be isolated. Coupled with PA, the exact changes before and after testing could then be determined.

## STUDY FINDINGS

Key findings from the investigation are as follows:

### Finding #1: PA analysis is superior to single beam.

The use of multiple beams in the ultrasonic probe allowed weld effects to be more easily distinguished from actual crack indications within the steel. This resulted in fewer indications being seen in some tanks during the pre-hydro tests. Additional indications seen in other tanks could be due to the increased precision of the PA device, but it is probable that many are indications of new cracks that nucleated since 2015.

### Finding #2: AE testing is useful in detecting changes in the tank.

The sensitivity of the equipment used was adequate to tell that changes were occurring in the tank during testing. Although 16 of 21 tanks had AE events, only 7 of these tanks had measurable differences in the post-hydro PA inspection.

### Finding #3: Changes produced by hydro testing are minimal.

Of the seven tanks where differences were seen pre- and post-hydro testing, the damage observed was minimal and not large enough to impact the life of the tank.

### Finding #4: Additional evidence was found that PWHT is beneficial.

Tanks which had undergone PWHT were found to have fewer cracks and less crack growth in the pre-hydro tests. They were also less likely to develop additional cracks during the hydro test.

## CONCLUSIONS

Based on the results of this study, the research team concluded that hydro testing of tanks does not constitute a significant threat to the safety of a tank and may have some safety benefits. The rationale for that statement is as follows. Anecdotally, farm cooperative personnel have said that hydro testing has caused tanks with significant cracks in them to fail prematurely in the past. Older tanks are still present in the U.S. fleet that have not undergone PWHT, and in which the entire length of the weld was not examined using x-ray techniques to ensure weld soundness. While the use of PA could determine the extent of cracking and the quality of welds in older tanks, the cost to agribusinesses would likely be prohibitive. Second, while PWHT will act to reduce SCC in new tanks, it will have less effect on locations where the application of cyclic mechanical stresses can be expected to produce fatigue, such as where supports for running gear are welded onto the tank. While pinhole leaks would most likely form first, this cannot be guaranteed.

# 1. INTRODUCTION

## 1.1 BACKGROUND

Anhydrous ammonia ($NH_3$) is a liquefied compressed gas used as a nitrogen-rich fertilizer in agriculture for crops that need annual or semi-annual nitrogen replacement in the soil. The filled cargo tanks, commonly referred to as nurse tanks, are used to transport anhydrous ammonia from agribusinesses to farm fields and are commonly towed across the fields themselves. An example of a 1,450-gallon nurse tank mounted on running gear for towing is shown in Figure 1.

Anhydrous ammonia is domestically classified as a Division 2.2 non-flammable compressed gas by the USDOT. It should be noted that ammonia vapor is flammable over a narrow range of 16 to 25 percent by volume in air when a strong ignition source is present. Internationally, anhydrous ammonia is classified as a Division 2.3 Zone D poison gas. While anhydrous ammonia exhibits the same characteristics both domestically and internationally, it is only anhydrous ammonia described, placarded, and transported as a Division 2.3 Zone D material that is subject to the FMCSA Hazardous Materials Safety Permit program for quantities over 3,500 gallons.(4)

**Figure 1. Photograph. Anhydrous ammonia nurse tank mounted on running gear.**

Source: FMCSA

The high pressure of the gas in the tank makes sudden release very dangerous. While anhydrous ammonia is a liquid when under pressure in the tank, ammonia has a high volumetric expansion ratio of 850 to 1 as it expands (i.e., boils into a gas). Adiabatic cooling during expansion results in a cloud of low-temperature gas which can cause frostbite in exposed tissue. The caustic nature of anhydrous ammonia can cause severe chemical burns through extreme absorption of water from tissues like eyes and lungs. Inhalation of a sufficient concentration can lead to death.

Use of anhydrous ammonia as a fertilizer started in the 1950s. There are still tanks in service that are more than 50 years old that use different steel types, thicknesses, and manufacturing processes. The Fertilizer Institute (TFI) estimates there are approximately 200,000 nurse tanks in use in the agriculture industry, and that some are removed from service each year for various reasons, including rollovers in ditches during spring planting, deterioration of the tank over time, and severe dents.

Nurse tanks are not a USDOT specification cargo tank but are manufactured to an American Society of Mechanical Engineers (ASME) standard.(5) Under the ASME code, the tanks have a maximum allowable working pressure (MAWP) of 250 pound-force per square inch (psi).

Originally there was a safety factor of four built into the design, so new tanks should have been able to withstand 1,000 psi without failing. The safety factor was reduced by a 2016 Pipeline and Hazardous Materials Safety Administration (PHMSA) regulation change.(6) This regulation change enforced a 1997 ASME specification change allowing the use of thinner steel in the shell of nurse tanks, provided that the manufacturer used 100-percent radiographic (x-ray) inspection of the longitudinal welds holding the steel shell into a cylinder.

Older nurse tanks are commonly found in 1,000-gallon and 1,450-gallon sizes, but new tanks are found in larger sizes (e.g., twin 1,450-gallon tanks on a single running carriage, 2,000-gallon tanks and 3,000-gallon tanks). Standard nurse tanks cannot exceed 3,000 gallons, but 5,000-gallon tanks are allowed if issued a special permit by PHMSA.(7) These 5,000-gallon tanks are operated by Farmers Grain. An example is shown in Figure 2.

**Figure 2. Photograph. Example of a 5,000-gallon nurse tank.**

The ages of the tanks now in service range from new to more than 50 years old. One tank examined in the Phase IV research was 51 years old. The tank that was tested to failure may have been even older. The majority of tanks are owned by farm cooperatives (co-ops) and agribusinesses within the U.S., although some farmers do own their own personal tanks.

## 1.2 DEGRADATION OF NURSE TANKS

Stress corrosion cracking (SCC) is a known phenomenon that occurs in nurse tanks used in anhydrous ammonia service. USDOT regulations require 0.2 percent water to be added to the anhydrous ammonia. The water helps inhibit the anhydrous ammonia's ability to cause SCC, but only from the fill line down—the lower 85 percent of the tank where the water is in solution with the anhydrous ammonia. Thus, especially in the upper 15 percent of the tank above the fill line—which contains anhydrous ammonia vapor only—SCC occurs at points where there are significant tensile stresses in the steel. This can due to either dents or unannealed welds in tanks, i.e., the tanks did not undergo post weld heat treatment (PWHT).

Cracking and leaking of anhydrous ammonia nurse tanks is not uncommon. Usually, the cracks are not very severe and the owner either has the cracks removed or the tank repaired (welded). The tank may also be sold for scrap metal. However, there may be hidden SCC that has not penetrated the entire thickness of the steel to cause a pinhole leak. This could weaken the tank enough to cause violent, catastrophic failure. This generally occurs through rupturing along a weld weakened by SCC. Such releases of the anhydrous ammonia can be sudden and dangerous. These catastrophic failures have caused fatalities and serious injuries, such as in the 2003 death of a co-op worker in Calamus, Iowa, and the 2005 incident that occurred in Morris, Minnesota.(8 9)

Currently, the USDOT does not require any type of testing on a large percentage of these tanks. However, regular inspection and testing is required for tanks that are either missing the ASME data plate or possess a plate that is no longer legible (see 49 CFR Section 173.315(m)(2)). Required tests include a visual inspection, a wall thickness measurement, and a hydro test. These tests are described in the Section 2 in more detail and are required once every 5 years.

## 1.3 INSPECTION AND TESTING OF NURSE TANKS

Because nurse tanks are not manufactured with any manways (i.e., passages allowing a human to enter the tank), internal inspections for cracks using wet magnetic florescent particle tests, such as those that can be performed inside standard semi-trailer cargo tanks with manways, cannot be conducted inside nurse tanks. Instead, the three inspection/test methods that are commonly used on nurse tanks without a legible data plate to judge a tank's structural integrity are:

- **External visual inspection:** This method effectively detects external damage such as dents, loose fittings, or paint flaws that may indicate a pinhole leak due to SCC that has penetrated through the tank—usually at a weld. The limitation of this test is that it is ineffective at assessing the presence and severity of internal SCC, which is a major cause of future tank failure.
- **Ultrasound measurement of wall thickness:** This method is effective at detecting tanks manufactured with steel that is too thin. The limitation of this test is that it rarely identifies a properly manufactured tank (i.e., one that was manufactured in conformance with the minimum thickness steel) that was subsequently reduced below minimum acceptable wall thickness over time. This is because uniform corrosion of interior steel tank walls by anhydrous ammonia is extremely slow making it difficult to quantify the

changes over time, except at tensile stressed locations (e.g., dents and unannealed welds that corrode and crack).

- **Hydro testing:** This method, at a specified elevated pressure level, is effective at determining whether the tank can withstand an elevated pressure without failing (i.e., the tank does not have a major flaw that fails at that elevated pressure). However, it is unknown whether this test is potentially destructive even for tanks that pass the test. This is because application of the elevated pressure may cause undetected crack growth in existing SCC locations. Also, the wide application of hydro tests is both time- and labor-intensive. It requires emptying the tank of anhydrous ammonia, moving the tank to a safe location to conduct the pressure test, filling the tank with water, applying the prescribed pressure, then removing the water. It is not practical for large-scale testing.

A comparison of these techniques to other methods that have been applied to nurse tank studies is given in Appendix A.

## 1.4 RECENT RESEARCH CONCERNING NURSE TANK EXAMINATION

Over the past decade, FMCSA has sponsored research related to the testing and examination of agricultural anhydrous ammonia nurse tanks. Those studies included use of relatively inexpensive single-beam angle ultrasonic testing (UT) to find and quantify both number and size of indications which have formed in the tanks, likely due to SCC. One advantage of this non-destructive testing (NDT) method is that it can be done without moving or emptying the tanks. Initial application of the methodology was performed under a contract awarded in 2008 (Phase I) as a screening test. Twenty donated, used tanks were extensively examined by a variety of destructive material science tests.(10) Subsequently, during the summer of 2012, that NDT method was then applied to 532 tanks (Phase II) owned by agricultural businesses located near Ames, Iowa.(11) A follow-up study (Phase III), again using single-beam angle UT, of 411 of the original 532 tanks was performed in the summer of 2015.(12) In addition to re-examining as many tanks from the 2012 study as could be found, this study also investigated the effects of N-Serve, a commercial product that is combined with anhydrous ammonia to reduce ammonia loss over time.

The initial study (Phase I) provided a base of information concerning average growth of SCC under constant stress. The subsequent field studies (Phases II and III) provided a base of measurement of stress distribution and detection of indications around weld seams, from the initial pool and relocated sub-pool of surveyed tanks. Information concerning number, size, location, and direction of indications was tabulated and verified in the latter two field studies. The indication data was analyzed in relation to the year of tank manufacture, the company of manufacture, the relevant industry standards to which the tank was manufactured (specifying steel type and thickness), and whether PWHT was performed. Full results from previous phases can be found in the reports cited.

The single-beam angle UT was successful in detecting indications that were perpendicular to the welds. In such cases, the residual stresses in the steel caused by unannealed welds quickly dissipate with distance from the weld beyond the heat affected zone (HAZ). The growth of indications perpendicular to the weld seam dramatically slows as they progress away from the weld into the tank shell or head and beyond the HAZ.

There were possible indications detected that may have been propagating parallel to the weld seam in unannealed tanks in a region of the HAZ, which has constant high stress that could support continued growth of a parallel crack in the HAZ. This is consistent with the history of tank failures which have commonly occurred at weld seams that rupture because of SCC. However, the single-beam angle UT does not have the resolution to unambiguously distinguish such possible parallel indications from the weld seam material and overlap metal itself. Inexperienced operators can easily be confused by the indications received from the instrument. In fact, it was observed that in tanks examined in 2012, the overall number of indications decreased in 2015. This difference is attributed to the 2015 operators having greater experience and expertise in using the ultrasonic equipment.

Recommendations for best practices were contained in the final reports and included:

- PWHT of all new nurse tanks should be performed.
- A regular schedule of single-beam angle UT for tanks currently in service should be implemented, even with its limitations.

At the conclusion of Phase III, the benefits of PWHT were apparent to the anhydrous ammonia tank company representatives present as part of the advisory council. Changes were made in production, and by 2016 all new tanks manufactured in the U.S. were receiving PWHT. It should be noted that this was done on a voluntary basis and is not currently required by law.

A final product of the previous studies is a listing of the nurse tanks tested in the previous research study, including each tank’s year of manufacture, identification number, owner, and the number and location of ultrasonic indications found in each tank during the 2015 summer study. That data is available from the report authors in Microsoft Excel format upon request.

## 1.5 QUESTIONS RAISED FROM PHASE III

The Phase II and Phase III studies established a database of nurse tanks in which cracks were known to be present. Phase III also raised two additional research questions related to nurse tank testing and safety, which were:

1. Does a hydro test cause undetected crack growth in existing SCC cracks, turning a safe tank into a potentially hazardous one?
2. Does the lower resolution of single-beam UT miss (or misdiagnose) SCC cracks that could be found using an NDT technique with better resolution, such as phased array (PA) UT examination?

This report summarizes the work performed to answer these research questions.

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# 2. PHASED ARRAY ULTRASONIC AND ACOUSTIC EMISSION TESTING OF NURSE TANKS

## 2.1 PROPOSED STUDY

The goal of Phase IV was to answer questions raised in Phase III (see Section 1.5). This would be done employing two different NDT methods: 1) PA ultrasonic examination and 2) AE monitoring during hydro testing. The plan involved examining a select number of tanks that had been previously examined in the Phase II and Phase III studies. These tanks would be chosen to span a range of possible conditions, such as whether they had received PWHT or not, and whether they were manufactured with thick or thinner steel (as the manufacturing regulations had changed).

Based on the results from the 2015 study of 411 nurse tanks owned by agribusinesses in central Iowa, the tanks sought out for testing could be divided into four distinct series:

- Series 1. Pre-1999 tanks that had not undergone PWHT.
- Series 2. Pre-1999 tanks that had undergone PWHT.
- Series 3. Post-1999 but pre-2015 tanks, none of which had undergone PWHT and all of which have the thinner shell steel allowed by ASME in 1997.
- Series 4. Post-2016 tanks that had undergone PWHT.

It should be noted that Series 4 would not have been included in prior phases and therefore would lack screening data available from previous studies.

At a minimum, two tanks from each of the series—namely, one tank with a high number of indications and one tank with a low number of indications—were desired for testing. The tanks were chosen from those still available and in use that had been examined in 2012 and 2015. In the selection process, managers and employees of Heartland Co-op—a major user of anhydrous ammonia nurse tanks in the Midwest—were instrumental in locating suitable tanks, making them available for examination, and conducting the hydro tests that were a critical part of the project.

The research plan involved first using PA to locate and characterize indications in the selected samples. This allowed for comparison to the 2012 and 2015 results to determine if additional indications or crack growth had occurred between the surveys. This also allowed for an evaluation of the ability of PA to distinguish an indication adjacent to a weld seam from the weld seam and/or possible metal overlap. Based on the quality of evidence, a recommendation either supporting or rejecting the suitability of PA to discriminate between these indications could then be made.

After this initial examination, AE monitoring was used during hydro testing to detect whether the pressure potentially causes crack growth and/or nucleation. All locations that emitted sound as a result of the applied hydrostatic pressure were triangulated and the location(s) logged for post-hydro examination. PA was then used to re-examine the indication(s) at the triangulated locations on the tank to compare the before and after of the hydro test. This allowed for determination of: 1) whether the hydro test resulted in damage to the tank and 2) whether PA has the discriminatory capability to measure if crack growth has occurred.

Brief descriptions of both PA and AE testing techniques are given below. A comparison of these techniques to other methods used to test and monitor the quality of tank construction is provided in Appendix A.

## 2.2 PHASED ARRAY ULTRASONIC TESTING

Standard PA ultrasonic testing offers improved measurement of crack or indication sizing due to the ability to effectively focus the probing energy electronically at positions throughout the medium under inspection. Electronic focusing and steering of the array minimizes the need for the inspector to make minute movements of the probe to hunt for maximum signal response, thereby speeding up the inspection process. PA uses a transducer with a series of small elements that emit the ultrasonic emissions in a phased progression. Since the early 2000s, its adoption has been a gamechanger for ultrasonic inspections of critical components in aerospace, oil and gas, heavy industry, and power generation plants.

Unlike the single-beam transducer that was used for the 2012 and 2015 ultrasonic methodology-based studies, PA can produce a higher resolution 2-D image of the indication. An indication means that the ultrasonic signal has been disrupted. Disruptions could be caused by cracks or by geometry effects or changes in the microstructure of the material. Considering that cracks in nurse tanks often happen in the region of welds, all of these causes are possible. This may result in false positives due to geometry or microstructure causes. PA provides a more accurate measurement of the indication, which may reduce the potential for false positives associated with indications located parallel to welds. In other words, PA would allow for better determination that indications are indeed cracks.

During the standard PA application process, the raw elementary signals from the scan are processed at the hardware level. An example of standard PA is shown in Figure 3.

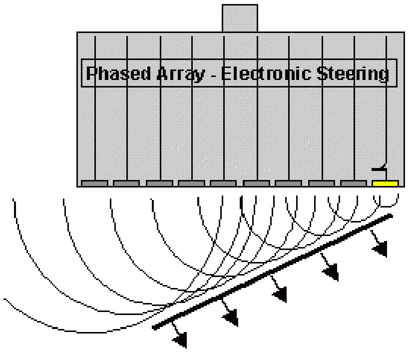

**Figure 3. Diagram. PA uses multiple sensors instead of a single one.**

Figure 4 shows an example output from a PA transducer. The weld line is shown at the top. Two cracks are seen, one severe (red, near the center of the image) and a smaller crack (green, right side of the image).

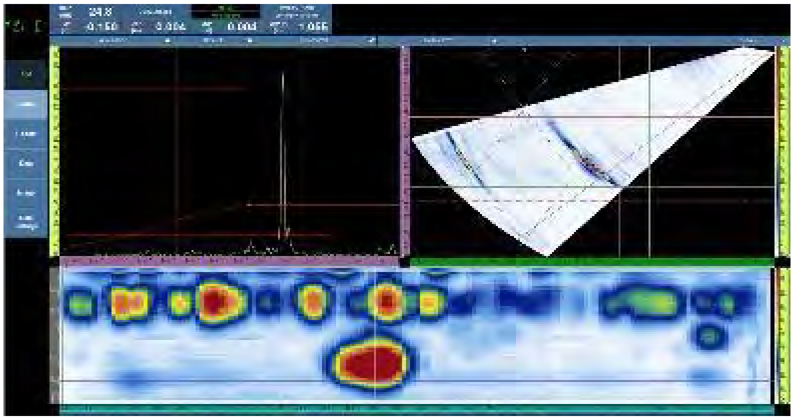

Figure 4. Screen. Output of a PA transducer.

## 2.3 ACOUSTIC EMISSION TESTING

AE testing involves placing sensors on carefully selected points on a tank (see Figure 5). This allows detailed measuring of any acoustic responses during hydro testing. It is based on the generation of waves produced by a sudden redistribution of stress in a material. With the right equipment and setup, motions can be identified in picometers ($10^{-12}$ m).

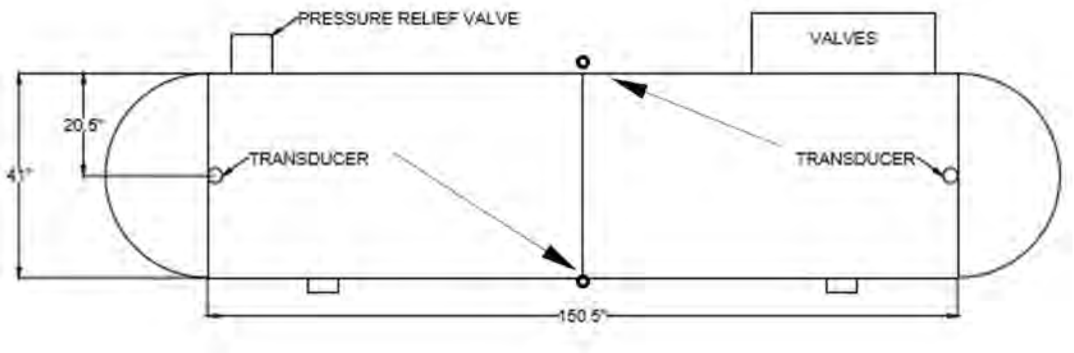

Figure 5. Schematic. Sensor placement.

Because of the versatility of AE, it has many industrial applications (e.g., assessing structural integrity, detecting flaws, testing for leaks, and monitoring weld quality) and is used extensively as a research tool. AE deals with dynamic processes, or changes, in a material. This is particularly meaningful because only active features (e.g., crack growth) are highlighted. AE events can be detected in frequency ranges under 1 kHz and have been reported at frequencies up to 100 MHz. However, most of the released energy is within the 1 kHz to 1 MHz range. Rapid stress-releasing events generate a spectrum of stress waves starting at very low frequency and typically fall off at several MHz.

The AE technique is based on the detection and conversion of high frequency elastic waves to electrical signals. This is accomplished by directly coupling piezoelectric transducers to the surface of the structure and loading the structure. Sensors are placed on the structure and the output of each piezoelectric sensor (during structure loading) is amplified through a low-noise preamplifier, filtered to remove any extraneous noise, and further processed by suitable electronic equipment.

In hydro tests of nurse tanks, as pressure builds up in the tank, AE events can result from tank deformation, active crack growth, or a combination of the two. Those signals are detected by the acoustic sensors. Software triangulates the received signals to enable the deformation/crack location to be accurately located on the tank, as shown in Figure 6.

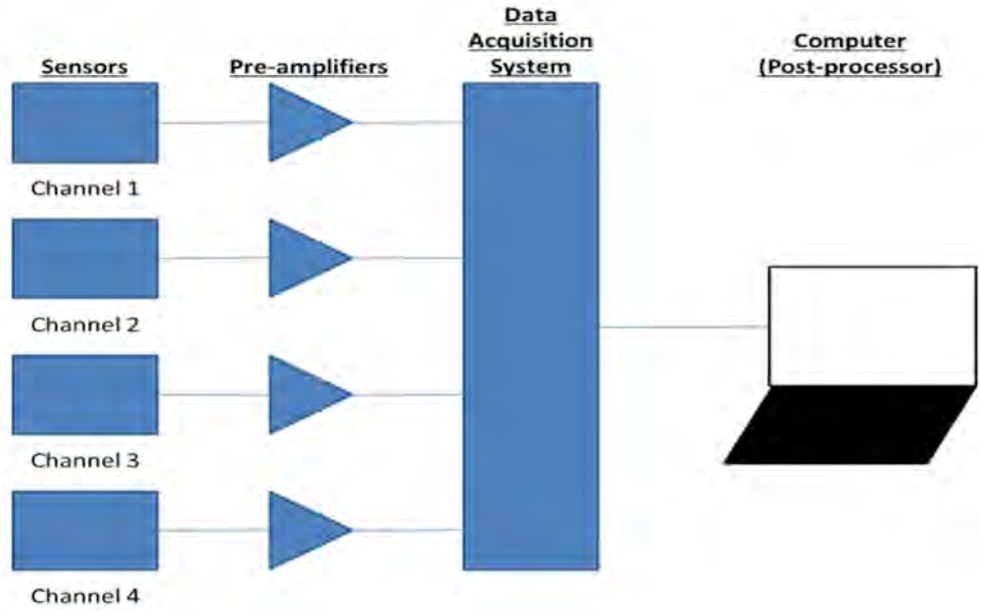

**Figure 6. Schematic. Signals from the sensors are collected using a laptop and triangulated to locate the spot that produced the AE.**

# 3. EXPERIMENTAL PROCEDURES

## 3.1 ULTRASONIC SYSTEM VERIFICATION

The plan was to include tanks that had undergone PWHT and tanks that had not undergone PWHT. Prior to the commencement of inspections, a reference plate was fabricated for PA testing from similar steel materials provided by one of the stakeholders, Quality Steel Corporation (QSC)—a fabricator of anhydrous ammonia tanks for agricultural use. QSC agreed to allow the research team to evaluate the effect of stresses developed in the fabrication (i.e., welding) of the tanks by comparing measured values of ultrasonic velocity before and after a heat treatment process designed for stress relief.

The velocity of sound in a material, such as the steel used in anhydrous ammonia tanks, will change with the application of stress. The interest is in the presence of stress, or lack of it, in the fabricated tanks related to the measurements, where crack dimensions were measured by ultrasonic means. If the velocity in the tanks varies (as some were stress relieved and others were not), crack measurements will be erroneous. A reference plate allowed subsequent research to control for any differences between treated and untreated tanks when evaluating sensor readings.

### 3.1.1 Reference Plate Measurements

Prior to the measurements on the tanks at QSC, velocity measurements were made on reference plates. The time for a shear wave to travel from the front surface of the reference sample, to the rear surface, and back to the front surface was captured. The thickness of the reference sample was measured using a micrometer. Velocity of the shear wave was calculated by the equation shown in Figure 7.

$$velocity,\ V = \frac{2\ x\ thickness}{time\ between\ echoes}$$

**Figure 7. Equation. Ultrasonic shear wave velocity.**

This value was input into the handheld ultrasonic flaw detector (see Figure 8 and Figure 9) with the instrument set up to output thickness on subsequent measurement. Note that in this approach, a fixed value of velocity is input into the instrument with a material thickness as an output. If a difference in thickness is seen via the instrument, the operator cannot know whether this is the result of a difference in actual thickness, a difference in material velocity (related to stress), or a combination of both. However, as the nominal thickness of the steel in the tanks is known—as well as the range of variation of that thickness—an operator can set bounds that would represent normally expected variation of thickness measurements. Indications outside those bounds would likely indicate changes in material velocity, which could then be attributed to stress.

The differences seen in the shear wave velocity with polarization directions in the reference plate were unexpected. The calibration plates provided by QSC are cut from as-received stock. As such, one might expect some residual compressive stress due to the rolling of the sheet. However, because the sample was cut from larger stock, for the residual stresses present in the as-received stock, cutting a smaller sample from the larger stock should have relieved a significant portion of that stress.

The measurements from the reference plates revealed a difference in shear wave velocity with polarization direction of approximately 1.5 percent. Differences in shear wave velocity with polarization are due to anisotropy, either in the mechanical properties (elastic constants) or in the stress state of the part/sample. If one expects the small reference sample to be relatively stress-free, then the differences seen must result from anisotropy in the microstructure—likely the result of the rolling process used to produce the plate stock. In a rolled structure, one could expect grains elongated in the rolling direction, and depending on the composition, some degree of alignment of ferrite/cementite plates within the pearlitic phase. Thus, any changes in velocity, which could be interpreted as a manifestation of residual stress, would need to be greater than 1.5 percent to be reliably measured.

**Figure 8. Photograph. Handheld Panametrics Epoch 4 unit used for the calibration tests - complete unit showing transducer.**

**Figure 9. Photograph. Handheld Panametrics Epoch 4 unit used for the calibration tests – close up of readout.**

### 3.1.2 Stress Measurements

To evaluate whether a significant level of residual stress is present in the newly fabricated tanks, shear wave time delay measurements were made on the tanks made available by QSC (see Figure 10 for the location of measurements). Images of the tank measured are provided in Figure 11 and Figure 12. Several different probe locations were selected on the tank, with the probe being orientated in orthogonal directions both along the direction of the weld seam and perpendicular to it. Readings were taken both near to and far from the weld seam.

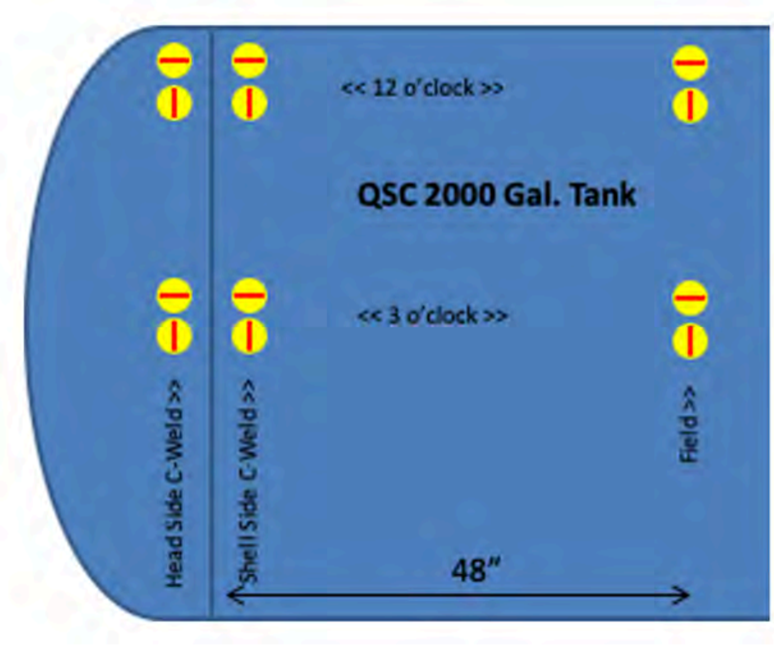

Figure 10. Schematic. Locations of measurements.

Figure 11. Photograph. Tank being measured.

**Figure 12. Photograph. View of a typical tank head.**

The methodology used for each measurement was:

1. At each location, a spot of ultrasonic couplant was placed on the tank surface.
2. The probe was pressed into the couplant and the operator recorded the ultrasonic echo signatures until a steady, consistent value displayed.
3. Without translating the probe on the surface of the tank, the probe was rotated first to have a polarization direction oriented around the tank circumference (parallel to the circumferential head/body weld), recording the displayed value.
4. The probe was again rotated such that the polarization direction was along the longitudinal axis of the tank and the displayed value was again recorded.

As noted earlier, with this type of measurement where the output is a calculated thickness using a fixed calibration velocity and a measured time-of-flight, a variation in time of flight equates either to a change in thickness (which can only vary between fixed bounds); a velocity variation due to other effects (e.g., stress); or a combination of both. The results of all the values obtained are displayed in Table 1 (post-weld stress relieved) and  (pre-weld stress relieved). Note that the differences for all positions were on the order of 1 percent or less, which is well within the mill tolerance for the supplied plate material thickness. The largest absolute span across all measurement locations on the shell is 1.7 percent, and 2 percent on the head. QSC staff confirmed that the head material is thicker than the shell material.

**Table 1. Ultrasonic measurements obtained from post-weld stress relieved tanks.**

| Position | Polarization | Head Side Weld | Shell Side Weld | Shell Field | Largest Head Span | Largest Shell Span |
|---|---|---|---|---|---|---|
| 12 ft | Circumferential | 7.60 / 7.61 | 6.90 / 6.90 | 6.86 / 6.87 | 2% | 1.7% |
| 12 ft | Longitudinal | 7.48 / 7.49 | 6.93 / 6.94 | 6.90 / 6.91 | - | - |
| 3 ft | Circumferential | 7.60 / 7.61 | 6.90 / 6.90 | 6.86 / 6.87 | - | - |
| 3 ft | Longitudinal | 7.48 / 7.49 | 6.93 / 6.94 | 6.90 / 6.91 | - | - |

**Table 2. Ultrasonic measurements obtained from pre-stress relieved tanks.**

| Position | Polarization | Head Side Weld | Shell Side Weld | Shell Field | Largest Head Span | Largest Shell Span |
|---|---|---|---|---|---|---|
| 12 ft | Circumferential | 7.62 / 7.63 | 6.87 / 6.88 | 6.87 / 6.88 | - | 0.8% |
| 12 ft | Longitudinal | 7.48 / 7.49 | 6.91 / 6.92 | 6.91 / 6.91 | - | 1.0% |
| 3 ft | Circumferential | 7.62 / 7.63 | 6.83 / 6.84 | 6.82 / 6.83 | - | 0.7% |
| 3 ft | Longitudinal | 7.53 / 7.54 | 6.87 / 6.88 | 6.86 / 6.87 | - | 0.7% |

Most of the measurements obtained were within the 1.5 percent deviation recorded for the reference plate, and were assumed to be due to microstructure. This indicates that the combination of true material velocities and true thickness variations is quite small. One should note that the largest absolute variances for both shell and head were across the maximum (a longitudinal polarization value) and the minimum (a circumferential polarization value)—which exaggerates the difference.

The important finding here was that any residual stress effects seen in later ultrasonic measurements on anhydrous ammonia tanks in the field should not be significant. It is suspected that most of the differences seen in these measurements were due to variation in anisotropy of the microstructure (anisotropy in grain and sub-grain phase dimensions/orientations) and true local thickness, as opposed to stress states. Subsequent measurements on tanks in the field used longitudinal waves, which show even less variation with stress than shear waves.

## 3.2 ACOUSTIC SYSTEM CALIBRATION

For the AE studies, a test of the equipment was run on a 1,450-gallon tank at Heartland Co-op in Slater, Iowa, to determine the sensitivity of the transducers on a large object. Simple lead-break tests, where transducers were placed at one end of a tank while a pencil lead was broken at various locations around the tank, were conducted on location. Based on these results, it was determined that a minimum of seven transducers would be necessary, with the configuration as per ASTM STP 687, Acoustic Emission Monitoring of Pressurized Systems.(13) Location was determined by taking the signals from the closest transducers to the event and determining the distance of the event from each transducer, followed by cross-checking that calculation with the distance determined from the third closest transducer. The geodesic curved shape of the heads of the nurse tank were accounted for by using the mathematical formulation given by Barat, et al. with assistance from the work of Beattis.(14 15) Other relevant ASTM standards consulted for this work included:

- ASTM E 569, Standard Practice for Acoustic Emission Monitoring of Structures During Controlled Stimulation.
- ASTM 650, Standard Guide for Mounting Piezoelectric Acoustic Emission Sensors.
- ASTM E 1930, Standard Test Method for Examination of Liquid-Filled Atmospheric and Low Pressure Metal Storage Tanks Using Acoustic Emission.

Valuable lessons learned during the initial testing of the first nurse tank in the summer of 2019 led to improvements in the experimental procedure and performance of the acoustic equipment. These improvements included the manufacture and subsequent use of better cables, the purchase of magnetic fasteners to hold the transducers to the tank more securely, and the use of amplifiers on all the cables.

## 3.3 EXPERIMENTAL METHODOLOGY

In cooperation with owner Heartland Co-op, tanks were selected to fulfill requirements for the four different series. The tanks also had to be relatively easy for Heartland Co-op to locate and make available for testing—in most cases, this meant moving the tanks to their Slater, Iowa, location. Once there, the research team identified the positions of prior indications on the previously studied tanks. Then they conducted a complete ultrasonic examination of the welds using PA (as shown in Figure 13). Details of the specific unit employed for the PA exam and the operating conditions are found in Appendix B. It was not unexpected to discover that many prior indications found in 2015 were due to scattering from weld geometry rather than SCC.

**Figure 13. Photograph. Testing of the end cap weld.**

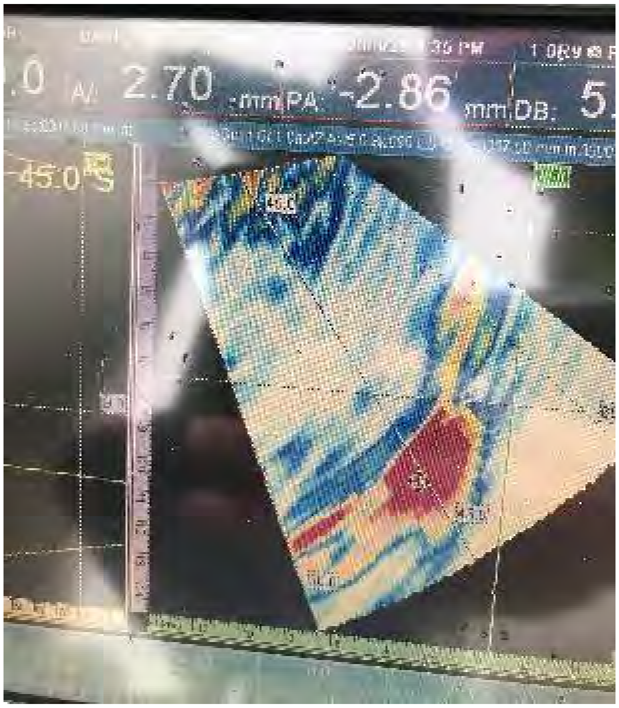

Figure 14. Screen. Phased array device output.

After conclusion of the PA testing, each tank was instrumented for AE monitoring. This may have occurred a few days after the initial ultrasound or immediately afterwards, depending on the number of indications and the availability of Heartland Co-op personnel. However, all the tanks were empty of product, so no changes are expected to have occurred in the time between the two tests. Instrumentation involved placing three transducers symmetrically around the head to body weld at both ends of the tank—where most SCC occurs. An additional transducer was placed in the center of the tank along the longitudinal weld. The acoustic equipment used is described in Appendix B.

After completion of the hydro test, the research team analyzed the data output (see Figure 15). On occasion, no AE events were recorded, meaning no change at all occurred during the test. Therefore, no post-hydro PA examination was needed. More often, further analysis was needed to separate out extraneous noise caused from the metal flexing and expanding from noise that was potentially caused by crack formation or growth. This would typically require two to four days to complete. Once the analysis was completed, a summary of possible crack-related AE events was compiled. A time was then scheduled with Heartland Co-op to return and complete the post-hydro PA examination that concentrated on those areas identified by AE as having a significant event. This examination was usually completed quickly since specific locations were provided for the examination. This eliminated the need to redo PA testing of the entire tank.

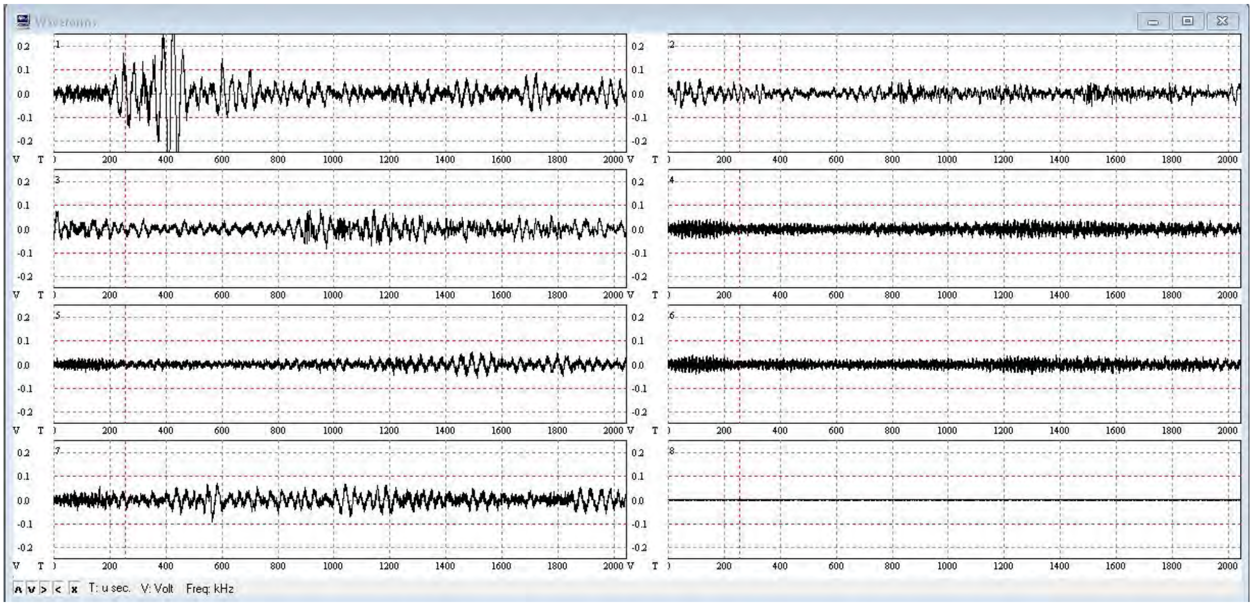

**Figure 15. Screen. Readout of AE events. Transducers are indicated by number in the top left of each scan. The higher the signal the closer the event is to that transducer.**

It should be noted that just because a significant event was recorded this still did not necessarily mean a new crack had formed or an existing crack had grown. AE signals recorded by the transducers are examined to see if the signals detected are consistent with one another. For example, consider an event detected on the shell/head weld of a tank, which was the most common type of event recorded. Since there are three transducers positioned around the shell/head weld, each one of them has to record the signal. Additionally, the time lags between the pairs of transducers (e.g., T1/T2 and T1/T3) had to satisfy the wave velocity for sound traveling through the steel and be consistent with each other. Only if this is true would the recorded event be considered a valid "hit".

In the example, let us say that an event occurred at some time, $T_0$, and was recorded at times $T_1$, $T_2$, and $T_3$ in the corresponding transducers. Let $T_1 < T_2 < T_3$. Hence, the time to travel to transducer T1 (i.e., $T_1$) has the relation shown in Figure 16.

$$T_1 - T_0 = V * de1$$

**Figure 16. Equation. Time of sound travel between transducers.**

Here, V is the wave velocity which had been measured and calibrated and de1 is the distance of the event location from transducer 1 (T1).

Similarly, the equations for sound travel between detecting transducers are shown in Figure 17.

$$T_2 - T_0 = V * de2$$

$$T_3 - T_0 = V * de3$$

$$T_1 - T_2 = V * (de1 - de2)$$

**Figure 17. Equation. Sound travel between detecting transducers.**

It is also known that de1 + de2 is the distance between transducers T1 and T2. Based on the magnitudes of T1 and T2, the distances de1 and de2 can be calculated, locating the event.

Now, since the $T_1 < T_2$ event is closest to transducer T1, the distance between the event and transducer T3 is the equation shown in Figure 18.

$$de3 = de1 + d13$$

**Figure 18. Equation. Determined distance of acoustic event.**

Here, d13 is the distance between transducers T1 and T3. As the transducers were carefully placed around the circumference of the tank and their spacings measured, these distances are known. Now, one can calculate the verification of travel time as shown in Figure 19.

$$T_3 - T_0 = V * de3$$

**Figure 19. Equation. Verification of travel time.**

This equation will verify the result with the actual, experimentally-obtained value. If the $T_3$ calculated equals $T_3$ measured, the event is real and has come from a crack formation and/or crack growth. If the three times do not agree and are not self-consistent, then the signal recorded was from some extraneous source. In this case, the event would be discarded.

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# 4. EXPERIMENTAL RESULTS

## 4.1 SUMMARY OF RESULTS

The total number and type of tanks that were examined deviated from the initial plan due to several factors, including the inability to locate specific tanks that were desired and the unwillingness of agribusinesses to test newer tanks for fear of causing damage. However, the total number of tanks examined was more than initially proposed and included at least one tank from each of the proposed series. The tanks examined included:

- Five tanks from Series 1: Pre-1999 tanks that had not undergone PWHT. See Table 3 for a summary.
- Six tanks from Series 2: Pre-1999 tanks that had undergone PWHT. See Table 4 for a summary.
- Nine tanks from Series 3: Post-1999 but pre-2015 tanks, none of which had undergone PWHT and all of which had the thinner steel allowed by ASME in 1997. See Table 5 for a summary.
- One new tank (manufactured after 2015) that had never been tested before (Series 4). See Table 6 for a summary.

A more complete description of the results for each tank is given in Appendix C. In monitoring AE events, it was common to have a considerable amount of activity occurring as pressure built within the tank. This activity was often minor, likely due to the elastic deformation occurring as the changing tank dimensions put stress on the baffles, fittings, and valves that are a part of the tank. Analysis of the acoustic results was then performed to identify those signals that required further investigation.

**Table 3. Summary of data for Series 1—Pre-1999 tanks that had not undergone PWHT.**

| Tank # (Year of Manufacture) | 2015 Indications | Pre-hydro Indications | Acoustic Results (T refers to transducer location) | Post-hydro Examination | Comments |
|---|---|---|---|---|---|
| #1129<br>(1998) | 2 | 9 | Events between T1 and T3. | Possible new crack or growth of a minimum crack or missed earlier. | - |
| #40201A<br>(1969) | 1 | 7 | One possible event near T1. | Minimum indication found. | Now labeled #3044A. |
| #40201B<br>(1967) | 1 | 5 | Event between T1 and T3. | New minimum indication found. | Now labeled #3044B. |
| #6044L<br>(1977) | 8 | 7 | Seven total events, including large event between T5 and T7. | No new indications or growth. | - |
| #4052<br>(1976) | 19 | 37 | No significant events. | No post-hydro testing necessary. | - |

**Table 4. Summary of data for Series 2—Pre-1999 tanks that had undergone PWHT.**

| Tank # (Year of Manufacture) | 2015 Indications | Pre-hydro Indications | Acoustic Results (T refers to transducer location) | Post-hydro Examination | Comments |
|---|---|---|---|---|---|
| #6030<br>(1991) | 1 | 1 | Event between T2 and T3; weak event 44 in. from T7. | New minimum indication near T7. | Now labeled #7030. |
| #2013A<br>(1968) | 0 | 12 | No significant events. | No post-hydro testing necessary. | - |
| #2022<br>(1996) | 1 | 0 | No events. | No post-hydro testing necessary. | - |
| #3002<br>(1994) | 2 | 5 | Large event between 1 and 3. | New indications found but not at event. | - |
| #1118<br>(1997) | 0 | 4 | Event between 1 and 2. | No indications found. | - |
| #2178<br>(1978) | 17 | 25 | One major event between T1 and T3, near T1. | No indications or growth found. | - |

**Table 5. Summary of data for Series 3—Post-1999 but pre-2015 tanks—none having PWHT but all having the thinner steel allowed by ASME in 1997.**

| Tank # (Year of Manufacture) | 2015 Indications | Pre-hydro Indications | Acoustic Results (T refers to transducer location) | Post-hydro Examination | Comments |
|---|---|---|---|---|---|
| #1138<br>(2008) | 2 | 6 | No events. | No post-hydro testing necessary. | - |
| #1140A<br>(2008) | 4 | 3 | Possible event near T2. | No new indications. | - |
| #1145A<br>(2009) | 5 | 5 | Two events between T2 and T3; one between T4 and T5; one between T5 and T6. | Strong indication between T5 and T6, nothing elsewhere. | - |
| #1189B<br>(2010) | 9 | 3 | No events. | No post-hydro testing necessary. | - |
| #1614<br>(1999) | 79 | 101 | Activity between T2 and T3, and between T4 and T6. | Nothing new seen at event locations. | - |
| #1146A<br>(2009) | 25 | 27 | Possible activity between T1 and T2. | New indication found. | - |
| #1193R<br>(2010) | 57 | 54 | Little activity, minor events between T2 and T3, T4 and T6. | No new indications or growth seen. | Now labeled #1193R. |
| #1138A<br>(2008) | 20 | 16 | One event between T4 and T6. | No new indications or growth seen. | - |
| #1189A<br>(2010) | 18 | 1 | Events between T1 and T3; T4 and T5; near T7. | No growth on existing cracks. | - |

**Table 6. Summary of data for Series 4—New tank never tested.**

| Tank # (Year of Manufacture) | 2015 Indications | Pre-hydro Indications | Acoustic Results (T refers to transducer location) | Post-hydro Examination | Comments |
|---|---|---|---|---|---|
| #8805N<br>(2017) | N/A | 0 | Two events seen on both end caps. | No indications seen at event locations. | - |

## 4.2 OBSERVATIONS ON PRE-HYDRO ULTRASONIC RESULTS

Out of the 20 previously tested tanks, 11 tanks showed more cracks had nucleated and grown in the intervening years; 2 tanks had the same number of indications; and 7 tanks had fewer indications than previously recorded. An examination of Appendix C shows that the 2015 numbers often deviated from the 2012 numbers, in many cases decreasing. As explained in the final report for Phase III, the quality of training and operator experience can play a large role in determining whether an indication noted is a true result of a crack or due to spurious scattering from the weld geometry itself. None of the tanks had undergone repairs between the two separate field examinations, so all decreases were attributed to this factor.

When considering the differences between 2015 and 2019/2020 data, both increases and decreases are noted. The decrease in number of cracks in this case is explained by the better performance of the equipment used and the expertise of the research team. A PA device allows greater discrimination of the signal since multiple reflections are expected from a true crack and these reflections can be tracked as the probe is swept across the site. Thus, weld geometry effects can more easily be identified. In some cases (e.g., tank #1189B and #1138A), the increased sensitivity of the PA system used allowed further weld scatter to be identified.

For tanks where an increase in the number of indications was seen between 2015 and 2019/2020, the reasoning is slightly less straightforward. First, consider that the same increase in sensitivity could be the reason for the increase in cracking seen in 11 tanks. The majority of the new cracks seen in the tanks were all at the PM level, meaning they were at the limit of detection for the PA unit employed. For example, in tank #4052, only 1 indication out of 37 was larger than the PM level. Even if one assumes no crack growth occurred between 2015 and 2019/2020, the indications most likely were below the detection limit for the simpler units used in 2015 and 2012. This uncertainty creates difficulties when comparing the 2015 and 2019/2020 data where new PM indications were found.

However, this is not true for instances where an indication could be tracked from year to year. For verifiable cracks, there were a few notable exceptions to the statement that most cracks were at the PM level. For example, in tank #1129 (Series 1), one verified crack had grown from 0.5 inches to 1.375 inches. Of the eight additional indications found in this tank, one was 1.5 inches long.

Observations of Table 2 and Appendix C suggest there is value in using PWHT as a means of slowing the effects of SCC. Of the 5 Series 1 (no PWHT) tanks examined, 4 of them showed additional cracking, with a total of 35 new cracks and significant crack growth in at least two instances. Of the nine Series 3 (no PWHT) tanks examined, 4 showed additional cracking, with a total of 50 new cracks and growth of 2 cracks in tanks #1189B. These numbers should be compared to the Series 2 (PWHT) tanks where 4 of the 6 tanks showed additional cracking, for a total of 27 new cracks. However, all new cracks were at the PM level, and no growth was seen in verified cracks.

## 4.3 OBSERVATIONS ON ACOUSTIC RESULTS DURING HYDRO TESTING

As mentioned earlier, it was common for the AE equipment to detect noise during the hydro test. This noise can be attributed to a number of sources, such as elastic expansion of the joints and flexing/movement of structures (e.g., baffle plates and valve inlets) within the tanks. True AE events needed to be separated from this noise and then the location determined by triangulation of the data received in the various transducers. A summary of all the tanks acoustically monitored during hydro testing follows:

- 21 tanks were examined in total—20 older tanks and 1 relatively new tank produced under current manufacturer guidelines where PWHT is a company practice.
- The 20 older tanks had been previously examined using ultrasonic techniques; the newer tank had not.
- The 20 older tanks had previously undergone at least one hydro test in their service life, some had undergone two. The newer tank had not.
- Six of the older 20 tanks had undergone PWHT during manufacture.
- Five tanks (all older) showed no AE events worthy of investigation during the hydro test for this study; 16 tanks (15 older and 1 newer) showed an AE event worthy of further examination using PA.
- The strength of the AE events noted varied between minor and significant acoustic signals.
- Of the 16 tanks that exhibited AE events, 5 had been manufactured with PWHT (4 older tanks and the newer tank). These 16 tanks were re-examined using PA testing.

## 4.4 POST-HYDRO ULTRASONIC RESULTS

Figure 20 shows a post-hydro PA examination of a tank that showed AE events during the hydro test. Of the 16 tanks flagged for further examination, only 7 tanks were found to have measurable differences between the pre- and post-hydro ultrasonic examinations. These tanks are discussed in more detail below.

Figure 20. Photograph. Post-hydro ultrasonic examination of suspected crack growth/nucleation sites.

### 4.4.1 Tank #1129

Tank #1129 (Series 1) was manufactured in 1998. In the 2012 survey, it was recorded as having four indications. In 2015, this tank had two indications—only one of which (a circumferential indication) was located at the same point as was found in 2012. This circumferential indication was not found in 2019, although several long indications were found on the head/shell weld at the front of the tank where the second 2015 indication was found. A total of nine indications were found in the pre-hydro PA examination. During hydro testing, an AE event was detected between T1 and T3, within the head/shell weld on the front of the tank. Post-hydro PA found what may have been a new crack at this location, at the PM level.

Another possible crack was found in a region where no AE event was recorded. There is uncertainty, however, as there were other pre-hydro 2019 cracks found. The new indication may have been an extension of a crack found in the pre-hydro PA exam (crack #4) that had not been detected. When moving past the location of the indication, the PA signal was seen to die out and then come back at the PM level. Given the PM size of the indication and the proximity to an existing crack, it is difficult to claim this as a new crack. Moreover, the absence of any AE event in this location would argue against this conclusion.

In any tank, it is possible that corrosion products fill small cracks over time, decreasing the ultrasonic reflectivity. As an increased pressure is applied above the normal operating condition, such as in a hydro test, one might expect to modify the crack tip/interfaces by opening the crack or sliding the interfaces with respect to one another—even if no growth occurs. Such a movement could increase the ultrasonic reflectivity of a crack after a hydro test, as compared to its pre-test conditions. This could explain why a different ultrasonic indication was found in the absence of any AE event.

### 4.4.2 Tank #40201A (#3044A)

Tank #40201A (Series 1) was manufactured in 1969. It is now identified as #3044A due to a location change since 2015. In the 2012 survey, it was recorded as having 17 indications. In 2015, due to greater training and experience of the operators, this number was reduced to a single indication located at the rear head/shell weld. The pre-hydro PA inspection carried out during the summer of 2019 found a total of six indications. The 2015 rear head/shell indication was now recorded as being two indications, and additional indications not seen in 2012 or 2015 were found in this same weld. All of these indications were at the PM level except for the one verified from 2015, which was seen to be longer. During hydro testing, an AE event was recorded very close to T1. The post-hydro PA inspection found a new indication 3.25 inches from T1 at the PM level on the front head/shell weld.

### 4.4.3 Tank #40201B (#3044B)

Tank #40201B (Series 1) is the companion tank of #40201A. Like its companion, it now has a new number, #3044B, due to relocation. It was built in 1967 and is the oldest tank that was examined. In the 2012 survey, a single indication was found on the head/shell weld at the front of the tank. In the 2015 survey, this same indication was found again. Although the recorded lengths showed a slight growth between the two years, the discrepancy (0.05 inches) is within the accuracy of the technique. In the 2019 survey, several additional indications were found in the same area as the 2012/2015 single indication. While the 2012/2015 indication was recorded as being from 20 to 21 inches down from the top center of the tank, indications were found at 14, 16.25, 18.5, and 22 inches down in 2019. All these indications were at the PM level or just slightly larger. In addition to these four, a new indication was found on the other side of this same weld 49 inches down from top center. AE monitoring recorded a single event between T1 and T3, closer to T1, which is in the region of the previous indications. Post-hydro PA examination found a new indication at the PM level at a position 20.75 inches down from T1, between T1 and T3.

### 4.4.4 Tank #6030 (#7030)

Tank #6030 (Series 2) was manufactured in 1991. Due to a change in location, it is now number #7030. In the 2012 survey, six indications were found. They were located on the head/shell weld at the back of the tank on the left side, on the center shell weld on the right side, and several were on the longitudinal shell weld on the right front at 5.75, 9.125, and 47.5 inches from the center circumferential weld. In 2015, none of these indications were found. Instead, two indications were found, one located on the center circumferential weld and one located on the longitudinal shell weld at the left rear of the tank—28.25 inches back from the circumferential weld and 1 inch away from the weld itself.

The pre-hydro PA test of this tank found one indication in an area where an indication was seen in 2012, but not verified in 2015. The indication was located along the center shell weld, approximately 49.5 inches from the top (one was seen 39 inches from the top in 2012). No other indications were seen in the pre-hydro PA test, and the 2015 indications are believed to be weld scatter.

AE monitoring indicated events occurred at two locations, one midway between T2 and T3, approximately the bottom center of the tank; and a smaller event roughly 44 inches from T7 along the shell longitudinal weld. This location corresponded roughly to an indication seen in the 2012 survey, but unverified in 2015 or 2019/2020 pre-hydro. Post-hydro PA inspection found no indications between T2 and T3, but a PM indication was seen on the longitudinal weld 42.25 inches from the center weld in the region of the 2012 indications. However, close inspection of this area revealed the steel had a slight ripple in this region, similar to a very shallow dent in the steel. Contact of the transducer with the surface is critical in producing a good reading and this ripple made measurement very difficult. Therefore, given that the signal in this area appeared in 2012, disappeared in 2015, and then reappeared in 2019/2020, it is possible that the indication is more associated with the surface roughness—in relation to how the probe contacted the steel—than an actual crack indication.

### 4.4.5 Tank #3002

Tank #3002 (Series 2) was manufactured in 1994. This tank is somewhat unusual for several reasons. First, four indications were seen in 2012, all on the head/shell weld at the front of the tank. This is a large number for a tank that had undergone PWHT. In 2015, only two indications were seen, both at PM level and at similar locations to indications from 2012. However, a total of nine indications were seen in the pre-hydro PA examination in 2019/2020. Second, while only a single, fairly large AE event was recorded during the hydro test, the post-hydro PA test found two new indications, neither of which were at the location indicated by the AE results. A large AE event was recorded between T1 and T3, large enough that it was also recorded by T7. This should have been on the right side of the tank on the head/shell weld. Two new ultrasonic indications were seen on this head/shell weld; however, one was on the left side of the front, where no events were recorded. The acoustic event seen on the right side of the tank was 72 inches from the crown of the tank, i.e., approximately 22 inches below T3 and between T3 and T2—not T1. Both of these indications were at PM level. It is suspected that these indications are most likely due to a change in the structure of a crack at the PM level caused by the hydro test, the result being that the reflectivity of the crack made it detectable post-hydro, whereas it was invisible pre-hydro.

### 4.4.6 Tank #1145A

Tank #1145A (Series 3) was manufactured in 2004. As such, it was made out of thinner steel than any of the other tanks showing new cracking. Pre-hydro PA testing found the same number of indications seen in the 2015 survey in the same locations. AE monitoring recorded a large number of events in this tank during hydro testing, four of which were significant enough to be considered worthy of investigation. Two events were recorded between T2 and T3. This region had no pre-hydro or post-hydro PA indications. One AE event was on the back of the tank between T4 and T5, but nothing was seen in the post-hydro PA examination. The last AE event was recorded between T5 and T6, but closer to T6. In this area, a PM indication was easily seen using PA where nothing had been noted before. The indication was 63.5 inches down from the top of the rear head as you face the tank, between T5 and T6, but closer to T5.

### 4.4.7 Tank #1146A

In 2012, tank #1146A (Series 3) had no indications recorded. In 2015, 25 were recorded. This may be an indication of better training and performance by the 2015 operators. The pre-hydro PA tests of 2019/2020 found all of the 2015 indications plus two additional ones. Some cracks measured shorter than the length that was noted in 2015, due to the greater sensitivity of PA equipment. All indications were on the head/shell weld at the rear of the tank. An AE event was noted between T1 and T2, and a PM crack was found in this location in the post-hydro PA examination. This crack is noteworthy because no previous ultrasonic scan had detected anything in this region.

## 4.5 SUMMARY OF RESULTS AND DISCUSSION

The majority of tanks tested showed no change in condition between pre- and post-hydro states. While AE events were commonly recorded in the tanks during hydro testing, analysis of the data showed that few of the events recorded could actually be considered as "hits" worthy of examination. These hits occurred both in regions that pre-hydro PA examination showed devoid of indications and in locations containing pre-existing cracks. Subsequent post-hydro PA examination of the regions of the events considered as "hits" showed either no PA indications or no measurable change in crack lengths in the majority of regions. This would indicate that if cracks had initiated, or growth of an existing crack had occurred, in both cases the change was below the detection level of the PA equipment.

When comparing the 2012, 2015, and 2019/2020 results, in almost all cases the number of indications seems to vary, going up and down, which points to important factors that need to be considered when using ultrasonic methods; namely, that the experience of the operator and the quality and type of equipment used can greatly impact results. Falling numbers of indications between 2012 and 2015 are attributed to better trained operators in 2015 since the equipment used was identical. Decreased indications in 2019/2020 compared to 2015 are almost certainly due to both better equipment and expertise, given that no repairs were made to the tanks during this time. This leaves the question of increased indications in 2019/2020 versus 2015.

Increased indications in the pre-hydro PA testing could be due to a more proficient operator, more sensitive equipment, and/or nucleation of new cracks. New indications at the PM level could have been missed in 2015 due to the accuracy of the equipment used. However, it was clear that new crack growth had occurred in several tanks, for example tank #1129. Thus, it is well established that additional crack nucleation and growth has occurred in the intervening four to five years.

Only 7 of the 21 tanks tested showed indications of possible new cracking in post-hydro PA testing, and a summary of the results in these tanks is given in Table 3. However, in most cases the evidence for the pre- and post-hydro differences is less than definitive. A qualitative assessment of the results is given in the last column of Table 7 concerning the confidence in saying this is new cracking appearing. This assessment is based upon the research teams experience in evaluating ultrasonic signals.

- Low confidence: The appearance, strength, and circumstances noted for the reading are less than ideal and the reading is called into question.
- Medium confidence: There is no reason to suspect the indication is false, but as it is at the detection limits of the equipment, there is always the possibility an operator missed it initially.

- High confidence: The operator is certain of the reading and the signal is of high strength and quality—it is unlikely an operator would have missed it initially.

Hydro testing could be expected to change crack shape and structure without increasing length. This might result in greater reflectivity of the ultrasonic signal, making a crack that was previously slightly below the detection level rise above the detection limit. Keeping this in mind, newly detected indications should only be considered as being the result of hydro testing if the crack indication was also accompanied by a corresponding AE event. This criterion would eliminate new cracks found in tanks #1129, #6030, and #3002.

There are four remaining tanks where a PA indication was coupled with an AE event. The question is what level of cracking is indicative of true damage to the tank? If one were to decide that all indications at the PM level were suspect and could not be trusted, then none of the new indications could be considered as evidence of damage. However, during testing a skilled operator can get a “feel” for whether a significant change has occurred by observation of the ultrasonic signal. For example, in tank #1145A, the tester quite readily detected a PM indication in the exact location predicted by the AE monitoring where he was certain nothing had been before. Thus, while definitive evidence is lacking, it appears that this indication was more than just an existing crack showing greater reflectivity, or a slight increase in crack length that made an existing crack appear above the minimum detectability level.

**Table 7. Summary of tanks with post-hydro PA indications.**

| Tank # | AE Event | Post-hydro PA Indications | Confidence? |
|---|---|---|---|
| 1129 | 1 | A PM crack was found in this area. | Medium |
| 1129 | 2 | A second crack was found where no event was recorded. It may be an extension of a nearby indication that was missed in the pre-hydro PA test. | Low |
| 40201A | 1 | A PM crack was found in this area. | Medium |
| 40291B | 1 | A PM crack was found in this area. | Medium |
| 6030 | 1 | No indication found. | N/A |
| 6030 | 2 | Indication found but shell was seen to be dimpled in this area. Suspect this to be a surface effect. | Low |
| 3002 | 1 | No indications found at this location. | N/A |
| 3002 | 2 | Two PM indications found away from event location. | Low |
| 1145A | 1 | No indications found at this location. | N/A |
| 1145A | 2 | No indications found at this location. | N/A |
| 1145A | 3 | No indications found at this location. | N/A |
| 1145A | 4 | A PM crack was found in this area where nothing was previously seen in 2012, 2015, or 2019/2020. | High |
| 1146A | 1 | A PM crack was found in this area. | Medium |

## 4.6 TANK TESTED TO FAILURE

An additional tank, #8161, was provided by Heartland Co-op for testing to failure. This tank had not been surveyed in either 2012 or 2015. Little was known about it, because the data plate was illegible. It could be deduced that the tank was a very old one by the size of the tank and its design, since the support for the running gear on which it originally sat had not been in use for several years. Furthermore, the end caps were full hemispherical shells. The tank was believed to be made of thicker steel and may or may not have undergone PWHT. The tank was surveyed using PA before the start of the hydro test. In addition to the head/shell welds, the center circumferential weld and the two shell longitudinal welds were surveyed. Twenty indications both parallel and perpendicular to the welds were noted and marked on the tank itself as possible locations where the failure was predicted to occur. Eight transducers were placed on this tank, three on each end and two on the shell itself.

When pressurized, the tank initially started leaking around the valve weld for the emergency pressure relief valve at the top of the tank. The pressure was dropped back to atmosphere, the leaking valve weld was reinforced with additional weld material. During the second pressurization of the tank, failure occurred along the center circumferential shell weld (as shown in Figure 21).

**Figure 21. Photograph. Tank #8161 tested to failure.**

Surprisingly, no leaking was seen at any of the 20 possible points flagged by the pre-hydro PA test. It is unknown exactly how high the pressure was in the tank when failure occurred, since all of the gauges were pegged at their maximum values of 600 psi. However, the tank was visibly deformed due to the test so it is known that the yield stress was exceeded.

After failure, this tank was evaluated, including 1) calculation of stresses; 2) evaluation of the AE events recorded during the pressurization; and 3) metallurgical sectioning and polishing of likely sections to see what effect was produced on existing cracks during pressurization. These examinations are discussed below.

### 4.6.1 Calculation of Stresses

The stresses present in a tank when under pressure can be calculated. A tank can be defined as a thin-walled cylinder with spherical end caps since the radii of the nurse tanks is much larger than the thickness of the steel used. For a vessel of this type, only the hoop stress on the cylinder walls needs to be considered, because the longitudinal stress in cylindrical vessels is approximately half of the hoop stress. Also, the stresses found in spherical pressure vessels were half the number of those found in the cylindrical vessel hoop stress. For nurse tanks, the limiting factor is the cylindrical hoop stress.

Hoop stress is essentially the tensile stress at every point in the cylindrical shell, which is why it can be compared to a material's yield strength. The typical yield strength of steel is approximately 350 MPa, which is much higher than all normal operating stresses for these tanks and all of the pressure test stresses. The thin-walled cylindrical vessel hoop stress equation is shown in Figure 22.

$$\sigma = \frac{Pr}{t} \quad \text{for a thin walled vessel } (r/t > 10)$$

**Figure 22. Equation. Thin-walled hoop stress.**

Where *r* = cylinder radius (20.5 inches for a 1000-gallon tank, 23.25 inches for a 1450-gallon tank); *t* = shell thickness (0.321 for pre-1991 tanks and 0.271 for post-1991 tanks); and *P* = pressure inside the tank in psi. Using this data, stresses for both 1,000-gallon and 1,450-gallon tanks can be calculated for the operating and hydro test pressures used. These values are shown in Table 8. Note that these are considered nominal values since the thickness of individual tanks may vary slightly from the values given above.

**Table 8. Calculated hoop stresses in nurse tanks.**

| Tank Size (gallon) | Operating Pressure (185 psi) | Testing Pressure (375 psi) |
|---|---|---|
| 1,000 | 81 MPa | 165 MPa |
| 1,450 | 109 MPa | 222 MPa |

These values are clearly less than the typical yield stress of 350 MPa. For tank #8161—tested to failure—if one assumes the yield stress of 350 MPa as the point at which failure occurred, then the pressure present inside the tank at the time of failure can be estimated as 795 psi.

An alternative way to consider stresses in a tank is to calculate what size crack would be necessary for a tank to fail in a sudden, catastrophic manner. In order to do this, one can apply Irwin's modification for a thin-walled pressure vessel to the Griffith theory to predict critical crack length. The principle stresses present in a thin-walled pressure vessel are the hoop stress ($\sigma_1$), the longitudinal stress ($\sigma_2$), and the radial stress ($\sigma_3$). The radial stress is negligible and is not considered in the calculations. The hoop stress equation is shown in Figure 23 and the longitudinal stress equation is shown in Figure 24.

$$\boldsymbol{\sigma_1 = \frac{Pr}{t}}$$

**Figure 23. Equation. Hoop stress.**

$$\boldsymbol{\sigma_2 = \frac{Pr}{2t}}$$

**Figure 24. Equation. Longitudinal stress.**

The combined stress present in the nurse tank walls is calculated with the von Mises (Figure 25) and Tresca (Figure 26) criteria to be used in the modified Griffith theory.

$$\boldsymbol{\sigma_y = \left(\frac{1}{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]\right)^{\frac{1}{2}}}$$

**Figure 25. Equation. Von Mises stress calculation.**

$$\boldsymbol{\sigma_y = \sigma_1 - \sigma_3}$$

**Figure 26. Equation. Tresca stress calculation.**

Given these expressions, the maximum stress using either the von Mises or Tresca equations can be calculated as shown in Table 9.

**Table 9. Stresses present in tanks using von Mises vs Tresca estimations.**

| Type of Stress | Operating Pressure (185 psi) | Testing Pressure (375 psi) |
|---|---|---|
| Max Hoop Stress | 110 MPa | 223 MPa |
| Max Long Stress | 55 MPa | 112 MPa |
| Radial Stress (Negligible) | 0 MPa | 0 MPa |
| Von Mises Max Stress | 95 MPa | 193 MPa |
| Tresca Max Stress | 110 MPa | 223 MPa |

Since the Tresca approximation results in a larger predicted stress than von Mises, those values are used below to calculate the critical crack length necessary to cause catastrophic failure. In this calculation, we simply use Irwin's modification to the Griffith theory, as shown in Figure 27.

$$\boldsymbol{\sigma_f = \left(\frac{EG}{\pi a}\right)^{\frac{1}{2}}}$$

$$\boldsymbol{G = 2\gamma + Gp}$$

$$\boldsymbol{G_{steel} \approx 1000\ \frac{J}{m^2}}$$

**Figure 27. Equation. Irwin's modifications of the Griffith theory.**

Here, $E$ = 210 GPa and $G$ = 1,000 J/m$^2$. Doing this gives critical crack sizes for catastrophic failure to be as shown in Table 10.

**Table 10. Predicted critical crack lengths using the Tresca stress approximation.**

| Crack Size Estimation Method | Operating Pressure (185 psi) | Testing Pressure (375 psi) |
|---|---|---|
| Tresca | 10.7 in. | 7.5 in. |

Clearly, any initiation and crack growth of this magnitude would create an incredibly large acoustic signature.

### 4.6.2 Acoustic Results and Post-hydro PA inspection

AE monitoring of tank #8161 during testing resulted in ten areas being identified as places to check with PA ultrasonic examination. These locations were subsequently scanned and additional indications were found. A summary of the results is included in Table 11.

**Table 11. Summary of AE events and PA indications from tank tested to failure.**

| Section (Pieces Removed for Examination) | Event Number | AE Event Location | Pre-hydro PA Indication | Post-hydro Indication | Comment |
|---|---|---|---|---|---|
| Section 1 | 1 | Midway between 2 and 3. | Near #6. | Crack at axle support found. | Previous indication was near the axle support, this AE event could be an extension of indication #6. |
| Section 1 | 2 | 13 in. from 2, between 2 and 3. | Near #6. | Crack at axle support found. | Previous indication was near the axle support, this AE event could be an extension of indication #6. |
| N/A | 3 | 8 in. from 1, between 1 and 3. | Near #1. | No new crack found at this location. | Possible extension of #1, found previously 5 in. from T1 and 2.5 in. long at that time. |

| Section (Pieces Removed for Examination) | Event Number | AE Event Location | Pre-hydro PA Indication | Post-hydro Indication | Comment |
|---|---|---|---|---|---|
| N/A | 4 | 5 in. from 3, between 2 and 3. | Near #4. | No new crack found at this location. | Possible extension of #4, previously found at T1 and 3.25 in. long at that time. |
| Section 2 | 5 | Almost under 4. | None. | New crack 4 in. from probe 4 (at PM level). | - |
| N/A | 6 | 19 in. from 4, between 4 and 5. | Near #19. | No new crack. | Indication #19 is 21 in. from T4, this could be an extension of #19. |
| N/A | 7 | Midway between 4 and 5. | Near #19. | No new crack. | This also could be an extension of #19. |
| N/A | 8 | 10 in. from 6, between 5 and 6. | None. | No new crack seen. | Location is at intersection of head/shell weld and horizontal seam weld. |
| Section 5 | 9 | Very close to 8, between 7 and 8. | Several long indications found in the area. | No growth of earlier indications. | - |
| Sections 3 and 4 | 10 | Equidistant from 7 and 8. | None. | In region of hydro leak. | Indication at leak started 6 in. from crown, 8 in. long. |

As can be seen from Table 11, the results are mixed. Seven of the 10 solid AE events were located near existing cracks that had been found in the pre-hydro PA examination, however, five showed no new cracking in these areas or growth of an existing crack. The two instances where cracks were seen (events #1 and #2) were located near a welded support for the running gear. So it is difficult to say whether these are new cracks, growth of the previously found existing cracks, or increased scatter from the distortion of the tank around these welds. At the three locations where nothing was seen in the pre-hydro PA testing, one region showed a PM sized crack (event #5, approximately 0.5 inches), no crack was seen using PA at the second region (event #8), while the third region final (event #10) where the tank failed PA was not used since the crack was visually apparent.

It was unexpected for the tank to fail in a region where nothing was indicated in the pre-hydro PA examination. Given the number of indications, it was assumed that one of them would lead to the final failure, but this was not the case.

Based on the AE and PA results, five distinct areas were identified for sectioning and subsequent metallographic examination. These areas are designated by section number in Table 11 and listed in Table 12. These studies are described in the next section.

**Table 12. Description of sectioned pieces from tank tested to failure.**

| Piece | Location | Indications Found |
|---|---|---|
| 1 | Front head/shell weld, bottom, where axle support plate was welded to the tank. | Two small indications from AE, near previous PA indication. |
| 2 | Back head/shell weld, near top. | One AE indication, no previous PA indications. |
| 3 | Circumferential shell center weld, top where leak occurred. | AE indication, no previous PA indications. |
| 4 | Circumferential shell center weld, down from where leak occurred. | AE indication, no previous PA indications. |
| 5 | Shell longitudinal weld, front half. | Several PA indications found here, no AE indications. |

### 4.6.3 Sectioning and Magnetic Particle Inspection

Five different areas were selected for sectioning and an example of one of the areas selected (section 5) is shown in Figure 28. The piece is shown leaning against a lab bench to provide scale. The AE and PA indications found within these sections are identified by the different section numbers used in Table 11. Sections removed from the tank were examined first in the as-received condition, and then again after they had been cleaned to better view the surface. An example of how a typical piece looked before and after cleaning is shown in Figure 29 and Figure 30.

Figure 28. Photograph. Section 5 from tank #8161.

Figure 29. Photograph. Section 4 from tank #8161, before cleaning.

**Figure 30. Photograph. Section 4 from tank #8161, after cleaning.**

Before any further sectioning was carried out, the rough ends produced by flame cutting were removed so that magnetic particle (MP) imaging could be done. Although several indications had been flagged on these pieces using PA and AE, MP imaging revealed only two regions where cracks were evident. These regions were a through-crack in section 3 that resulted when the tank was overpressurized (see Figure 31), and a crack that was found in section 4 (see Figure 32).

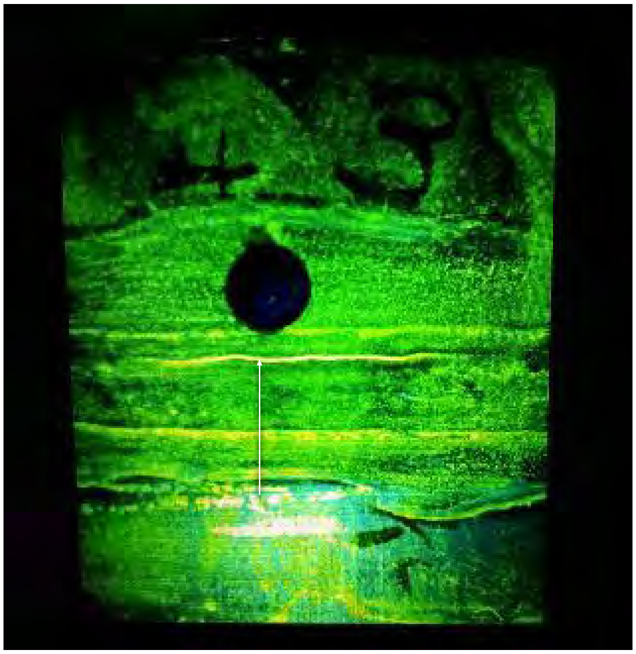

**Figure 31. Image. MP results from nurse tank #8161 - Section 3 showing through-crack (indicated by an arrow) that resulted from overpressure.**

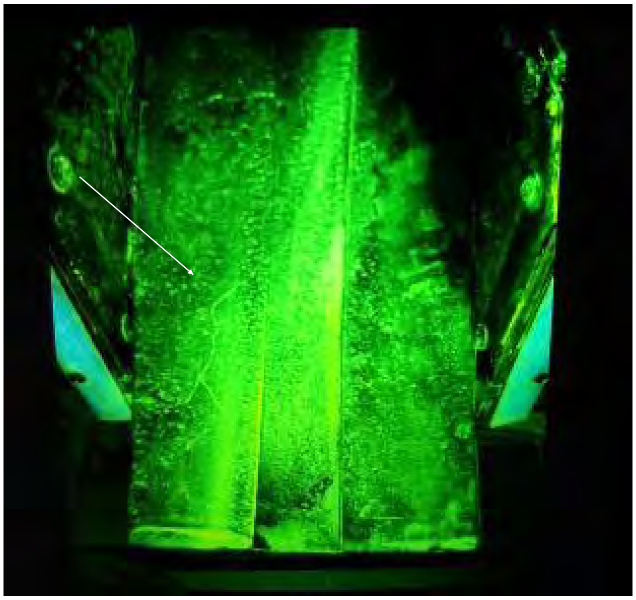

**Figure 32. Image. MP results from nurse tank #8161 - Crack found in section 4 (indicated by an arrow).**

The inability of MP to detect any of the other cracks flagged by PA is expected, given the presence of a joggle in these particular welds. Any cracks that exist below the joggle could not be imaged, and all of the cracks detected by PA were small and located within the joggle area.

While the crack in the region of rupture was expected, the large crack in section 4 (Figure 32) was unexpected and was not previously detected in the pre-hydro PA examination. This is a very large crack and appears branched. It is distant from the weld, which may account for it not being detected previously. Another reason may be because this crack did not exist when the pre-hydro PA examination was conducted, but developed during the overpressure test when the tank failed.

Subsequent metallographic sectioning and examination led to a better understanding of the MP results and provided a third reason why the crack seen in MP was not detected. These results are detailed in the next section.

### 4.6.4 Metallographic Sectioning and Polishing

The cracks identified using MP (Figure 31 and Figure 32) were sectioned from the larger tank pieces into smaller samples suitable for polishing and metallographic examination. Both cracks were sectioned through their center for further examination. The through-crack shown in Figure 33 separated during the sectioning (as expected). The crack indicated by MP in Figure 34 held together and was polished and viewed in cross section.

**Figure 33. Photograph. Sectioned pieces from section 3 with through-crack and AE indications.**

Figure 34. Photograph. Sectioned pieces from section 4 with AE and MP indications.

Figure 35 and Figure 36 show images obtained from the section 4 region where MP inspection indicated a crack. Despite polishing the sample in cross-section and etching, no clear sign of any type of crack was seen. A depressed region was seen on the surface of the piece. It is possible that this was responsible for the signal, or a crack does exist that is yet to be detected.

Figure 35. Image. Stereographic image of region of MP indication on section 4.

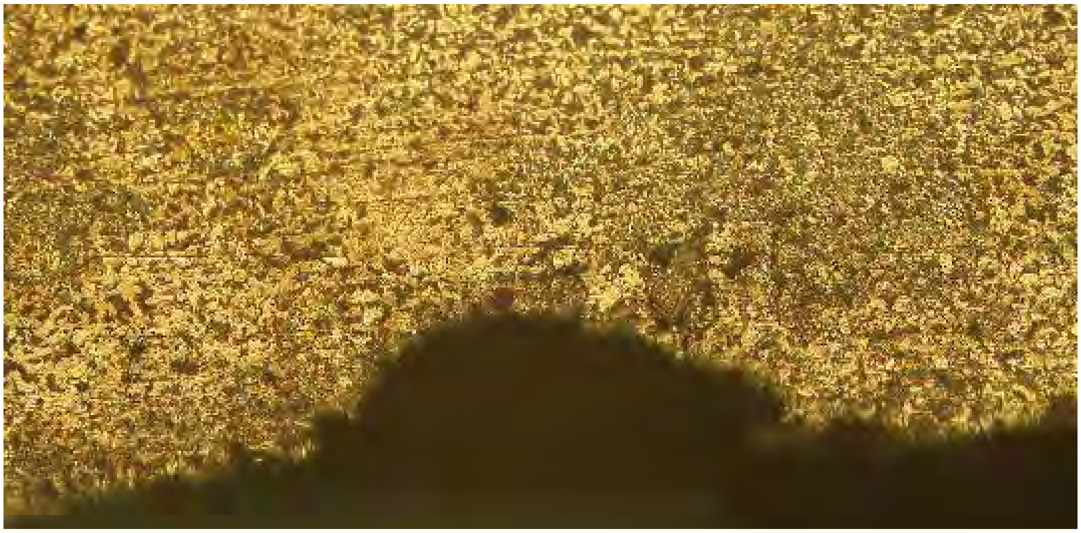

**Figure 36. Image. Optical microscopy view of cross section across the region of the MP crack indication.**

The cross-sectioned sample obtained from the through-crack located in section 3 is shown in macroscopic view in Figure 37 and in stereoscopic view in Figure 38. The section was covered with a large amount of oxidation products from the failure during the hydro test and had to be cleaned. Even after cleaning, a considerable amount of oxidation remained.

**Figure 37. Photograph. Macroscopic view of section 3 through-crack.**

**Figure 38. Image. Stereoscopic view of section 3 through-crack.**

The fracture surface was extremely rough, indicative of macroscopic ductile failure, as would be expected in an overload condition. The obvious texturing seen macroscopically appeared related to the welds and the solidification microstructure.

Scanning electron microscopy (SEM) examination showed ductile overload over the entire width of the fracture. No obvious signs of SCC were seen. It appears that overpressure caused a ductile overload of this region with pre-existing stress corrosion. The difference in appearance between the weld-side and base-side material is related to the grain structure within the material. Figure 39 (weld-side) shows a more equiaxed structure resulting from the molten pool. The aligned structure in Figure 40 (base-side) is likely related to the texture produced by rolling the steel used to fabricate the tank.

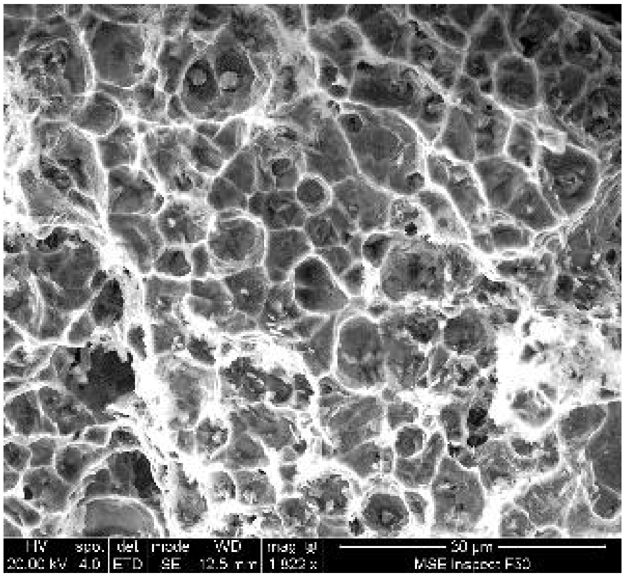

**Figure 39. Image. SEM examination of through-crack of section 3 (weld-side).**

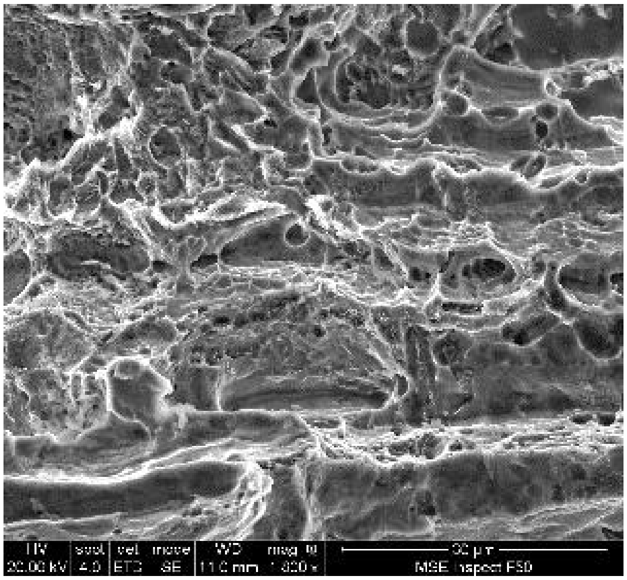

**Figure 40. Image. SEM examination of through-crack of section 3 (base-side).**

### 4.6.5 Summary

The failure of tank #8161 occurred without widespread growth of existing cracks within the structure as detected using PA testing. Failure occurred at a point that was not specifically related to any existing cracks. Metallographic examination showed that cracking occurred in a region where the grain structure of the material was more aligned, rather than the equiaxed structure that is desired to give the highest, most isotropic strength.

# 5. CONCLUSIONS

The following are the four findings from the Phase IV study.

**Finding #1: PA analysis is superior to single beam.**

The use of multiple beams in the ultrasonic probe allowed weld geometry effects to be more easily separated from actual crack indications within the steel. This resulted in fewer indications being seen in some tanks in the pre-hydro tests. Additional indications seen in other tanks could be the increased precision of the PA device; however, it is almost certain that many are an indication of new cracks that had nucleated or grown to a sufficient size for detection since 2015.

It should be noted that while PA analysis offers increased sensitivities, the cost of the unit itself (approximately $30,000) is also considerably more expensive than the cost of previous handheld units (approximately $5,000) used in Phases I-III and requires additional expertise to use. It is unlikely that agribusinesses would have the necessary funds to purchase such a unit, or the personnel resources to implement one without considerable training.

**Finding #2: AE is useful in detecting changes in the tank.**

The sensitivity of the equipment used was adequate to tell that changes were occurring in the tank during testing. However, while 16 of the 21 tanks had AE events, only seven of these tanks had measurable differences in the post-hydro PA examination. Thus, AE can provide areas to investigate but cannot tell if the acoustic event is definitively associated with the formation or growth of a crack.

**Finding #3: Changes produced by hydro testing are minimal.**

While it is almost certain that the hydro tests cause some change to the crack structure of the tank, it is less certain if the changes are large enough to constitute actual damage. It is possible that the hydro test opened existing cracks, making them easier to spot using PA. It is equally possible that a minor amount of crack growth has occurred. Of the seven tanks where differences were seen pre-hydro and post-hydro, the changes observed were not to the extent that one could say damage had been done that renders the tank significantly (or even marginally) less safe or significantly decreased the tank life.

**Finding #4: Additional evidence was found that PWHT is beneficial.**

Tanks which had undergone PWHT were found to have fewer, smaller cracks in the pre-hydro tests and no crack growth was seen from previous examinations. They were also less likely to develop additional cracks during the hydro test. As in Phases I-III, the benefits of a PWHT seem evident.

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# 6. RECOMMENDATIONS

Based on the results of this study, the research team concludes that hydro testing of tanks does not constitute a significant threat to the safety of a tank and may serve as an additional safety check. Hydro testing is a cost-effective way to verify proper operation of safety pressure valves used on nurse tanks. Failure of a safety pressure valve still represents a significant threat to public health, such as a catastrophic tank failure.

Hydro testing has been shown to cause tanks with significant cracks in them to fail prematurely. Older tanks where PWHT was not done, and where the entire length of the weld was not examined using x-ray techniques to ensure weld soundness, are still present in the U.S. fleet. While the use of PA ultrasonic technology could determine the extent of cracking and the quality of welds in older tanks, it is a costly solution that may not always be feasible to implement. Hydro testing is believed to be the most cost-effective way, at this time, to catch older, possibly defective tanks since the increased pressure would act to accelerate eminent failure in a safer, more controlled manner.

Hydro testing may also catch tanks where failure could occur from fatigue, rather than SCC. PWHT acts to significantly reduce residual stresses that lead to SCC and fatigue in new tanks. However, it will have less effect on locations where the application of cyclic mechanical stresses exists, such as where supports for running gear are welded onto the tank. While pinhole leaks would most likely form first, this cannot be guaranteed. Thus, hydro testing should continue as part of the safety regimen of anhydrous nurse tanks.

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# APPENDIX A: COMPARISON OF EXAMINATION METHODS

Different techniques have been used to monitor and examine anhydrous ammonia nurse tanks, either during the manufacturing process or once they are in the field. Table 13 is provided as a reference for the use and function of each technique. Note that if a legible data plate is still attached to a nurse tank, no post-manufacture examination is required.

**Table 13. Comparison of examination techniques.**

| Technique | Description | Advantages | Disadvantages | Comments |
|---|---|---|---|---|
| X-ray Radiography | NDT method used during manufacture to monitor the quality of a weld. This involves obtaining x-ray images of the weld joint. Required by code. | Ensures that no tanks with substandard welds are permitted into service. | Not a technique easily performed in the field to determine whether post-manufacture cracking has occurred. | 100% of the longitudinal seams of nurse tanks are x-rayed. 6 in. out of every 50 ft. of head/shell weld are x-rayed. |
| Visual Inspection | Simple examination to look for dents, scratches, any pinhole leaks, or other evidence of damage. | Quick and easy. Tank does not need to be emptied to conduct the test. | Gives no information concerning the internal state of the tank where corrosion is occurring. | Required of tanks without a legible data plate once every 5 years. Carried out by the tank owner. |
| Ultrasonic examination – single beam | NDT method that uses a single-beam transducer to investigate the steel. This can measure thickness of the steel and determine whether any cracks are present in the material. | Relatively inexpensive method that allows a skilled operator to examine and monitor tank quality including thickness and the presence of cracks. Tank does not need to be emptied to conduct the test. | Subject to interpretation and operator training, especially when trying to separate weld effects from true cracks. | Only used by co-ops and agribusinesses for thickness measurements where it is fairly reliable. Required of tanks without a legible data plate once every 5 years. |
| Ultrasonic examination – phased array | NDT method that uses multiple transducers to sweep through in an arc. | Much more sensitive than single beam, less subject to operator interpretation, better able to separate weld effects from true flaws. Tank does not need to be emptied to conduct the test. | Can be very expensive compared to single beam units. | Currently not widely used in the nurse tank industry. |

| Technique | Description | Advantages | Disadvantages | Comments |
|---|---|---|---|---|
| Hydro testing | Involves filling a tank with water to a pressure higher than the normal operating pressure. | Relatively easy to do, also allows safety valves to be checked at the same time. | Requires the tank to be emptied. Time-consuming. | Required of tanks without a legible data plate once every 5 years. Carried out by the tank owner. |
| Acoustic emission | Involves placing sound transducers on a tank and then monitoring acoustic signals during pressurization of the tank. | Can pinpoint locations where AE events might indicate cracking has occurred. | Must be used in conjunction with ultrasound to determine whether cracking has occurred. | A research method, not intended for operational monitoring of a tank. |

# APPENDIX B: EQUIPMENT SPECIFICS

## ULTRASONIC EQUIPMENT

The Olympus (previously RDTech) Omniscan MX (see Figure 41) is a PA instrument capable of operating 16 to 64 element array probes. The instrument has a bandwidth from 0.5 to 32 MHz, with 0 to 100 dB of receiver gain available, and a maximum pulse repetition rate of 10 kHz.

For this study, a 5 MHz longitudinal mode 16-element probe was employed with a Perspex angle beam wedge (45-degree beam in steel with no phasing). The instrument was operated in sector scan mode, with the beam sweeping between 30 and 70 degrees from the tank surface normal. Calibration was accomplished by locating the 45-degree corner trap signal from an EDM notch in a steel plate, adjusting the instrument gain so the corner trap produced an 80 percent full screen height signal. Then an additional 12 dB of gain was added. The steel plate was supplied from a tank manufacturer and was of similar thickness as the cylinder portion of newly manufactured tanks.

The cost of a new Omniscan MX2 unit starts at approximately $34,000.

Figure 41. Image. Olympus Omniscan MX PA unit.

## ACOUSTIC EQUIPMENT

AE testing was performed using a WaveExplorer Version 7.0 (Digital Wave Corp., Centennial, CO). This instrument is designed to capture AE waveforms with high-fidelity and sensitivity, with real-time extraneous noise rejection.

Figure 42. Photograph. WaveExplorer Version 7.0, by Digital Wave Corporation.

This unit can monitor up to eight compatible ultrasonic transducers. The transducers used to monitor the tanks were type B1025 made by the same company (see Figure 43). Either seven or eight transducers were used for each hydro test. Each 0.635 cm diameter transducer had a range between 5 kHz and 2 MHz and was mounted on the tank using a magnetic holder (see Figure 44). A PA-20 Pre-Amp 20 dB Gain amplifier was used in each transducer line for signal amplification.

Figure 43. Photograph. Transducer used in AE monitoring.

**Figure 44. Photograph. Magnetic holder used in AE monitoring.**

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# APPENDIX C: COMPLETE DATA TABLES

**Table 14. Series 1—Pre-1999 tanks that had not undergone PWHT.**

| Tank Number | Indications - 2012 | Indications – 2015 | Pre-hydro Indications – 2019/2020 | Acoustic Results | Post-hydro Indications | Comments |
|---|---|---|---|---|---|---|
| #1129 (1998) | 4 | 2 | 9 | Events between T1 and T3. | One new crack was found, crack #10, right side front, 10 in. down at PM. Another possible crack was located near crack #4 in the 2019/2020 pre-hydro scan. Crack #4 may have grown or not been fully detected previously (as the signal died out then came back). Little or no change in other cracks. | Several of the 2019/2020 indications were long—1 in. or longer. This points to crack formation and growth, not just missed previous cracks. |
| #40201A (1969) - now #3044A | 17 | 1 | 7 | Possible event close to T1. | A new PM indication found on right side front, head to shell, between T1 and T3, 3.5 in. from crown on head side, perpendicular to weld. | 2015 expertise eliminated several 2012 indications. 2019/2020 found several PM indications missed in 2015. Possible growth of 2015 indication. |
| #40201B (1967) - now #3044B | 1 | 1 | 5 | Event between T1 and T3. Event took place approximately 15 in. from T1 and 27 in. from T3. | A new indication was noted, right side front, head to shell, on head side, perpendicular, 20.75 in. down from crown between T1 and T3. | 2019/2020 indications found in same area where 2012 and 2015 single indication found. May be due to advanced discrimination. |

| Tank Number | Indications - 2012 | Indications – 2015 | Pre-hydro Indications – 2019/2020 | Acoustic Results | Post-hydro Indications | Comments |
|---|---|---|---|---|---|---|
| #6044L (1977) | 5 | 8 | 7 | Tank was tested twice. First time—recorded 103 events. Second time—recorded 19 events. T7 was placed near T4 and T5 since a larger crack had been found there in 2015. A big event was noted between T5 and T7. T5 was on the rear left head/shell weld, T7 was 42 in. away toward the front on the same level as T5. | All but one of the previous 2015 indications were found, but no apparent growth and no new indications, even where an acoustic event was noted. | Since a defect was observed in 2015 near the horizontal weld (and confirmed by pre-hydro ultrasound), T7 was mounted in the center of the longitudinal weld. A big event was noted between T5 and T7, but a computer glitch occurred, and the data was not saved. Repeating the test showed nothing since once the event occurs, only going to a higher pressure will cause any additional changes. |
| #4052 (1976) | 35 | 19 | 37 | 15 minor events recorded—none significant. | No post-hydro ultrasound deemed necessary. | Of the cracks seen in 2019/2020 pre-hydro, only one was larger than PM. |

**Table 15. Series 1—Summary of yearly surveys and discussion of crack growth.**

| Tank Number | 2012 vs. 2015 Comparisons | 2015 vs. 2019/2020 Comparisons | Comments |
|---|---|---|---|
| #1129 (1998) | Two of the four 2012 indications were verified in 2015 at slightly different locations. | One of the 2015 indications was verified in 2019/2020, having grown considerably from 0.5 in. to 1.375 in.<br>Eight additional indications found, sizes ranged from PM to 1.5 in. | Crack growth was considerable in one case with several new cracks found. |
| #40201A (1969) - now #3044A | Of the 17 indications seen in 2012, only one was found in 2015, and measured smaller than in 2012. | Two 2019/2020 indications roughly correspond to the 2015 indication, which is near two 2012 indications. No growth seen.<br>Five new indications were seen, the largest was 0.5 in. | Inaccuracy in measurement and cracks close together could be the cause for confusion between 2012 and 2015 indications seen in 2019/2020. Little or no growth is seen. |
| #40201B (1967) - now #3044B | Single 2012 indication confirmed in 2015 at a slightly different location, but size was approximately the same. | 2012/2015 indication confirmed but at smaller size.<br>Five new indications found, all except one at PM. | No crack growth seen in repeating indications. |
| #6044L (1977) | Two 2012 indications appear to be found in 2015 but at a 2 in. offset in measured position.<br>Six new indications found in 2015. | Seven of the eight 2015 indications were verified, no growth seen in any of them. One 2012 indication was found but at a much smaller size—1.75 in. instead of 4.875 in. | No crack growth seen in repeating indications. |
| #4052 (1976) | Of the 35 indications seen in 2012, 14 could be related to 2015 indications. Five additional indications did not correspond to any others with 1 to 2 in. of the 2012 locations, but they were in the same general area. Of the indications that seemed to be related, all sizes were at PM (i.e., smaller than the 2012 indications—in some cases, substantially so).<br>Five new indications seen in 2015. | Fifteen of the 2015 indications were confirmed with no crack growth, five 2015 indications could not be confirmed. One 2012 indication not seen in 2015 was confirmed. Four of the five new indications seen in 2015 were confirmed.<br>Nineteen new indications were seen in 2019/2020 compared to 2015. All were at PM level in the same areas as all the confirmed 2012 and 2015 indications. | This tank seems to have a lot of unknown issues with the axial welds. This may be causing the large number of indications at slightly different regions. This is supported somewhat by the fact that no crack growth was noted in 2019/2020, all indications were at PM level. |

Table 16. Series 2—Pre-1999 tanks that had undergone PWHT.

| Tank Number | Indications - 2012 | Indications – 2015 | Pre-hydro Indications – 2019/2020 | Acoustic Results | Post-hydro Indications | Comments |
|---|---|---|---|---|---|---|
| #6030 (1991) - now #7030 | 6 | 1 | 1 | Acoustic results found one event midway between T2 and T3 (approximately bottom center of tank) and something about 44 in. from T7 but was inconclusive. | Nothing seen between T2 and T3. A PM indication was found 42.25 in. from T7. | Six indications in 2012, one in 2015. 2020 found one before a new PM indication along center circumferential weld, could have been missed previous years. Indication on the longitudinal weld found 2012 was seen post-hydro, occurred at a dent. Not thought to be a crack. |
| #2013A (1968) - now #2013 | 2 | 0 | 12 | None significant—17 minor events recorded. | No post-hydro ultrasound deemed necessary. | All except one 2019/2020 indication were on longitudinal welds. |
| #2022 (1996) | 4 | 1 | 0 | No acoustic events recorded. | No post-hydro ultrasound deemed necessary. | PA showed no indications. |
| #3002 (1994) | 4 | 2 | 5 | An event occurred between T1 and T3. Event was 17.4 in. from T1 and 24.6 in. from T3. This event caused a signal on T7 also. | Two indications from 2015 not on pre-hydro test. Post-hydro had two new indications. First—right side front, head to shell, perpendicular to weld, shell side, 72 in. from crown, PM. This is below T3, not between T1 and T3. Second—left side front, head shell weld, shell side, perpendicular to weld, 64.75 in. down from crown (i.e., between T2 and T3). | Three 2012 indications only showed as one in 2015. Two 2015 indications not found. All indications at PM. Since new indications were not associated with AE events, these most likely were existing cracks that became more visible after hydro testing. |

| Tank Number | Indications - 2012 | Indications – 2015 | Pre-hydro Indications – 2019/2020 | Acoustic Results | Post-hydro Indications | Comments |
|---|---|---|---|---|---|---|
| #1118 (1997) | 3 | 0 | 4 | Event between T1 and T2, 13 in. from T1. | Pre- and post-hydro ultrasound found no indications in the event area. | 2012 indications were from the tank body circumferential weld. They were deemed to be scatter from the weld itself in 2015. 2019/2020 indications found on shell longitudinal weld (3) and center circumference weld (1). |
| #2178 (1978) | 46 | 17 | 25 | Of the 75 total events recorded, only 1 significant. Event occurred close to T1 between T1 and T3 at a low pressure. | Examined between T1 and T3, no discernable growth found. | Many 2012 indications eliminated in 2015. Two 2015 indications showed clear growth. |

**Table 17. Series 2—Summary of yearly surveys and discussion of crack growth.**

| Tank Number | 2012 vs. 2015 Comparisons | 2015 vs. 2019/2020 Comparisons | Comments |
|---|---|---|---|
| #6030 (1991) - now #7030 | None of the six indications from 2012 were verified in 2015.<br>One new indication at 1 in. was found in 2015. | The 2015 indication was seen in 2019/2020 but was much larger—3.5 in. However, it seemed to be associated with a dent in the metal.<br>Two additional PM indications were found. | The 2015 and 2019/2020 indication seems to be related to a dent in the metal and is not believed to be a crack. |
| #2013A (1968) - now #2013 | The two indications seen in 2012 were not verified in 2015. | None of the 10 indications found 2019/2020 corresponded to the 2012 indications. Sizes were all PM. | No statement can be made on crack growth since no repeating indications existed. |
| #2022 (1996) | None of the five 2012 indications could be verified in 2015.<br>Instead, one new indication was seen at 0.5. | None of the previous indication could be verified and no new indications were seen. | - |
| #3002 (1994) | Two of the four 2012 indications were verified.<br>Possible crack growth in one. | All four 2012 indications could be verified but two were at slightly different recorded positions. No crack growth seen.<br>Five new indications were seen at the PM. | No crack growth seen in repeating indications. |
| #1118 (1997) | None of the three 2012 indications were verified in 2015. | Four new indications seen at PM on both sides of weld. | No repeating indications were seen to provide crack growth data. |
| #2178 (1978) | Only 15 of the 2012 indications were verified. Mixed length results; most were unchanged, two had grown from 0.25 to 0.75, two had decreased from > 2.25 in. to 0.625 in. and PM.<br>Three new indications found in the same area where 2012 indications were found but > 1 to 2 in. away. | All 2015 indications found with no crack growth present.<br>Seven new indications found, all at PM. May have been missed in 2015 due to lower resolution. | No crack growth seen in repeating indications between 2015 and 2019/2020. Two crack length increases and two crack length decreases between 2012 and 2015. Probably related to operator. |

Table 18. Series 3—Post-1999 but pre-2015 tanks, no PWHT, thinner steel allowed by ASME in 1997.

| Tank Number | Indications - 2012 | Indications – 2015 | Pre-hydro Indications – 2019/2020 | Acoustic Results | Post-hydro Indications | Comments |
|---|---|---|---|---|---|---|
| #1138 (2008) - now #1138B | 11 | 2 | 6 | No acoustic events recorded. | No post-hydro ultrasound deemed necessary. | Nine 2012 indications due to weld. 2019/2020 increase over 2015 due to greater sensitivity. |
| #1140A (2008) | 6 | 4 | 3 | Very few hits. Possibly something around T2 and on both sides of it. | Tested near T2. Saw bad paint which may have caused some effect. No obvious indications. | Decrease from 2012 to 2015 to 2019/2020 although all indications in same area. |
| #1145A (2004) | 1 | 5 | 5 | Only four significant events out of 32. Two events occurred between T2 and T3, close to T3. One event between T4 and T5. One event between T5 and T6. Investigated close to six. | No previous indications found between T2 and T3. Post-hydro ultrasound in this area showed no new indications. Between T5 and T6 a new strong indication was found where nothing was reported before. The indication was still PM in size but easily detected. Location was 63.5 in. down on the right-rear-head as you face the front of the tank. | Confirmed the five 2015 results pre-hydro, new crack seen post-hydro at AE site. |
| #1189B (2010) | 6 | 9 | 3 | No events. | No post-hydro ultrasound deemed necessary. | Many of the 2012 and 2015 indications were ruled to be false positives in 2019/2020. |
| #1614 (1999) | 33 | 79 | 101 | There was some activity on the front between T2 and T3, also some activity between T4 and T6. | Indicated locations were examined, nothing new was seen. | Many indications, primarily in the head/shell welds at both ends. |
| #1146A (2009) | 0 | 25 | 27 | Forty total events. Some activity between T1 and T2 should be investigated, especially midway between them. | Examined between T1 and T2. a new indication was seen 11.5 in CW down from the crown. It is still small (PM). Not as strong as seen for tank 1145A but still across threshold. | New post-hydro indication found where nothing had been seen before. |
| #1193R (2010) – now 1193A | 32 | 57 | 54 | Very little activity. Possibly something between T2 and T3, and between T4 and T6. | Previous indications were found but no apparent growth and no new indications | Increase of cracks almost all found on left front head/shell weld where none were seen in 2012 or 2015. Points to better equipment as the reason. |

| Tank Number | Indications - 2012 | Indications – 2015 | Pre-hydro Indications – 2019/2020 | Acoustic Results | Post-hydro Indications | Comments |
|---|---|---|---|---|---|---|
| #1138A (2008) | 10 | 20 | 16 | Event between T4 and T6, 31 in. from T4. | Pre-hydro inspections had found seven indications in this region (six on left side, one on right side). Post-hydro inspections found the seven previous indications, with no new growth/extensions of indication boundaries and no new indications found. | Many 2015 indications were believed to be weld indications as determined using PA analysis. Many more found on rear head/shell weld, due to better sensitivity. |
| #1189A (2010) | 7 | 18 | 1 | Event between T4 and T5; event between T1 and T3; event in the middle of the tank. | Pre-hydro ultrasound found one possible crack at the PM length between T4 and T5. Acoustic results found consistent emission between T4 and T5; emission close to the middle of the tank between T1, T2, T3, and T7; and between T1 and T3, 10 in. from T1. Post-hydro ultrasound found unchanged condition between T4 and T5, an extremely small indication between T1 and T3 that may have been missed initially, and nothing on body welds between T7 and the head transducers. | 2012 indications were confusing. All 2015 indications were believed to be weld indications as determined using PA analysis. Only found one possible crack at the PM length between T4 and T5. |

**Table 19. Series 3—Summary of yearly surveys and discussion of crack growth.**

| Tank Number | 2012 vs. 2015 Comparisons | 2015 vs. 2019/2020 Comparisons | Comments |
|---|---|---|---|
| #1138 (2008) - now #1138B | None of the 2012 indications found.<br>Two new indications—7 in. and 9 in. | No prior indications found (weld scatter).<br>Five new indications, all at PM. | No repeating indications. |
| #1140A (2008) | Two of the six indications in 2012 found, but at 0.5 in., not 1 in.<br>Two new indications—both 0.5 in. | Three of the four 2015 indications verified, length unchanged.<br>No new indications. | No crack growth seen in repeating indications. |
| #1145A (2004) | The single 2012 indication not found in 2015.<br>Five new indications found. | All five 2015 indication verified, no crack growth.<br>A single new indication was found at PM. | No crack growth seen in repeating indications. |
| #1189B (2010) | Five of the six 2012 indications were verified, but all at PM.<br>Four new indications found—all at PM. | All nine 2015 indications verified, two showed growth from PM to ½ in. and ¾ in. | Substantial crack growth in two indications, the remainder had no change. |
| #1614 (1999) | Of the 33 indications found in 2012, 22 were verified. No growth, but one was smaller.<br>2015 found 57 new indications, all at PM. | All except four 2015 indications found and verified, all showing no growth. All except one indication was PM.<br>26 new indications over 2015 results, all at PM. | No growth seen in repeating indications. |
| #1146A (2009) | 2015 found 25 new indications. All listed as 0.5 in., except for two listed as 0.75 in. | All 2015 indications verified, one previous 0.75 in. crack measured as PM.<br>Two new PM cracks were found. | No crack growth seen in repeating indications between 2015 and 2019/2020, one showed shorter length. |
| #1193R (2010) - now 1193A | Verified 27 of the 32 indications from 2012, possible growth seen in 3 of the indications.<br>2015 found 30 new indications—majority at 0.5 in., 5 smaller, 1 larger. | Of the 57 2015 indications, 46 were verified. One crack increased from 0.5 in. to 0.625 in. (measurement uncertainty?), many went from 0.5 in. to PM (0.5 in. was default PM in 2015?), three went from 0.75 in. to PM.<br>Eight new indications found, all at PM. | Of the repeating indications, only one crack increased in length and that was questionable (0.125 in.). Most likely no growth occurred. |
| #1138A (2008) | Of the 10 indications found in 2012, 7 were verified. The possible growth for one was from 0.25 in. to 1 in.<br>Thirteen new indications found, all at 0.5 in. (one listed as 0.25 in.). | Only six of the 2015 indications verified, one from 2012 not seen in 2015 also possibly seen again. No growth, and one reduction in size.<br>Ten new indications seen, all at PM. | Huge variability between years in indications seen. No grow in repeating indication. |
| #1189A (2010) | All seven indications from 2012 found and verified, no growth.<br>Eleven new indications seen. | All 18 of 2015 indications verified, no change.<br>One new indication at PM. | No growth of repeating cracks. |

**Table 20. Series 4—New tank never tested.**

| Tank Number | Indications - 2012 | Indications – 2015 | Indications – 2019/2020 | Acoustic Results | Post-hydro Ultrasound Results | Comments |
|---|---|---|---|---|---|---|
| #8805N (2017) | N/A | N/A | 0 | Event between T1 and T3 about 16 in. from T1; Event between T1 and T2 about 8 in. from T1; Event between T4 and T5, 20 in. from T4; Event between T4 and T6 3 in. from T4. | No indications during pre-hydro ultrasound. No indications seen at any of the locations post-hydro. | Newer tank that had received PWHT. |

**Table 21. Tank tested to failure.**

| Tank Number | Indications - 2012 | Indications – 2015 | Indications – 2019/2020 | Acoustic Results | Post-hydro Ultrasound Results | Comments |
|---|---|---|---|---|---|---|
| #8161 (age unknown – clearly very old) | N/A | N/A | 20 | Events at several locations around the tank. | Areas examined before and where AE indicated events showed no discernable changes. | Samples sectioned from this tank were polished and examined. No additional cracking was seen at regions where significant AE was heard. |

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[7] An example of this type of special permit issued by PHMSA is special permit DOT-SP 16618, second revision, expiration date 2022-04-30, which was issued to Farmers Grain Company upon its application submitted in accordance with Section 107.109.

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