Testing and Recommended Practices to Improve Nurse Tank Safety: Phase III

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

July 2018

FOREWORD

This report summarizes the findings obtained from using the single-beam ultrasonic nondestructive testing method to re-examine 411 tanks located out of a previously examined 532 anhydrous ammonia (NH_3) nurse tanks. The tanks had been examined previously in Phase II of this research (conducted in 2012) in a survey of 532 nurse tanks. In comparison to the earlier study, the Phase III effort (conducted in 2015) provided better training to the student examiners and applied a more deliberate effort to discriminate between indications resulting from stress corrosion cracking and those likely caused by weld geometry issues. Important findings include:

- Observation that the average growth rate of existing perpendicular indications found in the Phase II study (measured again in the Phase III study) were slower than observed by the constant stress laboratory tests conducted as part of Phase II.
- However, numerous new perpendicular indications were found that developed in the 3 years since the Phase II survey.
- There was a substantially greater nucleation/initiation and growth of such perpendicular indications in newer tanks (manufactured in 1999 or later).

NOTICE

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16. Abstract
This report summarizes findings from a re-examination of 411 tanks that were relocated of 532 previously examined anhydrous ammonia (NH_3) nurse tanks using the single-beam side-angle ultrasonic nondestructive evaluation method. There were 532 tanks examined previously in phase II of this research (conducted in 2012). In comparison to the earlier study, the Phase III effort (conducted in 2015) provided better training to its undergraduate student examiners majoring in material science and deliberately attempted to discriminate between ultrasonic indications that resulted from stress corrosion, almost exclusively perpendicular to the weld seam, versus those more likely caused by issues in the geometry of the weld seam. Important findings include:

- **Growth rate of many existing perpendicular indications found in the Phase II and Phase III studies were slower than observed by the constant stress laboratory tests conducted as part of Phase II.**
- **Even though indication growth of existing perpendicular cracks was less than found in the constant stress laboratory tests, there were numerous new perpendicular indications found to have developed in the 3 years since the Phase II survey.**
- **Perpendicular cracks were the only ones single-beam ultrasound could reliably distinguish. A phased-array approach would be necessary to try seeing into the weld seams for distinguishing parallel cracks.**
- **Growth of existing indications and development of new indications were both disproportionately greater in newer tanks. Possible reasons why newer tanks are having more problems are discussed in the body of this report.**
- **There was a decrease in shell wall thickness following the 1997 American Society of Mechanical Engineers (ASME) change in guidance, which may be associated with the increase in the number of indications in newer tanks.**
- **Tank wall thickness measurements showed 5 percent of tanks inspected were near or below thickness standards that would be applied if the tanks were missing their ASME data plates, which would make them subject to 5-year periodic testing.**
- **Post-weld heat treatment (PWHT, annealing) reduces residual stresses remaining in steel after welding and is associated with dramatic reductions in both initiation of indications and their subsequent growth.**

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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	poundforce	4.45	newtons	N
lbf/in^2	poundforce 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	poundforce	lbf
kPa	kilopascals	0.145	poundforce 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
ASTM	American Society for Testing of Materials
CO_2	carbon dioxide
FMCSA	Federal Motor Carrier Safety Administration
HAZ	heat-affected zone
LPG	liquid petroleum gas
MPa	Megapascal (the mega version of a pascal unit, which is used to quantify internal pressure (or stress) and ultimately tensile strength)
NDE	non-destructive evaluation
NTIP	Nurse Tank Inspection Program (for nurse tanks without a legible data plate)
NH_3	anhydrous ammonia
NTSB	National Transportation Safety Board
OSHA	Occupational Safety and Health Administration
PHMSA	Pipeline and Hazardous Materials Safety Administration
ppm	parts per million
psig	Pounds per square inch gauge (this is a variation on the better known psi)
PWHT	post-weld heat treatment
R	correlation variable describing how closely the line of best fit fits the data
SCC	stress corrosion crack
TFI	The Fertilizer Institute
TWA	time weighted average

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EXECUTIVE SUMMARY

PURPOSE

Anhydrous ammonia (NH_3) is a hazardous material that can cause chemical burns, frostbite, and suffocation. Nurse tanks hold NH_3 as a liquid at multiple times atmospheric pressure. Nurse tank failures can release this pressure with catastrophic force, posing the additional risk of impact injury to workers and bystanders. To address related safety issues, the Federal Motor Carrier Safety Administration (FMCSA), which is responsible for safe operation of these tanks on roadways, has sponsored a multi-phased study of nurse tanks, focusing on the safety impacts of stress corrosion cracks (SCCs), how to detect them, and how to prevent them. Reports detailing findings from the first two phases of this research were published in 2013.[2, 3] The Phase II study was conducted in 2012. The two follow-on activities addressed by this Phase III research (initiated in May of 2015) were as follows:

1. **Nurse tank ultrasonic survey:** The 411 tanks found out of the 532 previously examined in-service nurse tanks were re-surveyed using single-beam side-angle ultrasound to measure how far indications found during the Phase II survey had progressed, if at all. Indications found perpendicular to welds were commonly judged to be likely SCCs, while many parallel indications in the head-to-shell seams, though they can be SCCs, were believed to more likely be the result of weld geometry. Single-beam side-angle ultrasound lacks sufficient resolution to make undoubtable judgements about the depth of perpendicular indications, and parallel indications are particularly difficult to interpret from the weld geometry. This re-survey demonstrated that many indications found in the Phase II survey could be located again. Additionally, the relative amount of growth of most of the perpendicular cracks was smaller than could be reliably measured with the manual single-beam side-angle ultrasonic method used in Phases II and III.

   The majority of ultrasound indications (both repeat finds and new indications) were once again found in the unannealed heat-affected zone (HAZ) near welds (i.e., the metal that got very hot during welding, but did not actually melt). Most indications lay perpendicular to head-to-shell welds and dominantly on the head side of the weld. Just as in the Phase II study, most of the indications found by this Phase III effort also occurred at or above the 80-percent fill line. In that portion of the tank, NH_3 has vaporized, and the NH_3 vapor is mostly pure, with none of the added water having evaporated as part of the mix with the gaseous NH_3. That enables the NH_3 vapor to contact and condense on the tank's inner wall surface with a high corrosiveness. Below the 80-percent fill line, liquid NH_3 is required to contain 0.2% of added water. When the NH_3 with the very small amount of added water contacts the tank's inner wall surface, the added largely non-corrosive water adheres to the steel, largely preventing the NH_3 from facilitating initiation of SCCs in that portion of the tank.

2. **Nurse tank ultrasonic thickness:** A longitudinal wave single-beam ultrasound survey of the 411 re-located in-service nurse tanks was performed to measure their tank wall thickness. This survey showed that the steel thickness of 95 percent of tanks inspected were greater than the minimum thickness listed in the Fertilizer Institute's Nurse Tank

Inspection Program (NTIP) procedures, which are used to guide the required 5-year re-testing of nurse tanks without data plates. However, 2.4 percent (10 tanks) were within 0.01 inches of the minimum and another 2.4 percent were below the minimum. Under current regulations, since all of the tanks inspected for this study had data plates, none are required to have thickness testing performed, as tanks with legible data plates affixed are exempt from such periodic testing.

This report may interest nurse tank owners (e.g., agricultural cooperatives), manufacturers, tank repair businesses, and farmers using nurse tanks to add nitrogen fertilizer to their soil, as well as all other parties concerned about public roadway safety.

PROCESS

This study represents a comprehensive re-examination of 411 anhydrous NH_3 nurse tanks previously studied in the Phase II study for evidence related to SCC occurrences in those tanks. The Phase II study examined 532 tanks, but not all could be relocated. Stress corrosion cracking in these tanks is caused by a process that requires both a corrosive action by the NH_3 in the tank, and increased susceptibility of the metal because of strains/stresses in the metal. These stresses can be either residual ones left after the welding of the tanks or mechanically applied tensile stresses, e.g., dents. For example, a dent in the tank because of an external impact will create local stress in the steel around the dent. The rate at which stress corrosion cracking damages a material is determined by the material type, tank environment, and applied mechanical loading and residual stress.

The occurrence of SCC formation and propagation is a stochastic process. The understanding of stress corrosion cracking was inadequate to allow reliable prediction of whether a given piece of steel will develop a SCC when subject to stress and exposed to a corrosive substance like NH_3. Once an indication is present, model estimates were developed to make predictions of how rapidly the indication may propagate with known, constant stress. However, these models are approximate at best; the interplay of factors affecting indication growth rate is complex, and how stress levels vary throughout the metal was unknown. Moreover, data was lacking on the number, size, and orientation of indications in nurse tanks that have been in service for many years.

To address these points, the Phase I study provided data on how stress in the tank steel varies around a weld seam. The Phase II study provided data on how the stress in welded steel was reduced by post-weld heat treatment (PWHT). Phase II also provided information on the presence of SCCs and other flaws in a population of nurse tanks that were currently in service, also evaluating the differences between tanks with and without PWHT.

Phase I Study

Among the many metallurgical tests performed in Phase I, one of the tests was to cut out a section of a nurse tank that was not PWHTed and include the weld for attaching the head to the shell. That section was taken to the facility at the Los Alamos laboratory for measuring latent residual stresses in the steel around the weld using neutron diffraction. Those measurements indicate that the residual stresses fall off rapidly as you move away from the weld. The areas with the high stresses around a weld are referred to as the Heat Affected Zone (HAZ). The measured stresses close to the head-to-shell weld seam were just below the level where the steel would fail if that level of stress were applied to the steel.

Phase II Study

From June through August of 2012, 532 tanks owned by farm cooperative companies in central Iowa were examined by single-beam side-angle ultrasound. Only areas near welds were examined, generally in a band approximately 200 mm (7.9 inches) wide, centered on the weld. Single-beam side-angle ultrasound has very limited resolution, and thus cannot discriminate reliably between SCCs and other defects in tank steel, e.g., an irregularity in the weld seam. In recognition of this fact, the term “indications” is generally used in this report to describe ultrasound reflections that reveal a discontinuity in the metal. Indications perpendicular to the weld are usually SCCs, but other types of discontinuities, such as weld geometry, that are not SCCs can also generate indications.

A mixture of 3,800-liter (1,000-gallon) and 5,500-liter (1,450-gallon) tanks were inspected. In 2012, the Iowa Department of Agriculture and Land Stewardship staff inspected 21,522 sets of nurse tank running gear (the wheels and suspension for nurse tanks) in Iowa; each set of running gear holds one or two tanks. Thus, the number of tanks tested by this research project represents roughly 2 percent of the total nurse tank fleet in Iowa.

The Phase II study showed that newer tanks built from 1999 forward generally had significantly more indications than older tanks. Three factors may have contributed to the higher count of indications for the newer tanks. First, there is a greater length of circumferential weld-line on the 5,500-liter tanks (which are more prevalent among newer tanks in central Iowa, where this research was conducted) than on the 3,800-liter tanks that were more commonly manufactured in the 1980s and earlier.

Second, changes in American Society of Mechanical Engineers (ASME) specifications in 1997 allow newer tanks to be built (beginning in 1998) with thinner shells, if the manufacturer follows a 100 percent longitudinal radiographic inspection regimen. Both remaining U.S. nurse tank manufacturers do this. This means the thinner steel must carry the same loads as the previously required thicker steel, so the stress from the operating pressure of the NH_3 in the thinner metal is greater. That greater tensile stress can affect SCC rates, because tensile stress is one of the main driving forces of crack growth. (Note. Phased-array ultrasonic testing claims it can produce results comparable to radiographic testing, and the pipeline industry is using portable units in the field to examine pipeline welds.)

Third, as of 2015 (when Phase III was conducted) neither of the remaining U.S. nurse tank manufacturers now performs full tank stress relief annealing treatments—also called post-weld heat treatment (PWHT)—on nurse tanks, unless requested by the customer. (It is reported one of those manufacturers recently relocated its facilities to Mexico.) From 1991 to 1998, all tanks manufactured by a certain manufacturer received a full-body PWHT, but that practice was discontinued in 1999 when the company was acquired by one of the remaining two manufacturers mentioned. The number of indications in the tanks tested that were manufactured without PWHT after the acquisition had a noticeably higher number of indications.

The effectiveness of stress relief annealing on reducing or eliminating stress corrosion cracking was readily apparent and documented by neutron diffraction analysis at the Los Alamos Neutron Science Center in the Phase II results. Just as in the Phase I study, a section of a nurse tank was cut out, but this time from a tank that had been PWHTed and taken to the Los Alamos neutron diffraction laboratory. The amount of residual stresses that remained in the steel adjacent to the weld were dramatically reduced.

The data show that 74 percent of the total indications found (2,104 of 2,834 indications) were found in the newer, un-annealed, thinner shell steel tanks manufactured from 1999 and later, even though these tanks comprised only 32 percent of the total tanks tested (168 of 532 tanks).

Some key findings from the Phase II study are as follows:

- Most indications (84 percent) were in the HAZ of the welds, where residual stresses in the steel are predicted from the neutron diffraction analysis at the Los Alamos Neutron Science Center to be greatest. Note, these residual stresses are greater in the shell-to-head welds than in the shell-to-shell welds. This is explained below.
- The circumferential welds that join the heads to the shell accounted for 81 percent of indications. Of those circumferential weld indications, 72 percent were located in the vapor space above the 80 percent fill line.
- The 168 tanks tested that were manufactured in 1999 or later accounted for 74 percent of the indications found in the HAZ, even though those tanks comprised only 32 percent of the total tanks examined.
- PWHT sharply reduces the number and severity of indications.
- Single-beam side-angle ultrasonic testing is an effective method for determining the location and size of perpendicular indications, but it does not have the resolution to deal with false echoes from weld geometry that can introduce uncertainties into measurements for parallel indications. Parallel SCCs could be more dangerous than perpendicular SCCs because they can grow in the area with high residual stresses that is adjacent to the weld.

Every one of the 532 tanks examined in the Phase II survey remained in-service after examination. Thus, it was possible to conduct a follow-up re-examination to study indication growth and initiation as a function of time. This resulted in the Phase III study.

Phase III Study

The Phase III study differed from the Phase II study in several ways. First, the actual surveying of the tanks was done under the direction of Mr. Darrel Enyart, a full-time non-destructive evaluation (NDE) scientist employed by the researcher. This allowed for a more careful examination of the data than was possible in Phase II, as Mr. Enyart helped the undergraduate student inspectors more carefully assess the relevance of indications found in the field. It was also his experience that brought about the acquisition of more advanced single-beam ultrasonic probes that provided better resolution than those used in Phase II. This increased resolution of the probes improved the study's ability to assess the location of reflections from within the material.

Mr. Enyart's expertise also allowed for a more critical examination of the acquired data, with the end result being further verification that a percentage of parallel indications found in the Phase II study were likely due to scattering of the single-beam of ultrasound by the geometry of the welds, rather than a result of SCC formation. It is pointed out later in this report that application of phased-array angle-beam ultrasonic technology is gaining usage in industrial applications, and almost certainly would provide superior resolution, enabling more accurate statements both about depth of a perpendicular crack and about parallel indications in the HAZ.(1)

The first task associated with the Phase III study was to locate the tanks examined in Phase II and obtain permission to re-examine them using the single-beam ultrasound NDE method. This task of locating the previously tested tanks actually consumed a significant amount of time. Numerous tanks had been moved to various other locations, sold to other entities, or taken out of service for one reason or another. Ultimately, only 411 of the original 532 tanks tested in Phase II could be located. This indicates there is dynamic movement of such nurse tanks, even over only a three-year span.

RATIONALE AND BACKGROUND

Only tanks with legible data plates (which display the year of manufacture) were inspected in Phase II and Phase III. The rationale was that these tanks could presumably be tracked better than tanks without data plates. If two tanks were mounted on the same running gear, those tanks were accepted for inspection, although a short strip, about 40 cm long (15.7 inches) of each tank's circumferential welds could not be inspected due to insufficient clearance between the two tanks to allow the single-beam side-angle transducer access. This uninspected space was located below the 80 percent fill level and therefore is less likely to have contained many indications.

A typical field inspection involved locating a tank that was part of the Phase II study and creating paperwork to record the Phase III results. In all cases, the tank thickness results from the Phase III measurements were recorded on this paperwork, and if any indications were located and determined to be relevant, they were also recorded.

The single-beam side-angle ultrasonic gain for each inspection was set using the same through-hole setup bar that was used in Phase II in order to keep inspection thresholding the same as in the previous study. This bar is a known sample of material into which known imperfections have been introduced, such as by a hole or holes drilled through the material from the side. The purpose is to detect those holes from the top of the block of material, and to set the gain to produce a known level of response from the detection of those holes.

After a day of inspections and before researchers left a tank farm, the Phase III results were compared to the Phase II results. This was to allow inspectors to double-check any tank with significant changes from the Phase II results.

The combined effect of fewer tanks to examine and a much more rigorous standard for declaring an indication to be classified as relevant (i.e., a likely SCC) resulted in a number of parallel in-the-weld indications recorded in Phase II being declared as most likely weld seam issues, not SCCs. This meant that many of the longest indications noted in Phase II were deemed non-relevant weld seam issues in Phase III (due to likely being caused by weld geometry). So, comparison of indication lengths between Phase II and Phase III was strictly focused on those indications (mostly perpendicular) that were identified as likely being due to stress corrosion cracking in both studies.

PHASE III STUDY FINDINGS

Key findings from the re-investigation are as follows:

- Of the 3,326 indications found in the Phase II study, 1,719 indications were either eliminated as likely non-SCC indications caused by reflections from geometry of the weld or were not located in Phase III. Those eliminated as likely non-SCC were possibly due to the increased training of the inspectors, increased resolution of the transducers, or judgement of the NDE expert on this project. Thus, a total of 1607 indications from Phase II were not eliminated and were found in Phase III.
    - 1,174 of those 1,607 indications retained from the Phase II study showed essentially no change in length (±0.25-inch change or less).
    - The remaining 433 of those indications were found to have grown in size from Phase II (2012) to Phase III (2015).
- 1,148 indications were recorded as new in Phase III.
- The total indications from Phase II not eliminated and found in Phase III, plus the new indications found in Phase III is 2,755. Of those 2,755 indications, 2,712 were associated with circumferential welds. Of this number, 2,691 were in head-to-shell circumferential welds, while 21 were found in shell-to-shell circumferential welds. The reason for so few indications in the shell-to-shell welds is explained in section 2.2 below.
- Only 40 indications were found in axial welds in the tanks’ shell region for a similar reason as the limited number of indications in the shell-to-shell welds.
- Three indications were associated with leg welds, and these likely were not SCCs but fatigue cracks. (This was possible to determine with single-beam technology because leg welds are entirely on the outside of the shell, much like lifting lugs, i.e., there is no internal metal joint like there is in the shell-to-head or shell-to-shell joints. Thus, even with the limited resolution of single-beam it is possible to distinguish likely metal fatigue crack indications in the continuous steel around a leg weld.)

The preponderance of perpendicular indications in the head-to-shell circumferential welds shows the significance of higher residual stresses in this critical region. The amount of residual stresses in the shell-to-shell circumferential and axial welds are expected to be much less due to the type of weld geometry. During the shell-to-shell welding process, circumferential and longitudinal expansions are not as constrained and the steel can move more easily when heated, resulting in fewer residual stresses after welding and not being annealed. Conversely, in a head-to-shell weld, the shape of the head constrains the steel of the welded shell cylinder and especially of the head from expanding/contracting, creating considerably more post-welding residual stress than occurs in welding that is entirely within the shell.

A direct comparison of the average length of previously existing perpendicular indications clearly identified in both Phase II and Phase III would appear to indicate an on-average indication length decrease of -0.12 inches. This makes no physical sense, but there are straightforward explanations for this observed change.

One explanation is that the width of the probe was approximately 0.5 inches. As a result, the inspectors in Phase II may have made errors of perhaps up to 0.5 inches (or certainly up to half the width of the probe, or 0.25) in estimating the length of each indication. Even the better trained and supervised inspectors in Phase III would have limitations on absolute accuracy of indication length because of the width of the probe. Thus, a final difference of ±0.12 inches on average is well within the noise range of the ability to estimate indication length. The fact that the change in average length of previously existing perpendicular cracks was within that noise range indicates that, on average, the perpendicular indications detected in Phase II have not dramatically grown in the intervening 3 years. Other reasons are discussed later in this report.

The general conclusion that can be drawn from the findings of this research is that perpendicular indication growth rates are small in context of the accuracy of indication length measurement possible with single-beam side-angle ultrasound inspection. The higher quality training and experience of the Phase III examiners, coupled with the improved transducers, are believed to be the more accurate assessment of the two studies.

However, slow growth of existing perpendicular indications is only part of the important measure of indications. There were 1,148 new indications found in the 411 tanks re-examined in Phase III. Of these, 1,039 (90.5 percent) were found to occur in tanks manufactured in 1999 or after (following the 1997 change in ASME guidance to allow thinner steel and the 1999 discontinuance of PWHT)[1]. Further, of the 433 indications analyzed that did show growth, 422 (97.5 percent) were found in tanks manufactured in 1999 and after with no PWHT. This could be quite concerning for the overall safety of such newer tanks.

This Phase III study added a survey of the tank wall thicknesses, a measurement not performed in Phase II. For this aspect of the study, the wall thickness of each tank was measured using the 32 locations specified in the Fertilizer Institute’s NTIP procedures, which are discussed in

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[1] As of 2016 the two remaining manufacturers of nurse tanks in the U.S. began PWHT of all new nurse tanks as part of their manufacturing process. Both participated in this research and were aware of the finding that PWHT was an extremely effective and relatively inexpensive means for substantially reducing SCC.

section 3.6 below. Comparing results from the thickness measurement to the NTIP requirements, it was determined there were 20 tanks that had 1 or more spots that measured within 0.01inches of the NTIP minimum or less than the minimum required thickness.

Of particular interest is a series of three 1,000-gallon tanks manufactured by Manufacturer A in the year 2000. These tanks actually had ASME plate values of 0.202 inches for the head and 0.238 inches for the shell. These values are both less than the minimum allowed for NTIP-inspected tanks, and all three of these tanks would likely be scrapped if they lost their data plates and thus became subject to 5-year periodic testing, following the NTIP protocols.

CONCLUSIONS

General conclusions that can be drawn from this study are as follows:

- The simple procedure used in both Phase II and Phase III for denoting indication location has limited precision.
- Better training and better transducers produced superior results; fewer indications located parallel to the weld likely attributable to weld geometry were considered SCCs.
- Despite the slower than expected growth rate of perpendicular indications, nucleation (initiation) of new perpendicular indications continued between Phase II and Phase III, with approximately 1,148 new indications.
- Most tanks meet the minimum thickness requirements.
- Tanks manufactured after ASME allowed thinner steel in 1997, and after PWHT was abandoned by all U.S. manufacturers by 1999, showed a significantly higher rate of nucleation/initiation of new perpendicular indications and a higher growth rate in length of existing indications.

Considering FMCSA's and the Pipeline and Hazardous Materials Safety Administration's (PHMSA's) roles in providing safety guidelines to this industry, it is recommended that a rulemaking requiring all anhydrous ammonia tanks to receive PWHT should be pursued.

1. SUMMARY OF PHASE I STUDY

This report is the third in a series of research efforts to provide data to aid in the safety regulation of nurse tanks. In order to provide an overview of all the research performed, this section of this report presents a brief summary of the Phase I and II study approaches and key findings as background. It then focuses on the Phase I study findings.

The Phase I report is largely a metallurgical analysis of nurse tanks and the reasons that stress corrosion cracking occurs. The report was published in October 2013 and is available on the Federal Motor Carrier Safety Administration (FMCSA) Web site.(2) The Phase II report expands on the basic metallurgical study of Phase I. Among other things, it introduces an analysis of the difference in residual stress left in the un-annealed nurse tank examined in the Phase I study and the residual stress left in a nurse tank where the entire tank was annealed after the welding fabrication, examined during the Phase II study. Measurement of those residual stresses were analyzed using neutron diffraction at the Los Alamos Neutron Science Center.

The Phase II study also includes the results of analyzing 532 tanks with single-beam side-angle ultrasonic instruments to detect indications of flaws in the steel. The report was published in December 2013 and is available on the FMCSA Web site.(3) Phase II's survey of the tanks was conducted in 2012.

Anhydrous ammonia (NH_3) is a commonly used agricultural nitrogen fertilizer used for continuously raising certain crops in the same field, like corn that depletes the soil of nitrogen, without having to rotate crops in that field to replenish the nitrogen. The nitrogen-containing compound is distributed to the fields in nurse tanks. Nurse tanks are cylindrical steel tanks designed to hold NH_3 in liquid form under pressure. The tanks are mounted on running gear to allow them to be towed over roadways and across farm fields. The tanks studied in this report are smaller (1,000 – 1,450 gallons) than a typical tractor-trailer (10,000 gallons) and have no man-way to enable internal inspection via either visual, magnetic particle, or fluorescent-dye penetrant. Nurse tanks are towed by trucks or tractors to transport NH_3 to farm fields from retail distribution sites, such as farm cooperatives. The nurse tank is then towed across the farm field while NH_3 is injected into the soil. The Fertilizer Institute (TFI) previously estimated that about 200,000 nurse tanks are in operation across the United States; many of these tanks are 25–50 years old. It is estimated that perhaps one-third have an unreadable or missing data plate and are subject to retesting every five years. The other two-thirds are never tested.

An international survey conducted in 1982 found that more than half of all inspected spherical NH_3 tanks were reported to have cracks.(4) Anhydrous NH_3 was reported to be the number one released hazardous substance in 1997 by the Hazardous Substances Emergency Events Surveillance branch of the U.S. Department of Health and Human Services.(5) Liquefied NH_3 flash vaporizes upon depressurization and causes severe freeze burns when in contact with human tissue. NH_3 is also very caustic and most severely affects the high-moisture-bearing eye, skin, gastrointestinal, and respiratory systems. Exposure to greater than 140 parts per million (ppm) NH_3 can cause corneal ulcerations, iritis, cataracts, glaucoma, and retinal atrophy. Exposure to 1,700 ppm NH_3 results in permanent respiratory damage. Even short exposure to more than 2,500 ppm NH_3 will result in death.(6) In light of these hazards, the safe storage and transport of NH_3 is important to anyone dealing with its handling or transportation.

1.1 STRESS CORROSION CRACKING

Stress corrosion cracking nurse tanks occurs by a process involving a corrosive material that interacts with areas of the tank steel with greater levels of residual or mechanically applied tensile stresses. The extent to which stress corrosion cracking damages a material is determined by the material type, its environment, and applied mechanical or residual stress. Steel is the only commonly used metal, and with the addition of 0.2 percent water it has a reasonable tolerance for the corrosiveness of anhydrous ammonia. Most previous studies of stress corrosion cracking caused by NH_3 were performed in the 1960s and 1980s. More recent literature on the topic is scarce, increasing the importance of this research investigating the structural integrity of nurse tanks.

Stress corrosion cracking can be classified according to three broad categories: active path dissolution, hydrogen embrittlement, and film-induced cleavage.

Active path dissolution occurs in metals with passive protective layers. Accelerated corrosion occurs along crack tips, grain boundaries, or other paths of high corrosion susceptibility.(7) When steel is exposed to a corrosive solution and is under tensile stress, the stress serves to open small cracks. The crack tips act as stress risers and provide a pathway for accelerated corrosion. Thus, the combined effect of a corrosive solution and tensile stress serve as an "electrochemical knife" that slices through the metal.(8) The speed of active path dissolution is limited by the rate of corrosion at the crack tip. Thus, cracks generally grow at rates of less than 1 mm per year.(7)

Hydrogen embrittlement occurs when a source of hydrogen is present in a metal's environment. Hydrogen can damage nearly all metals by filling interstitial sites, which causes the metal to become more brittle. Because of their small size, hydrogen atoms can diffuse into metals very quickly. Furthermore, hydrogen easily diffuses into regions ahead of crack tips when local stresses and lattice dilations are present.(7)

Film-induced cleavage occurs in ductile materials that form brittle films in the presence of a corrosive substance. When stresses crack open the brittle outer layer, the ductile material underneath blunts the crack tip. The film reforms, and the process repeats, causing the metal to continually corrode away.(7)

1.1.1 Mechanisms of Ammonia Stress Corrosion Cracking in Steel

Wilde has shown that hydrogen embrittlement does not contribute to NH_3 stress corrosion cracking, but that NH_3 stress corrosion cracking in steel is of the active path dissolution type.(9) Both intergranular and transgranular cracking occurs as the result of NH_3 stress corrosion cracking. Pure NH_3 does not cause stress corrosion cracking, but in normal environments when mixed with as little as 0.5 ppm oxygen, it does. Adding 0.10 weight percent water to NH_3 has been shown to inhibit NH_3 stress corrosion cracking completely. A standard was established requiring 0.2 percent water must be added to NH_3.

However, because of the different vapor pressures of NH_3 and water, the addition of the water is only effective in the 80 percent of the tank that is in the liquid phase, which contains the 0.2 percent water. Lunde and Nyborg demonstrated that the addition of water to liquid NH_3 fails to provide protection against stress corrosion cracking in regions of the tank above the liquid fill level. Because NH_3 and water have very different vapor pressures, the 20 percent of the tank above the liquid fill level only contains the corrosive NH_3 vapor. This vaporized NH_3 (which is free of the added water) can condense on the upper surfaces of the tank.(10)

Oxygen dissolved in NH_3 increases the corrosion potential of steel. While dissolved nitrogen has little effect on the polarization potential (nitrogen has no electrochemical effect on steel), it accelerates stress corrosion cracking when in the presence of oxygen.(11) Oxygen and oxygen-nitrogen contaminations of NH_3 have been shown to increase stress corrosion cracking; nitrogen-only contamination of NH_3 has not. Though carbon dioxide (CO_2) has been shown to be generally corrosive, it does not appear to contribute to NH_3 stress corrosion cracking.(9)

Several theories have been developed to explain the process of NH_3 stress corrosion cracking.(see references 7, 8, 9, 10, 11, and 12) A film-rupture model has been proposed by Wilde based upon electrochemical studies; it proceeds as follows: steel in contact with NH_3 exists in: (i) a film-free active state, and (ii) a passive state formed by dissolved oxygen. The oxygen forms a noble adsorbed film on all steel surfaces. When the steel is stressed and plastic deformation occurs at slip steps, the oxygen film is ruptured. Direct galvanic coupling between the bare steel at the slip step and the still-intact portion of the oxygen film causes anodic dissolution of the steel until the oxygen film reforms.

Nitrogen competes with oxygen to adsorb to the steel, but nitrogen does not form a protective film itself, hindering re-passivation of the exposed steel. When the oxygen film is ruptured by an applied stress, nitrogen adsorbs in place of oxygen and anodic dissolution is allowed to occur for a much longer time. In the absence of dissolved nitrogen, the oxygen film quickly recovers and crack growth is slow. The nitrogen-oxygen combination causes more rapid dissolution of steel and thus more severe cracking.

Water also has an affinity for adsorption on steel since it is a polar molecule, but unlike nitrogen, it acts as an additional passive film, thus aiding oxygen in slowing stress corrosion cracking.

1.1.2 Examples of Catastrophic Failure by Stress Corrosion Cracking

In 1956, Dawson reported that 3 percent of anhydrous NH_3 nurse tanks failed within 3 years of service in a southern State with a large number of vessels.(13) As a result, standards were put in place, but failures have continued to occur in aging tanks.

1.1.2.1 Calamus, Iowa Incident

In the spring of 2003, a Calamus, IA cooperative worker was killed when the nurse tank he and another man were filling ruptured. The combination of the catastrophic failure and release of NH_3 gas threw one man against a truck, knocking him unconscious. When his coworker came to his aid and pulled him to safety, the coworker inhaled NH_3 gas and eventually died of pneumonia resulting from inhalation burns. After the accident, a detailed investigation was performed by the National Transportation Safety Board (NTSB).(14) The tank was constructed of 3/8 inch SA-455 steel in 1976 and was designed to withstand 250 pounds per square inch gauge (psig), as dictated by the ASME Boiler and Pressure Vessel Code: Section VIII, “Rules for Construction of Pressure Vessels.” Furthermore, the tank was hydrostatically pressure tested at 375 psig after manufacture. Some 27 years after construction, the nurse tank ruptured along a longitudinal weld seam that ran along the bottom of the tank for 53.5 inches.(15)

NTSB determined that the probable cause for the nurse tank's sudden failure was inadequate welding and insufficient radiographic inspection during the tank's manufacture, in addition to lack of periodic testing during the tank's service life. Radioscopic inspection of 100 percent of longitudinal welds was recommended in place of spot radiography, which the current ASME code still allows.(14) However, in 1998 that code added allowing substitution of thinner steel for the tank shell if the longitudinal weld seam is 100 percent radiographically inspected. The latter is the manufacturing practice of both current U.S. nurse tank fabricators.

1.1.2.2 Morris, Minnesota Incident

On June 6, 2005, at approximately 6:00 p.m., a 1,000-gallon anhydrous NH_3 tank catastrophically failed in Morris, MN at the Cenex Cooperative site. The tank had been filled to 85 percent capacity 3 hours prior to the rupture, and it was still sitting at the filling station dock before failure. When the tank failed, a portion of the rear head was blown off, releasing more than 841 gallons of anhydrous NH_3. The bulk of the tank shot 100 yards across the lot, split a utility tractor in half, and hit a parked automobile before coming to rest. The tank's path missed other filled nurse tanks by only 25 yards. Since the failure happened in the evening, no employees were in the area, and no workers were injured or killed. However, a farmer living 0.3 miles to the west of the Cenex Cooperative site was hospitalized for NH_3 inhalation treatment. This tank was dubbed the "Morris Missile" because of the ballistic nature of its motion.(16)

1.1.2.3 Silver Lake, Minnesota Incident

On December 21, 2007, a 1,000-gallon nurse tank being towed by a farmer with his pick-up truck catastrophically failed. The tank tore away from its running gear, slammed into the back of the truck, and then flew across the farmer's front yard. All of the NH_3 in the tank vaporized, and the farmer was hospitalized for NH_3 exposure. Packer Engineering performed an investigation of the accident for the Department of Transportation (DOT). The tank was constructed in 1973. The nameplate information indicated that, upon manufacture, the tank was partially inspected by radiography, and the heads had been stress relieved before being welded to the tank. Visual examination revealed that the crack originated on the inside diameter of the rear head at a region that had previously been dented by an impact with some other object, creating a very high local stress at the dent. Metallographic examination of the crack initiation site revealed that severe crack branching, intergranular brittle fracturing, and transgranular brittle fracturing had occurred. The cause of the accident was reported as rupture due to stress corrosion cracking, accelerated by residual stresses from the dent.(17)

1.1.2.4 Middleton, Ohio Tanker Accident

On August 22, 2003, a DOT MC 331 cargo tank head (not a nurse tank) ruptured while the tank was being filled with anhydrous NH_3 in Middleton, OH. The cargo tank was manufactured in 1977 of American Society for Testing of Materials (ASTM) A517 quenched and tempered steel. The quenched and tempered process is significantly different from annealing. Like annealing, the steel is heated, but to a higher temperature and then cooled very quickly. It is then reheated in a process that seems similar to annealing, but the goal is to reduce the brittleness of the material from the quenching operation. Quenching and tempering operations produce a harder and higher yield strength but more brittle steel than annealing.

This particular cargo tank had a nominal shell thickness of 0.399 inches, minimum head thickness of 0.250 inches, and maximum allowable working pressure of 265 psig at 150^{o}F. The tank's capacity was 10,600 gallons. The head failure occurred when the tanker was about half full of NH_3 at 80^{o}F with an internal pressure of 170 psig. The release of NH_3 caused 100 employees to be evacuated from buildings downwind of the tank. Five people were given medical treatment for inhalation injuries, but no one was seriously injured. The damage from the tank rupture caused an estimated $25,000 in damages to equipment. Before the accident, the tank had been inspected with magnetic particle and hydrostatic testing in March of 2002 and visual inspection in 2003 in accordance with U.S. Department of Transportation (USDOT) mandates. An NTSB investigation into the accident revealed that a 16-inch through-wall crack next to a radial weld on the head had developed. Post-mortem magnetic particle inspection revealed cracks along other radial head welds that had not yet penetrated completely through the wall. When investigators opened the 16-inch through-wall crack to examine it with a scanning electron microscope, an undetected 3-inch through-wall crack opened, as well. Both through-wall cracks exhibited intergranular corrosion and separation (this may be an example of poor cargo tank inspection quality, a separate issue being addressed by FMCSA and the Pipeline and Hazardous Materials Safety Administration [PHMSA]).

Investigation into the NH_3 filling process revealed that water was not being added to the liquid NH_3, though the tanker company handbook stated that 0.2 percent water by weight was to be added to NH_3 carried in its liquid petroleum gas (LPG) tanks. The NH_3 being pumped into the tanker when it ruptured contained less than 0.1 percent water. The reported cause of the failure was stress corrosion cracking, which developed because company practices were not established to explicitly prohibit quenched and tempered steel tankers from carrying NH_3 with less than 0.2 percent water.[(18)]

Collectively, these accidents have raised interest in better characterizing the number, location, size, orientation, and growth rate of SCCs in nurse tanks.

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2. SUMMARY OF PHASE II STUDY

This section of the current report presents a summary of the Phase II study approach and key findings, as background.

As described in Section 1, nurse tanks hold NH_3 in liquid form under pressure. The steels now used to manufacture nurse tanks are all low-carbon, low-alloy steels with mixed ferrite-pearlite microstructures (e.g., ASTM A285, ASTM A455, and ASTM A516 grade 70). TFI previously estimated that about 200,000 nurse tanks are in use in the United States; many are between 20 and 50 years old. The dangers posed by unintended NH_3 releases make the safe storage and transport of anhydrous NH_3 an important concern for both agricultural workers and the general public.

Nurse tank failures can occur either by leaking or by catastrophic failure. Some catastrophic failures, such as those documented in the previous section, have caused severe extensive property damage, injury, and death. Such failures are often attributed to stress corrosion cracking.[see references 13, 14, 15, 16 and 17] Stress corrosion cracking in nurse tanks is crack formation and propagation in the steel caused by the combined effects of a corrosive material in the tank and stresses in the tank's steel from residual or applied tensile stresses. Since nurse tanks do not contain manways by which to enter the tank, magnetic particle and fluorescent-dye penetrant inspection methods on the inside surface cannot be used to find incipient cracks on the tank's interior surfaces unless the tank is cut open. Hydrostatic pressure testing, external visual examination, and ultrasound wall thickness measurements are the only inspection methods in wide use today, and such tests are only applied to the estimated one-third of nurse tanks without data plates.

Prior studies have shown that stress corrosion cracking can occur by three mechanisms: active path dissolution, hydrogen embrittlement, and film-induced cleavage [see references 7, 8, 9, 10, 11, and 12]. Numerous reports have been published on the effects of water, oxygen, nitrogen, and CO_2 on SCCs in NH_3 tanks.[see references 18, 19, 20, 21, 22, 23, and 24]

Nurse tanks are fabricated by forming steel plates into cylindrical, hemispherical, and elliptical shapes, then welding those components into a completed tank. Steel in the heat-affected zones (HAZ) of welds is particularly susceptible to stress corrosion cracking. The HAZ on the head side in the shell to head welds is the most susceptible to stress corrosion cracking. Unless the tank receives post-weld heat treatment (PWHT), the metal in the HAZ retains very high residual stresses from welding, which remain in the tank's steel throughout its service life.[25,26] Some regions near a weld retain a tensile residual stress, others retain a residual compressive stress. Tensile stresses are essential for SCC initiation and propagation, so only those regions with residual tensile stresses are vulnerable to stress corrosion cracking.

Some nurse tanks made before 1999 by one manufacturer were given PWHT after fabrication welding to reduce residual stresses. However, since 1999, with that only manufacturer who was performing PWHT being bought out, no new U.S. manufactured nurse tanks receive such a treatment. PWHT has become an optional item that customers must request and pay for. As such, effectively no new tanks (manufactured in 1999 or later) in the U.S. nurse tank fleet have received PWHT. Analyses performed on failed nurse tanks often report that the crack leading to failure started near a weld.[10] Observations of cracks in and near welds typically show transgranular crack propagation in the fusion zone and intergranular propagation in the HAZ.

Initiation of SCC formation and propagation is a stochastic process. The availability of information about variable stress levels in the steel was inadequate to allow reliable prediction of how likely stressed steel is to develop an SCC when exposed to NH_3. Once an indication is present, laboratory data based on constant tension for crack propagation are available (from Phases I and II of this research) that provide models to make approximate predictions of how rapidly the indication may propagate under constant levels of tension. However, as an SCC propagates through the steel of the tank, say in a HAZ or near a dent, there likely will not be a constant tension at each new point in the tank.

In a nurse tank, there are two possible orientations for an indication that is propagating. If the indication is perpendicular to the weld, then the indication is propagating through a region of the steel where the residual stress levels are far from constant. First they increase dramatically and then decrease to nominal. However, if the indication is parallel to the weld, e.g., propagating around the circumference of the tank in the HAZ of the weld, then the indication indeed may propagate around the tank in a region with a fairly constant stress level.

This research employed single-beam side-angle ultrasound technology. That technology has limited resolution, analogous to having only one eye; i.e., it does not have the resolution to distinguish more than simple things. It can reliably distinguish indications that are perpendicular to the weld seam. However, it cannot tell what their depth of penetration is within the steel, i.e., how close is it to being a crack all the way through the steel. This study points out that phased-array angle-beam ultrasound instruments are increasingly being used in industrial applications, and the greater resolution of such technology is far more likely to make it possible to distinguish indications that are lying close and parallel to the weld joint that are propagating circumferentially around a head-to-shell weld joint or a shell-to-shell weld that joins sections of longer tanks, or longitudinally along a weld joint that connects a shell section to itself, parallel to the weld in the HAZ.

One of the earlier examples of a tank failure might be of the parallel propagation type, namely the Calamus, IA incident. The longitudinal weld along the shell failed. In that case, the SCC could have been propagating along the weld in the HAZ of the longitudinal weld until it reached critical length for failure to occur. The Phase II and III studies were not capable of focusing on parallel propagation possibility, as the instruments used did not have sufficient resolution and thus were unable to collect the needed data to evaluate the risk of an SCC propagating parallel to the weld. As a result, this study says nothing about the level of this risk.

The currently available models based on constant stress for predicting indication propagation are likely meaningless for perpendicular indications, since the stress levels change. This is because the interplay of factors affecting indication growth rates is complex, and the Los Alamos studies documented stress levels vary substantially as you move through the tank perpendicularly away from the weld.

Because of the lack of data on the number, size, and orientation of indications in nurse tanks that have been in service for many years, the Phase II study was performed in 2012 to provide information on indications for cracks and other flaws in a sample of nurse tanks that were currently in service.

2.1 MATERIALS AND METHODS FOR MEASURING FLAW SIZE, LOCATION, AND ORIENTATION

In the Phase II study, an FMCSA-sponsored study examined 532 nurse tanks in central Iowa using single-beam side-angle ultrasound technology to determine the flaw indication populations of those tanks. That technology detected perpendicular indications, which were almost certainly SCCs, as well as long parallel indications in weld joints. Unfortunately, the single-beam technology does not have the resolution needed to distinguish details within the weld joints to determine which indications are SCCs and which are simply the result of a weld joint's geometry.

This use of single-beam ultrasound examination of the nurse tanks was generally performed in accordance with the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code 2011a Section V Article 4: Ultrasonic Examination Methods for Welds. Both the Phase II and III ultrasonic examination of nurse tanks followed this standard, with one exception. In both of these studies, undergraduate student employees who were majoring in material science performed the inspections, and they did not have the number of hours of experience to be certified inspectors, as required by the ASME code. For both the Phase II and III studies, the undergraduate student inspectors were given 80 hours of training (40 classroom and 40 hands-on) in ultrasound inspection by an Air Force-certified Level 7 inspector, the highest level in the Air Force.

For Phase II, the transducers used were 12.7 mm (1/2 inch), 5 Megahertz (MHz), 45-degree, quick-change wedges. Transducer wedges had to be replaced frequently because the areas being measured often contained weld spatter, which caused rapid wear on the wedges when being pushed across these rough surfaces. EZAvenger ultrasound units were used for all inspections. Details of the inspection methods used are described more fully in the Phase II report.[(27)] The sensitivity level set for inspection was capable of detecting indications as small as 1 mm deep and 6 mm (0.24 inch) long.

From June through August 2012, 532 tanks owned by farm cooperative companies in central Iowa were examined by single-beam ultrasound. Only areas near welds were examined, generally in a band approximately 200 mm (7.8 inches) wide centered on the weld. Single-beam side-angle ultrasound cannot discriminate perfectly between likely cracks and other defects in tank steel. In recognition of this fact, the term "indications" is generally used to describe reflections detected by a single-beam side-angle ultrasound inspection that reveals a discontinuity in the metal. Indications perpendicular to the weld are usually SCCs, but other types of discontinuities, usually found in weld joints, are not considered defects, and they too can generate indications.

A mixture of 3,800-liter (1,000-gallon) and 5,500-liter (1,450-gallon) tanks were inspected. In 2012, the Iowa Department of Agriculture and Land Stewardship staff inspected 21,522 sets of nurse tank running gear (e.g., the wheels and suspension for nurse tanks) in Iowa; each set of running gear holds one or two nurse tanks. Thus, the number of nurse tanks tested by this research project is roughly 2 percent of the total nurse tank fleet in Iowa. Figure 1 displays the numbers and years of manufacture for the tanks inspected. As Figure 1 shows for the tanks examined in central Iowa, most tanks manufactured before the mid-1980s had a 3,800-liter capacity, and more recently manufactured tanks found in central Iowa more commonly had a 5,500-liter capacity. The representative from Manufacturer A advised that 3,800-liter tanks are still commonly sold by his company, but apparently in locations other than central Iowa.

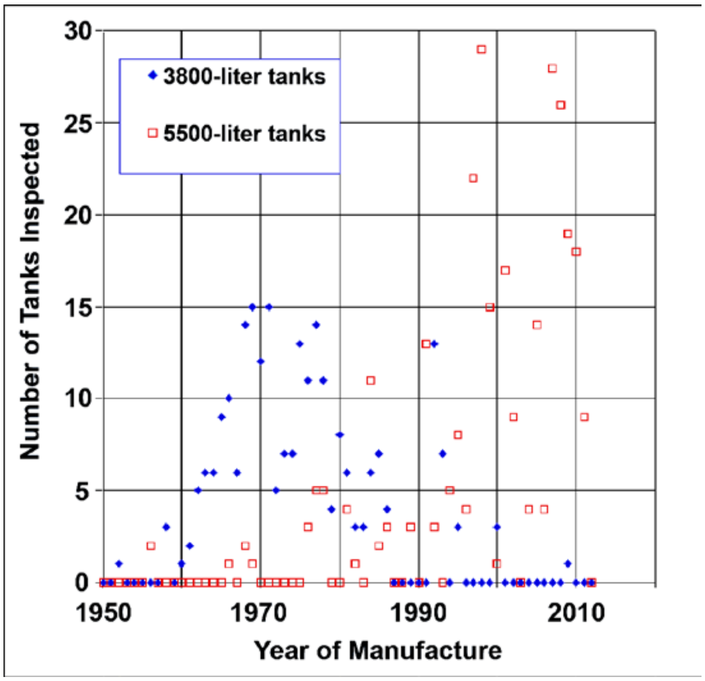

Figure 1. Scatterplot. Tanks inspected as a function of year of manufacture.

2.1.1 Methods Used to Select Tanks for Inspection

Only tanks with legible data plates (which display the year of manufacture) were inspected. If two tanks were mounted on the same running gear, those tanks were accepted for inspection, although a short strip (about 40 cm or 15.7 inches long) of each nurse tank's circumferential welds could not be inspected due to insufficient clearance between the two tanks to allow transducer access. This strip of insufficient clearance was at the mid-point between the top and bottom on the circumferential weld, and as such was below the 80 percent fill line, thus less likely to contain indications.

2.1.1.1 Relation Between Tank Age and the Number of Ultrasound Indications

The ultrasound examinations found more perpendicular indications in newer tanks with the thinner steel allowed starting in 1998 than in older tanks with thicker steel. Figure 2 shows the distribution of indications as a function of year of manufacture. Three factors may have raised the count of indications for the newer tanks.

First, there is a greater circumferential length of weld line on the 5,500-liter tanks (which are more prevalent among newer tanks in central Iowa) than on the 3,800-liter tanks that were more commonly manufactured in the 1980s and earlier.

Second, the change in ASME specifications in 1997 allows tanks to be built with thinner shell steel (beginning in 1998) if the manufacturer follows a 100 percent longitudinal radiographic inspection regimen. Both surviving U.S. nurse tank manufacturers use such an inspection regimen and the thinner shell steel. The thinner steel must carry the same pressure loads as the previously used thicker sections, so the stress within the thinner metal is greater. That greater tensile stress can affect SCC rates, because tensile stress is one of the main driving forces behind crack initiation and growth.

Third, the total absence of full body stress relief annealing treatments (i.e., PWHT) in all tanks manufactured since 1999 (discussed in the following section) means all newer tanks have extremely elevated residual stress in the HAZ from the welding fabrication, which is associated with an increased number of indications.

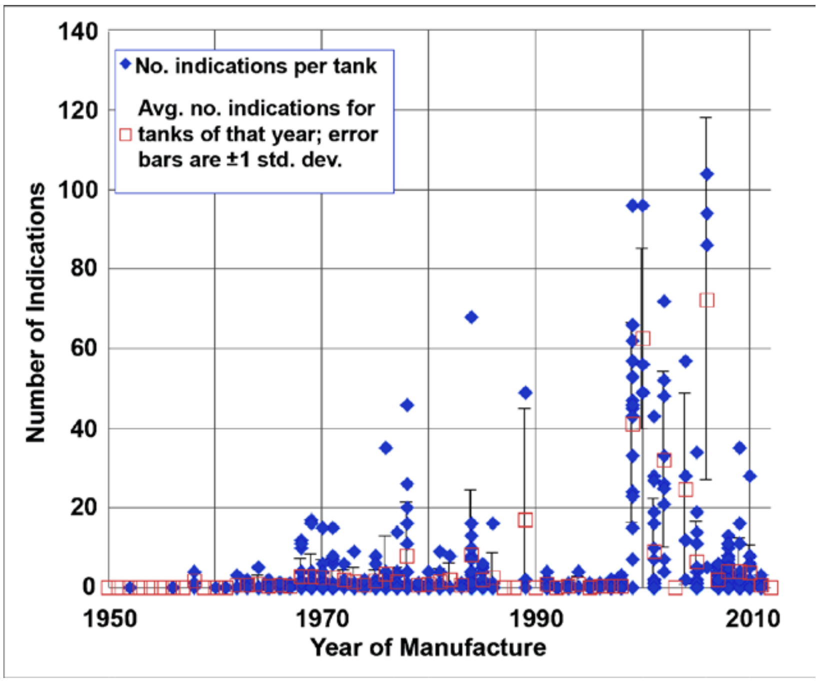

Figure 2. Scatterplot. Number of indications per tank as a function of year of manufacture.

2.1.2 Relation Between Stress Relief Annealing and the Number of Parallel Ultrasound Indications

The effectiveness of PWHT on reducing or eliminating stress corrosion is readily apparent in Figure 2. For tanks tested by this study that were manufactured from 1991 to 1998, 96.8 percent (92 out of 95) were made by Manufacturer C, then a major U.S. tank manufacturer in the Iowa area. That manufacturer's tanks received full-body PWHT. That manufacturer was acquired by manufacturer A in 1999, and as of the date of this research neither of the surviving U.S.

manufacturers PWHT their nurse tanks. That 1991-1999 time period corresponds to the "notch" of tanks with lower indication counts plotted in Figure 2.

The data show that 74 percent of the indications (2,104 of 2,834) were found in the newer, unannealed, thinner steel tanks manufactured in 1999 or later, even though these tanks comprised only 32 percent of the total tanks tested (168 of 532). Data interpretation may be confounded to some extent by the fact that this cessation of PWHT occurred only 1 year after initiation of thinner tank walls.

It is clear that age alone is a poor indicator of the number of flaws in tanks. Some tanks of considerable age have few indications, while much younger tanks can have many indications.

Other factors may also contribute to the observed relation between the number of indications and the age of tanks. For example, if a crack grows to the point that it begins to leak, the tank will either be repaired or taken out of service (if the repair is a weld, it will introduce high residual stresses in the HAZ of that weld repair). Old tanks with leaks may be more likely to have been removed from service than new tanks. If so, then some older tanks that contained flaws may have already been selectively removed from the possible data pool by their owners.

When only tanks manufactured in 1999 or later are considered, the differential effects of decreased wall thickness and discontinuance of PWHT practices are removed/controlled, and the trend one might expect (i.e., more indications in older tanks) does appear somewhat (see Figure 3). The bivariate fit of the data from the 168 tanks shows a less-than-ideal correlation between the number of indications and tank age. The correlation variable describing how closely the line of best fit fits the data (R^2) value of the line on Figure 3 is a bit low, but positive at 0.27.

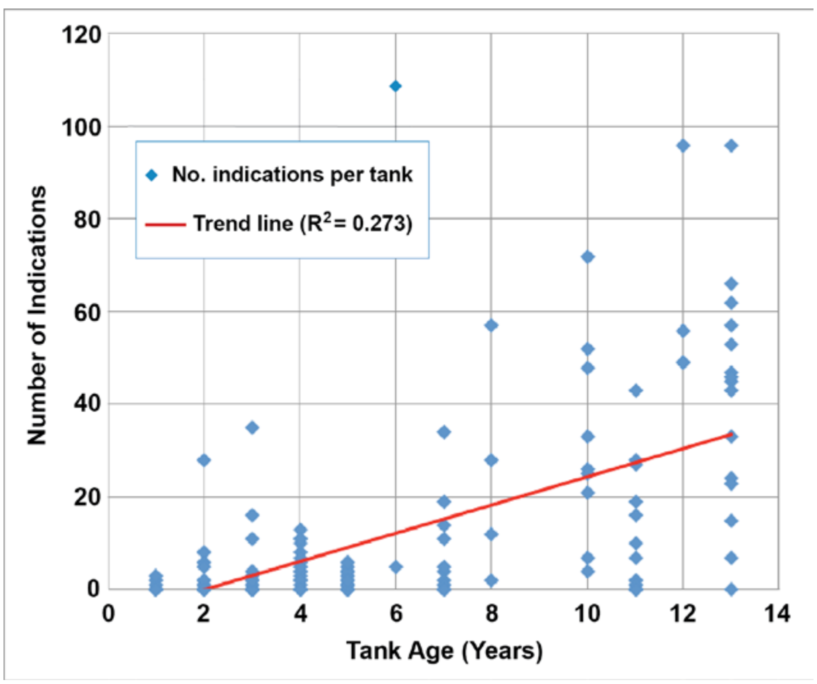

Figure 3. Scatterplot. Bivariate fit of indication number per tank versus tank age (during the Phase II study in 2012) for tanks manufactured from 1999 to 2011.

However, this also dramatically illustrates that both the decision by ASME to allow use of thinner shell steel, and the decision by the manufacturers not to anneal the whole tank after welding, had a dramatic contribution to the greater number of indications that develop. Of the 532 tanks inspected for Phase II, the mean indications per tank was 6.25, with a standard deviation of 14.5. In statistical analyses, such a low mean with a large dispersion indicates a sharply skewed distribution, where the majority of tanks have few indications, but a small fraction of the total population has a large number of indications (the latter may have something to do with poor manufacturing quality control).

Nearly all tanks inspected in Phase II (and re-examined in Phase III) were either 3,800-liter or 5,500-liter tanks. Figure 4 shows that wide distributions of indication counts were seen for both tank sizes, indicating again that age is not a good indicator of propensity for cracking. In fact, newer unannealed 5,500-liter tanks with thinner shells have a larger number of indications on average than older 3,800-liter tanks with thicker steel.

Two types of tank head shapes were found: elliptical and hemispherical. The number of indications per tank for these two populations is plotted in Figure 5. Statistical data is listed in Table 1. Tanks with elliptical-shaped heads had a higher incidence of indications than tanks with hemispherical heads. This is affected by the fact that most newer larger 5,500-liter tanks had elliptical heads, and most of the older 3,800-liter tanks had hemispherical heads. Since the use of newer 5,500-liter tanks is more recent in central Iowa, the majority of the 5,500-liter units tested also had thinner shell walls, and they were not PWHTed. The combination makes elliptically headed tanks appear to have higher numbers of indications. As noted elsewhere, a large proportion of the indications are in the head HAZ.

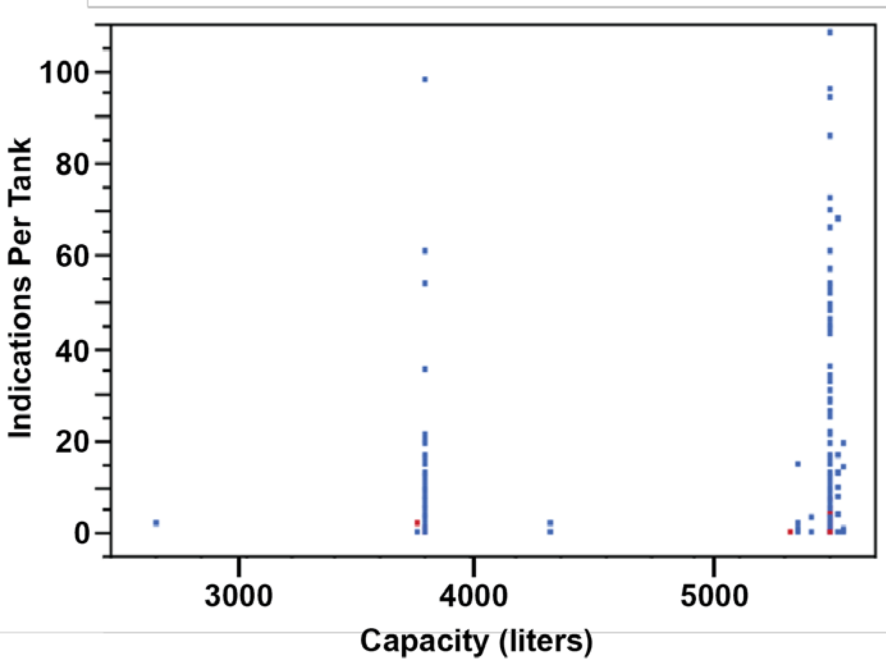

Figure 4. Graph. Number of indications per tank versus tank capacity.

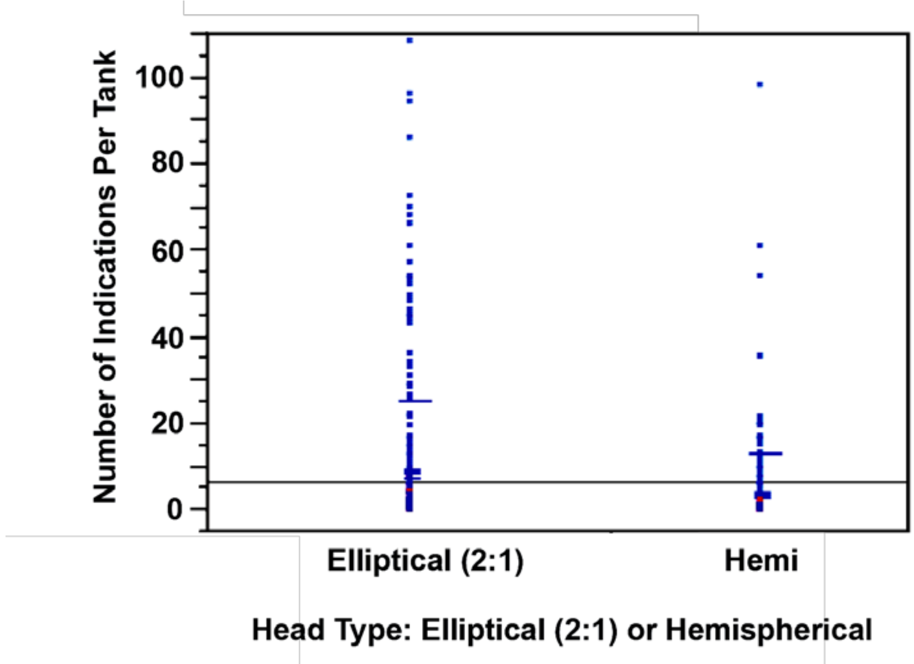

Figure 5. Graph. Number of indications per tank versus head shape. Horizontal lines indicate the mean number of indications for each head type.

Table 1. Mean and standard deviation data on the number of indications for populations of tanks with elliptical and hemispherical heads. This data was not recorded for seven tanks.

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Elliptical 2:1	303	8.26	17.0	0.978	6.34	10.2
Hemi	222	3.58	9.5	0.640	2.32	4.84

Nurse tank heads are fabricated (shaped) from flat steel plate by plastic deformation to form the curvature of the head. This plastic deformation causes residual stresses in the metal. In general, such metal that has been plastically deformed (bent) at a temperature below about 40 percent of the metal's absolute melting temperature (435˚C for steel) will be work-hardened by that deformation. This makes the metal stronger, harder, and less ductile, but more vulnerable to failing by crack growth.

Thus, metal fabricators often include an annealing treatment (holding the metal at an elevated temperature for a period of time, followed by slow cooling) to "relax" the changes in the metal caused by the plastic deformation. This returns the metal closer to the condition it had before the plastic deformation, while preserving the change in dimensions achieved by the plastic deformation. In short, annealing "erases" a portion of the changes in the metal's strength and ductility, while preserving the part's overall shape change.

Residual stresses in the head-to-shell circumferential welds are much higher due to the type of weld geometry than in a shell to shell weld joint. The head-to-shell geometry imposes a greater constraint on the ability of the steel in those weld joints to yield to the high stresses created by the high local temperatures during the welding. The shape of the head constrains the steel of the welded cylinder/shell from expanding/contracting during welding, creating more residual stress than when manufacturing the cylinder/shell body, where circumferential and longitudinal expansions of the steel are not constrained when welded. It is suspected that the elliptical heads are even more constraining on this head-to-shell weld joint than the hemispherical heads. (This could be verified the same way as the weld seam residual stresses in the Phase I and II studies using neutron diffraction analysis at Los Alamos.) Thus, because of the greater constraint on the joint from the heads and the resulting higher residual stresses in such joints, there were more indications found on unannealed tanks at the head-to-shell weld seam.

Stress relief annealing (PWHT) of the entire tank had an even stronger influence on the number of indications per tank than did head geometry. The data from the Phase II report provides a comparison of full-body stress relief versus head-only stress relief, shown in Figure 6, with corresponding statistical data in Table 2. None of the tanks that received full-body stress relief had more than 7 indications, while 1 of the tanks that had only the head's stress relieved had 108 indications. (It is important to note that stress-relieved heads are deformed from plate, given a stress-relief anneal, *then* welded to the tank shell. Thus, the subsequent residual stresses created by the welding of the head-to-shell weld seam are not relieved.) The mean number of indications was nearly 10 times less for tanks where the entire tank had been stress relieved after welding than for tanks without full-body stress-relief annealing. This is an order of magnitude of better performance associated with full-body PWHT.

This order of magnitude difference in the number of indications has relevance for policy regarding the desirability of full-body heat treatment post-welding.

Note: For tanks that will be given a full-body stress-relief heat treatment after welding, it seems that it would not be necessary to separately heat treat/anneal the heads after they are formed, before they are welded to the shell. Stress relief would be achieved in the heads as well as all the other regions of the tank by the full-body stress-relief anneal performed after all welding has been completed on the tank.

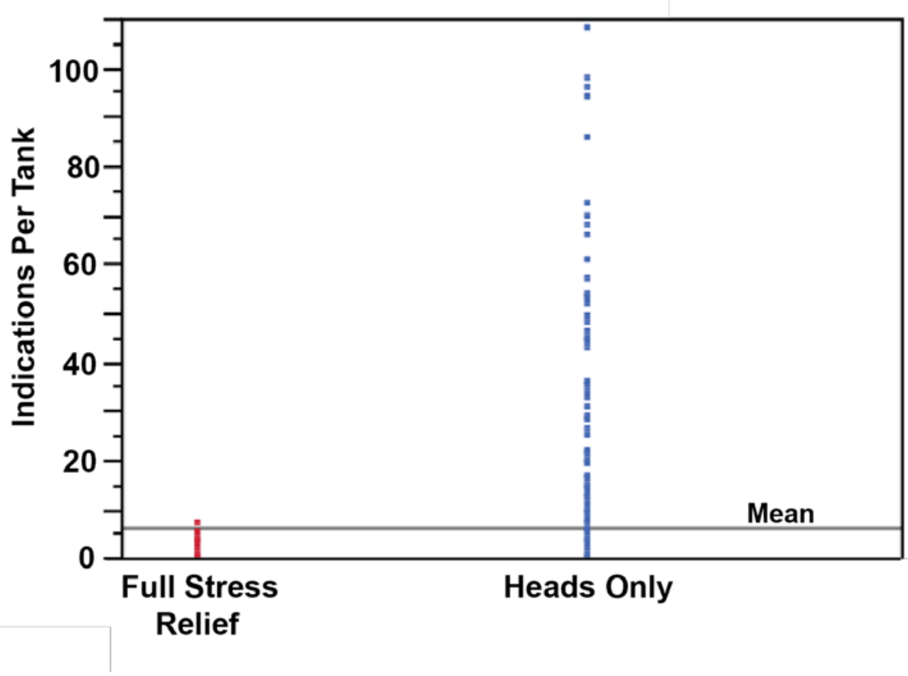

Figure 6. Graph. Average number of indications per tank for fully stress-relieved tanks compared to tanks where only the heads were annealed prior to welding the heads to the shell. The mean number of indications per tank (6.3) for the entire population of 532 tanks is marked with a horizontal line.

Table 2. Number of indications in tanks with or without full stress relief.

Level	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
Full Stress Relief	104	0.769	1.30	0.128	0.516	1.02
Heads Only	428	7.55	15.8	0.764	6.051	9.06

2.1.3 Locations, Numbers, and Orientations of Indications

Of the 532 nurse tanks examined by single-beam side-angle ultrasound, 214 (40.2 percent) had no indications, and 318 (59.8 percent) had at least 1 indication. A total of 3,326 indications were detected. An indication means some irregularity was seen in the ultrasound signal from the steel. Generally this was either the weld itself or from a perpendicular indication in the HAZ next to the weld. Indications in the weld may result from several conditions, namely SCCs, inadequate weld fusion, and the geometry of the weld bead itself.

Perpendicular indications in the HAZ are easier to explain with the limited resolution of the single-beam technology, as they must come from (a) a flaw in the steel used, such as a pre-existing scratch or crack from steel processing, or (b) a post-fabrication crack, which is probably the result of stress corrosion.

Of the 3,326 total indications observed:

- 83.8 percent (2,788) were in the HAZ.
- 14.8 percent (493) were located in the weld.

- 1.4 percent (45) were located in various places not characterized as weld or HAZ. These include baffle plate attachment points, surface flaws, substandard rework with cutting torch causing indications, and surface toe indications.
- 25.0 percent (832) were parallel to the weld line.
- 72.7 percent (2,419) were perpendicular to the weld line.
- 20.8 percent (690) were located in the shell.
- 76.6 percent (2,548) were located in the head.
- 81.4 percent (2,709) were located in or around the head-to-shell circumferential welds.
- 7.37 percent (245) were located in or around the shell-to-shell circumferential welds.
- 5.98 percent (199) were located in or around the shell-to-shell longitudinal welds.
- 2.47 percent (82) were located in or around the leg welds.
- 72.0 percent (2,127 out of 2,954) of the indications in the circumferential welds were located at or above the 80 percent fill line.

There were 2,788 total indications detected within the HAZ. Of the total number of tanks examined (532), 51.9 percent (276) had no indications in the HAZ while 48.1 percent (256) had at least one HAZ indication. The results pertaining to only the HAZ indications are summarized in this list:

- 85.0 percent (2,371) were perpendicular to the weld line.
- 14.8 percent (412) were parallel to the weld line.
- 85.3 percent (2,377) were located in the head.
- 14.5 percent (405) were located in the shell.
- 90.0 percent (2,528) were located in or around the head-to-shell circumferential welds.
- 3.6 percent (99) were located in or around the shell-to-shell circumferential welds.
- 5.3 percent (147) were located in or around the shell-to-shell longitudinal welds.
- 0.3 percent (8) were located in or around the leg welds.
- 75.3 percent (1,978 out of 2,627) of the indications in the circumferential welds were located at or above the 80 percent fill line.
- 78.8 percent (82 out of 104) of the tanks with full-body stress relief (PWHT) had no indications in the HAZ.

For the subset of circumferential welds that join the heads to the shell, they accounted for 81 percent of indications. Of those circumferential shell-to-head weld indications, 72 percent were located in the vapor space above the 80 percent fill line. This is a significant, disproportionately large percentage, since only about one-fourth of circumferential weld length lies above the 80 percent fill line.

2.1.4 Causes of Indications Unrelated to Stress Corrosion Cracking

Not all indications in the nurse tanks examined were related to stress corrosion cracking. As mentioned earlier, given the limited resolution capability of the single-beam technology, indications close to the weld itself are difficult to quantify with certainty using the single-beam side-angle ultrasound. Many of these non-SCC indications are flaws from tank manufacture. Two examples are illustrated below.

Example 1: Cutting a lifting lug from a tank has shown that the regions showing an indication often were caused by voids in the weld between the base of the lifting lug handle steel and the shell. These voids occur because the tank lifting lug handles are T welds that are fillet welded on each side. Figure 7 shows one of these tank lifting lug handles. If complete penetration underneath the T lug is achieved, the welds from either side of the handle meet and no void in the weld under the lifting lug results. However, as shown in Figure 8, if penetration of the welds from each side is incomplete, a gap can exist underneath the lifting lug between the T of the handle and the base metal of the tank shell. These lifting lug gaps may appear to be flaws, since complete weld penetration was not achieved; however, this type of weld does meet ASME Boiler and Pressure Vessel Code because the welds are at least 6.4 mm thick.

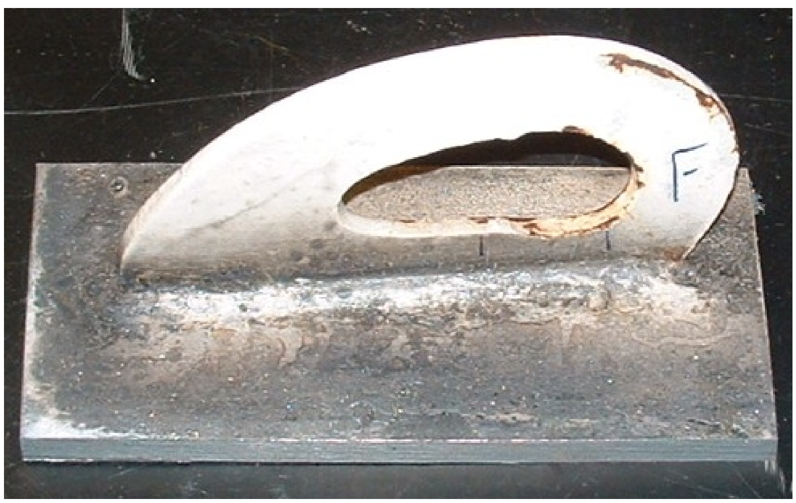

Figure 7. Photograph. Example of one type of tank lifting lug.

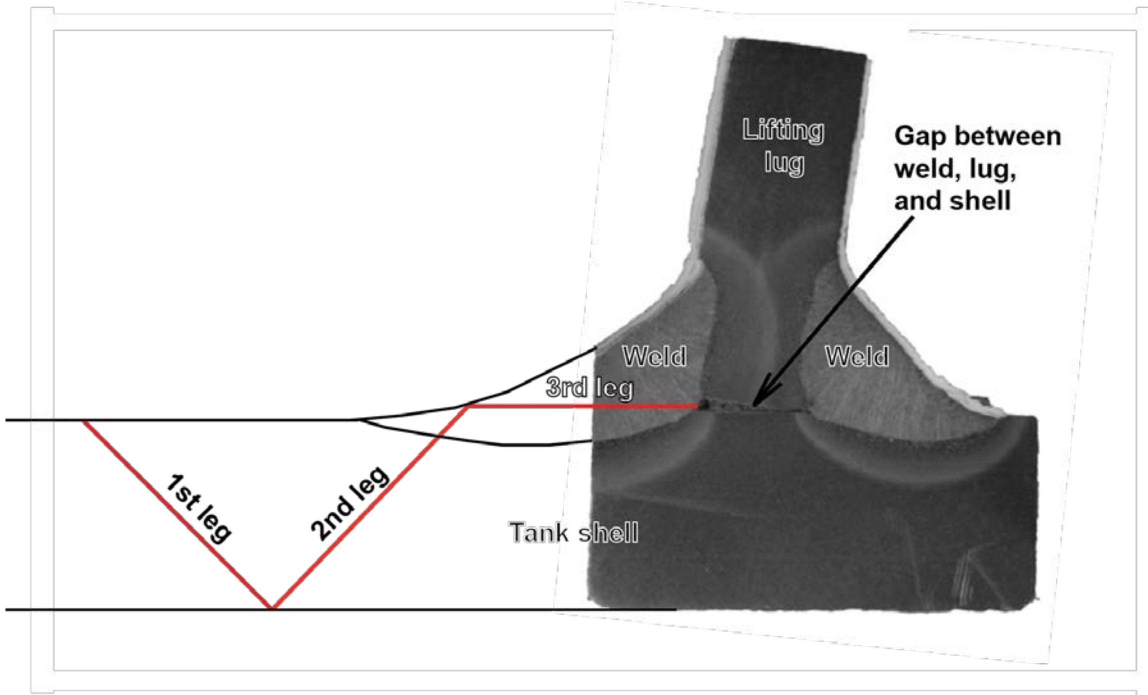

Figure 8. Diagram. Schematic showing how a third 'leg' response in the ultrasound acoustic signal can be caused by a gap between the lug and the base metal, resulting in an indication.

<u>Example 2:</u> Many indications found were at lap welds, such as the head-to-shell weld. The representative for one manufacturer refers to these as joggles (see Figure 9 and Figure 10). These were recorded separately as indications "in the weld" and were classified differently than those from the HAZ. One such tank containing such lap/joggle indications was acquired for structural analysis in the Phase II study. That was done by cutting a section out of the tank to enable direct observation of the weld. Photographs of polished cross sections taken from regions of that tank which had such "in the weld" indications showed that such readings can occur because of the nature of the joint between the two welded sections (see Figure 10).

Other extracted tank sections were cut from a series of tanks that had been removed from service by the tank owners and donated to the Phase I study. In these regions of the tank, the weld bead does not penetrate to include the curved surface of the overlapping plate. This produces a "corner trap" (shown in Figure 9) where the acoustic signal can be reflected, producing an indication from the un-welded corner, which is not a SCC. For comparison, Figure 10 shows an example of a weld where complete penetration has been achieved.

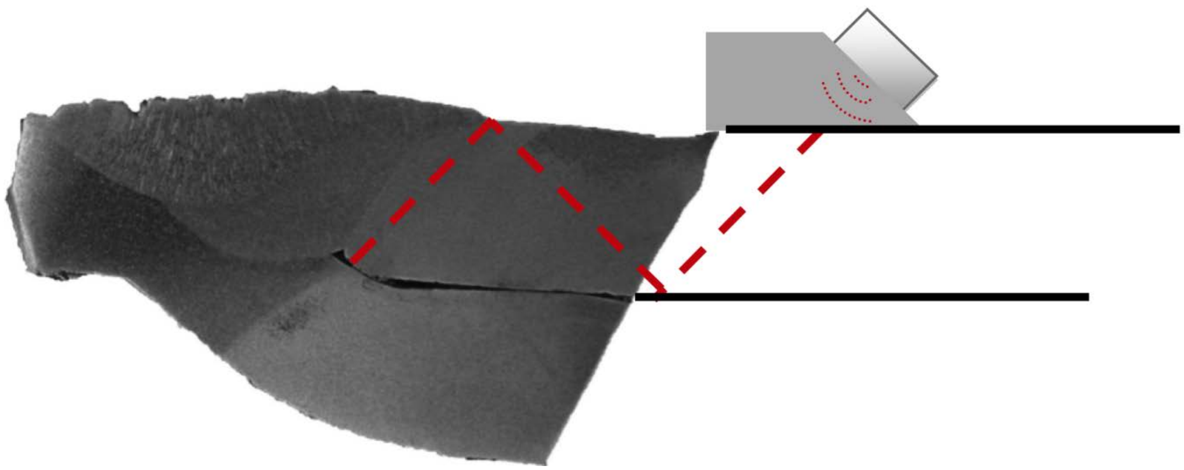

Figure 9. Photograph. A cross section of a lap/joggle joint with a schematic showing why a signal is generated at a weld containing a "blind corner."

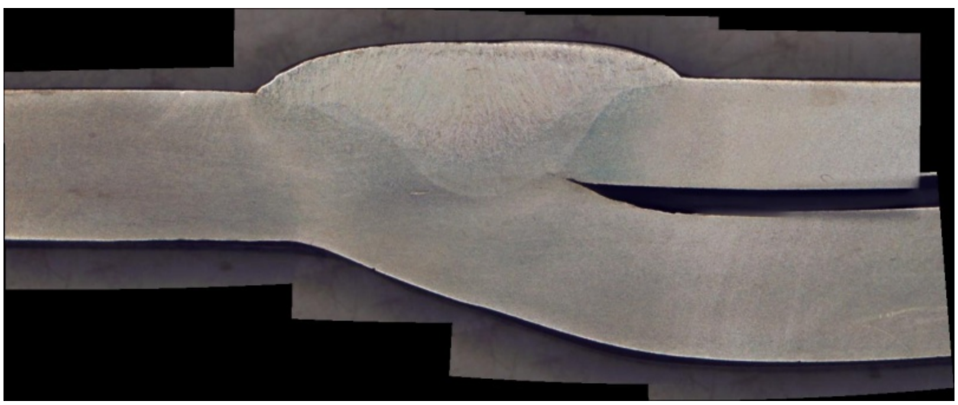

Figure 10. Photograph. A cross-section of a lap/joggle joint showing full penetration of the weld bead. This section of weld did not have indications "in the weld."

These "in the weld" indications were seen in the majority of tanks. Figure 9 illustrates why "in the weld" indications were detectable from only one side of a girth weld, and often more than 50 percent of the length of the circumferential welds were suspected of containing a "blind corner" region. Figure 10 shows a cross section from a full penetration weld with little to no geometric distortion, which yields a greatly reduced chance of causing a "false-call" ultrasonic indication.

The ASME Boiler and Pressure Vessel Code does not call this a lap or joggle joint. Instead, ASME categorizes this type of joint as a "single-welded butt joint with backing strip" and states that maximum allowable joint efficiency for calculation of the strength of such a weld with no radiographic inspection is 0.65 (Section VIII, Div. 1). If there is one or more section of the shell, there is a similar butt joint with backing strip used to make those joints.

Even with this ASME allowance, the preponderance of tanks with blind corner weld indications and the pervasiveness of indications on some tanks (more than 50 percent of circumferential welds) give cause for concern. This is because tanks have shown evidence of poor welding at these joints in post-failure analysis.

It is worth noting that the heads are added to the tank after all other fabrications are completed, and thus can only be welded from the outside. In contrast, the longitudinal weld along the shell holding it together is done from both sides, since it is possible to get inside the shell without the heads. The same is true for the possible one or more sections of the shell that may be joined together using overlapped joints. Again, since there are no heads on, just like for the longitudinal seam, the shell joint(s) can be welded from the inside, as well.

Details of head-to-shell indications parallel to the weld cannot be adequately distinguished with single-beam side-angle transducer ultrasound inspection because of the inherent resolution limitations of a single beam. That makes it nearly impossible to distinguish with single-beam side-angle ultrasound which one of multiple possible geometries is causing a particular indication.

An alternative that was not tested in this research is the use of phased-array (multi-beam) ultrasonic inspection, which uses multiple small transducers. Such instruments can provide better resolution for more involved indications, plus possibly detect the depth of the indication (the amount of penetration it has through the tank).

2.2 INDICATIONS ATTRIBUTABLE TO STRESS CORROSION CRACKING AND THEIR THREAT TO TANK INTEGRITY

While many indications were found in the 532 tanks, none of these indications could be confirmed to pose an imminent threat to the structural integrity of the tank, because single-beam side-angle ultrasound cannot determine the depth of the indication. Factors that need to be considered in judging the safety risk posed by a given indication include:

- Location of the indication—is it found where false echoes are typically found?
- Size of the indication—is it long enough (or nearly so) to be a critical-sized indication if one assumes that it penetrates completely from the tank interior wall to the tank exterior?
- Orientation of the indication—how dangerous is an indication in that orientation?

Indications in the weld tend to remain static as the tank is used. However, HAZ indications are a greater safety concern because the only explanations for these indications are a pre-existing crack from manufacturing or a crack that resulted from stress corrosion cracking, and the latter cracks can grow as the tank is used. The incidence of cracks from manufacturing in rolled, mild steel plate that is subsequently welded is extremely low, so indications in the HAZ are almost certainly SCCs.

Since HAZ indications pose greater safety concerns than in-weld indications, a Pareto plot (Figure 11) was developed showing the distribution of HAZ indication locations found in the tanks tested with the limited single-beam technology, as well as whether the indication is parallel or perpendicular to the weld. This plot shows what types of indications occur most often and where they are located. Nearly 80 percent of the indications are found at the head-to-shell weld on the head side, perpendicular to the weld.

As noted above, the head side has greater stresses after welding due to elements of its shaping and the type of weld used when joining it to the shell. When a head/cap is placed on the end of the cylinder/shell, the steel at that end cannot expand as freely when heated; the shape of the head/cap prevents this. Although the head/cap itself is also heated at the weld site, the metal that forms the head/cap restricts expansion much more than is expected in a simple hoop section of a shell-to-shell weld. The design and geometry of the shell-to-head weld is also different, providing a larger mass of metal subject to expansion/contraction, which again results in higher residual stresses after welding.

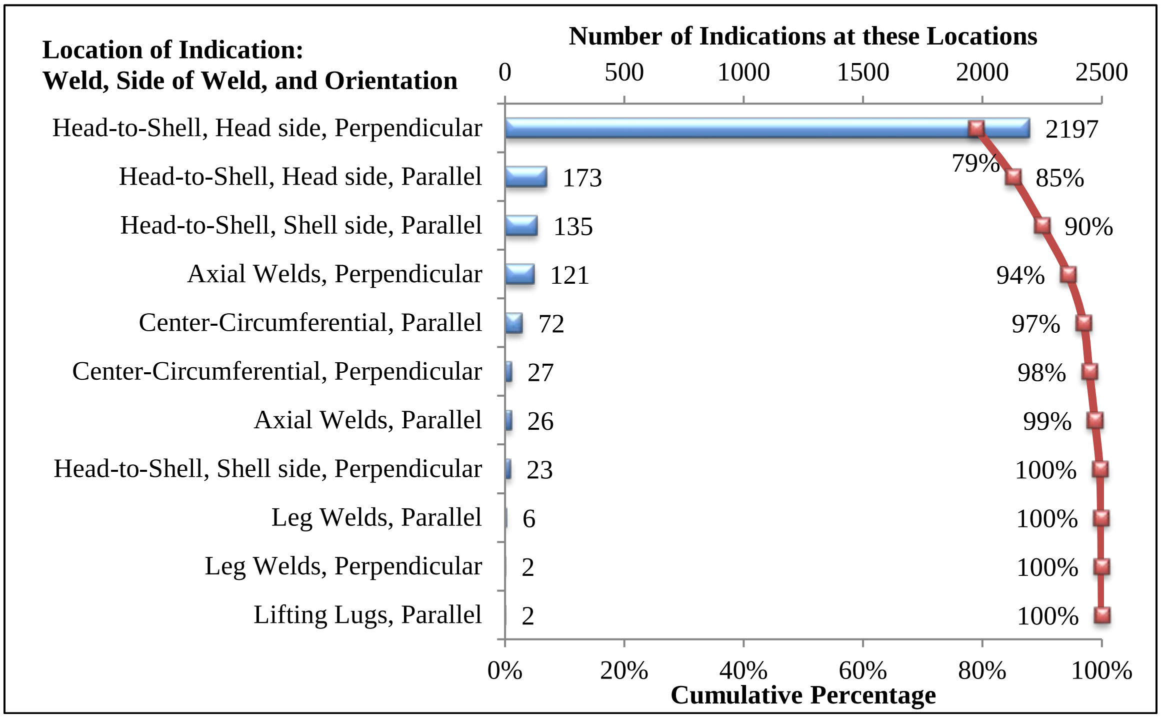

Figure 11. Plot. Location of HAZ indications in a population of 532 nurse tanks.

Data concerning the length of the indications were collected, but it is difficult to draw definitive conclusions as to the nature of the indication. For example, most of the indications of great length run parallel to the weld. However, single-beam side-angle ultrasound does not have the resolution necessary to distinguish whether these indications are due to the shape of the weld bead or incomplete weld penetration rather than a parallel SCC. There were 538 of those, and as noted previously, the Phase II study coded them separately. Obviously, none of those indications found are through-cracks, as a through-crack results in immediate escape of anhydrous NH_3, which is readily detected by the odor and corrosion discoloration at the point of penetration.

If one assumed a worst case scenario by allowing that the indications recorded in the HAZ did represent through-cracks, then of the 2,784 total indications found in the HAZ, only 93 of them in 55 tanks (10 percent of all tanks) would be of critical length at -70°C, where the stress concentration factor is only 85 Megapascals (MPa)•$m^{1/2}$. Only 57 indications from 35 tanks (6.5 percent of all tanks) would be of critical length at 20°C, where the stress concentration factor is 158 MPa•$m^{1/2}$. These results are shown in Figure 12. Note again, this assumes the worst case scenario that through-cracks are present; this clearly is not the case (details of why these conditions are cited are discussed in the Phase I final report). [1]

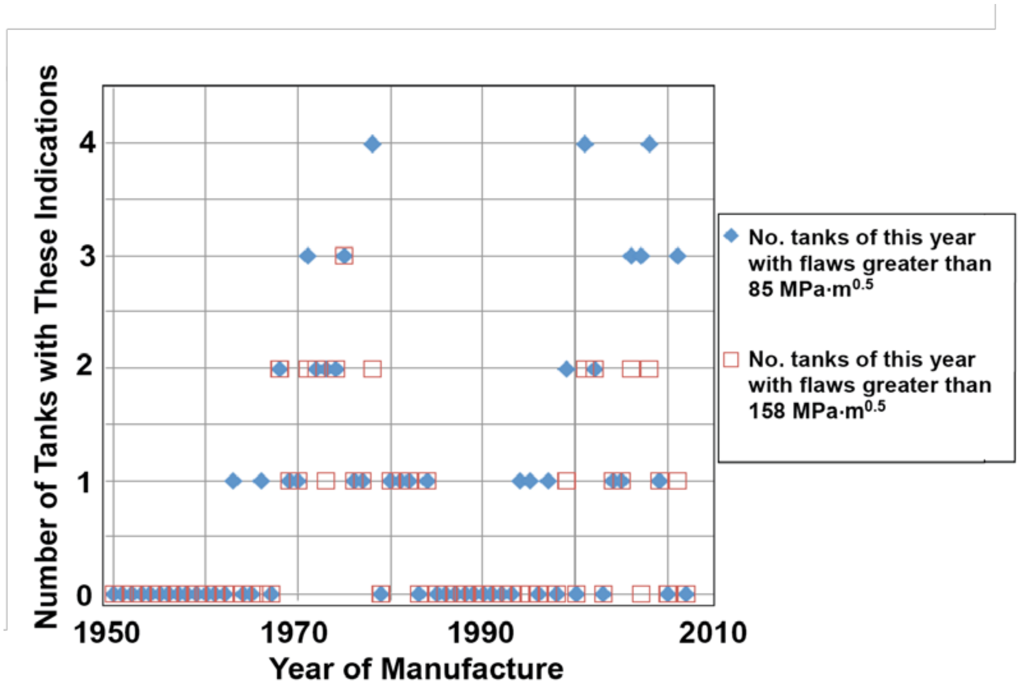

Figure 12. Scatterplot. Tanks with critical crack lengths assuming through-cracking exists. An 85 MPa·m$^{1/2}$ flaw is a critical-sized flaw at -70˚C, the temperature reached when compressed NH_3 is vented to the atmosphere. A 158 MPa·m$^{1/2}$ flaw is a critical-sized flaw at 20˚C.

Indication orientation is relevant because the direction and magnitude of the residual tensile stresses near welds vary between hoop (circumferential), axial (longitudinal), and radial directions and as a function of distance from the weld. In general, residual hoop stresses are the largest of the three types, and all three of the stresses diminish substantially as one moves away from the weld.[26] SCCs propagate faster where the tensile stress is greater in the HAZ, thus they are less likely to continue propagating perpendicularly away from the weld beyond the HAZ.

Classification of these indications is complicated by the fact that some cracks are present in branched networks (Figure 13). Where gently curving indications were detected, the lengths of branched indications were classified as being aligned with whatever direction comprised the largest portion of the indication complex.

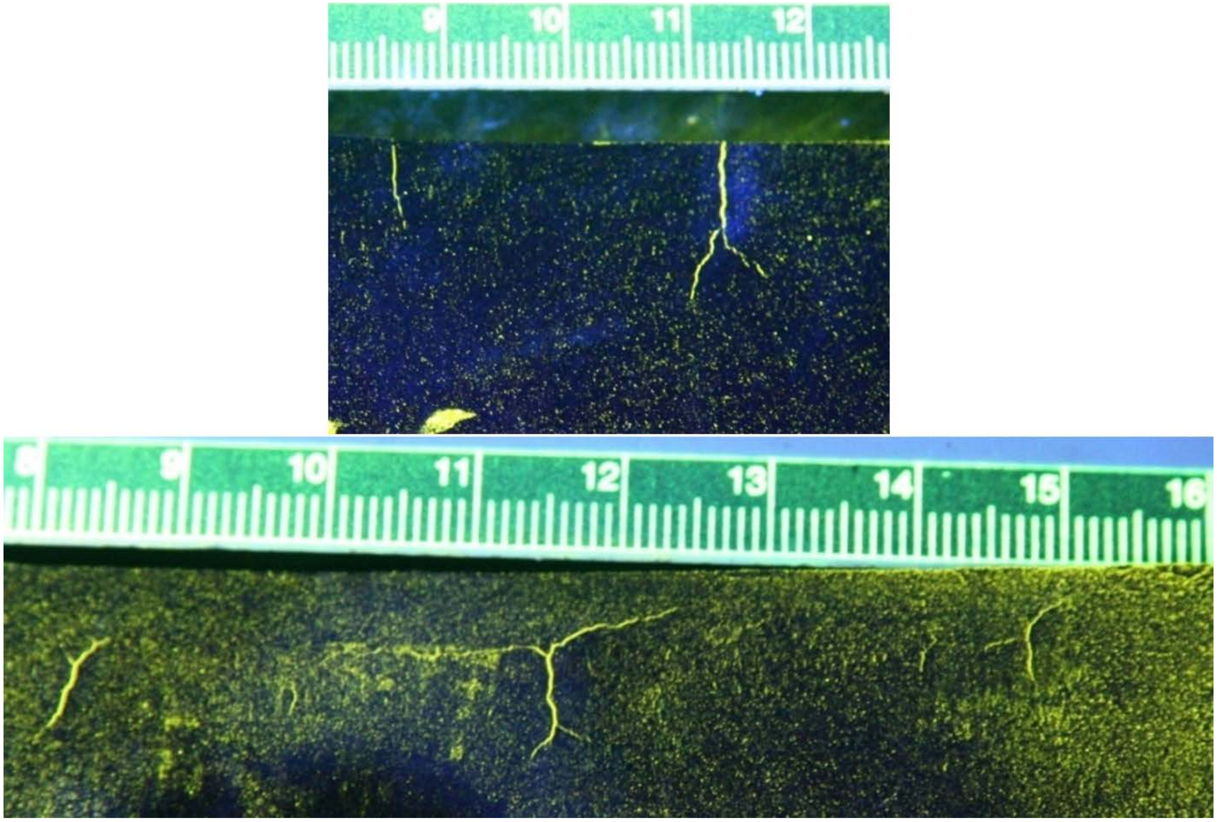

Figure 13. Photograph. Magnetic particle-highlighted examples of crack branching in nurse tank SCCs. Finest divisions on the scales shown are millimeters.

2.2.1 Effects of Tank Age, Size, and Wall Thickness

The number of indications observed varied with tank age, tank size, and tank wall thickness. Unexpectedly, younger tanks had more indications than older tanks. This is probably due to a combination of factors; the younger tanks used in central Iowa were mostly the larger 5,500-liter tanks with more steel for indications to occur on, while older tanks were mostly 3,800-liter tanks. Larger tanks have more material and more linear feet of weld, so even at the same percentage levels (X indications per foot of weld), indications would be expected to be more numerous in larger tanks. However, as pointed out below, the number of indications in the newer larger tanks far exceeds such an expected proportionate increase.

ASME guidance issued in 1997 said that thinner steel could be used for the shell if the longitudinal welds on the shells receive 100 percent radio graphical examination. As a result, all younger tanks have thinner shell walls. Per the testing specifications of the NTIP, the same thickness of thinner steel is allowed for both the 3,800 and 5,500-liter tanks.

Older, thicker tanks that were given a PWHT had far fewer indications than even-older tanks with the thicker steel but no PWHT. These data are summarized in Table 3 and Table 4. Of the 104 fully stress-relieved tanks shown in Table 3, 81 were 5,500-liter tanks and 23 were 3,800-liter tanks. The far lower indication count of the PWHT group, largely composed of 5,500-liter tanks, than even the 3,800-liter group seems to indicate that even if the larger size led to more indications, the PWHT more than overcame the greater risk of larger size.

Table 3. Number of indications, mean, and standard deviation data on the number of indications for 5,500-liter, 3,800-liter, with and without PWHT.

Group	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
5,500-liter	208	11.63	19.65	1.36	8.95	14.32
3,800-liter	220	3.70	9.58	0.65	2.42	4.97
PWHT*	104	0.77	1.30	0.13	0.51	1.02

*Almost 80 percent of the PWHT tanks were the larger 5,500-liter tanks. There are not enough data points to meaningfully separate into two rows.

The 3,800-liter tanks have approximately 790 cm of welds; 5,500-liter tanks have approximately 1,025 cm of welds, which is 1.3 times that of the 3,800-liter tanks. Most of the 5,500-liter tanks happened to be newer tanks manufactured using the thinner shell steel. However, they had 3.15 times (11.63/3.70), not 1.3 times, more indications than the older 3,800-liter tanks with thicker shell steel.

For further insight into this, we removed/controlled for the effect of newer tanks being manufactured with thinner steel by removing the thinner steel tanks manufactured beginning in 1998. This left only those tanks manufactured before 1998 in the analysis. The identified trends are shown in Table 4.

Table 4. Number of indications, mean, and standard deviation data for tanks manufactured on or before 1998, with and without PWHT.

Group	Number	Mean	Std Dev	Std Err Mean	Lower 95%	Upper 95%
5500 liter	45	8.07	14.64	2.18	3.67	12.47
3800 liter	216	2.77	4.92	0.34	2.11	3.43
PWHT*	104	0.77	1.30	0.13	0.51	1.02

*Almost 80 percent of the PWHT tanks were the larger 5,500-liter tanks. There are not enough data points to meaningfully separate into two rows.

In Table 4, the 5,500-liter tanks manufactured in 1998 or earlier have 2.91 times (8.07/2.77) as many indications as the 3,800-liter tanks. Thus, the larger 5,500-liter tanks still have considerably more indications per weld inch, even when the effect of the reduced wall thicknesses used in newer tanks is eliminated.

2.2.2 Importance of Tank Size and Wall Thickness on Hoop Stress

In any cylindrical pressure vessel, stress induced by the pressure inside the tank causes hoop stress in the tank. This hoop stress scales relative to the ratio of the tank radius divided by the tank wall thickness, as shown in the following equation:

Hoop Stress= (Pressure x Tank Radius)/Wall Thickness

If one assumes the same level of residual stresses result due to welding in the thinner tanks as exists in the thicker tanks, then for each size tank a higher hoop stress will occur in the thinner steel tanks than in the older thicker steel tanks. This is because the force generated by the anhydrous NH_3 must be absorbed by a now thinner cross-sectional area of steel sheet. Slightly restating the above equations, we see F = stress/cross-sectional area of the steel sheet. Thus, indications are expected to nucleate and grow faster in the thinner steel, given the same root cause of stress corrosion cracking. This seems consistent with the higher rate of indication formation and growth observed in the tanks with the newer, thinner steel, regardless of size.

In addition, if you want tanks made with a larger radius, e.g., 5,500-liter versus 3,800-liter tanks, to have the same hoop stress regardless of the size of the tank, then larger tanks would require correspondingly greater wall thickness to keep hoop stresses the same. However, as permitted by the NTIP standards, the 5,500-liter tanks are made with the same steel thickness as the 3,800-liter tank. Thus, while using the same steel thickness is allowed by the current NTIP, it means larger hoop stress exists in larger tanks.

2.2.3 Importance of Head Thickness

In Section 3.6 below, it is noted that the NTIP minimum thickness specification for the heads is less than that of the shells. While this research did not focus on this aspect, the substantially higher percentage of perpendicular indications in the heads of tanks, and the fact that design specifications allow thinner steel in heads than in the shell, appear to be related.

2.2.4 Importance of PWHT

The Phase II report points out that while PWHT substantially reduces the residual stresses in the HAZ to below-residual levels that approach the critical yield point of the steel, PWHT does not remove all residual stress. Thus, as highlighted above, the larger the tank, the larger the hoop stresses imposed by the larger size. Any residual stresses not removed by PWHT are going to add to the increased hoop stress from the larger size and thinner steel.

After PWHT, the total remaining residual hoop stress in the larger, thinner steel tanks will still be higher than what was achieved by post-weld heat-treating the smaller, thicker steel tanks. Even so, the post-weld heat-treated tanks of any size will have the residual stress in the HAZ of the hoop reduced to levels considerably below the yield point of the steel and thus will be considerably less likely to have nucleation/initiation of an SCC.

2.3 CONCLUSION

Various conclusions can be drawn from these findings (see Figure 14 for a visual representation):

1. The Phase II survey examined 532 in-service nurse tanks and found 3,326 total indications. Most indications (84 percent) were in the HAZ, but a significant number (16 percent) were in the weld fusion zone. About three-fourths (73 percent) of the indications were perpendicular to the weld line, and one-fourth (25 percent) were parallel to the weld line. Only 21 percent of indications were located in the shell, which is the cylindrical main body of the tank, while 77 percent were located in the heads, previously hemispherical on 3,800-liter tanks and now elliptical ends on 5,500-liter tanks.
2. The circumferential welds that join the heads to the shell accounted for 81 percent of total indications. Of those circumferential weld indications, 72 percent were located in the

vapor space above the 80 percent fill line, a disproportionately large percentage, since only about one fourth of circumferential weld length lies above the 80 percent fill line. The vapor area is filled with 100 percent corrosive NH_3 vapor, with no water present in the vapor to prevent the SCC, significantly increasing the SCC rate above the 80 percent fill line.

3. Only 7 percent of indications were in shell-to-shell circumferential welds, and 6 percent were in longitudinal (girth) welds in the shell.

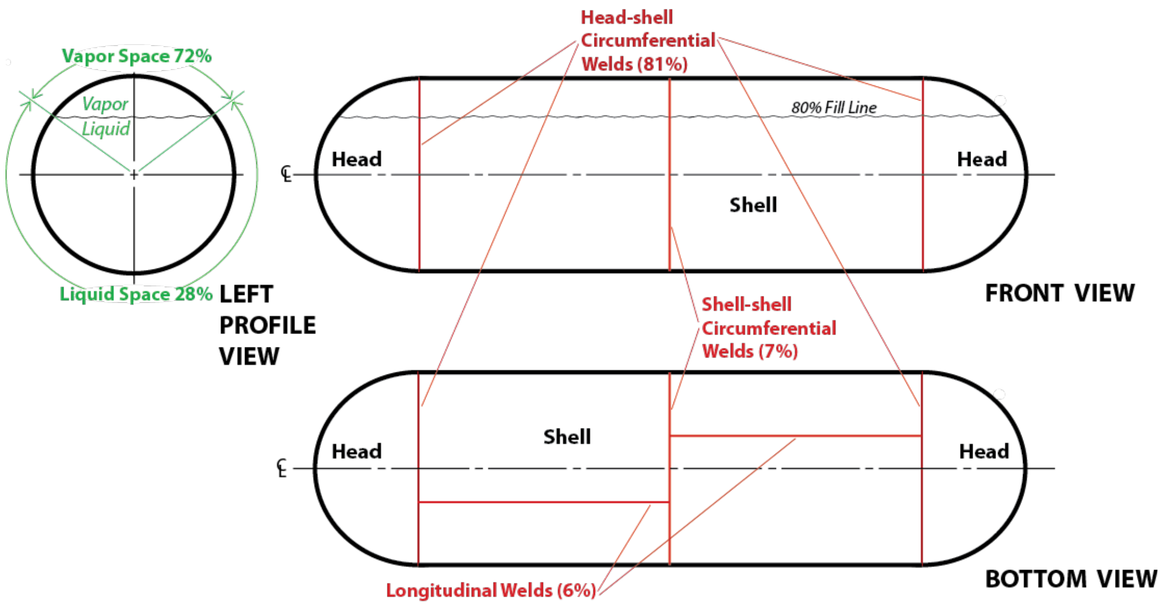

Figure 14. Schematic. Distribution of indications in nurse tanks.

4. There were 168 tanks examined that were manufactured in 1999 or later and thus had no PWHT. They accounted for 74 percent of the indications found in the HAZ, even though those tanks comprised only 32 percent of the total tanks inspected.

5. Full stress-relief annealing (PWHT) sharply reduced the number and severity of SCCs. Of the tanks with full-body PWHT, 79 percent had no indications in the HAZ. Both of the two remaining U.S. companies now actively manufacturing nurse tanks have and use (for other tank fabrications) annealing facilities/ovens that could perform full-body PWHT anneals on the nurse tanks they manufacture. Such full-body annealing presumably could replace the current stress relief annealing of heads being performed prior to welding the heads to the shells.

6. Single-beam side-angle ultrasonic testing is an effective method for determining the location and size of perpendicular indications in the HAZ, but because it is only a single beam, it does not have the resolution for distinguishing indications parallel to the weld in the HAZ from weld geometry. This introduces uncertainties into those measurements. It also cannot determine the depth of the indication in the steel (how much the crack penetrates the hull). Location and size of indications need to be considered when determining whether a true SCC exists.

7. Value of Annealing Nurse Tanks

The substantial effectiveness of stress relief annealing—sometimes called post-weld heat treatment (PWHT)—on reducing or eliminating stress corrosion cracking in nurse tanks was documented by this research.

Data demonstrating the effectiveness of PWHT was documented by two different methods of measurement by the Phase II research. First, empirically by neutron diffraction analysis at the Los Alamos Neutron Science Center. The reduction achieved in residual stresses around annealed welds was quantitatively measured versus the residual stresses around un-annealed welds. In tanks that were not PWHTed, the remaining residual stress in the metal in the Heat Affected Zone (HAZ) left after the weld was just below the level where the steel would structurally fail. Unless relieved, that level of stress remains in the steel for the life of the tank. It provides a strong catalyst for the initiation of a SCC in the presence of the corrosive anhydrous ammonia. In tanks that were PWHTed, the remaining residual stresses in the steel were reduced dramatically below the level where the steel would structurally fail. The remaining levels of residual stress are substantially less likely to provide an effective catalyst for initiation of SCCs.

Second. Field data was collected by examining a sample of nurse tanks being used by agricultural cooperatives in the mid-west around Ames, Iowa. That field data found that 74 percent of the total indications detected by single-beam ultrasonic examination were found in the newer, un-annealed tanks manufactured in 1999 or later, when no nurse tanks were manufactured with PWHT. The newer tanks comprised only 32 percent of the total tanks tested (168 of 532 tanks).

This combination of empirical measures of metallurgical residual stress and field measures of the number of cracks detected in a sample of operational tanks indicate that annealing/PWHT is associated with the following: 1) a sharp reduction in a principal cause of stress corrosion cracking (residual stresses remaining in the HAZ of the tanks) and 2) substantially fewer and less severe indications observed in tanks that received PWHT compared to those that did not.

The manufacturers of nurse tanks already own the ovens needed to perform PWHT on their nurse tanks. This is because they also manufacture other large steel containers that by regulation are required to be annealed/PWHTed. That means it would not be a significant new investment expense for those manufacturers to PWHT the nurse tanks they manufacturer. Representatives of the manufacturers who participated in the technical oversight group for the nurse tank research were asked by one of the members of the oversight group who represented an agricultural cooperative if they would PWHT tanks he ordered for his cooperative. They responded that if asked by the customer, they would anneal nurse tanks for that order. They approximated off the top of their heads that the additional cost for doing so would likely be no more than $100 per tank, or possibly less. For a new 1,450 gallon nurse tank that costs approximately $5,400 (tank only, no running gear), that would be slightly less than a 2 percent increase in cost.

Based on the benefits of avoiding development of SCCs in PWHTed nurse tanks, it may be worthwhile for The Fertilizer Institute, who represents the agricultural cooperatives and others who use nurse tanks for distribution of anhydrous ammonia, to point out on their website and other materials to their members that for a minimal increase in cost they can have their nurse tanks PWHTed. It could be financially beneficial in the long-term for the cooperatives to insist that nurse tanks they order must be PWHTed.[2]

[2] As of 2016 the two remaining manufacturers of nurse tanks in the U.S. began PWHT of all new nurse tanks as part of their manufacturing process. Both participated in this research and were aware of the finding that PWHT was an extremely effective and relatively inexpensive means for substantially reducing SCC.

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3. PHASE III STUDY

In Phase III, a second series of single-beam side-angle ultrasound examinations were performed on 411 tanks that could be located of the same 532 tanks examined in Phase II to assess the effects of 3 years of continuing use on the length of the predominantly perpendicular indications previously found and on the formation of new indications. This Phase III survey of tanks was conducted in 2015.

The Phase III study differed from the Phase II study in several ways. First, the actual surveying of the tanks was done under the direction of Mr. Darrel Enyart, a full-time non-destructive evaluation (NDE) scientist at the Center for NDE. This allowed for a more careful examination of the data than was possible in Phase II. In the field, Mr. Enyart helped the undergraduate student inspectors assess the relevance of indications. It was also his experience that brought about the acquisition of different ultrasonic probes for the instruments.

The new probes performed better than those used on the same instruments in Phase II. The increased resolution of the new probes improved assessment of the location of reflections from within the material. Mr. Enyart's expertise also allowed for a more critical examination of the acquired data after it was collected. The end result was that many of the suspicious parallel indications found and recorded in the Phase II study were judged to be most likely due to the single beam scattering from the welds, rather than a result of an actual parallel crack formation in the HAZ next to the weld. That had been suspected in the Phase II study, but Mr. Enyart's expertise enabled the researcher to confirm that suspicion more clearly.

The first task associated with the Phase III study was to locate as many of the tanks examined in Phase II as possible and obtain permission to re-examine them using NDE methods. This task consumed a significant amount of time as numerous tanks had been moved to various other locations, sold to other entities, or taken out of service for one reason or another. This is an indication that there is considerable movement of nurse tanks over even the short period of 3 years.

The cooperatives (co-ops) contacted included Heartland Cooperative, West Central Cooperative, and FS Cooperative, and the authors are grateful for their assistance in locating tanks and giving permission to examine the tanks. Ultimately, only 411 of the original 532 tanks (or 77 percent) could be located.

The Phase III study again used undergraduate student trainees majoring in material science to carry out the actual inspections, assisted by Mr. Enyart. Six students were selected and trained in basic ultrasonic testing via an 80-hour training program comprised of 40 hours of classroom plus 40 hours of hands-on training and testing. This training culminated in a final 40-question fundamental knowledge test and an individual hands-on test using samples of actual nurse tank material with real, known flaws that had been previously located and verified from the internal side by magnetic particle examination.

A typical field inspection involved locating a tank that was part of the Phase II study and creating paperwork to record the Phase III results. In all cases, this included the new tank thickness results, which were only taken for the Phase III study. If any indications were located and determined to be relevant, they were also recorded. The single-beam side-angle ultrasonic gain of the side-angle probes was set for each inspection using the same through-hole setup bar that was used in Phase II, in order to keep inspection thresholding the same as the previous study. This bar is a known sample with known defects, e.g., holes drilled through from the side, that must be located from the top of the bar. The purpose is to enable setting of the gain of the instrument to produce a known return.

After a day of inspections, before leaving a cooperative's tank farm, the Phase III results were compared to Phase II results. This allowed inspectors to double-check any tank with significant changes from the Phase II results.

After inspections were concluded at a location, the results were entered into a tracking spreadsheet, and indications that were located in the same location on a tank were entered as a new entry on the same row as the corresponding Phase II indication's information. If an indication appeared to be unique to the Phase III study, it was given a new row.

Safety Protocol

In all inspection locations, the inspectors followed a two-person safety principle. No inspector would ever go to any tank farm or remote location of a tank farm alone. At the tank farm locations, the inspectors had access to a battery-powered NH_3 detector set to trigger an alarm at the Occupational Safety and Health Administration (OSHA) Permissible Exposure Limit [time weighted average (TWA) = 50 ppm (35 mg/m^3)] and OSHA Short Term Exposure Limit [TWA = 35ppm (24 mg/m^3)]. Tanks that leaked at a level to be detected by significant odor were subjected to inspection only if the NH_3 detector showed the exposure level was below OSHA safety limits or if the inspector wore a full-face respirator mask with appropriate NH_3 filter. If inspected with a respirator, the student inspector had to first be trained by Iowa State Environmental Health and Safety on respirator safety and have a mask fit test done to verify protection.

Once protected by the respirator, the inspector would only inspect a tank if the detection level remained below 140 ppm and no detectable odor of NH_3 was present in the mask. Since tanks have failed immediately after filling or within some hours of time after filling while equilibrating, tanks that were being filled or had been filled within 2 hours were not inspected and inspectors remained 50 feet away or further from any active filling platforms or recently filled tanks.

Inspectors each had a water bottle within close reach, and for best practices, a filled dunk tank needed to be available at the tank farm before inspections began. The dunk tank availability best practice was easily met since each co-op location visited already had a dunk tank safety protocol in place for their own workers. Dunk tanks are large open-top containers filled with water that are large enough for a worker to submerge completely immediately after an accidental NH_3 exposure. This immediate application of water can greatly reduce the damage caused by the exposure.

Safety procedures were changed slightly from the Phase II study with the goal of maximizing inspector ergonomics and therefore improving inspection quality. These included using regular laboratory gloves rather than thick, NH_3-resistant gloves, and safety glasses rather than ventless goggles. For both of these changes, it was determined that the safety protocol was adequate, since inspectors were not handling hoses or valves and, as noted above, deliberately followed a protocol of not being near recently filled tanks, thus having no significant risk of an unintended catastrophic release of NH_3. The only risk of unintended, limited release would come from a hardware failure on a tank (e.g., a valve or relief valve). Inspectors were instructed to remain aware of valves and relief valve locations and to pay special attention to relief valves on days of exceptionally high summer temperatures. Only on one occasion did a pressure relief valve release NH_3 while the inspectors were close enough to notice the release. Based on their training, they quickly moved upwind of the tank, preventing any significant exposure.

3.1 LOCATION, NUMBER, AND ORIENTATION OF INDICATIONS

The combined effect of fewer tanks to examine and a more rigorous standard for declaring an indication as relevant resulted in far fewer indications being declared in Phase III than in Phase II. Many of the suspicious parallel indications located in Phase II were judged to be likely non-relevant in Phase III due to weld geometry. However, those were the longest parallel indications separately noted in Phase II. For these reasons, comparison of indication lengths between Phase II and Phase III could only be done for indications that were found relevant in both studies.

The results (shown in Figure 15) are summarized as follows:

- Of the 3,326 indications found in the Phase II study, 1,719 indications were either eliminated as likely non-SCC indications caused by reflections from geometry of the weld or were not located in Phase III. Eliminating indications as likely non-SCC was possible due to the increased training of the inspectors, increased resolution of the transducers, and judgement of the NDE expert.
- Thus, a total of 1,607 indications from Phase II were neither eliminated and were found in Phase III (3,326 – 1,719).
    - 1,174 of those Phase II indications showed essentially no change in length (±0.25-inch change or less).
    - 433 of those indications were found to have grown in size from Phase II to Phase III.
- An additional 1,148 were recorded as new indications in Phase III
    - The total of indications from Phase II not eliminated and found in Phase III, plus the new indications, is a total of 2,755 indications found in Phase III.
- 183 tanks had no indications in either year.

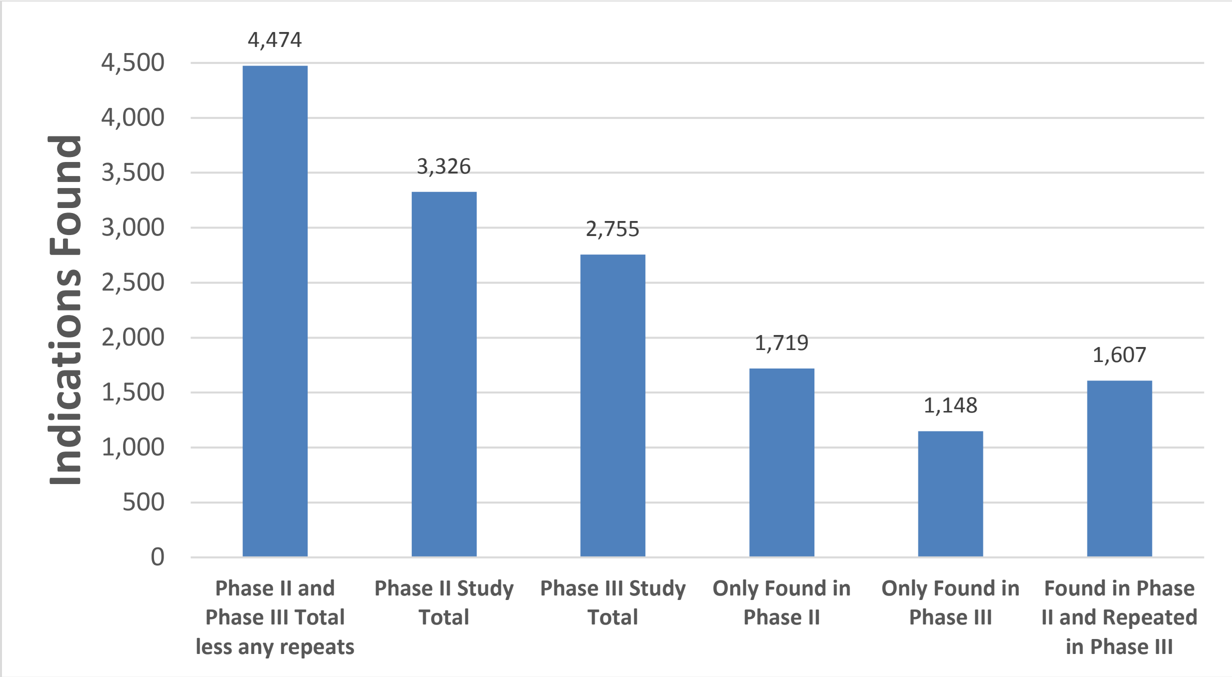

Figure 15. Chart. Total numbers of indications found with ultrasonic testing. Left to right: total both years combined less any repeats, total found in Phase II, total found in Phase III, total found only in Phase II, total found only in Phase III, total found in Phase II and repeated in Phase III.

The locations of the perpendicular total of Phase III indications determined to not be associated with weld geometry are shown in Figure 16 and are summarized as follows:

- 2,755 total indications were recorded in Phase III.
- 2,712 of those Phase III indications were associated with circumferential welds. Of this number, 2,691 were in head-to-shell circumferential welds, while 21 were found in shell-to-shell circumferential welds. The reason for so few indications in the shell-to-shell welds is explained in section 2.2 above.
- Only 40 indications were found in axial welds in the tanks' shell region for a similar reason as the limited number of indications in the circumferential shell-to-shell welds.
- Three indications were associated with leg welds, and these likely were not SCCs but fatigue cracks. (This was possible to determine with single-beam technology because leg welds are entirely on the outside of the shell, much like lifting lugs, plus there is no internal metal joint like there is in the shell-to-head or shell-to-shell joints. Thus, even with the limited resolution of single-beam it is possible to distinguish likely-metal-fatigue indications in the continuous steel around a leg weld.)

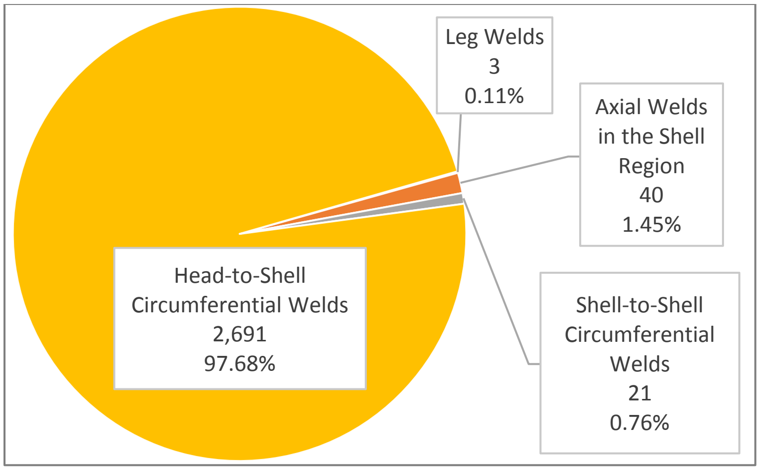

Figure 16. Chart. Number of indications found in Phase III as a function of location on the tank.

3.2 CRACK INITIATION

In Phase III, 1,148 new indications were found. However, it is difficult to state with certainty whether all of these are truly new indications. This is because several conditions exist that might occasionally lead to a false positive situation in the data. These include the following:

- This study determined that it was sometimes difficult to align Phase III indications with records of a Phase II indication. The studies had an inability to record exactly the indication location using the simple measuring method adopted in Phase II and repeated in Phase III. Thus, some indications listed as "new" may be indications reported in Phase II as being at a very slightly different location.
- Because the Phase III study used better probes with increased sensitivity, some of the Phase III indications were too small to be detected in Phase II; the indication existed but was below detection threshold for the Phase II measuring equipment.
- Human error may have resulted in a false positive in Phase III or a false negative in Phase II. The likelihood of either occurring has not been tested in any statistical way.

Given that the Phase II inspectors listed every possible indication (Phase II inspectors separately listed indications from suspicious parallel weld geometry, most of which were determined to be likely related to weld geometry in the Phase III study and were therefore filtered out of the Phase III data) it is likely that the majority of new indications listed in Phase III are, in fact, new and represent indications that initiated in the intervening 3 years.

Considerable effort was made to train the Phase III investigators in how to interpret the single-beam ultrasound imaging to note indications in welds only when the signal was definitely different from the usual weld geometry indications. This admittedly is a somewhat subjective, operator-dependent variable when using the limited resolution of single-beam technology. In making this assessment, the operator looked for localized areas of significantly higher signal level as the weld was scanned.

Also, it should be noted that the reflection of any signals returning from an area in the tank that is still in the HAZ adjacent to the fused weld material, but not all the way in the weld material itself, will arrive earlier in time than the reflection from the weld. Thus, even with the simplistic single-beam technology used, it is possible to locate the indication on the screen of the device in such a way that it is possible to determine that the reflection return is from a relevant discontinuity on the edge of the HAZ next to the weld. How the greater resolution provided by phased-array could assist with this discrimination is discussed in section 5.3 below.

The additional training provided by Mr. Enyart and his direct oversight allowed the students in the current study to interpret the relevance of indications more confidently. The students from Phase II, with less experience and less direct supervision from a trained NDE examiner, were not trained or expected to make this type of relevance assessment. However, as discussed earlier, the Phase II report recognizes many parallel indications as possibly being weld geometry issues instead of SCCs, and hence they were recorded separately.

The above discussion is meant to suggest that extremely long, parallel indications in the weld are more likely due to weld configuration. Based on orientation and length, the Phase III study deems that these indications are likely from poor welds with lack of fusion or a much more significant base metal misalignment than usual, rather than stress corrosion cracking (see Figure 9 above for an example of such a joint with a blind corner). In any case, the response was recorded as an indication concerning a possible problem with the tank, whether by stress corrosion cracking or for a different reason, though the weld-zone position and likely non-SCC nature of such parallel indications was noted.

Figure 17 displays the measured length of new indications detected in Phase III as a function of year and company of manufacture. Notice that some indications are extremely long, the largest being greater than 20 inches. Those flaws that were new and long are all ones where the inspectors were looking into the welds (i.e., parallel to a weld).

There clearly is a need to examine the phased-array technology that has greater resolution and can better differentiate details within such geometries.

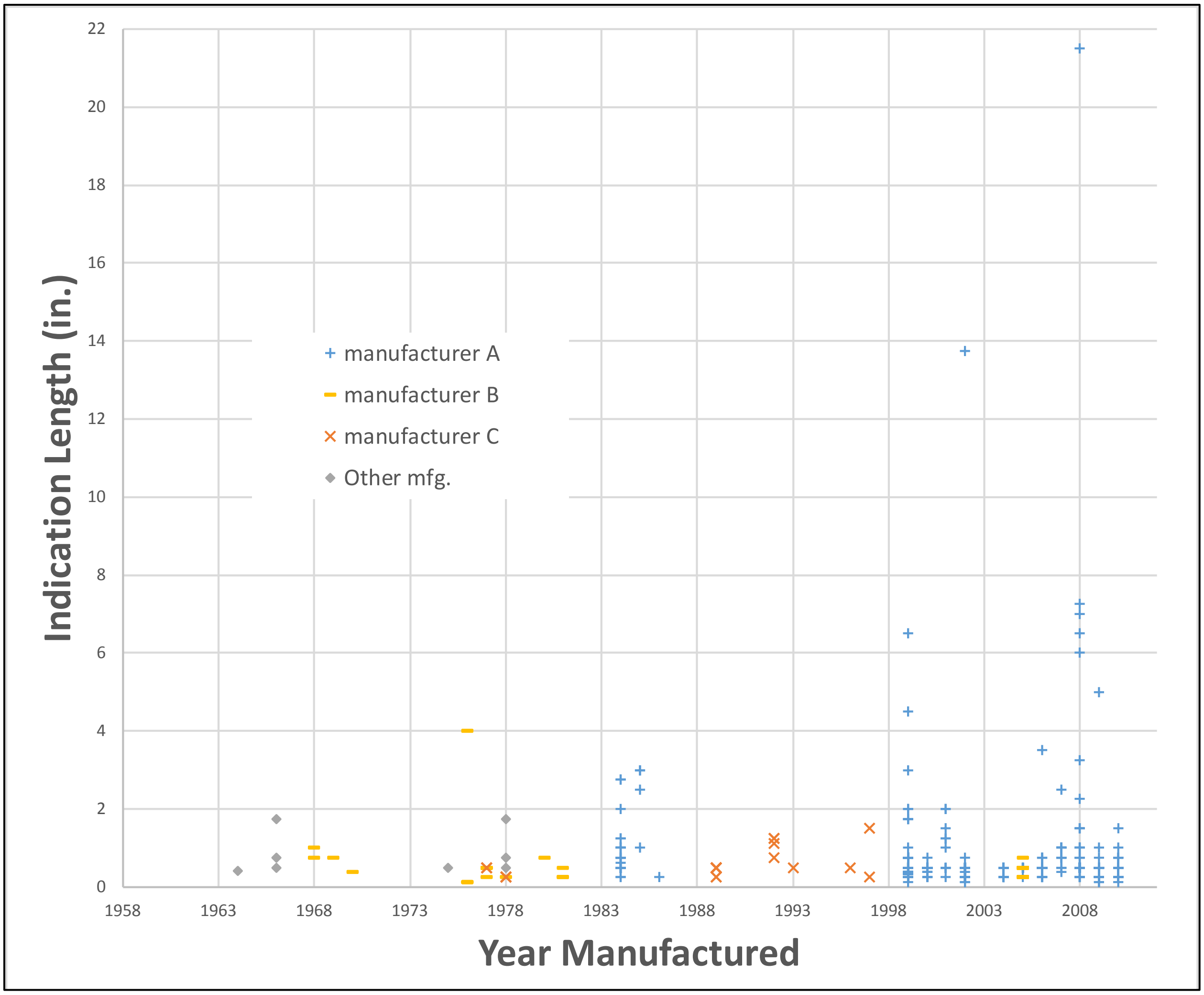

Figure 17. Scatterplot. Length of new indications found in Phase III as a function of tank's year of manufacture and tank manufacturer.

3.3 CORRELATION BETWEEN STEEL THICKNESS AND RATE OF INDICATION INITIATION BY MANUFACTURER

The number of indications as a function of tank age and as a function of manufacturer was also monitored. The number of new indications found in Phase III are as follows:

- 1,039 new indications in Manufacturer A's tanks.
- 75 new indications in Manufacturer B's tanks.
- 25 new indications in Manufacturer C's tanks.
- 9 new indications in other manufacturers' tanks.

A summary of these results is shown in Table 5. A simple comparison of the indications and tank manufacturers shows that Manufacturer A has a disproportionate number of tanks with new indications. It is also of note that the largest indications (see Figure 17) were also found in tanks made by Manufacturer A. However, such an analysis is an over-simplification of the data. Table 6 shows that Manufacturer A accounted for the vast majority of the newer tanks examined in these central Iowa studies (tanks made beginning in 1998 after the ASME specifications were changed in 1997). At the same time, full-body PWHT was discontinued after 1999, because the manufacturer doing so was acquired by another manufacturer.

Table 5. Percentage of tanks examined, by manufacturer.

Manufacturer	% of tanks tested Phase III	% of new indications
A	38.5	90.5
B	30.6	6.5
C	27.5	2.3
Other	3.4	0.8

If one considers the number of 1999 and newer tanks (after Manufacturer A acquired Manufacturer C) versus pre-1999 tanks, Manufacturer A is responsible for approximately 94 percent of the 1999 and newer tanks studied in central Iowa. Due to the data being dominantly from one manufacturer, there was not enough data about the other manufacturers to make any valid statistical evaluation that Manufacturer A's tanks vary in quality from those of manufacturers B or C (when it existed, other than that Manufacturer C PWHTed their tanks, which made a significant difference). Rather, this data points to the fact that the reduced factor of safety from the change in ASME specifications for tank shell thickness, and the elimination of PWHT that manufacturer C had been doing, had a measurable effect on the number of indications and the growth of existing indications.

Table 6. Number and percentage of examined tanks manufactured between 1999 and 2011, by manufacturer.

Manufacturer	Number of 1999-2011 tanks	% of 1999-2011 tanks
A	135	93.8
B	8	5.5
C	1	0.7

3.4 INDICATION GROWTH

Figure 18 shows the scatterplot for measured growth of indications. A comparison of average indication length for all indications cannot be meaningfully made between the Phase II and Phase III results because of the number of factors discussed above, including that not all indications from the Phase II study could be matched exactly to those of the Phase III study. Such a comparison would give a meaningless result that the average length for indications found in Phase III was substantially less than that from Phase II. While it is theoretically possible for cracks in steel to grow shorter by re-establishing a metallic bond across the crack ("heal"), this is a complex process that can occur only in very limited, special conditions where cracks are atomically clean and devoid of adsorbed gases and oxide layers. These conditions are not possible for nurse tank cracks.

First, since a large number of Phase II's longer parallel indications from weld geometry were excluded, a totally different set of values was used to determine Phase III's average indication length. Second, estimating indication length using ultrasonic measurements is difficult at best. The more limited guidance oversight provided to the Phase II testers and less sensitive probes might have led to an overestimation of 2012 indication size. Third, many of the indications from weld geometry that this Phase III study deemed irrelevant, as opposed to suspicious, were long parallel indications recorded in Phase II.

Finally, if perpendicular indication initiation in HAZ high residual stress areas is a more dominant phenomenon than indication growth away from the high residual stress locations, then the Phase III study's addition of numerous new small indications can easily cause a general decrease in average indication length.

The only possibly meaningful indication growth is a direct comparison of perpendicular indications clearly identified and located in both the Phase II and Phase III studies, as long as they are not caused by weld geometry, i.e., excludes the long parallel cracks in the HAZ. When considering only these indications, the average change in indication length was -0.12 inches. This makes no physical sense**,** and as discussed in the conclusions, there is a straightforward explanation for this outcome.

The width of the probe was 0.5 inches. As a result, the inspectors in Phase II may have made errors of perhaps up to 0.5 inches (or certainly up to half the width of the probe, 0.25 inches) in estimating the length of the indications. Even the better-trained and supervised inspectors in Phase III would have limitations because of the width of the probe. Thus, a final difference of ±0.12 inches is well within the statistical noise range of the ability to estimate indication length. The fact that the result is within that statistical noise range strongly indicates that the average indications detected in Phase II have not dramatically grown in the intervening 3 years.

The general conclusion from these findings is that the dominantly perpendicular indications have slow growth rates in context of the accuracy of indication length measurement possible with single-beam side-angle ultrasound inspection.

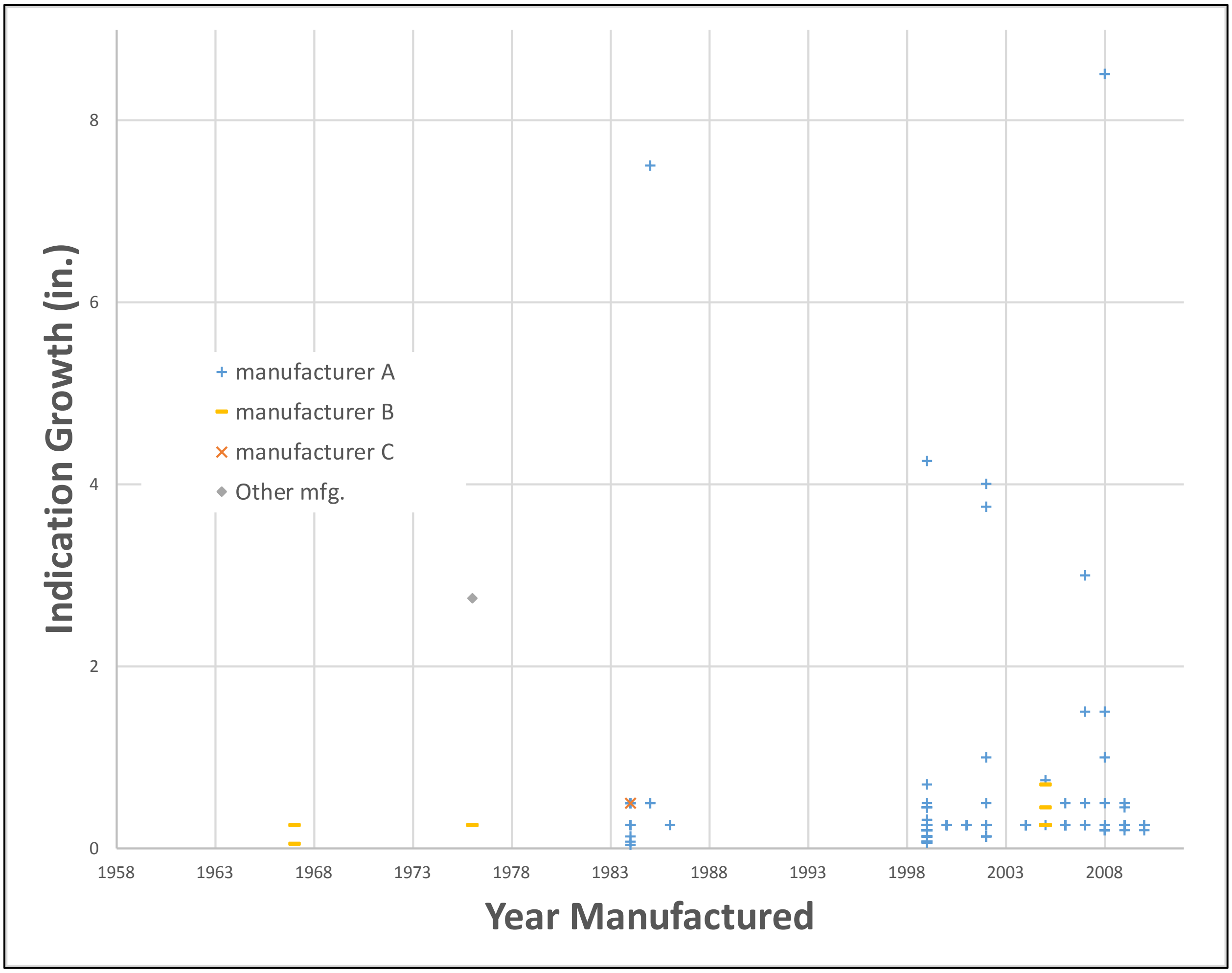

Figure 18. Scatterplot. Growth measured for indications found in both 2012 and 2015 as a function of year of manufacture and tank manufacturer.

3.5 CORRELATION BETWEEN TANK AGES AND RATE OF INDICATION GROWTH

The same rationale described in Section 3.2 concerning initiation of an indication (illustrated in Figure 17) also applies when considering indication growth. Faster indication growth is expected in younger tanks over older ones. Perpendicular indication growth during the earlier stages occurs through HAZ regions of higher stress nearer the welds. Thus, just as indication initiation is more common in younger tanks, growth of perpendicular indications is more apparent in newer tanks than in older tanks.

The 433 indications that showed recorded growth from Phase II to Phase III categorized by manufacturer were also analyzed. The breakdown of the 433 indications showing growth in Phase III is as follows:

- 469 growing indications in Manufacturer A’s tanks.
- 10 growing indications in Manufacturer B’s tanks.

- 1 growing indication in a Manufacturer C's tank.
- 1 growing indication in another manufacturer's tank.

In general, one can conclude from the data shown in Figure 17 and Figure 18 that newer tanks are showing more new initiations and more growth of existing perpendicular indications over this 3-year period than older tanks. This follows expectations for the size of a perpendicular SCC indication to grow quickly through the HAZ region of high residual stress once initiated, but then the growth of that indication is expected to slow once the indication reaches an area beyond the HAZ with little to no residual stress. It would be logical to expect many of the older tanks to have reached the point where the perpendicular SCC indications have grown to the point beyond the HAZ where there is no residual stress present at the crack tip.

The only location and orientation where this phenomenon would not slow indication growth before a crack reaches critical length is for cracks parallel to the weld. This flaw orientation and location pose a challenge for the single-beam side-angle inspection method used, since actual cracks located parallel and close to welds could be misinterpreted using that technology as irrelevant weld geometry indications. This might be addressed by the use of multi-beam phased-array ultrasound inspection. It is recommended this option be evaluated by future research.

Figure 17 and Figure 18 also point to some possible concerns with tanks manufactured under the revised ASME specification established in 1997 that allows thinner shell steel. It is clear that most of the newer tanks examined in these central Iowa studies (mostly of the 5,500-liter size) showed an increased number of indications and faster indication growth than older tanks present in the sample study. The fact that the majority of tanks in this age range were all manufactured by the same manufacturer is unfortunate, as it prevents making any clear attribution of the cause for both the increased number of indications and the increased indication growth rate to be definitively assigned to the change in ASME specification for shell thickness. However, the percentage of new indications by manufacturer matches with the percentage of post-1999 tanks examined by manufacturer. Thus, it is believed that the change in ASME thickness specification and lack of PWHT are the more probable root causes for the observed results.

3.6 TANK WALL THICKNESS MEASUREMENTS

The Phase III study added a survey of the tank wall thicknesses, a measurement not performed in Phase II. For this aspect of the study, the wall thickness was measured in the 32 tank locations specified in the Fertilizer Institute's NTIP protocol.[(28)] The inspection protocol emulated the current ultrasonic thickness testing done as part of the DOT SP 13554 inspection required for tanks that are missing their ASME data plates, and the location of the measurements were taken according to the standard form used in NTIP inspections, reproduced for convenience in Figure 19. It is important to note that none of the tanks inspected in either the Phase II or Phase III studies were missing their ASME data plates and therefore would not require inspection for wall thickness according to any current PHMSA regulations.

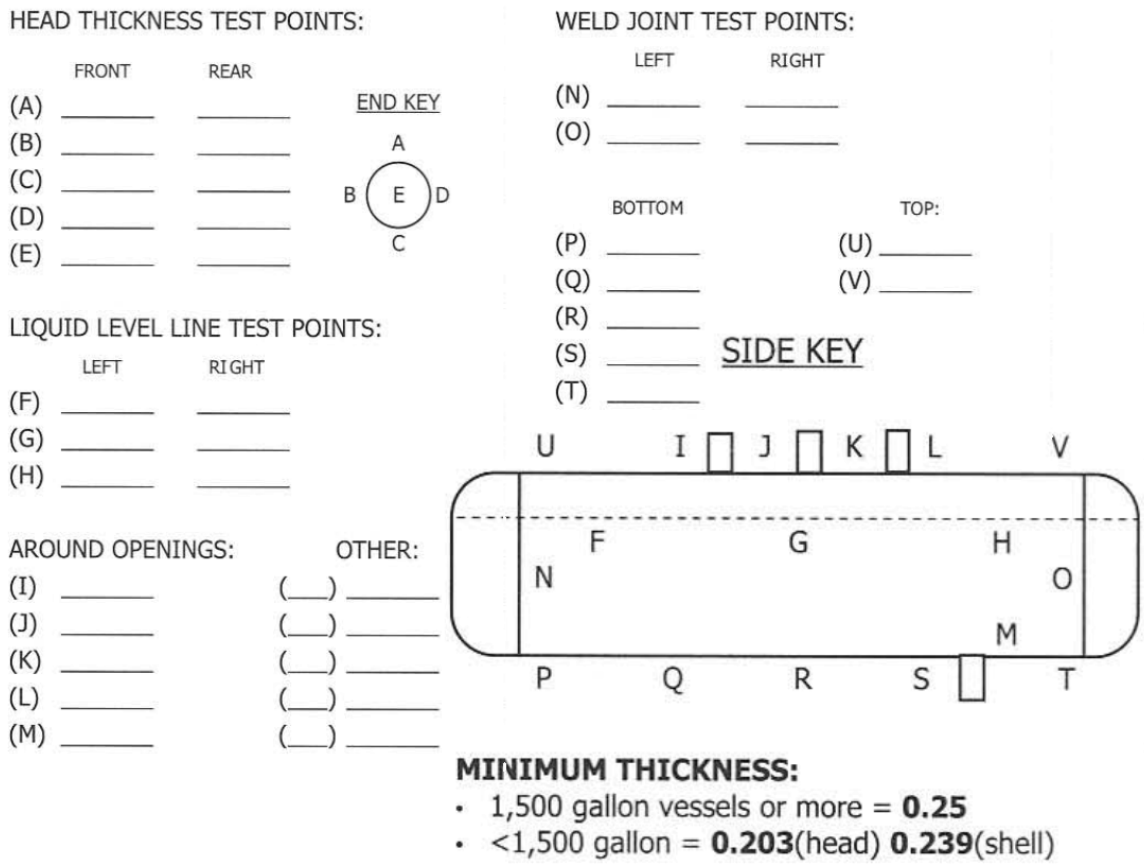

Figure 19. Schematic. Tank wall thickness measurement locations used in NTIP inspection program.
Source: http://www.nursetank.org/forms/SampleWorksheet.pdf, January 2016

3.7 TANKS NEAR OR BELOW SPECIFIED MINIMUM THICKNESS

After results from the thickness measurement were compared to the NTIP requirements, it was determined that 20 tanks had 1 or more spots measuring within 0.01inches of the NTIP minimum or less than the minimum required thickness. Of these 20 tanks, 10 were within 0.01 inches but were above minimum. These tanks would be acceptable for wall thickness, but are very close to the minimum and could measure as too thin, depending on variability of ultrasonic thickness measurements. An additional 10 tanks had 1 or more spots that, per the above steel thickness specification for tanks less than 1,500 gallons in size (i.e., 0.203 inches in head, 0.239 inches in shell—see Figure 19) measured below minimum acceptable thickness. All tanks in this study were 5,500-liter (1,450-gallon) capacity or smaller, and the NTIP requirements for steel thickness in tanks without a data plate are the same for both 1,000-gallon and 1,450-gallon tanks.

It is worth noting NTIP requirements for post-manufacture field testing for thickness only apply when a tank has lost its ASME data plate. If any of these 10 tanks were required to be inspected for tank wall thickness, they would fail that inspection.

As noted in Section 2, the specification of thinner steel for the heads appears to correlate with the greater number of indications that occur on the head side of the head-to-shell weld.

Of particular interest is a series of three 1,000-gallon tanks manufactured by Manufacturer A in the year 2000. These tanks actually had ASME plate values of 0.202 (should be 0.203) inches and 0.238 (should be 0.239) inches for the head and shell, respectively. These values are both marginally below the minimum for NTIP-inspected tanks, and all three of these tanks would likely be scrapped if they didn't have their data plates and were subject to periodic inspection.

Manufacturer	Year	Capacity, Gal.	Anneal	ASME Plate Head Thickness, in	Head Avg 2015, in	Head Min. 2015, in	Change from ASME Plate Head, in	ASME Plate Shell thickness, in	Shell Avg. 2015, in	Shell Min. 2015, in	Change from ASME Plate Shell, in
Other	1963	1000		0.231	0.246	0.238	0.015	0.32	0.317	0.240	-0.003
B	1967	1000		0.2306	0.259	0.238	0.028	0.32	0.324	0.237	0.004
Other	1970	1000		0.2306	0.258	0.239	0.027	0.32	0.317	0.230	-0.003
B	1971	1000		0.23	0.232	0.213	0.002	0.32	0.322	0.310	0.002
B	1971	1000		0.2306	0.232	0.203	0.001	0.32	0.326	0.291	0.006
B	1975	1000			0.246	0.217			0.325	0.234	
B	1975	1000		0.2306	0.236	0.205	0.005	0.32	0.326	0.323	0.006
B	1975	1000		0.2306	0.243	0.212	0.013	0.32	0.326	0.323	0.006
B	1976	1000		0.23	0.241	0.21	0.011	0.32	0.327	0.315	0.007
B	1976	1000			0.238	0.211			0.322	0.318	
B	1977	1000		0.2306	0.243	0.211	0.013	0.32	0.317	0.310	-0.003
B	1978	1000		0.23	0.248	0.209	0.018	0.32	0.324	0.320	0.004
C	1991	1450	Full S.R.	0.307	0.315	0.298	0.008	0.309	0.255	0.235	-0.054
C	1992	1000	Full S.R.	0.2306	0.248	0.227	0.017	0.272	0.249	0.210	-0.023
B	1992	1000	Full S.R.	0.2306	0.263	0.236	0.033	0.272	0.267	0.220	-0.005
C	1992	1000	Full S.R.	0.2306	0.252	0.204	0.021	0.272	0.284	0.279	0.012
C	1993	1000	Full S.R.	0.2306	0.240	0.201	0.010	0.272	0.275	0.252	0.003
A	2000	1000		0.202	0.226	0.205	0.024	0.238	0.237	0.236	-0.001
A	2000	1000		0.202	0.227	0.202	0.025	0.238	0.235	0.231	-0.003
A	2000	1000		0.202	0.227	0.205	0.025	0.238	0.238	0.230	0.000

*within 0.01in of minimum thickness — *thinner than minimum thickness

avg. thickness less than data plate — avg. thickness greater than data plate

Figure 20. Screen clipping. Average head and shell thicknesses measured close to or above ASME plate value in most cases.

Figure 20 is a section from the thickness spreadsheet that graphically demonstrates the results for the 20 tanks found to be within 0.01 inches or below the minimum thickness. The light yellow cells correspond to tanks that are merely within 0.01 inches of the minimum. The light red cells highlight the tanks with thickness results that would fail an NTIP thickness inspection. The columns marked as "Change from ASME Plate" have highlighting that displays the relative difference between the average thickness measured in the heads and shells of those tanks from what was listed on their respective data plates.

As shown by the majority of blue bars in these cells, the tanks are mostly still averaging thicker than their data plates, with only nine tanks having shell thickness averages less than the minimum allowed. Only two tanks had head thickness less than the minimum allowed, and one of those also had a shell thickness less than the minimum allowed. Four tanks had illegible head and shell thickness markings. It is notable that the ages of these tanks cover a broad range, being manufactured anywhere from 1967 to 2000.

Figure 21 shows this same data displayed in a somewhat different manner. In this plot, the difference between actual head thickness and what is stated on the data plate is shown. Any value above zero on this plot indicates a thickness equivalent to or above the thickness listed on the data plate.

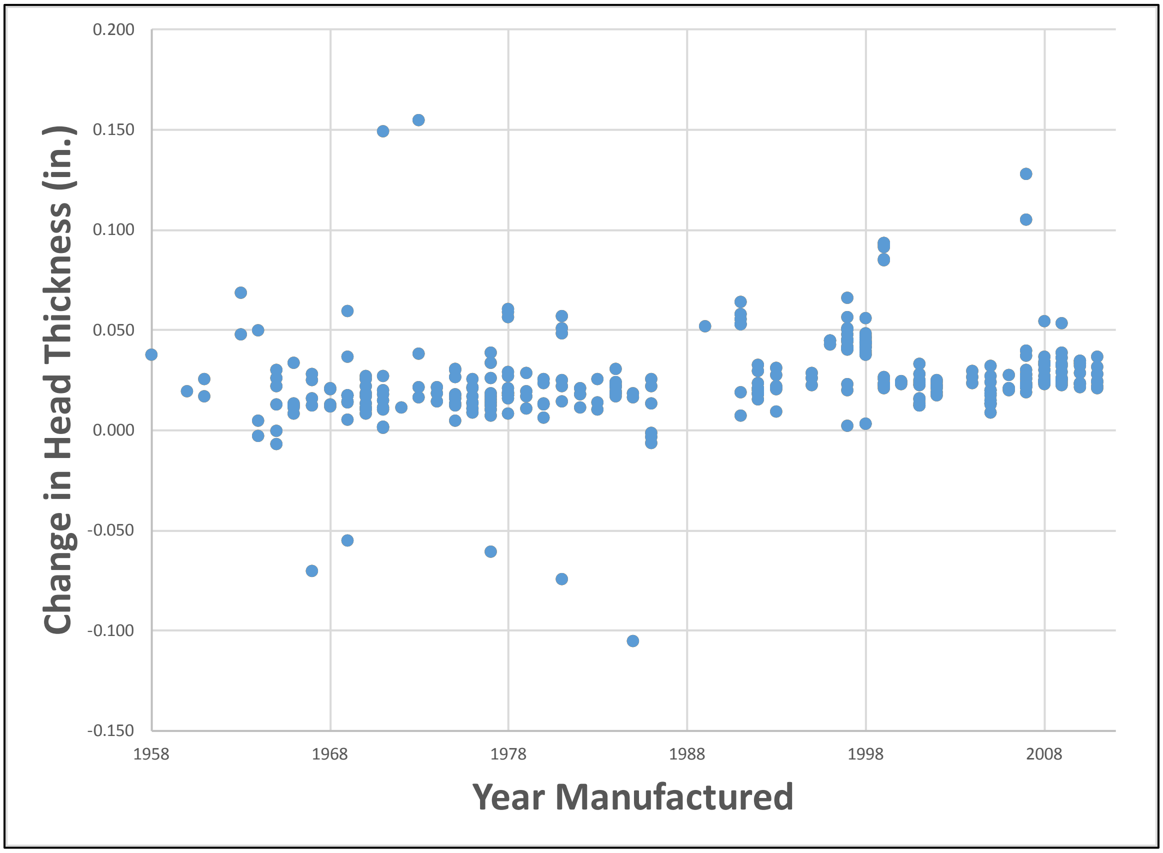

Figure 21. Scatterplot. Plot showing the difference between average head thickness of individual tanks measured in Phase III and their listed ASME data plate head thickness. This only represents tanks with legible values for head thickness. Tanks that measured thinner than the data plate listing are negative.

Measured values of average head thickness were still thicker than the stated ASME plate value in most cases. Tank manufacturers have presumably made most tanks from steel material that was thicker than the value listed on the ASME data plates.

A similar plot is shown in Figure 22, except the values shown correspond to the shell thickness. In this case there are far more tanks where the thickness of the shell is below the stated thickness on the data plate. In fact, approximately one-half of the shells are thinner than what is stated on the data plate. However, they are all within 0.1 inch of the stated value on the data plate.

The averages of all the measurements obtained in Phase III for shells and heads are shown in Figure 23 and Figure 24, respectively. The plots show that only a small number of tanks tested have wall thicknesses of concern (i.e., that lie more than 0.1 inch below the stated value on the data plates). It is noted that the shell thickness values are clearly trending towards thinner walls, while the head thicknesses for the most part remain comfortably above the specified minimum thickness. This trend adds credibility to the Phase I and Phase II reports' suggestion that newer tanks are thinner than older tanks. As discussed in Section 2.2.1, this observation is one possible explanation for an increase in indication initiation and growth in newer tanks.

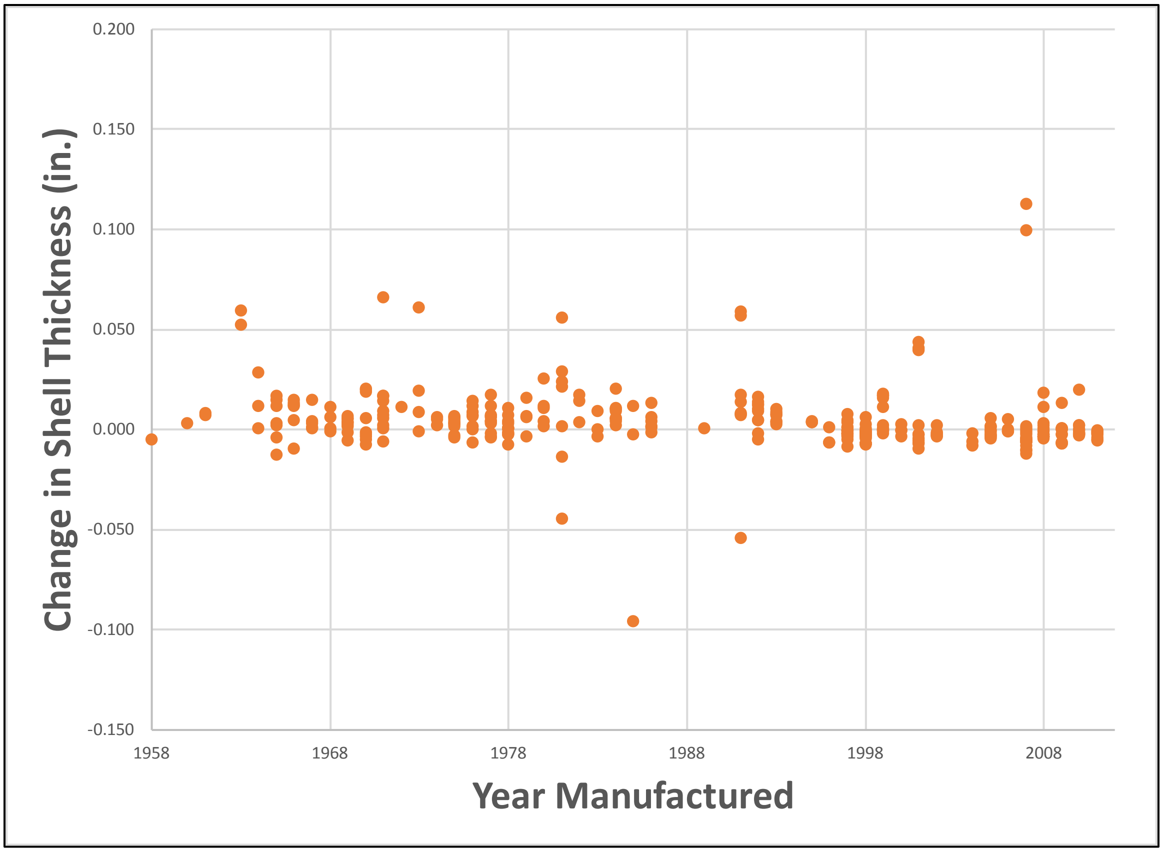

Figure 22. Scatterplot. Plot showing the difference between average shell thickness on individual tanks measured in Phase III and the listed ASME data plate shell thickness for those tanks. This only represents tanks with legible plate values for shell thickness. Tanks that measured thinner than the data plate listing are negative.

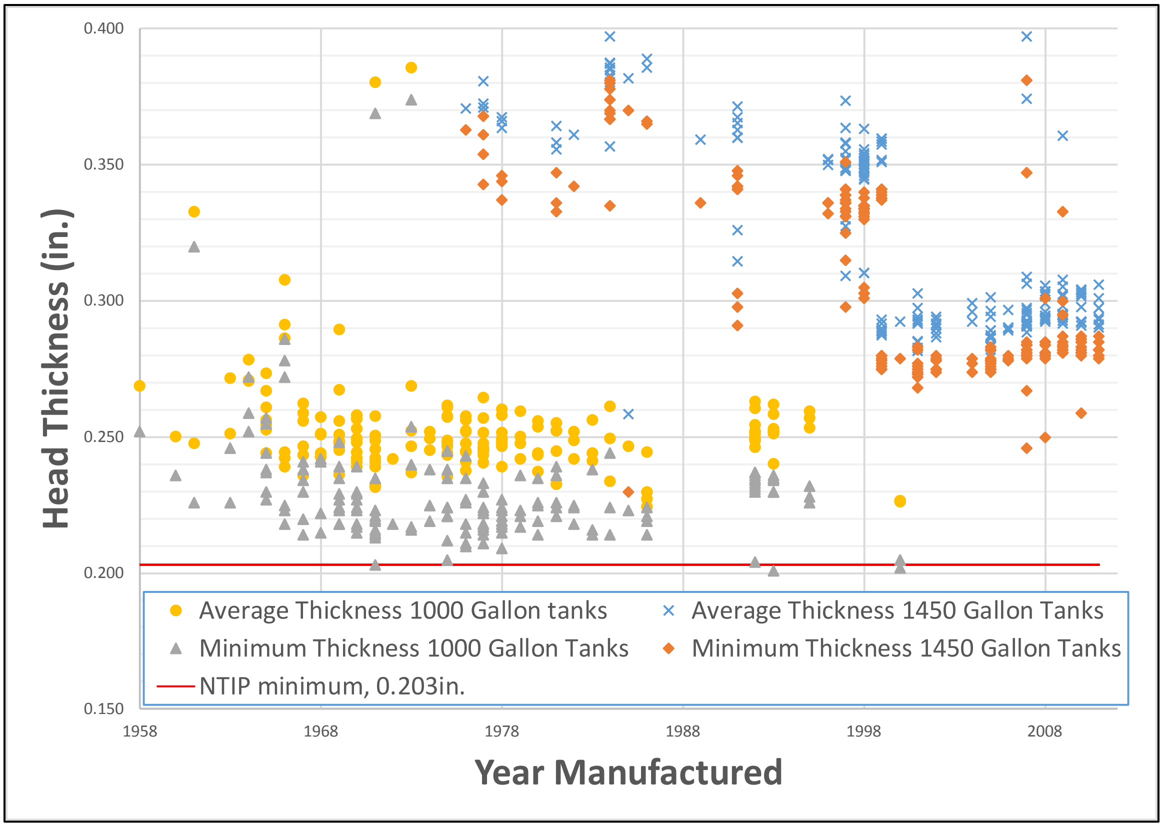

Figure 23. Scatterplot. Plot showing the average and minimum head thicknesses measured on individual tanks. Different approximate tank capacities are indicated by different markers, and any measurements (either average or minimum) that measured thinner than the NTIP minimum values are below the red line.

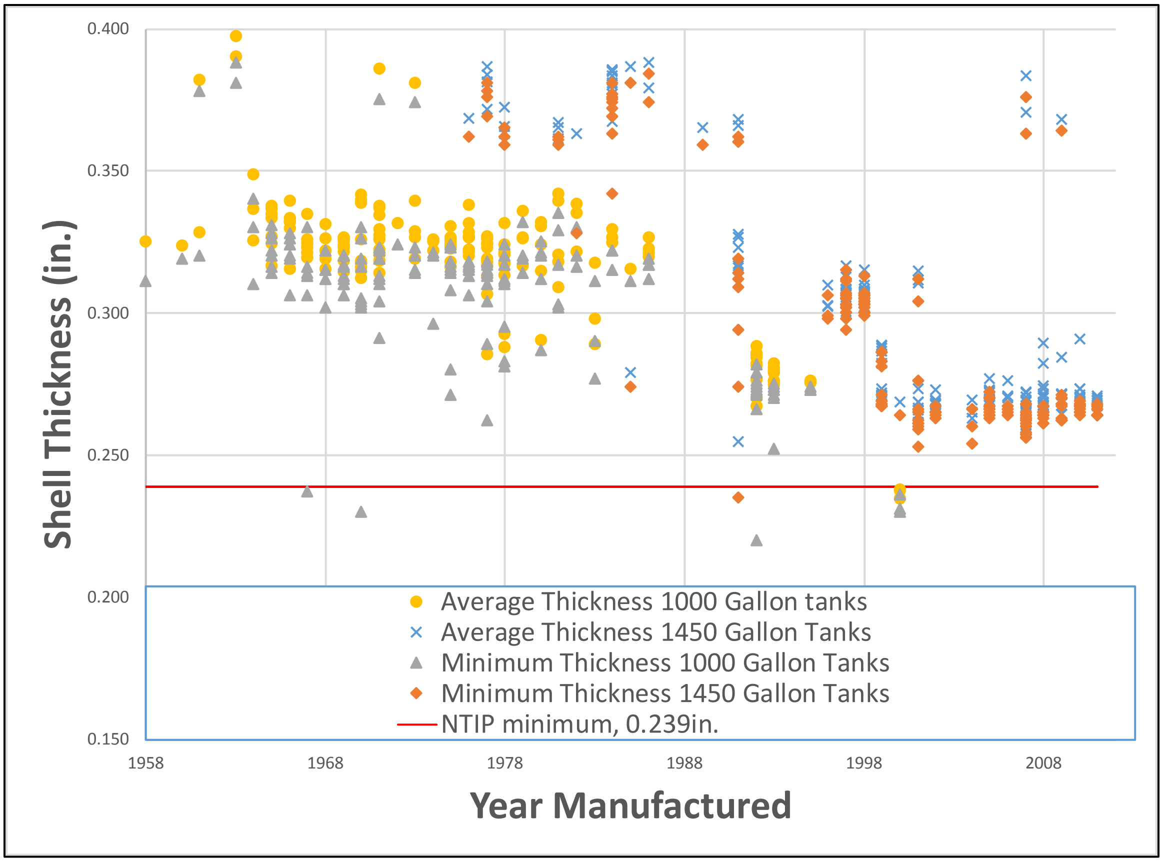

Figure 24. Scatterplot. Plot showing the average and minimum shell thicknesses measured on individual tanks. Different approximate tank capacities are indicated by different markers, and any measurements (either average or minimum) that measured thinner than the NTIP minimum values are below the red line.

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4. PHASE III CONCLUSIONS

Direct comparison of the results from the Phase II and Phase III studies is complicated by the more rigorous standards for reporting indications in the Phase III study. This resulted in many parallel head-to-shell weld seam indications reported in Phase II being removed from consideration because the single-beam technology does not provide sufficient resolution to discriminate the details of the indication. There is also the problem of exactly matching indications from the two studies given the very simple location recording methodology. However, the following conclusions can be drawn:

- It was difficult at times to exactly match indications found in Phase III with those found in Phase II, due to uncertainties in precisely locating the geometric position of a Phase II indication. While care was taken in making measurements to record indication location from fixed points on the tank in both studies, there is still enough uncertainty to cause difficulty in precisely locating the Phase II indication position versus the Phase III location using different examiners and then conducting the actual measurements.

  The recorded location of indications was found to vary as much as ±2 inches from reference points. In general practice, the inspectors would consider an indication to be a repeat indication if there was no other indication in the vicinity on the tank and the measured location from Phase III was within 2 inches of the Phase II record. If there were many indications located in close proximity, the inspectors would only consider it a repeat indication if the measured location in Phase III was within 0.25 or 0.5 inches of the Phase II location information.

  Thus, if this type of testing protocol were adopted in the future for periodically performing NDE testing of all nurse tanks, even if with phase-array, a more precise methodology for documenting the location of indications will be needed for monitoring the growth of each specific indication.

- Some uncertainty also exists in estimation of indication length. This is due to both the nature of the measurement technique used in these studies and the skill of the operator. (There likely would also be a similar issue if phased-array imaging were used.) Recorded indication lengths from inexperienced operators are only accurate to ±0.5 inches (the approximate width of the single-beam ultrasonic probe) in the case where an inspector is measuring an indication by hand. Many of the indications that were recorded as having decreased in size may have a different length measurement simply because more-skilled operators with more sensitive probes made the measurements in Phase III.

- For Phase II indications that were clearly matched and measured again in Phase III, the perpendicular indication growth rate is believed to be very slow and lower than the accuracy of the measurement method employed. The average length of all such matched perpendicular indications found in Phase II and again in Phase III was -0.12 inches shorter than the same indications when measured in Phase II. That is well within the statistical noise range of this method’s estimated accuracy.

  This slow rate of growth is less than observed in the laboratory tests of Phase II. Those tests were conducted with a constant stress level, which is not the case for perpendicular indications propagating through the HAZ.

However, a constant stress level could be the case for parallel indications in the tanks. That could mean that parallel SCCs, which single-beam technology cannot distinguish from indications caused by weld geometry, could be propagating in the HAZ parallel to the weld, and could be dangerous.

Nothing can be said about the depth of the discontinuities themselves since the single-beam side-angle ultrasound inspection protocol employed does not have the resolution to record a three-dimensional view that can reliably indicate indication depth within the steel.

- Despite the overall slow growth rate of most existing perpendicular indications, nucleation (initiation) of new indications attributed to SCC continued over the 3 years, with approximately 1,148 new indications. The average head thickness of tanks has remained essentially the same. Because of the change in ASME guidance in 1997 and subsequent manufacturing decisions, the shells experienced a fairly substantial decrease in average thickness beginning in 1998, incrementally decreasing more in recent years. The vast majority of the tanks tested in Phase III meet the current minimum shell thickness requirements.
- Heads use thinner steel than shells, and in addition to the geometry that exacerbates the HAZ on the head side of the weld, that might relate to the disproportionate amount of indications found in heads over anywhere else in the tank.

5. RECOMMENDATIONS FROM THE PHASE II AND PHASE III STUDIES REGARDING FUTURE RESEARCH

5.1 PRECISE DOCUMENTATION OF LOCATION OF INDICATIONS IN A TANK.

As discovered in the Phase III study, the problem associated with recording an indication's location is that the current method (also used in the Phase II study) is not precise enough to reliably locate the indications in future follow-up NDE tests of that tank. It would be desirable to develop a more precise two- or three-point measurement system to record location, eliminating location uncertainties in the future.

5.2 BENEFIT OF BETTER-TRAINED EXAMINERS

Having better-trained and supervised NDE examiners conducting the study helped discriminate between true SCCs and possible scattering of single-beam side-angle ultrasound signal from a weld region. The earlier Phase II study had students trained by the same experienced examiner, but it did not have that examiner on staff after the training to answer day-to-day questions and assist in making judgment calls, resulting in the Phase II study being less accurate and perhaps overly conservative. Thus, although a number of indications were suspected of being structural weld issues rather than SCCs, under the "better safe than sorry" mentality, the indications were recorded as a separate category of possible indication.

It is recommended that all future NDE work in this area use trained and supervised examiners to reduce the number of potential SCC indications that can be clearly attributed to weld design and geometry.

5.3 ADVANTAGES OF MULTI-PHASED ARRAY SIDE-ANGLE ULTRASONIC SYSTEMS

The limitations and uncertainties associated with the low resolution of single-beam side-angle ultrasonic systems employed should also be addressed. Both the Phase II and Phase III studies used standard 45˚ transducer single-beam shapes. The Phase II study surveyed various transducer shapes, and the final Phase II report recommended consideration of phased-array.

More-accurate phased-array NDE systems are available and are being used in other industries. They do have a higher cost than single-beam side-angle ultrasound. Both the Phase II and Phase III studies strove to keep the technology simple and thus did not seriously examine the potential benefits of using such multi-transducer technology and methodology, such as phased-array ultrasonic testing (PAUT).

The PAUT technology represents a substantial increase in resolution performance and discriminatory capabilities over the cheaper, simple single-beam methods and transducers used in the Phase II and Phase III studies. PAUT would be able to determine extent (depth) of indication, unlike the one-dimensional single-beam side-angle method used in Phase II and Phase III.

PAUT also may be able to discriminate between a long parallel indication running along through the high-stress area of the HAZ close to a weld seam from the weld seam/joint itself, or the metal discontinuity of the overlap from the head. Such a capability could be invaluable in determining whether there are potentially dangerous, long parallel cracks propagating in the HAZ of circumferential and longitudinal welds that could lead to failure of the tank.

A well-known example of a multi-phased array in medical application is a sonogram, which provides insight into the shape of the things it is looking at in people. The phased-array technology is similar and is being widely used in other industries, such as for performing NDE inspection of welds on pipelines in the field.[29]

A study to determine the applicability and performance of PAUT for use in imaging of parallel indications located in the HAZ is highly recommended.

5.4 ACOUSTIC EMISSION ANALYSIS

Acoustic emission (AE) monitoring has the potential to locate cracks if they form or grow due to over-pressurization in pressure testing. If coupled with PAUT, the severity of these crack formations or expansions could be determined. (Both AE and phased-array techniques were mentioned by the Phase II study as recommendations for future study.) Such a combined study could also result in significant improvements in the location and monitoring of possible crack growth.

Nurse tanks without or with illegible data plates must receive hydrostatic pressure tests every 5 years. It has always been a question as to whether such pressure tests are actually causing indications to grow, making these tests possibly more of a hazard than a safety feature. Research using AE to monitor such tanks while being pressure tested, with detailed before and after phased-array NDE examinations, could answer this question. Answering this question about the effects of hydrostatic pressure testing would have applicability for testing for all pressurized cargo tanks requiring pressure testing, not simply nurse tanks.

5.5 THINNER STEEL APPEARS TO CONTRIBUTE TO AN INCREASED NUMBER OF INDICATIONS

Finally, the substantial increase in indications in tanks manufactured after 1999 is somewhat troubling. It is strongly suggested that the decision to allow thinner steel in tank shells may have contributed to lowering the safety of newer nurse tanks. The decision to lower the allowed minimum shell thickness should be revisited.

5.6 POST-WELD HEAT TREATMENT WOULD SIGNIFICANTLY REDUCE NURSE TANK SUSCEPTIBILITY TO STRESS CORROSION CRACKING

Even if the decision is to continue allowing such thinner shell steel, it should be considered critical that full PWHT of tanks be required to remove residual stresses in the HAZ that are introduced during the manufacturing process by welding. This is even more critical if thinner steel shells are allowed to continue and nurse tanks continue to increase in size. This critical importance of requiring PWHT is a restatement of the recommendation made in the Phase II report and in the conclusion regarding PWHT stated at the end of section 2 of this report.[3]

[3] As of 2016 the two remaining manufacturers of nurse tanks in the U.S. began PWHT of all new nurse tanks as part of their manufacturing process. Both participated in this research and were aware of the finding that PWHT was an extremely effective and relatively inexpensive means for substantially reducing SCC.

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