Anhydrous Ammonia Nurse Tank Stress and Service Life Research Study

FINAL REPORT

Michael Carolan, Laura Sullivan, Mark Raney, Andrew Skrzypczak

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1200 New Jersey Ave SE, Washington, DC, 20590

U.S. Department of Transportation
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Notice

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List of Abbreviations

Abbreviation	Term
AE	Acoustic emission
ARA	Agricultural Retailers' Association
ASME	American Society of Mechanical Engineers
AWT	American Welding and Tank
B&PVC	Boiler and Pressure Vessel Code
CFR	Code of Federal Regulations
C.G.	Center of Gravity
CGA	Compressed Gass Association
CSA	Canadian Standards Association
CTMV	Cargo tank motor vehicle
ETT	Edge-to-tank foot geometry
FE	Finite element
FMCSA	Federal Motor Carrier Safety Administration
FTT	Face-to-tank foot geometry
GVWR	Gross Vehicle Weight Rating
HCG	Height of vehicle's C.G.
HMR	Hazardous Materials Regulations
IBR	Incorporated by reference
MAWP	Maximum allowable working pressure
NDT	Non-destructive testing
NIST	National Institute of Standards and Technology
NH3	Anhydrous ammonia
NTIP	Nurse Tank Inspection Program
NTSB	National Transportation Safety Board
PA	Phased array
PHMSA	Pipeline and Hazardous Materials Safety Administration
PWHT	Post-weld heat treatment
RFI	Request for Information
SCC	Stress corrosion cracking
SSC	Shell-to-solid coupling
SSF	Static Stability Factor
TC	Transport Canada
TDG	Transportation of Dangerous Goods
TFI	The Fertilizer Institute
TW	Track Width
U	Translational displacements
UR	Rotational displacements
UT	Ultrasonic testing
UTS	Ultimate Tensile Strength

Executive Summary

In 2020, the Pipeline and Hazardous Materials Safety Administration (PHMSA) partnered with the John A. Volpe National Transportation Systems Center (Volpe Center) to study the performance, service life, and structural stresses of nurse tanks used for agricultural anhydrous ammonia (NH3). The research was scoped into two phases. The purpose of Phase 1 was to conduct upfront investigative research to better understand the variety of manufactured nurse tank designs, the current fleet of operating nurse tanks, what is known regarding nurse tank incidents, whether nurse tank failure rates and occurrences warrant further research, and, if warranted, to define the approach and requirements for performing a larger modeling and analytical effort under Phase 2. This report documents Phase 2 of the study, which built upon Phase 1 findings that found no single cause for tank failures in the field but identified the need for further research.

Phase 2 was initiated in September 2022. The primary objective of Phase 2 was to determine whether the requirements of the Hazardous Materials Regulations (HMR) applicable to nurse tanks provide a level of safety equivalent to the requirements for other regulated cargo tanks. The research approach included literature and regulatory reviews, analysis of anonymized nurse tank inspection data, finite element (FE) modeling, and investigation of fatigue screening methodologies.

Design and Regulatory Findings

Nurse tanks must be constructed in accordance with American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel code Section VIII, Division 1. Changes made in 1998 to Section VIII, Division 1 of the Boiler and Pressure Vessel Code allow modern nurse tanks to be manufactured with thinner heads and shells compared to older "legacy" tanks. Under the current HMR nurse tanks are not required to feature accident damage protection, use mounting pads, or undergo Post-Weld Heat Treatment (PWHT) during manufacturing. However, many manufacturers voluntarily include these features.

Inspection Data Analysis

Researchers analyzed anonymized data from the Nurse Tank Inspection Program (NTIP) covering over 31,000 tanks inspected between 2006 and 2022. Key insights include:

- **Failure Locations:** For 1,000 and 1,450 gallon tanks, failures most frequently occurred near the head-shell junction or directly on the head.
- **Material Thinning:** Some modern (post-1998) 1,000 gallon tanks recorded thicknesses below the HMR minimums across all measured locations. Because modern tanks are built with thinner steel to begin with, they may be prematurely removed from service due to perceived thinning when compared to thicker legacy tanks.
- **Modeling Alignment:** The NTIP data broadly aligned with the FE modeling, which also identified

the head-shell junction, the bottom of the tank, and the heads of modern 1,450 gallon tanks as primary areas of high stress.

Stress and Load Modeling

Using FE modeling and simplified calculations for generalized, simplified nurse tanks, the research team evaluated how internal pressure, gravity, and transportation loads affected the tank stresses for a variety of nurse tank designs:

- **Foot Attachments:** High localized stresses occurred around the areas where feet were attached to the tank. Using mounting pads between the foot and the tank generally lowered these stresses.
- **Stress Corrosion Cracking (SCC):** High tensile (pulling) stresses on the interior surface of the tank is a concern because contact with NH3 makes these areas susceptible to SCC. Exterior tensile stress at the bottom of the tank is less concerning because the outside of the tank is not exposed to NH3 and therefore not vulnerable to SCC.
- **Transportation Forces:** Simulations of physical forces caused by acceleration and deceleration (G-loads) during transit showed that lateral (side-to-side) and upward vertical loads caused the highest structural stress, regardless of the tank's age or capacity.

Fatigue and Service Life

Section VIII, Division 1 of the ASME Boiler and Pressure Vessel Code does not explicitly require a separate fatigue analysis. The research team investigated the applicability and requirements of different screening methodologies under Section VIII, Division 2 of the ASME Boiler and Pressure Vessel Code, as well as the fatigue life calculations in Section XII of the ASME Boiler and Pressure Vessel Code that are applicable to certain specification cargo tank motor vehicles (CTMVs). Researchers attempted to estimate a lifetime load history for nurse tanks to evaluate fatigue but identified a significant data gap: there was insufficient data regarding the frequency and severity of dynamic G-loads during on-road and in-field transit.

When comparing nurse tank estimated loads to the fatigue cycles laid out for other specification tanks by Section XII of the ASME Boiler and Pressure Vessel Code:

- The requirement to withstand 100,000 pressure cycles at 20% of the tank's Maximum Allowable Working Pressure (MAWP) is highly conservative and exceeds the daily temperature cycles a nurse tank would experience over a 60-year lifespan.
- Because of the lack of real-world transportation data, researchers could not determine if the Section XII requirement to withstand 8 billion G-load cycles is similarly conservative or appropriate for nurse tanks. To address this, this report includes calculated boundaries for the practical G-loads a nurse tank might encounter during a typical service life.

1 Introduction

Current hazardous materials regulations allow cargo tanks to operate indefinitely if periodic inspection and requalification of cargo tanks are met through 49 CFR Part 180. Anhydrous ammonia (NH3) nurse tanks, a non-specification subset of cargo tanks, are exempt from 49 CFR Part 180 if they meet American Society of Mechanical Engineers (ASME) code specifications and commodity limitation requirements. Manufacturing requirements under 49 CFR and ASME code have varied over time. Due to these historical changes not all nurse tanks in operation have been manufactured to the same specification. Some nurse tanks have been operating without incident for decades. However, in recent years the performance of nurse tanks has been a subject of interest. There have been incidents involving nurse tanks and significant releases of NH3 that have resulted in serious injuries, risks to public safety, and environmental impacts.

Although nurse tanks have operated for many years, there is a limited amount of information and data available regarding the service life and performance of nurse tanks. In 2020 PHMSA partnered with the Volpe Center to initiate a multi-phase NH3 Nurse Tank Stress and Service Life Research Study to better understand the performance, service life, and stresses of nurse tanks currently in operation. The research was scoped into two phases. The purpose of Phase1 being to perform upfront investigative research to better understand the variety of manufactured nurse tank designs, the current fleet of operating nurse tanks, what is known regarding nurse tank incidents, whether nurse tank failure rates and occurrences warrant further research, and, if warranted, to define the approach and requirements for performing a larger modeling and analytical effort under Phase 2.

The Phase 1 investigation did not identify a single tank design feature or operational condition that causes nurse tank failures in the field, nor evidence that nurse tanks are failing at concerning rates. Phase 1 indicated that further research and modeling be performed under Phase 2. Phase 1 confirmed that limited information is available regarding the performance, service, and fatigue life of nurse tanks, and it is unknown whether these tanks would exceed the tanks' useful lifespan (i.e., the endurance limit) for the remainder of their operations. Further, it is unknown whether changes to the design specifications and/or the operational environment have occurred over time that would cause the service lives of modern tanks to differ from that of historical tanks. Phase 1 activities and findings are further summarized in Section 2.1.1 below.

This report documents the activities and findings of research performed under Phase 2 of the NH3 Nurse Tank Stress and Service Life Research Study. It is divided into the following six main sections:

- Section 1 introduces the research study and provides an overview of Phase 2 of the study.
- Section 2 provides background information on prior research including Phase 1 of the study, regulatory requirements, and variations in nurse tank designs.
- Section 3 discusses an analysis of an anonymized dataset of nurse tank inspections.
- Section 4 summarizes modeling and analysis performed under Phase 2.
- Section 5 describes an analysis of fatigue screening methodologies that was performed.
- Section 6 summarizes the findings and conclusions of the overall research study.

1.1 Phase 2 Overview

In September 2022 the Volpe Center and PHMSA initiated Phase 2 of the NH3 Nurse Tank Stress and Service Life Research Study. Phase 2 builds on the findings from the Phase 1 investigation (see Section 2.1.1 below) to conduct finite element (FE) modeling and other analytical activities to better understand the stresses and performance of nurse tanks of interest under normal operations and service life impacts. Phase 2 includes investigating whether changes to design specifications could result in the service life of modern tanks differing from that of historical tanks. For purposes of the study modern tanks are defined as tanks manufactured after the 1998 ASME Code changed the safety factor for Section VIII, Division 1 pressure vessels, which includes nurse tanks, from 4.0 to 3.5. The 1998 ASME specification change allowed the use of thinner steel in the heads and shells of nurse tanks by increasing the allowable stress that could develop in the tank. The findings from Phase 2 are expected to help PHMSA better understand whether requirements dictated by the hazardous materials regulations provide an equivalent level of safety as the requirements for other, specification cargo tanks. For example, MC331 specification cargo tanks transport NH3 but are subject to different requirements as a specification packaging, compared to non-specification NH3 nurse tanks.

FE modeling is used to analyze pre-1998 (“legacy”) and post-1998 (“modern”) 1,000 gallon and 1,450 gallon nurse tanks with different foot styles and foot attachments to understand how the in-service stresses vary for each under differing load conditions. Each type of foot style and foot attachment was considered independent of the others, yielding a total of 16 unique combinations and models. The variety of nurse tank designs considered are further discussed in Section 2.3 below.

The FE modeling is performed following a top-down approach, using more generalized FE models of a nurse tank and its load environment. This is different from a bottom-up approach in which a specific nurse tank design and prescribed load environment is examined. Under a top-down approach, a more generalized model of both the tank and its conditions would first be developed. Parameters for the tank design (e.g. tank thickness, absence/presence of pads, tank dimensions, etc.) and/or for the loading conditions (e.g. pressure, dynamic load spectrum from in-service loads) are then varied over a range of values until a target criterion is reached. The top-down modeling approach requires less specific information on the actual nurse tank design and the loading conditions it will be subjected to but requires more simulations to evaluate the full range of parameters. This approach will allow use of FE models to examine how several wide-ranging or difficult-to-quantify parameters may ultimately affect the service life of nurse tanks. This approach will also allow for a “what-if?” study to be conducted to examine which parameter(s) may be the most influential in terms of affecting the in-service stresses and ultimately, the fatigue life of the nurse tank. Field measurements (e.g., photographs and physical measurements of the tank dimensions, tank mountings (feet, pads, etc.) were used to inform model parameters for tank designs. The modeling approach, plan, results and takeaways are described in detail in Section 4.

Phase 2 also includes an analysis of a dataset of nurse tank inspection data extracted from a Nurse Tank Inspection Program (NTIP) database. The data extract was provided by the Asmark Institute and was anonymized by Asmark to remove any identifying owner or retailer information. The data extract provided a limited set of information on the tanks' manufacturing, capacity, thickness measurements taken across different tank locations, and the inspection outcome (i.e., pass/fail) for over 31,000 nurse tanks inspected between 2006 and 2022. The objective of the inspection database analysis was to better understand the current fleet of nurse tanks and investigate observable trends in thickness changes and locations, failure rates and trends, and to compare with and inform the FEA modeling. The dataset, analytical methodology, observations and takeaways are further detailed in Section 3.

Nurse tanks must be constructed in accordance with ASME Boiler and Pressure Vessel code Section VIII, Division 1, which does not explicitly require a separate fatigue analysis. Following the FE modeling stress analysis the research team investigated the applicability and requirements of the different screening methods under the fatigue screening methodology from Section VIII, Division 2 for nurse tanks. The effort included investigating the different parameters and assumptions for the various expected loading events for nurse tanks and fatigue analysis utilizing manual calculations (e.g., MathCAD software) according to the applicable ASME screening method. The fatigue screening effort is further detailed in Section 5.

2 Background

This section provides additional background information on NH3 nurse tanks. Summarizing core prior U.S. DOT research (Section 2.1), background into the history of and current regulatory requirements (Section 2.2), and typical variations in nurse tank design and features (Section 2.3).

2.1 Prior Research

This section summarizes prior research carried out by U.S DOT to improve the safety of NH3 nurse tanks. Section 2.1.1 below summarizes the prior activities and findings from Phase 1 of this research study. Section 2.1.2 summarizes a Federal Motor Carrier Safety Administration (FMCSA) multi-phased research effort that examined the presence, causes, and propagation of stress corrosion cracking (SCC), as well as the ability and practicality of different non-destructive testing techniques to detect crack indications.

2.1.1 Phase 1, Summary of Activities and Findings

Between March 2020 and December 2021, the Volpe Center and PHMSA worked to complete Phase 1 of the NH3 Nurse Tank Stress and Service Life Research Study. The intent of Phase 1 of the study was to perform upfront investigative research to better understand (1) the variety of manufactured nurse tanks, (2) the current fleet and operating conditions, (3) known information on nurse tank failures and failure rates, and (4) objectives, requirements, data needs and approach for performing a larger modeling and analytical effort under Phase 2. The Phase 1 investigation was conducted by means of a focused literature review, cursory level data and modeling analysis, and stakeholder outreach.

Areas of focus under the literature review included investigating current and historical nurse tank regulatory requirements, variations in nurse tank design, construction and running gear, nurse tank operations, other relevant available studies related to nurse tank failures and operations, and nurse tank inspection, testing and maintenance practices.

The Phase 1 data analysis included searching PHMSA’s incident database for incidents involving nurse tanks and specification tanks carrying NH3. The identified incidents were analyzed to better understand the frequency of incidents, common causes of reportable incidents, common areas/structures of nurse tanks that result in release, and how NH3 nurse tank incidents compare with NH3 in specification tanks (MC 330/331). A preliminary stress analysis was also conducted on a generalized NH3 nurse tank. Simplified hand calculations were performed to examine the static pressure and self-weight loads acting on the nurse tank. Additionally, the inertial loads applicable to DOT-406/407/412 Cargo Tank Motor Vehicles (CTMVs) under 49 CFR 178.345 were adapted to the nurse tank and applied using the methodology contained in an industry standard, TTMA RP-96 [1]. Separately, a simplified FE model of the same generalized NH3 nurse tank was analyzed for the case of a tank standing under static pressure and self-weight. The FE results were compared with the hand calculations.

Phase 1 outreach activities included publishing two Requests for Information (RFIs) on SAM.gov., discussions with industry stakeholders (owners, operators, associations, etc.), Federal Motor Carrier Safety Administration (FMCSA) researchers, and Transport Canada.

Outreach activities first focused on obtaining background level information of regulatory requirements and similar available prior and planned research. The research team met with Transport Canada to discuss Canada's nurse tank requirements, related research and safety concerns. Discussions included regulatory changes introduced in the 2020 editions of Canadian Standards Association (CSA), standards CSA B620 and CSA B622. The team also held multiple discussions with FMCSA researchers to better understand FMCSA's research program which focused on nurse tank inspections and the influence of SCC on nurse tank crack growth and nurse tank incidents. Information on FMCSA's related research is summarized in Section 2.1.2 below.

The next phase of the outreach focused on obtaining information to better understand the current fleet of operating nurse tanks, nurse tank operations, and determining the needs and approach for a potential future larger analysis and modeling effort. As a first step two RFIs were published in 2021, *Procuring Testing Services and Simulated Service Environments for Agricultural NH3 Nurse Tanks* (Notice ID 326-01) and *Procurement and Operations of Agricultural NH3 Nurse Tanks and/or Running Gear Specimens* (Notice ID 326-02). Notice ID 326-01 sought to obtain preliminary information from testing entities to enlighten testing requirements to consider if future nurse tank research were to include some focused testing to address identified data gaps. Notice ID 326-02 sought information from manufacturers, owners, and retailers of nurse tanks to inform data needs for modeling and availability of testing articles for planning subsequent research under a future phase of the study. Unfortunately, the RFIs resulted in only a single response. The next step was outreach to industry stakeholders. Discussions were held with representatives from The Fertilizer Institute (TFI) and the Agricultural Researchers' Association (ARA), culminating in a roundtable discussion with members of both organizations. The roundtable included several nurse tank users (agricultural cooperatives) and provided constructive input to the research. During discussions, industry attendees expressed concerns that any future regulations be applied consistently from nurse tank builder down to nurse tank end-users, and if nurse tank inspection requirements were to expand in the future whether additional qualified inspectors/inspection facilities would be available. The research team also met with staff from the Asmark Institute. Asmark administers the Nurse Tank Inspection Program (NTIP), a database where nurse tanks with missing or illegible data plates can be registered and their inspection reports uploaded.

Below is a high-level summary of key findings from the Phase 1 investigation.

- Manufacturing requirements under the CFR and ASME Code have varied over time. It was outside the scope of this project to attempt to identify all differences between ASME Code versions applicable to nurse tank design that may affect service life. Also, attributing any actual or perceived change in the performance of nurse tanks built to different versions of the ASME Code to a single change in the ASME Code will be a challenge due to the numerous changes that could have occurred between the 1998 and 2017 versions of the ASME Code.

- The Canadian requirements for nurse tanks have also changed over time. Nurse tanks used in Canada are subject to Transport Canada's (TC's) Transportation of Dangerous Goods (TDG) regulations, which incorporate several CSA standards by reference. TC's requirements for nurse tanks, as specified in CSA B620-20 and B622-20, exceed the requirements of nurse tanks in the U.S. in several ways. Regulatory requirements are discussed in greater detail in Section 2.2 below.

- No publicly available database or source detailing the current fleet of operating nurse tanks could be identified. Consequently, neither a defined number of operating nurse tanks or a breakdown of the current fleet by varying manufacturing specification and/or nurse tank design (e.g., capacity, vintage, materials of construction, etc.) could be identified. According to anecdotal discussions with industry stakeholders there are approximately 175,000 to 200,000 nurse tanks operating in the U.S in contrast to an estimated 12,000 to 18,000 nurse tanks throughout all of Canada.

- Nurse tank configurations and operations can vary significantly. According to industry stakeholders there is no one single industry standard nurse tank configuration. Nurse tanks may be mounted with a single tank on a set of running gear, or with multiple tanks on a single running gear. The U.S. regulations at 49 CFR 173.315(m) state that a nurse tank must be "securely mounted" to either a farm wagon or field truck but does not provide additional requirements for how this would be demonstrated. The design of the running gear and therefore the dynamic loads imparted to the nurse tank by normal operations may differ based on whether a single tank or multiple tanks are mounted to the running gear. Additionally, there may be different handling characteristics between a single running gear with two nurse tanks mounted on it, or a train of two nurse tanks each mounted on an individual running gear. Stakeholder discussions revealed that the industry is trending towards using more powerful towing vehicles, such as farm tractors. This enables the use of running gear with two nurse tanks where a farmer may have historically used a single tank. The use of more powerful tractors also raises a potential concern of whether the more powerful tractor's ability to pull a running gear with a single nurse tank at a higher speed than an older, less powerful tractor, could potentially subject the tank to higher dynamic forces and potentially accelerate tank fatigue and failures.

- The literature review, data analysis of PHMSA's incident database, and discussions with stakeholders did not determine an obvious single tank design feature or operational condition that causes nurse tanks to fail in the field. The largest number of reported incidents involving nurse tanks encompass a rollover accident in which an accessory to the tank (e.g., piping, fittings, valves, hoses) was torn off or damaged. This suggests two potential areas of focus for further investigation in subsequent phases of research include: reducing the likelihood of a nurse tank rollover (e.g., lowering tank C.G., changing tank-running gear parameters, or addressing driver Inputs leading to rollover), and reducing the consequences of a nurse tank rollover (e.g., adequacy of accident damage protection structures).

- Recent to when Phase 1 was conducted, Transport Canada representatives indicated seeing evidence that some of the additives added into NH_3 nurse tanks have led to corrosion of tanks and components and gumming or fouling of pressure relief devices and valves. Transport Canada also indicated a concern that some of these additives can lead to SCC in older tanks. For these reasons in August of 2020 TC issued a Safety Advisory regarding the effects of additives on tanks and other equipment. Unless the practice of including additives in the tank is eliminated, additional investigation of the effect of additives and rate of corrosion on thickness may be appropriate.

- In the U.S., thickness testing is currently only required on nurse tanks with a missing or illegible nameplate, but it may be possible to use existing thickness measurement data to identify whether thinning is occurring. If so, determine whether the tanks that are thinning have had an additive injected into the NH3 within the tank. Industry stakeholders indicated “very few” nurse tanks are removed from service based on internal corrosion. Typically, nurse tanks are “removed from service due to external corrosion (visual test), gouges, dents, and dislodged internal baffle plates.”
- Additionally, operators noted weld quality concerns with some newer tanks, specifically "pinhole" leaks in the circumferential weld between tank head and shell. These findings were in some cases observed by operators immediately upon putting nurse tanks into service. As a result, and to ensure safety, some operators will perform hydrostatic tests on brand new nurse tanks, with some operators reporting that as many as three-fourths of these tanks can fail and must then be repaired under warranty prior to first use.

Phase 1 concluded that further research and modeling is warranted. The Phase 1 investigation did not identify a single tank design feature or operational condition that causes nurse tank failures in the field, nor evidence that nurse tanks are failing at concerning rates. Phase 1 did confirm there is limited information available regarding the performance, service life, and stresses of nurse tanks currently in operation. Although some tanks have been operating without incident for decades it is unknown whether these tanks would exceed the tanks’ useful lifespan (i.e., the endurance limit) for the remainder of their operations. Additional research will also be informative to assessing differences between U.S and Canadian requirements.

The overall modeling plan resulting from Phase 1, to be refined, finalized, and implemented in Phase 2 entailed conducting a FE analysis following a top-down modeling approach. The finalized Phase 2 modeling plan and analysis is discussed in greater detail in Section 4.2 below.

2.1.2 Other USDOT-sponsored Nurse Tank Research

Between 2008 and 2022 the FMCSA sponsored a four-phased research study with Iowa State University focused on the testing and examination of NH3 nurse tanks. A secondary objective of the study was to determine whether single-beam angle ultrasonic testing (UT) could serve as a practical alternative non-destructive testing (NDT) method to the current visual inspection and hydrostatic pressure test requirements. Single-beam angle UT is a relatively inexpensive NDT method which can be performed without moving or emptying the nurse tanks. Single-beam angle UT was used to find and quantify both the number and size of indications that had formed in the tanks, likely due to SCC. Information concerning number, size, location, and direction of indications was tabulated and verified in the latter two field studies. The indication data was analyzed in relation to the year of tank manufacture, the company of manufacture, the relevant industry standards to which the tank was manufactured (specifying steel type and thickness), and whether annealing (post weld heat treatment) was performed. Post weld heat treatment (PWHT) is performed to reduce residual stress in the metal. At the time of FMCSA's research, PWHT was not required for nurse tanks, but could optionally be performed by a manufacturer.

- Phase I of the FMCSA study entailed performing a variety of metallurgical tests on 20 used in-service nurse tanks and on laboratory specimens cut from the tanks and/or created from the steel commonly used to construct nurse tanks [2].
- Phase II was conducted in 2012 and entailed using the single-beam angle UT method developed in Phase I to examine an additional 532 in-service nurse tanks. Phase II also resulted in a calculated average crack growth rate of SCC under constant stress [3].
- Phase III was conducted in 2015 and entailed re-examining 411 of the 532 tanks were re-examined using single-beam angle UT to compare real crack growth rates to the Phase II calculated rate, and to measure whether new cracks had initiated. In addition, Phase III investigated the effect of the nitrogen additive N-Serve on crack formation and growth. N-Serve is a commercial product that is combined with NH3 to reduce ammonia loss over time [4].
- Phase IV utilized phased array (PA) ultrasonic, a more advanced NDT technique, to determine whether more accurate results could be obtained to resolve discrepancies between the 2012 and 2015 UT data (Phases II and III). Twenty of the tanks examined in Phases II and III were re-examined with PA, in addition to one relatively new tank (2017 manufacture) and one older tank (age undetermined) that was tested to failure. Phase IV also investigated whether the pressure required by hydrostatic test requirements, which is much higher than a nurse tank's normal operating conditions, could cause undetected growth in existing SCC cracks, potentially reducing the life of a tank subjected to repeated hydrostatic testing. Acoustic emission (AE) was used to monitor for changes while a nurse tank undergoes hydrostatic testing. Coupled with PA, the exact changes before and after testing could then be determined [5].

The research study corroborated the conclusion from other studies that SCC is the principal threat to nurse tank integrity. Manufacturing defects are also a possible issue, but many quality control practices have improved. They now include 100-percent radiographic testing of longitudinal welds on the tank shell. It found that SCC was likely in NH3 nurse tanks, especially those which had not undergone PWHT. This was due to the high residual stresses present after welding, especially in the end caps [2]. At the conclusion of Phase III, the benefits of PWHT were apparent and by 2016 U.S manufacturers were voluntarily producing new nurse tanks that had received PWHT [5].

The single-beam angle UT was successful in detecting indications that were perpendicular to the welds. However, the single-beam angle UT does not have the resolution to unambiguously distinguish such possible parallel indications from the weld seam material and overlap metal itself. It was found that the performance of the inexpensive single-beam angle UT units was largely dependent upon operator experience and expertise in using ultrasonic equipment to distinguish small cracks from weld geometry effects. PA ultrasonic devices are a considerable improvement over the handheld single-beam angle UT units, providing better discrimination capabilities between weld geometry effects and true crack indications, although at a higher cost [5].

Acoustic Emission (AE) monitoring could detect changes in the tank during hydrostatic testing but could not definitively tell if a recorded AE event was associated with the formation of a new crack or growth of an existing crack, versus an extraneous source of noise that was detected (e.g., the tank deforming elastically during the test). Also, the changes detected were not large enough to render the tank even marginally less safe or decrease the tank life [5].

2.2 Regulatory Overview

This section presents several aspects of the regulations governing nurse tank design and operations. Section 2.2.1 compares and contrasts the regulations applicable to nurse tanks, a non-specification tank, and MC331 tanks, the specification container authorized for highway transportation of NH3. Section 2.2.2 includes a discussion of the history of nurse tank regulations in the U.S. Section 2.2.3 includes discussion of recent notifications related to nurse tanks, such as safety advisories and incident investigations. Finally, Section 2.2.4 includes a discussion of the regulations applicable to nurse tanks operated in Canada.

2.2.1 Compare/Contrast with MC331 Regulations

NH3 may be shipped by road in MC 330/331 CTMVs but specific exceptions are made for NH3 shipped by private carrier exclusively for agricultural use. MC 331 CTMVs must meet design requirements specified in 49 CFR 178.337. The regulations applicable to nurse tanks are found in 49 CFR 173.315(m).

Nurse tanks are limited in size to no more than 3,000 gallons. Limiting the operation of nurse tanks means that travel via highway or public roadway is limited to trips to and from anhydrous ammonia filling facilities. A significant amount of nurse tank travel will be on farm property and while in use applying NH3 to fields (see further discussion in Section 5.2). This type of operation may limit the potential for a collision with another highway vehicle and exposure to the general public but running on unpaved and irregular surfaces can present a harsher normal loading environment to the tank.

Any tank carrying NH3 must meet structural requirements for construction. Requirements include loading from the static pressure of the tank and stress evaluations from Section VIII, Division 1 of the ASME Boiler and Pressure Vessel code. Section VIII, Division 1 is applicable to a variety of pressure vessels, including stationary tanks, and does not include dynamic loads for evaluating the resulting stresses in a nurse tank. Allowable stresses in the ASME Boiler and Pressure vessel code are evaluated against the tensile strength of the material, generally using a factor of safety of 3.5 since 1998. Prior to 1998, Section VIII, Division 1 generally used a factor of 4.0 to determine the allowable stress. An MC 331 is required to meet the static loading requirements in the ASME BPVC, however 49 CFR 178.337-3 requires that the stresses continue to be evaluated against the tensile strength of the material using a factor of safety of 4. In addition, there are dynamic load cases in the CFR to evaluate normal and extreme loading scenarios applicable to highway vehicles. Nurse tanks are not required to meet any dynamic load requirements.

There are additional structural requirements for an MC 331 CTMV in part 178. Any appurtenance mounted to the tank must either be considered lightweight and be designed to break away or be mounted with a pad. The mounting pad is intended to prevent loading of an appurtenance to cause damage to the tank wall. There are also accident damage protection requirements for the MC 331. These require that any valve or opening to the tank be protected during collision or rollover scenarios. Rear-end protection is required to protect the read head of the tank from damage during a collision with another vehicle. A nurse tank is exempt from meeting the structural requirements in part 178 and therefore not required to use mounting pads or to have prescribed accident damage protection features.

Finally, MC331 tanks must undergo periodic inspection and testing as required by 49 CFR 180. As discussed in Section 2.2.2, a nurse tank that is not mounted on a field truck or mounted to a wagon and has a present and legible nameplate is not required to undergo any periodic inspection or testing to remain in service.

2.2.2 History of Nurse Tank Regulations and Requirements

The nurse tank regulations currently located at 49 CFR 173.315(m) were initially promulgated by a Final Rule (HM-139) effective April 27, 1978 [6].

> *(m) A cargo tank (commonly known as a nurse tank and considered an implement of husbandry) transporting anhydrous ammonia, and operated by a private carrier exclusively for agricultural purposes does not have to meet the requirements of Part 178 of this subchapter if it:*
>
> *(1) Has a minimum design pressure of 250 psig and meets the requirements of the edition of the ASME code in effect at the time it was manufactured and is marked accordingly;*
>
> *(2) Is equipped with safety relief valves meeting the requirements of CGA pamphlet S1.2;*
>
> *(3) Is painted white or aluminum;*
>
> *(4) Has capacity of 3,000 gallons or less;*
>
> *(5) Is loaded to a filling density no greater than 56 percent; and*
>
> *(6) Is securely mounted on a farm wagon.*

By the 1996 edition of the HMR, an additional requirement had been added:

> *(7) Is in conformance with the requirements of part 172 of this subchapter except that shipping papers are not required; and it need not be marked or placarded on one end if that end contains*

> *valves, fittings, regulators or gauges when those appurtenances prevent the markings and placard from being properly placed and visible.*

In a 2011 rulemaking (76 FR 5483), two additional situations were addressed related to nurse tanks. The first situation concerned nurse tanks with missing or illegible data plates. Normally, a tank with a missing or illegible data plate would need to be removed from service. Under specific conditions, nurse tanks with missing or illegible data plates have been allowed to remain in service:

> *(2) Nurse tanks with missing or illegible ASME plates. Nurse tanks with missing or illegible ASME plates may continue to be operated provided they conform to the following requirements:*
>
> *(i) Each nurse tank must undergo an external visual inspection and testing in accordance with § 180.407(d) of this subchapter.*
>
> *(ii) Each nurse tank must be thickness tested in accordance with § 180.407(i) of this subchapter. A nurse tank with a capacity of less than 1,500 gallons must have a minimum head thickness of 0.203 inch and a minimum shell thickness of 0.239 inch. A nurse tank with a capacity of 1,500 gallons or more must have a minimum thickness of 0.250 inch. Any nurse tank with a thickness test reading of less than that specified in this paragraph at any point must be removed from hazardous materials service.*
>
> *(iii) Each nurse tank must be pressure tested in accordance with § 180.407(g) of this subchapter. The minimum test pressure is 375 psig. Pneumatic testing is not authorized.*
>
> *(iv) Each nurse tank must be inspected and tested by a person meeting the requirements of § 180.409(d) of this subchapter. Furthermore, each nurse tank must have the tests performed at least once every five years after the completion of the initial tests.*
>
> *(v) After each nurse tank has successfully passed the visual, thickness, and pressure tests, welded repairs on the tank are prohibited.*
>
> *(vi) After the nurse tank has successfully passed the visual, thickness, and pressure tests, it must be marked in accordance with § 180.415(b), and permanently marked near the test and inspection markings with a unique owner's identification number in letters and numbers at least 1⁄2 inch in height and width.*
>
> *(vii) Each nurse tank owner must maintain a copy of the test inspection report prepared by the inspector. The test report must contain the results of the test and meet the requirements in § 180.417(b) and be made available to a DOT representative upon request.*

The second situation addressed by the 2011 rulemaking concerned nurse tanks that were mounted to field trucks rather than towed wagons.

> *(3) Field truck mounted tanks. A non-DOT specification cargo tank (nurse tank) securely mounted*

> *on a field truck is authorized under the following conditions:*
>
> *(i) The tank is in conformance with all the requirements of paragraph (m)(1) of this section, except that the requirement in paragraph (m)(1)(vi) does not apply;*
>
> *(ii) The tank is inspected and tested in accordance with subpart E of part 180 of this subchapter as specified for an MC 331 cargo tank;*
>
> *(iii) The tank is restricted to rural roads in areas within 50 miles of the fertilizer distribution point where the nurse tank is loaded; and*
>
> *(iv) For the purposes of this section, a field truck means a vehicle on which a nurse tank is mounted that is designed to withstand off-road driving on hilly terrain. Specifically, the vehicle must be outfitted with stiffer suspension (for example, additional springs or airbags) than would be necessary for a comparable on-road vehicle, a rear axle ratio that provides greater low end torque, and a braking system and tires designed to ensure stability in hilly terrain. The field truck must have low annual over-the-road mileage and be used exclusively for agricultural purposes.*

Most recently, 49 CFR 173.315(m) was updated in 2016 (81 FR 25613) to refer to the latest version of the ASME Boiler and Pressure Vessel Code that was Incorporated by Reference (IBR) into the HMR. Only the modified paragraph is excerpted below:

> *(m) General. (1) A cargo tank that is commonly known as a nurse tank and considered an implement of husbandry transporting anhydrous ammonia and operated by a private motor carrier exclusively for agricultural purposes is excepted from the specification requirements of part 178 of this subchapter if it:*
>
> *(i) Has a minimum design pressure of 250 psig, meets the requirements of Section VIII of the ASME Code (IBR, see § 171.7 of this subchapter), and is marked with a valid ASME plate.*

This latest revision to 49 CFR 173.315(m) makes clear that nurse tanks must be designed to the version of Section VIII, Division I of the ASME Boiler and Pressure Vessel Code that has been IBR into the HMR. In a 2020 Rulemaking (HM-219C) PHMSA updated the IBR version of Section VIII, Division 1 of the ASME Code to the 2017 edition.

2.2.3 Nurse Tank Notifications (Safety Advisories, ANPRMs, NTSB Recommendations etc.)

Since the last revision to the Code of Federal Regulations applicable to nurse tanks in 2016, there have been several nonregulatory activities related to the manufacture and inspection of nurse tanks. In February of 2024, FMCSA issued a Safety Advisory citing concerns with tanks manufactured between January 1, 2007, and December 31, 2011, constructed by America Welding and Tank (AWT). There had been previous inspection by FMCSA of tanks manufactured from 2009 to 2010, and improper manufacturing procedures were identified. The safety advisory was issued as the result of the catastrophic failure of a 2009 AWT nurse tank and subsequent testing to examine a series of tanks manufactured by AWT. The testing indicated concerns with the tanks manufactured between 2007 and 2011. This Safety Advisory recommended that owners of these tanks conduct voluntary periodic visual inspection in accordance with 49 CFR §173.315(m)(2)(i); thickness testing in accordance with 49 CFR §173.315(m)(2)(ii), and pressure testing in accordance with 49 CFR §173.315(m)(2)(iii). Transport Canada issued a similar Safety Advisory in April 2024.

In October of 2024, PHMSA issued a Notice of Proposed Rulemaking (89 FR 85590). Included in this proposal was a change to the requirements for the manufacture of nurse tanks. PHMSA proposes to add a paragraph requiring that all nurse tanks manufactured 90 days after the effective date of a final rule be stress relieved through full post-weld heat treatment. Research undertaken by FMCSA and Iowa State University had identified post-weld heat treatment as an effective process to reduce the occurrence of SCC. This practice had already been widely accepted by the industry.

The NPRM addressed in part, the NTSB Safety recommendation H-04-023. This recommendation was the result of the 2003 Calamus, IA incident, where a nurse tank split open after being filled with anhydrous ammonia at a nurse tank filling facility [7]. Approximately 1,300 gallons were released resulting in one serious injury and one fatality. Post-examination of the tank revealed insufficient welding and the NTSB identified the adequacy of standards for initial qualification and periodic testing of nurse tanks as a safety issue. The 2011 rulemaking addressed the periodic inspection and testing of nurse tanks without name plates.

2.2.4 Summary of Canadian Nurse Tank Requirements

Nurse tanks used in Canada are subject to Transport Canada's (TC's) Transportation of Dangerous Goods (TDG) regulations, which incorporate several Canadian Standards Association (CSA) standards by reference. Two relevant standards are CSA B620 "Highway tanks and TC portable tanks for the transportation of dangerous goods" and CSA B622 "Selection and use of highway tanks and TC portable tanks for the transportation of dangerous goods, Class 2." At the time the Phase II nurse tank study was performed the 2020 versions of CSA B620 and CSA B622 were incorporated within the TDG. These editions were published in November 2020, but some provisions of the new standards were not in effect immediately due to a "phase-in" period.

Prior to the 2020 editions of CSA B620 and B622, the 2014 editions of these standards were specified by the TDG regulations. Prior to that, the 2009 editions of the standards were specified by the TDG regulations. Significant changes were made between the 2009 and 2014 editions of the standard that affected nurse tank design and operations. Additional changes between the 2014 and 2020 editions of the standards further affected nurse tank design and operations.

CSA B622-20 appears to categorize nurse tanks into three categories, based on their date of construction. Table 2 of CSA B622-20 contains "Specific tank requirements for dangerous goods, Class 2, by UN Number." UN1005, Anhydrous Ammonia, is included within this table. Specific requirements 54 and 55 lay out additional details on the use of tanks other than TC-51 specification tanks as NH3 nurse tanks.

Specific Requirement 54 allows the use of "a tank that meets the requirements of the edition of the ASME Code, Section VIII, Division 1, under which it was built" under specific conditions, including the condition that the tank was constructed prior to July 1, 1998. Specific Requirement 54 still requires periodic inspection and testing for these tanks, and references CSA B620-14's requirements for tank securement and rear-end protection.

Specific Requirement 55 provides another set of specific conditions under which a nurse tank does not have to meet the specification requirements for a TC 51 tank or other mounting, protection, and piping requirements if such a tank was manufactured prior to January 12, 2018. Specific Requirement 55 still requires periodic inspection and testing for these nurse tanks.

Based on CSA B620-20 and B622-20, any new tank constructed for use in Canada as an NH3 nurse tank after the effective date of the standard must be constructed according to specification TC 51. Transport Canada provided a summary of the new requirements that became applicable to nurse tanks constructed to TC 51, including mounting strength requirements, rear end protection requirements, and piping and emergency discharge control requirements [8]. Additionally, an annual leakage test is now applicable to nurse tanks constructed to TC 51, which had not been applicable to previously constructed nurse tanks in Canada.

Our understanding of the CSA B620/B622 inspection and testing intervals for the three most recent editions of the specifications are summarized in Table 2. Each specification (B620 and B622) references the other specification extensively, so it is important to consult the actual documents to understand the conditions under which particular inspection/test requirements and timing are applicable. Based on our understanding of the standards, there are no conditions under which a nurse tank can continue in service indefinitely in Canada without undergoing some periodic testing and inspections.

Table 2. Summary of CSA B620/622 Inspection and Test Requirements [9]

	B620/B622-09	B620/B622-14	B620/B622-20
Visual Inspection	Every 2 to 3 years	Annually	Annually
Pressure Test	Every 5 years	Every 3 years	Every 3 or 5 years
Leakage Test	Not required	Not required	Annually

TC's requirements for nurse tanks, as specified in CSA B620-20 and B622-20, exceed the requirements of nurse tanks in the U.S. in several ways. TC has required periodic visual inspection and pressure testing for at least the last decade, for all nurse tanks, regardless of year of construction. The newest version of the regulations also adds a leakage test to the periodic inspections and tests. Nurse tanks used in

Canada have also been subjected to a rear-end protection requirement, which must now (as of the 2020 editions of the standards) be certified by an engineer to meet the applicable requirements. B622-20 also contains language that "[a] portable tank that is loaded or unloaded without being removed from the vehicle shall be completely contained within the length of the vehicle into or on which it is loaded or to which it is attached." The U.S. has no such requirement, and it is quite common for nurse tanks (especially a single nurse tank) to extend beyond the length of the running gear to which it is attached. See, for example, Figure 1, showing several nurse tanks with rear heads extending beyond the running gear.

Figure 1. Nurse Tanks on Single Running Gear with Heads Extending Beyond Running Gear

CSA B622-20 states that either the vehicle or the portable tank shall provide "suitable damage protection to protect all valves, safety devices, and other accessories from damage by collision, jackknifing, or overturning." While a requirement for accident damage protection is a positive aspect of improving nurse tank safety, the requirement is vague. The standard does not define "suitable" damage protection, nor what loads would be appropriate to consider in assessing how "suitable" the damage protection is.

2.3 Summary of Nurse Tank Design Variations Identified in Project

The fleet of nurse tanks in the United States today has developed over time. Nurse tanks in the current fleet have been constructed over the course of many years, by different manufacturers. Depending on the needs of the user, nurse tanks may be manufactured in a variety of capacities up to the 3,000 gallon limit imposed by 49 CFR 173.315(m)(1)(iv). Design standards, such as Section VIII, Division 1 of the ASME Boiler and Pressure Vessel Code, have changed with time, affecting nurse tank design.

The researchers reviewed a variety of sources to understand the variety of nurse tank design features representative of "typical" nurse tanks in the fleet. The goal was not to conduct analyses on every conceivable variation of nurse tank design during this study. Rather, the goal of the research was to develop models that were representative of commonly occurring nurse tank design features.

2.3.1 Capacities and Overall Dimensions

Based on a literature review and field visit in December 2022, researchers identified nurse tank capacities between 1,000 and 3,000 gallons as common in the fleet. Based on inspection data and field visit the researchers determined that 1,000 and 1,450 gallon tanks were more common in the fleet than tanks of a larger capacity. These two capacities were carried into the analysis phase of the study. Figure 2 shows several 1,000 gallon nurse tanks, each mounted on a single running gear. Figure 3 shows a 1,450 gallon tank on a single running gear. While these images show single nurse tanks mounted on running gear, both the 1,000 gallon and 1,450 gallon capacity tanks can be mounted side-by-side on appropriate running gear.

Figure 2. 1,000 gallon nurse tanks on a Single Running Gear

Figure 3. 1,450 gallon nurse tank on a Single Running Gear

In addition to the overall capacity of the nurse tank differing between the 1,000 gallon and 1,450 gallon tanks, the overall length, diameter, and head shapes also varied. In general, 1,000 gallon tanks had a smaller diameter than 1,450 gallon tanks. The 1,000 gallon tanks used a hemispherical head, while the 1,450 gallon tanks typically featured a 2:1 ellipsoidal head. Tank diameters varied based on year of manufacture and manufacturer. Researchers found that 1000 gallon tanks typically had an outside diameter of approximately 41 inches and 1,450 gallon tanks typically had an outside diameter of approximately 46-47 inches.

Larger capacity nurse tanks do exist within the fleet, up to the 3,000 gallon limit imposed by 49 CFR 173.315(m)(4). These tanks differ significantly from the 1,000 and 1,450 gallon tanks in both their overall dimensions and their running gear. An exemplar 3,000 gallon nurse tank on a “gooseneck” running gear is shown in Figure 4.

Figure 4. 3,000 gallon nurse tank

2.3.2 Head and Shell Thickness

The researchers compiled head and shell thickness data from several sources, including data plates observed during a site visit, data from nurse tank auction web sites, tank manufacturer or retailer data sheets, and accident reports. Many of these data sources also included information on the manufacturer of the nurse tank, the year of manufacturer, the tank capacity, and the tank diameter. Some information, such as the shape of the nurse tank heads (e.g., hemispherical or ellipsoidal) was apparent from photographs or direct observation of the tanks.

Where such data was available for a particular nurse tank the head and shell thickness values were organized by the year of tank manufacture and the tank's nominal capacity. Scatter plots of these data are shown in Figure 5 for 1,000 gallon tanks, Figure 6 for 1,450 gallon tanks, Figure 7 for 2,000 gallon tanks, and Figure 8 for 3,000 gallon tanks. Each figure also has a horizontal line (spanning all years) corresponding to the minimum thickness allowed under 49 CFR 173.315(m)(2)(ii) for heads or shells of nurse tanks with missing or illegible data plates. Note that while regulations allowing nurse tanks with missing or illegible name plates did not exist in all years shown, tanks built in those years could remain in service today with a missing or illegible name plate if they continued to meet the minimum thickness requirements.

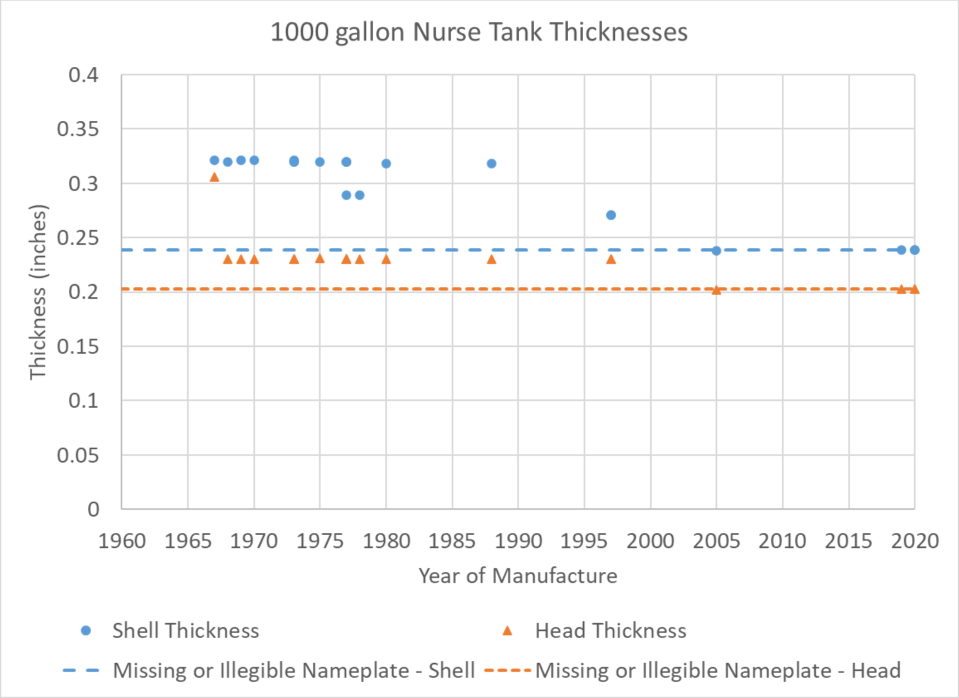


Figure 5. Scatter Plot of Head and Shell Thicknesses for Various 1,000 gallon Nurse Tanks by Year of Manufacture

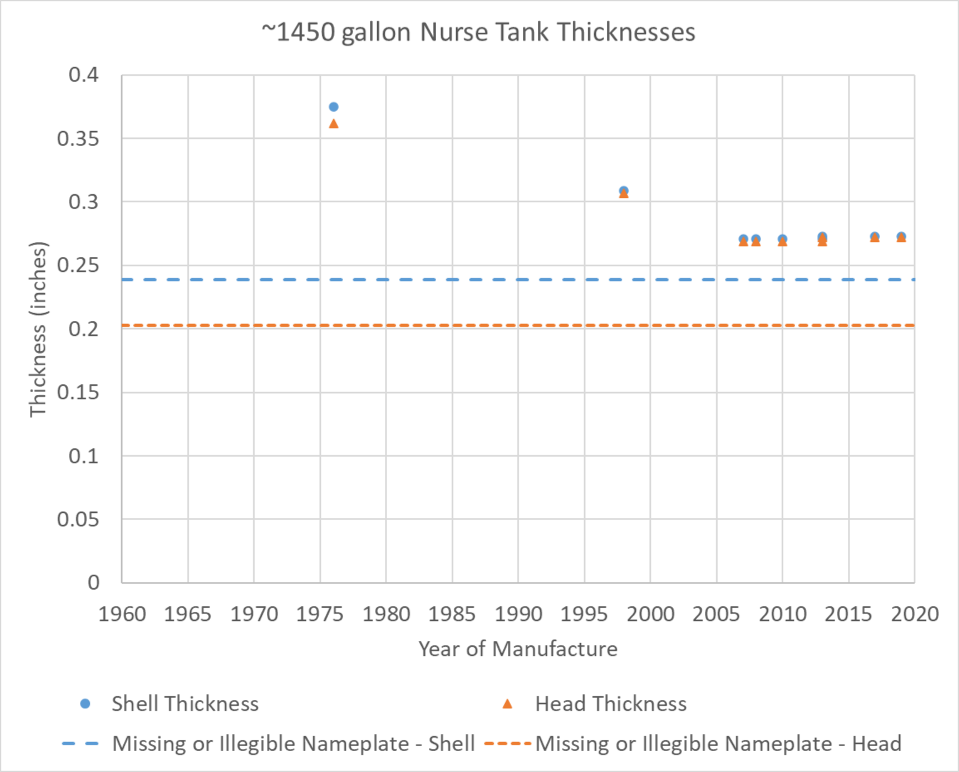


Figure 6. Scatter Plot of Head and Shell Thicknesses for Various 1,450 gallon Nurse Tanks by Year of Manufacture

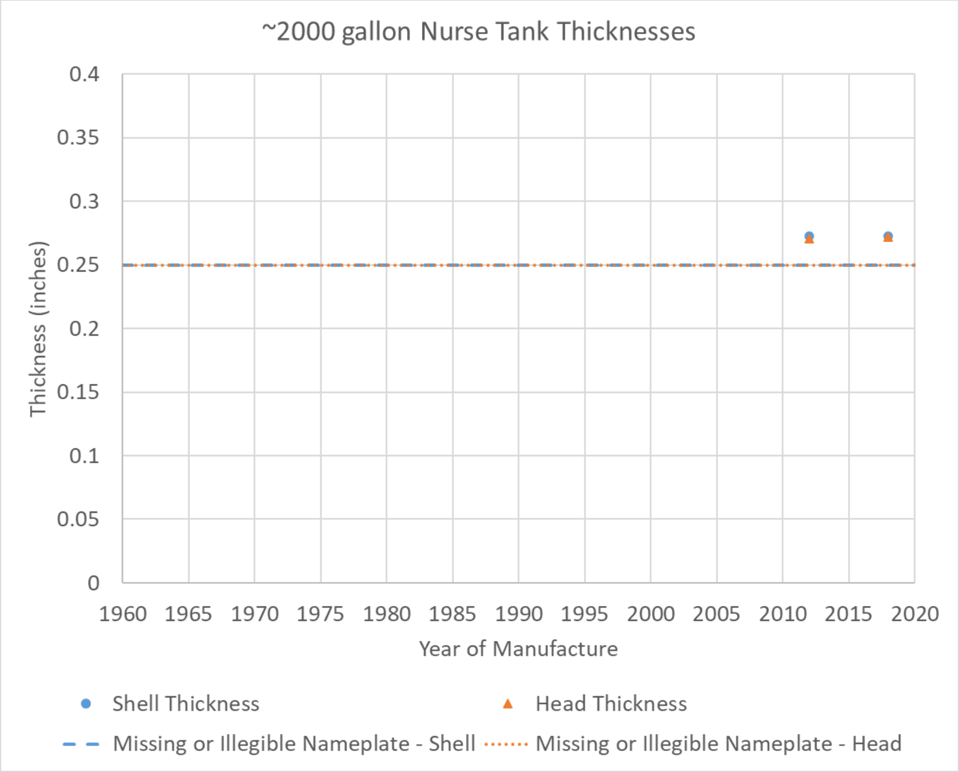


Figure 7. Scatter Plot of Head and Shell Thicknesses for Various 2,000 gallon Nurse Tanks by Year of Manufacture

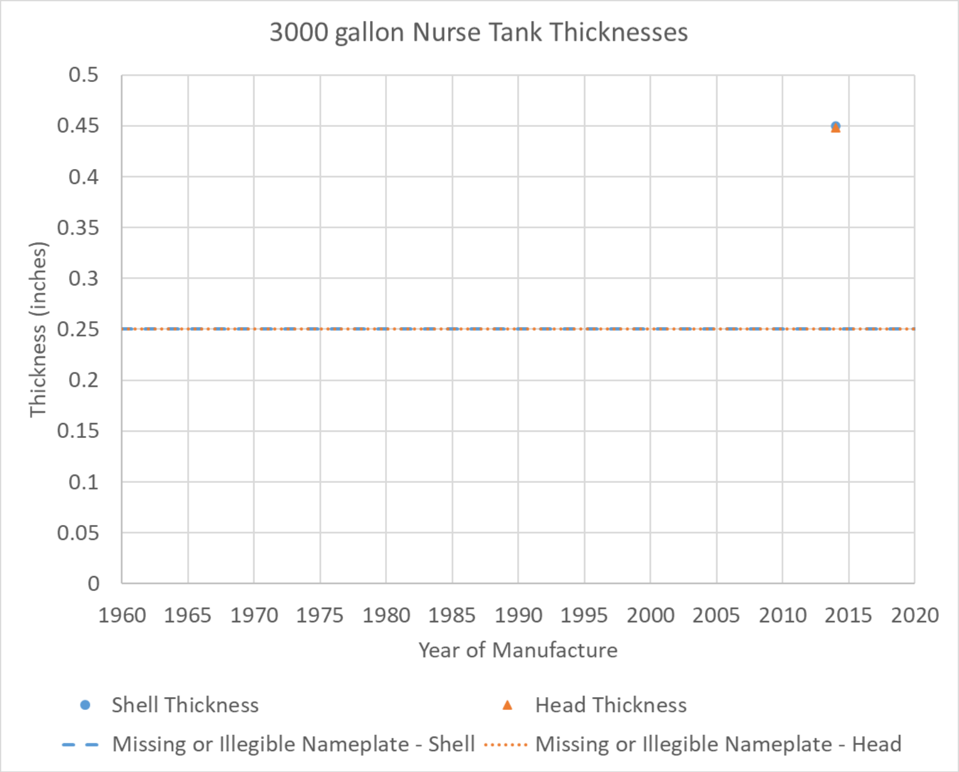


Figure 8. Scatter Plot of Head and Shell Thicknesses for Various 3,000 gallon Nurse Tanks by Year of Manufacture

The researchers reached several conclusions from the assembled data. Many more examples of 1,000 and 1,450 gallon nurse tanks could be found than for the 2,000 or 3,000 gallon tanks. Because of the number of 1,000 and 1,450 gallon tanks with known data it is apparent that both the heads and shells of “legacy” tanks (pre-1998) are thicker than “modern” (post-1998) tanks. In the 1999 Addenda to the 1998 edition of Section VIII, Division 1 of the ASME Boiler and Pressure Vessel Code ASME reduced the design factor used to calculate the allowable stress used in thickness calculations from 4.0 to 3.5 [10]. Reducing the design factor increased the allowable stress in a vessel designed according to Section VIII, Division 1. Since the maximum allowable working pressure (MAWP) of a nurse tank remained at 250 psig, vessels constructed according to editions of Section VIII, Division 1 after 1998 have been allowed to have a thinner head and shell than the older vessels.

It is apparent from Figure 5 that the minimum head and shell thickness values given in 49 CFR 173.315(m)(2)(ii) for nurse tanks with a missing or illegible data plate and a capacity of 1,500 gallons or less are based on the typical head and shell thicknesses used in modern 1,000 gallon tanks. Since 1,450 gallon tanks with missing or illegible name plates have the same minimum thicknesses as 1,000 gallon tanks, examination of Figure 6 shows that even a modern 1,450 gallon tank is expected to have heads and shells that are significantly above the minimum value that would lead to a tank with missing or illegible name plates being removed from service.

While the 2,000 and 3,000 gallon tanks were not included in the analysis phase of this research, the researchers note that the minimum thicknesses for nurse tanks with missing or illegible name plates do not align with the limited number of typical thickness values found for these larger tank capacities. As shown in Figure 7, the limited number of 2,000 gallon nurse tanks identified during this research had thicknesses of approximately 0.275 inches for both head and shell. Similarly, Figure 8 shows that for one example of a 3,000 gallon nurse tank the head and shell thickness were both approximately 0.45 inches. The minimum head and shell thickness values from the CFR for 2,000 gallon and 3,000 gallon nurse tanks with missing or illegible ASME plates are 0.25 inches.

The researchers chose to include both the legacy and modern thicknesses for 1,000 gallon and 1,450 gallon tanks in the analysis matrix, to better understand whether the change in thickness and increase in allowable stress influenced the fatigue and service life of the nurse tanks. This decision led to four variations of nurse tank designs being considered: legacy thickness 1,000 gallon tanks, modern thickness 1,000 gallon tanks, legacy thickness 1,450 gallon tanks, and modern thickness 1,450 gallon tanks.

2.3.3 Foot Design and Pads between Feet and Tank

Typically, a nurse tank is attached to a wagon via four feet, two on each end of the tank. The feet are bolted to the wagon. Researchers observed a variety of foot designs in the current nurse tank fleet. In general, two styles were investigated in this study to investigate the effect of foot design on the stresses that develop in the nurse tank under typical loading conditions.

One style of foot has a J- or fishhook shaped profile. This style is referred to as edge-to-tank (ETT) throughout this report, as the foot makes contact with the tank or pad only along two edges. These edges would be welded to the tank or pad, providing a relatively small area of contact between the foot and the tank or pad. Figure 9 shows an ETT foot attached to the tank with and without a pad.

Figure 9. Edge-to-tank Foot attached via Pad (left) and Directly to Tank (right)

The second style of foot features two additional flanges at the ends of the J-shaped portion of the foot. This style of foot is referred to as face-to-tank (FTT) in this report, as the flanges create a face that is in contact with the pad or the tank. The FTT feet observed in the field were typically welded all around the flanges, offering a larger surface area and longer weld length than the ETT feet. Figure 10 shows a face-to-tank foot attached to the tank with and without a pad.

Figure 10. Face-to-tank Foot attached via Pad (left) and Directly to Tank (right)

Nurse tank feet may be attached directly to the tank, or they may be attached via pads that are in turn attached to the tank. Current nurse tank design standards and regulations do not require the use of pads. Researchers identified nurse tanks using both ETT and FTT foot designs with and without pads. This produced four combinations of foot and pad configuration to be studied: ETT/No pad, ETT/pad, FTT/No Pad, and FTT/pad.

2.3.4 Summary of Tank Design Matrix

The variations in tank capacities, head and shell thickness, and mounting foot attachment details produced a matrix of 16 combinations of configurations. This matrix is shown in Table 1.

Table 1. Matrix of Design Variations Considered in Modeling Plan

Capacity	Steel Thickness	Foot Style	Foot Attachment
1,000 gallons	Legacy	Edge-to-tank	Pads
1,000 gallons	Legacy	Edge-to-tank	No Pads
1,000 gallons	Legacy	Face-to-tank	Pads
1,000 gallons	Legacy	Face-to-tank	No Pads
1,000 gallons	Modern	Edge-to-tank	Pads
1,000 gallons	Modern	Edge-to-tank	No Pads
1,000 gallons	Modern	Face-to-tank	Pads
1,000 gallons	Modern	Face-to-tank	No Pads
1,450 gallons	Legacy	Edge-to-tank	Pads
1,450 gallons	Legacy	Edge-to-tank	No Pads
1,450 gallons	Legacy	Face-to-tank	Pads
1,450 gallons	Legacy	Face-to-tank	No Pads
1,450 gallons	Modern	Edge-to-tank	Pads
1,450 gallons	Modern	Edge-to-tank	No Pads
1,450 gallons	Modern	Face-to-tank	Pads
1,450 gallons	Modern	Face-to-tank	No Pads

3 Nurse Tank Inspection Data Analysis

While not all nurse tanks are required to undergo periodic inspection and testing, nurse tanks with missing or illegible data plates must undergo periodic inspection and thickness testing. Additionally, some owners of nurse tanks may choose to proactively conduct periodic inspections and testing on their nurse tanks that are not required to be inspected or tested. Asmark Institute (Asmark) maintains a database of nurse tank inspection records as a part of its Nurse Tank Inspection Program (NTIP). Nurse tank inspection records are not required to be submitted within the NTIP, but the database includes a large dataset. The NTIP was established in 2005.

As a part of this research project Asmark agreed to share anonymized NTIP thickness testing data with Volpe Center researchers. That dataset and how it was used in this project are discussed in this chapter.

3.1 Dataset Overview and Limitations

The NTIP Inspection Data consisted of 62,712 unique reports for 31,775 unique nurse tanks of various capacities, dates of manufacture, and manufacturers. Given the number of unique tanks is smaller than the total number of reports, many of the tanks in the NTIP Inspection Database appear in multiple reports. Most of the reports in the database contained at least one incomplete field, but since the dataset was so large, the number of tanks with complete or mostly-complete reports was large enough to provide significant insights.

The following information was present in all the reports in the database:

- Tank ID
- Date of Inspection/Report
- Whether the tank passed/failed inspection

The following information was present in some but not all reports in the database:

- Tank Manufacturer
- Date of Manufacture
- Tank Capacity
- Tank Thicknesses at numerous locations per tank

A breakdown of present or missing fields for the reports of each tank in the database is contained in Figure 11. While most of the tanks are missing a manufacturer and/or manufacturing date, tank capacity is noted for most of the unique tanks in the database. The reports for a majority of tanks do include at least some thickness data, but in many cases this thickness data is partially or even mostly incomplete. Nonetheless, enough data was present to obtain significant findings, which are discussed in Section 3.3.

It should also be noted that no data on the specific shape (e.g., ellipsoidal or hemispherical heads), geographic location, owners, or construction (e.g., PWHT status) of each tank was provided in the NTIP reports.

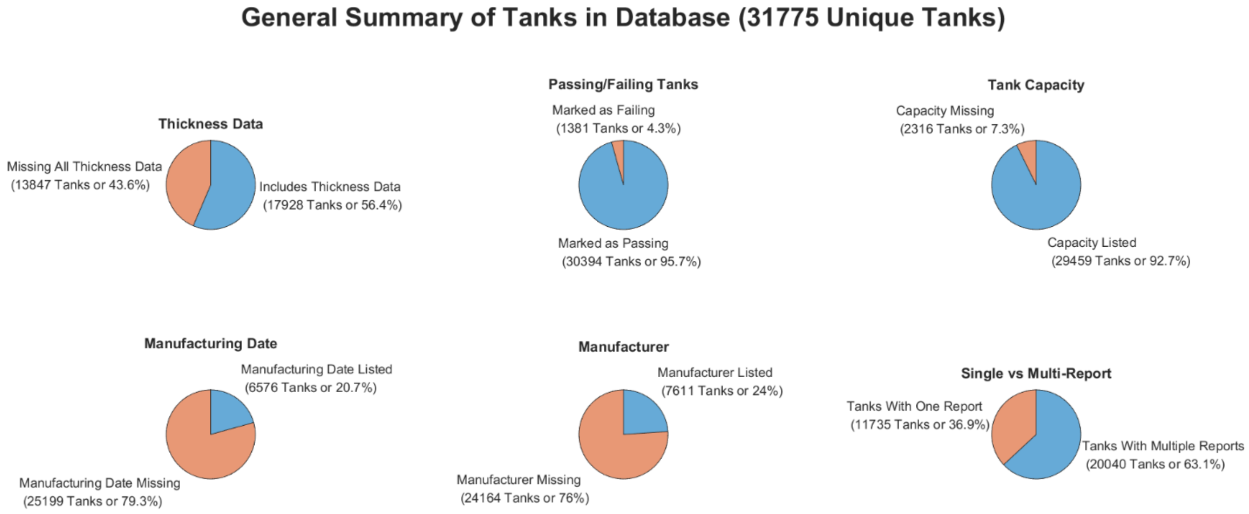


Figure 11. Summary of Nurse Tanks in the NTIP Report Database

The majority of tanks in the database had a listed capacity of either 1,000 or 1,450 gal, while the remaining tanks were either missing a capacity in their reports or had a different capacity listed. A breakdown of the tanks in the database by capacity is contained in Figure 12.

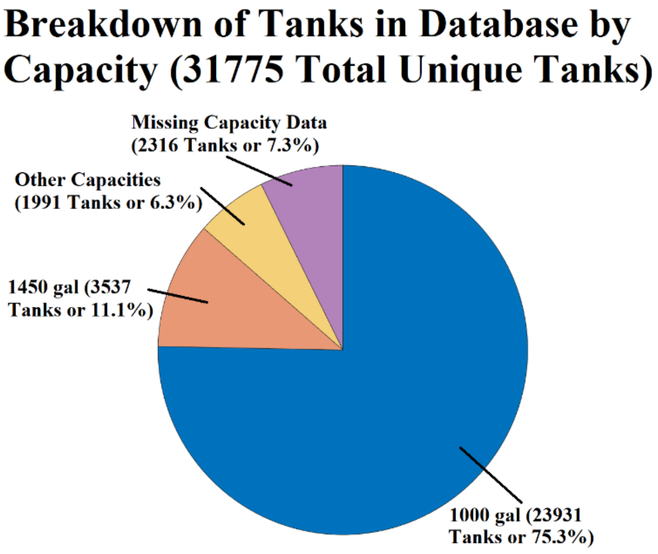


Figure 12. Capacities of Tanks in the NTIP Database

3.2 Data Analysis Methodology

To analyze the data from the NTIP inspection reports together, the data from all reports were compiled into a single spreadsheet. The number of “Raw” reports was slightly higher than the final number of reports due to some reports having duplicate entries in the database. Additionally, reports belonging to a small number of Tank IDs contained contradictory information, such as different manufacturers or capacities. In cases where one report for a unique Tank ID included a manufacturer, manufacturing date, or capacity that was missing in other reports, the fields in missing reports were filled with the known value. In other cases where values were listed but contradictory, the reports belonging to one of the values were assigned a new Tank ID.

Due to the very large number of entries in the NTIP data spreadsheet, data processing after resolving duplicate/contradictory entries was performed using MATLAB rather than Excel. This was achieved by first filtering the report data into subsets based on values in a singular data category. The following categories were used to create these first-order subsets:

- Number of recurrences for a Tank ID (i.e., tanks that have multiple inspection data reports in the database)
- Empty, Partially-Filled, or Complete Thickness Data
- Passing vs Failing
- Tank Capacity
- Date of Manufacture by year
- Manufacture Date before vs. after the 1998 change in ASME Code
- Tank Manufacturer

By finding reports common to multiple first-order subsets, additional second-, third-, and other higher-order subsets of the NTIP report data based on combinations of parameters were obtained. Since all reports included a Tank ID, the list and count of tank IDs for each subset were also extracted for each subset of data. Additionally, this enabled the creation of a few unique second-order subsets based on whether reports for a particular tank exclusively fall into a particular first-order subset. The findings presented in Sections 3.3.1 and 3.3.23.3.2 were obtained directly from filtered subsets of the NTIP data.

The thickness rate change (i.e., change in thickness over time) results in Section 3.3.3 were obtained with a slightly different method of processing. For tanks with multiple reports in the database, entries for thickness rate change data were obtained by taking the differences in each thickness between inspection reports for a tank and dividing that difference by the time between inspections to obtain average change in thickness for that tank location between inspection dates. For a particular tank, the number of entries for thickness rate change would thus be one less than the number of total reports in the database. Filters based on all categories listed above, except for number of recurrences, could then be applied similarly to the regular thickness data to obtain subsets of interest for comparison.

Thickness rate change results for each location were also compared across various subsets of tanks by calculating the mean rate for each location (e.g., center of tank head). Figure 13 shows a typical distribution for the values of thickness rate change at a particular location. Rate changes with a magnitude greater than 50 x 10^{-3} in/year were excluded from the mean calculations, as these outlying values tended to be inflated by their source reports being closer chronologically than the typical 5 year interval, or from one of the thickness values being missing from the report. Mean rather than median was used since as shown in Figure 13, the typical distribution of thickness rate values for a particular location would produce a median rate change of 0. Also of note is the lack of small thickness rate change values with a magnitude below 0.1 x 10^{-3} in/year. but above 0. This is due to the precision of the raw data being limited to 1 x 10^{-3} in/year and the lack of report pairs with intervals greater than 10 years.

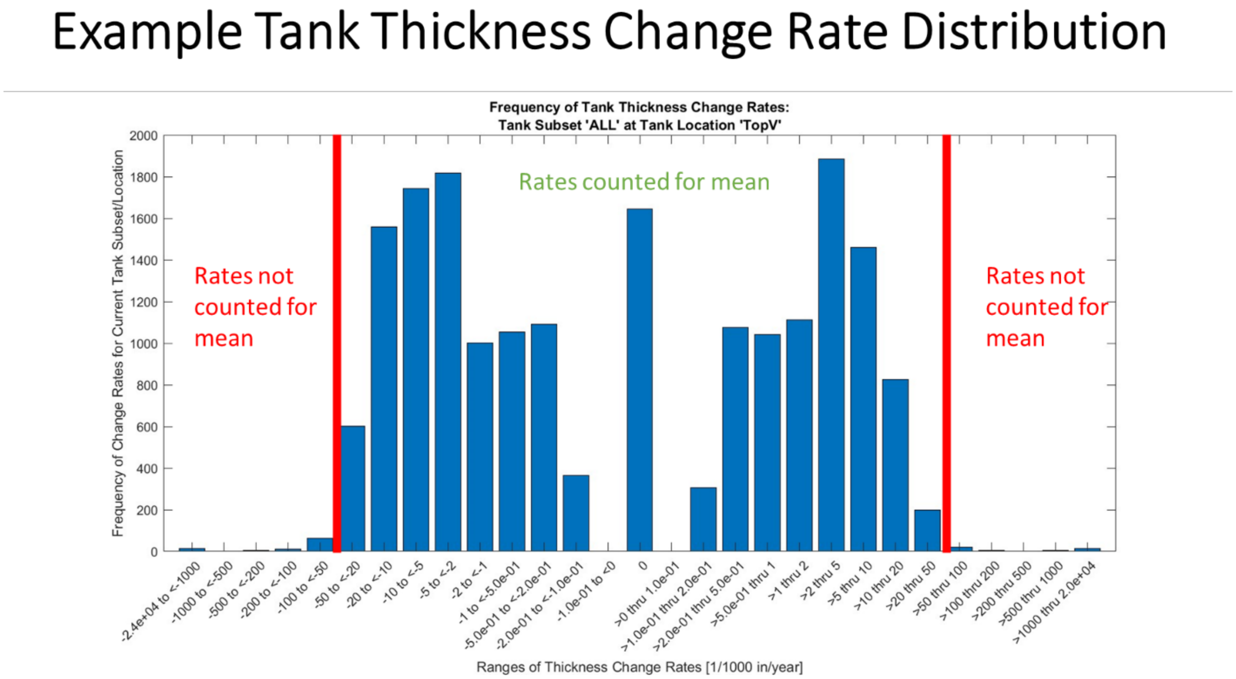


Figure 13. Typical thickness rate change distribution

3.3 Analysis and Observations

This section includes discussion of various analyses performed on the NTIP database and trends observed in subsets of the data.

3.3.1 General findings

Of the 31,775 unique tanks in the NTIP database, 1,381 (4.35 %) are marked as having failed inspection in a report. The percentage of failed tanks differs somewhat for tanks of differing capacities, as shown in Figure 14. Generally, higher-capacity tanks saw lower failure rates, as is seen in comparing the failure rates of 500 and 1,000 gallon nurse tanks to tanks with higher capacities. It should also be noted that there are far fewer 500 and 1,140 gallon tanks in the database compared to other capacities. The percentage data in Figure 14 only includes capacities having five or more reported failures in the database.

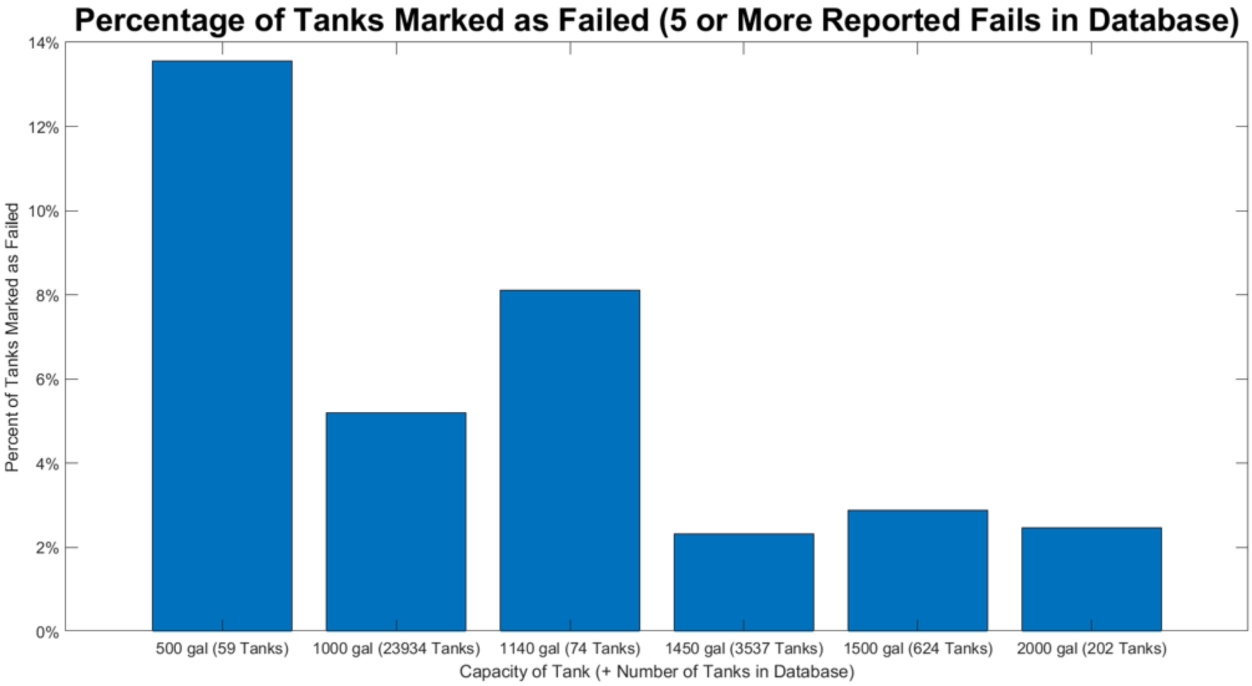


Figure 14. Percentage of Failed Tanks for Various Capacities.

Given that 1,000 and 1,450 gallon tanks are most common both in the database and in service, analysis primarily centered around tanks of these capacities. Differences in thickness trends for tanks manufactured before (i.e., legacy) versus after (i.e., modern) the 1998 ASME Code change were also of key interest, though only tanks with reports that include the manufacturing date could be used for this comparison. One trend of note is that compared to modern tanks, legacy tanks with complete or near-complete thickness measurement data tended to include a wider range of measured thicknesses, as demonstrated in Figure 15. This figure presents the range of thicknesses measured on a single exemplar tank's shell in each category of capacity and vintage. The dashed horizontal line represents the minimum allowable shell thickness for tanks of less than 1,500 gallon capacity with a missing or illegible data plate, per 49 CFR 173.315(m)(2)(ii). Although this figure displays data from only one tank in each category of interest, similar distributions in shell thickness variation were observed in other tanks with similarly-complete thickness data.

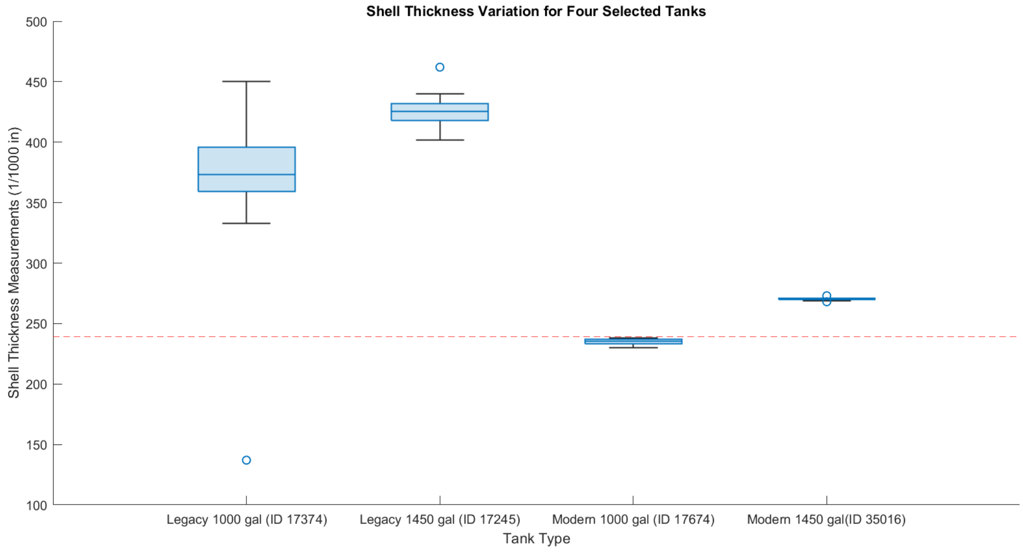
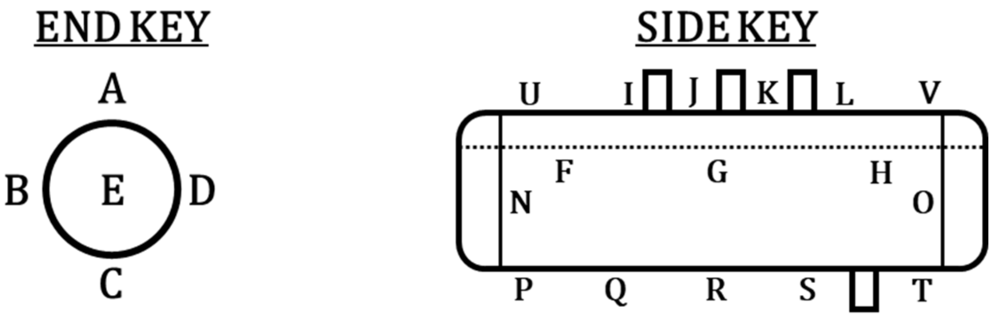


Figure 15. Shell Thickness Variation for Four Selected Tanks

3.3.2 Confirmed Failure percentage by tank location and vintage

For this study, it was assumed that there are no “false negatives” where a tank is marked as having failed inspection when in reality it should have passed. In cases where a tank is marked as having failed and a thickness value below the failure threshold was noted (0.250 in. for heads and shells of tanks of more than 1,500 gal capacity and 0.203 in. head thickness/0.239 in. shell thickness for tanks of less than 1,500 gal capacity), that failure is considered “confirmed.” Given that 228 confirmed failing reports were identified in the database for tanks of various capacities and vintages and at various locations, it is useful to compare failure rates within each of these categories.

In the NTIP inspection worksheet, 22 test locations for thickness are specified for measurement. These were organized into three broad regions, as shown in Figure 16 for analysis purposes and easier comparison between failures across different locations.



"Head Values" refers to thicknesses at points A, B, C, D, and E on either end of the tank

"Outlet Values" refers to thicknesses at points I, J, K, and L, and M. "Shell Values" refers to thicknesses at all other locations

Figure 16. Definition of "Head", "Shell", and "Outlet" Regions for NTIP Data Analysis

For a particular confirmed-failed tank, it may be the case that confirmed failing thicknesses occurred at multiple regions or locations within a region for that tank. Figure 17 provides a summary of this by breaking down, by region, the number of reports with different numbers of confirmed failures in each region. This data indicates that for tanks which experienced a confirmed failure in any region, it most often did so at a single location, hence the large count of "0" failures for each region when the confirmed failures are divided by region. Figure 17 also indicates that numerous tanks were documented as having multiple confirmed failures, with fewer reports noting progressively higher numbers of confirmed failures. Additionally, a significant number of reports are noted with 22 confirmed failures (i.e., a measured thickness below the minimum at every location indicated in Figure 16). These correspond to several modern-vintage 1,000 gal tanks with shell and outlet thicknesses noted as slightly under the failure threshold, such as thicknesses in the mid-high 0.230 range compared to a 0.239 in failure threshold.

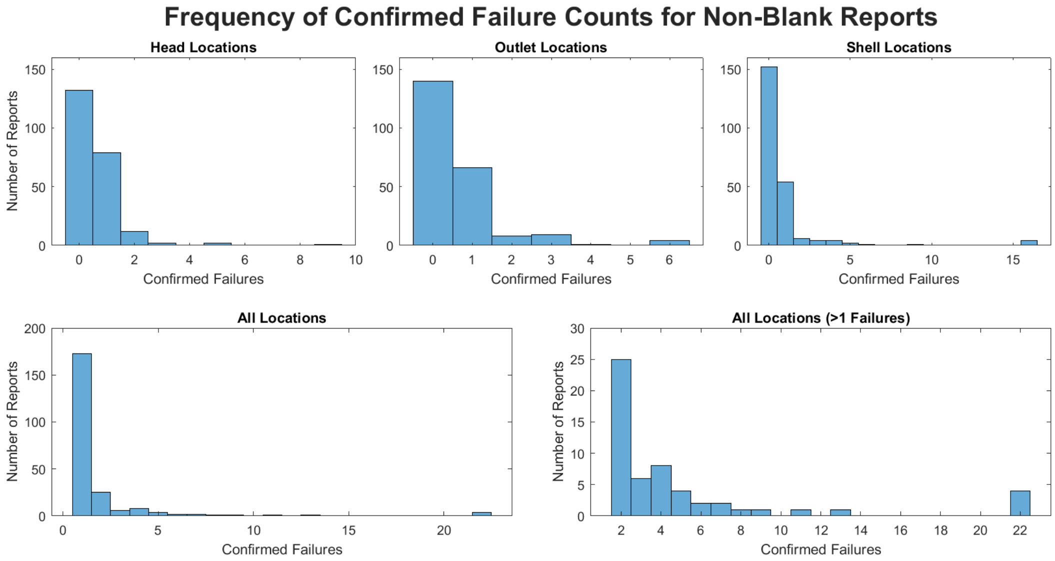


Figure 17. Frequency Summary of Confirmed Failing Thicknesses

For legacy and modern tanks of 1,000 and 1,450 gal capacities, another item of interest was the percent of confirmed-failed tanks with a confirmed failure per each location, as shown in Figure 18. This highlights the trend that for 1,450 gal tanks, confirmed failures occurred most often on the shell close to the head-shell junction and the center of the head, while for 1,000 gal tanks, failures were more evenly distributed with higher rates on the head.

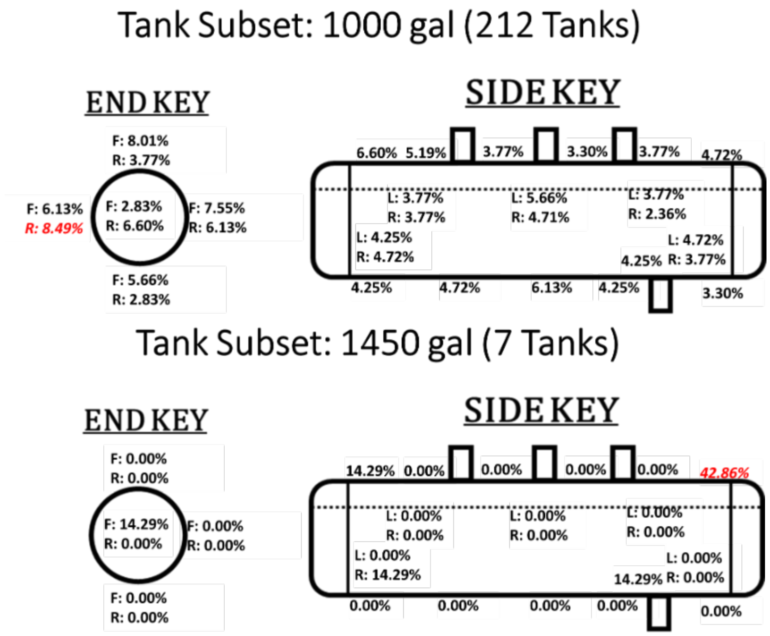


Figure 18. Percent of Confirmed-Failed Tanks with Failures at Each Location

Figure 19 provides a visual breakdown of the regions of failure present for each of the 228 confirmed failure reports in the database. Most failures occurred in a single of the three regions as stated above, with head- and outlet-only failures occurring in more reports than shell-only failures. A small number of reports have confirmed failures in two of the three regions, while five have confirmed failures in all regions.

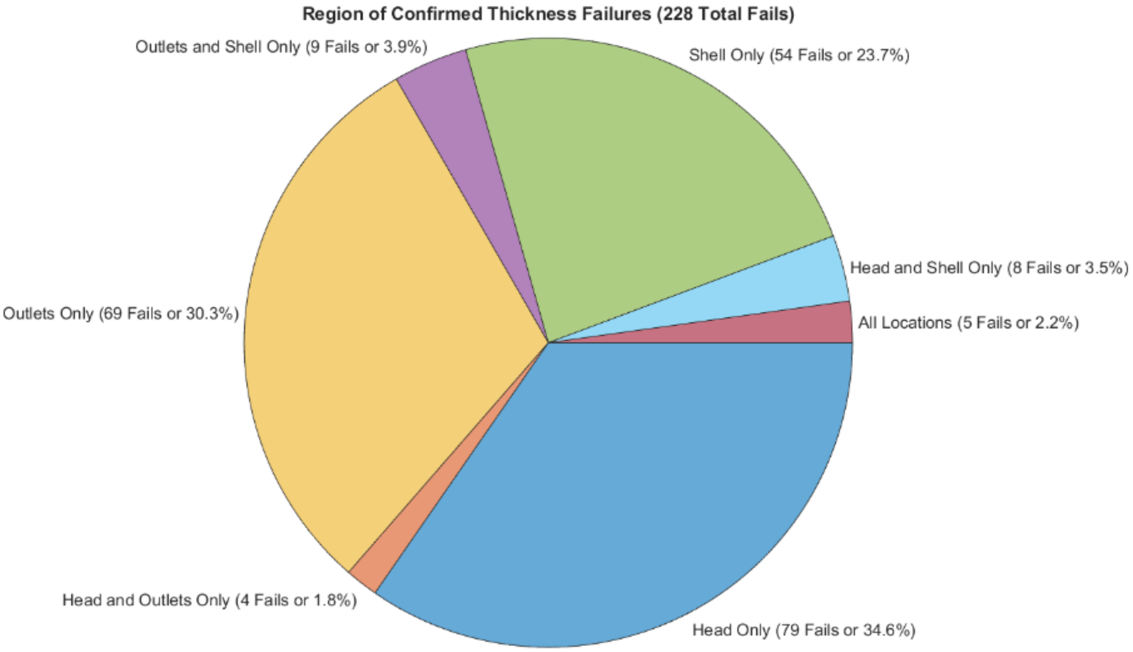


Figure 19. Breakdown of Confirmed Failures by Region for Individual Tanks

Confirmed failures can also be compared between tanks of differing vintage, as shown in Figure 20. In this figure, each bar represents the percent of tanks in the database manufactured in a particular year that had a confirmed thickness failure. It is also key to note that given the lack of a manufacture date in most reports, the number of tanks which can be considered “legacy” or “modern” is much smaller than “undated” tanks. The dotted line represents the end of 1998, as tanks manufactured after this date use a reduced design factor based on the 1999 Addenda to the 1998 edition of Section VIII, Division 1 of the ASME Boiler and Pressure Vessel Code. Generally, tanks with an older vintage see higher percentages of confirmed failures, though there are occasional outlying years. However, there does not appear to be a significant difference in failure rate for tanks manufactured in the years surrounding 1998/1999 as a whole.

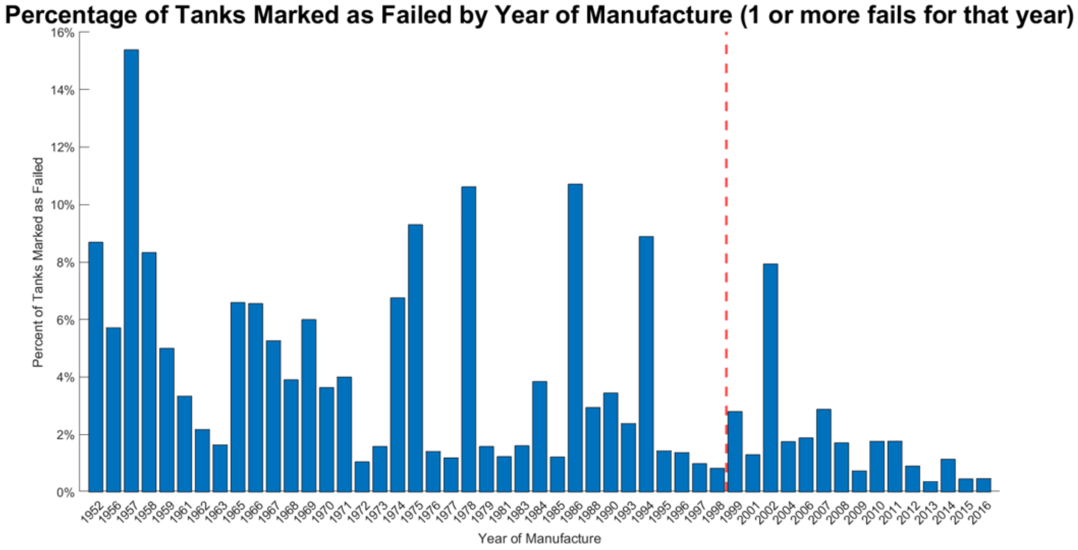


Figure 20. Percent of Failed Tanks by Year of Manufacture

Specifically considering 1,000 and 1,450 gal tanks with a reported date of manufacture, the number of confirmed failing tanks is much smaller than the total number of failed tanks as seen in Figure 21. This, along with the rarity of dated tanks in the database, contributes to a very small sample size for confirmed failing tanks known to be legacy or modern, though useful information was nonetheless able to be obtained from these tanks.

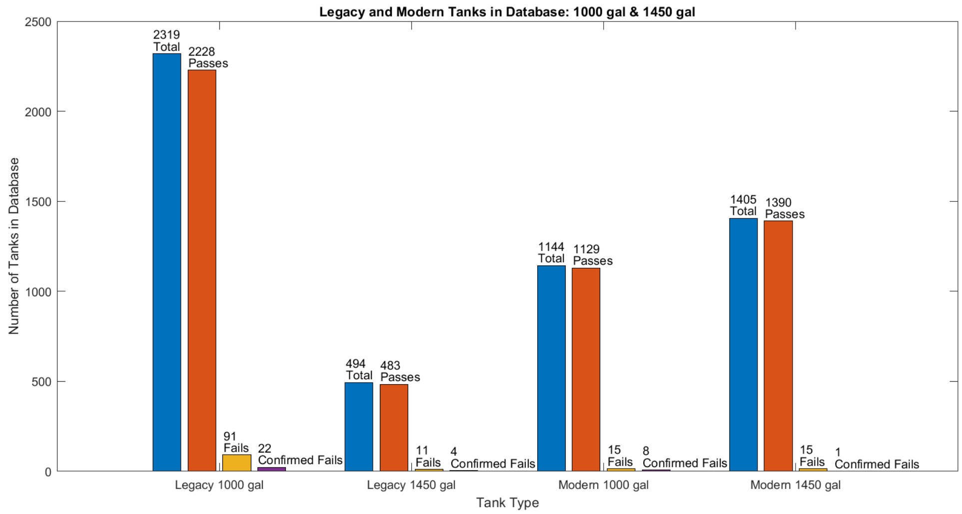


Figure 21. Pass/Fail/Confirmed Fail Count for Tanks in Key Categories

3.3.3 Mean thickness change rates by tank location and vintage

The mean thickness change rates were obtained for the following subsets of recurrent tanks (i.e., tank IDs that appear more than once in the inspection database).

First-Order:

- All Tanks (29,729 Report pairs, 19,479 Tanks)
- Tanks with Complete Data (9,079 Report pairs, 8,023 Tanks)

Second-Order:

- 1,000-gal Tanks with Complete Data (6,962 Report pairs, 6,234 Tanks)
- 1,450-gal Tanks with Complete Data (1,303 Report pairs, 1,080 Tanks)

Third-Order:

- Legacy 1,000-gal Tanks with Complete Data (338 Report pairs, 318 Tanks)
- Legacy 1,450-gal Tanks with Complete Data
- Modern 1,000-gal Tanks with Complete Data
- Modern 1,450-gal Tanks with Complete Data

The values for the relative rate of mean thickness change in thousandths of an inch per year are contained in Table 2. These values have been adjusted from the initial calculations such that the least negative/most positive rate is set to 0, with other rates being relative to that. It is worth noting and of possible concern that many subsets included mean thickness change rates greater than 0, which imply an increase in tank thickness over time. This may be due to outlying values, measurement error (e.g. difference in temperature compensation, or inherent limits of measurement tools), or other factors such as repainting of tanks, but is ultimately impossible to determine with certainty in the scope of this study. However, these positive rates were never observed in isolation: they were typically present in multiple locations for a particular subset and were accompanied by smaller magnitudes of negative rates. With this, it is assumed that the factor inducing these positive rates is affecting tanks uniformly, so looking at the thickness rate changes relative to the least negative/most positive value can still provide insight into local variations in thickness change rates.

Table 2. Relative Mean Thickness Change Rates for Key Subsets. All rates are in 1/1000 in per year.

Location on Tank	All Reports	Tanks with Complete Data	1,000 gal Tanks with Complete Data	1,450 gal Tanks with Complete Data	1,000 gal Legacy Tanks with Complete Data	1,450 gal Legacy Tanks with Complete Data	1,000 gal Modern Tanks with Complete Data	1,450 gal Modern Tanks with Complete Data
A (Front)	-0.087	-0.218	-0.281	-0.297	-1.429	-0.883	-0.413	-0.376
A (Rear)	-0.125	-0.261	-0.330	-0.165	-1.593	-0.031	0.000	-0.233
B (Front)	-0.140	-0.180	-0.253	0.000	-1.410	-0.176	-0.390	0.000
B (Rear)	-0.156	-0.173	-0.255	-0.069	-1.584	-0.267	-0.293	-0.073
C (Front)	-0.087	-0.125	-0.126	-0.350	-1.651	-1.009	-0.569	-0.385
C (Rear)	-0.177	-0.161	-0.205	-0.177	-1.490	0.000	-0.669	-0.364
D (Front)	-0.138	-0.175	-0.227	-0.265	-1.728	-1.106	-0.432	-0.389
D (Rear)	-0.089	-0.103	-0.147	-0.158	-1.411	-0.490	-0.457	-0.352
E (Front)	-0.017	-0.057	-0.084	-0.300	-0.329	-0.803	-0.854	-0.708
E (Rear)	0.000	0.000	0.000	-0.373	-0.632	-0.800	-0.901	-0.913
F (Front)	-0.227	-0.435	-0.592	-0.104	-0.680	-0.449	-1.350	-0.188
F (Rear)	-0.275	-0.466	-0.584	-0.288	-0.810	-1.086	-1.428	-0.236
G (Front)	-0.191	-0.350	-0.482	-0.119	-0.863	-0.496	-1.356	-0.111
G (Rear)	-0.243	-0.452	-0.551	-0.309	-0.768	-0.735	-1.460	-0.322
H (Front)	-0.160	-0.409	-0.506	-0.297	-0.999	-1.028	-1.258	-0.101
H (Rear)	-0.220	-0.427	-0.550	-0.205	-0.722	-0.791	-1.440	-0.156
I	-0.275	-0.588	-0.701	-0.444	-0.895	-0.345	-1.366	-0.275
J	-0.246	-0.526	-0.629	-0.441	-0.918	-0.496	-1.366	-0.382
K	-0.281	-0.585	-0.683	-0.528	-0.779	-0.331	-1.340	-0.313
L	-0.232	-0.525	-0.622	-0.473	-0.758	-0.590	-1.303	-0.289
M	-0.319	-0.689	-0.820	-0.539	-1.443	-0.363	-1.372	-0.502
N (Left)	-0.828	-1.436	-1.753	-1.035	-1.152	-0.352	-1.224	-0.382
N (Right)	-1.025	-1.716	-2.012	-1.425	-1.089	-0.531	-1.435	-0.782
O (Left)	-0.892	-1.503	-1.794	-1.201	-1.518	-0.608	-1.247	-0.558
O (Right)	-0.971	-1.639	-1.954	-1.266	-1.678	-0.309	-1.430	-0.427
P	-0.820	-1.335	-1.594	-0.835	-1.304	-0.953	-1.379	-0.373
Q	-0.459	-0.661	-0.835	-0.369	-1.074	-0.837	-1.358	-0.403
R	-0.402	-0.639	-0.769	-0.529	-0.704	-0.624	-1.335	-0.530
S	-0.406	-0.611	-0.761	-0.422	-1.126	-0.503	-1.424	-0.530
T	-0.755	-1.267	-1.500	-1.034	-1.129	-0.797	-1.354	-0.380
U	-0.904	-1.534	-1.769	-1.394	-0.473	-0.666	-1.356	-0.553
V	-0.928	-1.587	-1.809	-1.489	0.000	-0.505	-1.406	-0.499

The locations seeing the highest relative rate of thinning on average vary significantly by the subset of tanks used in calculations. Looking at tanks as a whole, those with complete data, and all 1,000 and 1,450 gal tanks, the highest thinning rates are observed at locations close to the head-shell junction and along the bottom of the tank. However, for legacy 1,000 gal tanks (and to a lesser extent, modern 1,000 gal tanks), high relative rates of thinning also occur on the tank head. For 1,450 gal tanks, those of a legacy vintage exhibit relatively uniform thinning rates along the tank shell, with lower rates observed on the tank head. The inverse is the case for modern 1,450 gal tanks, though the head-shell junction and bottom of the tank in this subset saw higher thinning rates than the rest of the shell.

3.4 Takeaways from Inspection Dataset

From the inspection dataset, the primary key findings relate to the locations of tank failures and rates of highest average thinning. For the 1,000 gal and 1,450 tanks in the database, confirmed failures occurred most frequently at locations close to the head-shell junction, or on the head itself. For 1,450 gal tanks, this is in good agreement with the results of the FE modeling discussed in Section 4.4.3. Those results show that under a combined internal pressure equal to the minimum MAWP and 1G vertical load, peak principal stresses in modern tanks tend to occur along the bottom of the shell, as well as following the head-shell junction. They also show that for modern 1,450 gal tanks, there is a principal stress concentration on the center of the head, where failure has been observed in the NTIP dataset. It is also crucial to note the small sample size of 1,450 gal tanks with confirmed failures, which may diminish applicability of these takeaways to 1,450 gal tanks generally.

As discussed in Section 2.3.2, tanks of a modern vintage tend to be manufactured with lower thicknesses per the 1998 change in the allowable stresses under Section VIII, Division 1 of the ASME Code. Given this, it is notable that every single one of the tanks marked as having 22 confirmed failure locations as per Figure 17 was a 1,000 gal modern tank. Since the failure criteria for tanks with missing or illegible nameplates is based on thickness, it seems that only minor thinning is required for many locations to fall below the thickness failure threshold. As a result, it could be the case that modern tanks are being prematurely removed from service solely based on thickness and without consideration for the design material or vintage.

There is relatively strong agreement between the location distributions of relative thickness change rates for dated 1,000 and 1,450 tanks with the principal stress distribution of the FE model as shown in Section 4.4.3. In both cases, the areas of most concern are along the head-shell junction and bottom of the tank, as well as on the heads of modern 1,450 gal tanks. The thickness rate change data also suggests the heads of legacy tanks and modern 1,450 gal tanks may also be more likely to fail thickness tests, which is in agreement with the confirmed failure location distribution of legacy 1,000 gal tanks. Otherwise, there is relatively weak correlation between the location distributions of relative thickness change rates and confirmed failures.

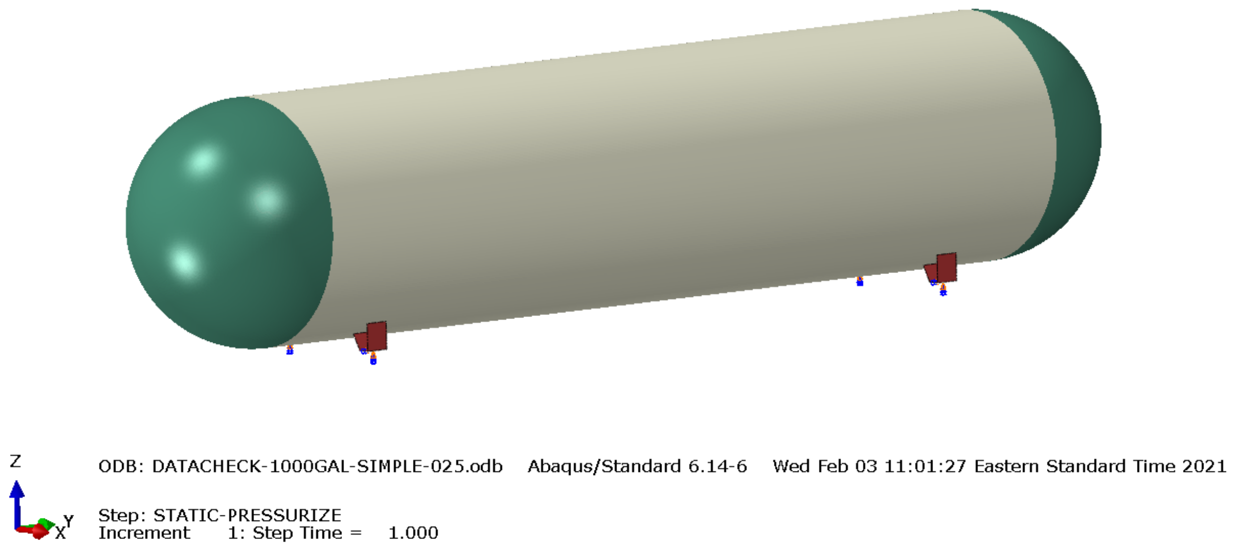
4 FE Modeling and Analysis

Volpe Center researchers developed detailed FE models of 1,000 gallon and 1,450 gallon nurse tanks. For each capacity, separate models were developed to study variations in tank design features, such as attaching feet directly to the tank or via a pad or modeling tank thicknesses based on modern versus legacy tank thicknesses.

4.1 Modeling Approach and Limitations

The general approach was to develop a detailed FE model of nurse tank designs of interest that could be evaluated for two kinds of loads: internal pressure loads and quasi-static “G” loads in the vertical, lateral, and longitudinal directions representing the dynamic loads acting on the nurse tank in transit. The mass of the NH3 within the tank was included in each model, but the quasi-static modeling techniques did not include any fluid dynamics (e.g., sloshing). The models included the tank head, shell, circumferential weld joint between head and shell, feel, and pads (as applicable). The models did not include internal baffles or openings in the tank. The model did not include the running gear. The model did not include any internal baffles since the quasi-static simulations do not include any fluid dynamic effects. The FE modeling techniques used in Phase 2 are discussed in detail in Appendix C – FE Model Development.

Additionally, a simplified model of a nurse tank was developed in an earlier phase of this study and used as a point of comparison with hand calculations to verify the modeling techniques were in reasonable agreement with hand calculations. This simplified model was meshed using shell elements and included simplified representations of the feet. The simplified model did not include pads or the joggle joint between the tank head and shell. The simplified model is shown in Figure 22.



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Step: STATIC-PRESSURIZE
Increment      1: Step Time =     1.000
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Figure 22. Simplified 1000 gallon Nurse Tank Model from Phase I

The 16 variations in tank geometry as shown in Table 1 were each simulated, to assess the influence of each parameter on the overall stress results. For each unique tank geometry two loads were common to all simulations: a 1G vertical downward acceleration to represent the weight of the loaded tank, and an internal pressure to represent the tank at its MAWP. Additional static G-loads were added to the model to represent, individually, a lateral, longitudinal, vertical-down, or vertical-up load. Because in-service data on the load environment of nurse tanks was not available to the project team, values for typical G-loads in service were not known. As a first approach the project team simulated the acceleration in each direction as a series of static G-loads between 1G and 4G. The maximum principal stresses throughout the model were extracted for each load step (i.e., MAWP + self-weight, 1/2/3/4-G in each direction). The maximum principal stress was chosen for comparison in this study as this is the stress used to evaluate structural integrity of DOT-406, -407, and -412 specification tanks, per 49 CFR 178.345-3(c). While nurse tanks are not required to comply with this regulation, researchers chose to use an approach that was already codified in regulations for a similar type of vessel.

A linear elastic material behavior was used to represent the steel material throughout all the nurse tank models. Values for allowable stress were inferred based on typical alloys used in NH3 nurse tanks and the version of the ASME Code used for evaluation.

4.2 Modeling Plan

The treatment of each of the four parameters varied in the simulations are discussed individually in the following subsections. Abaqus/Standard, version 6.14-6 FE software was used to perform the simulations in this report [11]. Subsequent releases of the Abaqus/Standard software may include product updates or bug fixes that affect the simulation techniques used to create these models. A comprehensive review of change logs in subsequent releases of the Abaqus/Standard software was not performed within the scope of this project. Therefore, the version of the software used may be considered a contributor to uncertainty if earlier or subsequent releases of the Abaqus/Standard software are used to reproduce these simulation results.

4.2.1 Simplified Model

The simplified FE model from Phase 1 was used to conduct initial simulations. This model did not include sufficient detail to evaluate stresses around the feet or at the head-shell joint with a high level of confidence but did produce results worth discussing. Figure 23 contains a plot of the maximum in-plane principal stress for a tank under 1G plus its MAWP. The contours have been limited to +/- 18750 psi, which was the assumed value for allowable stress for the tank's material of construction and vintage (75,000 psi UTS and a design factor of 4.0, corresponding to a legacy tank).

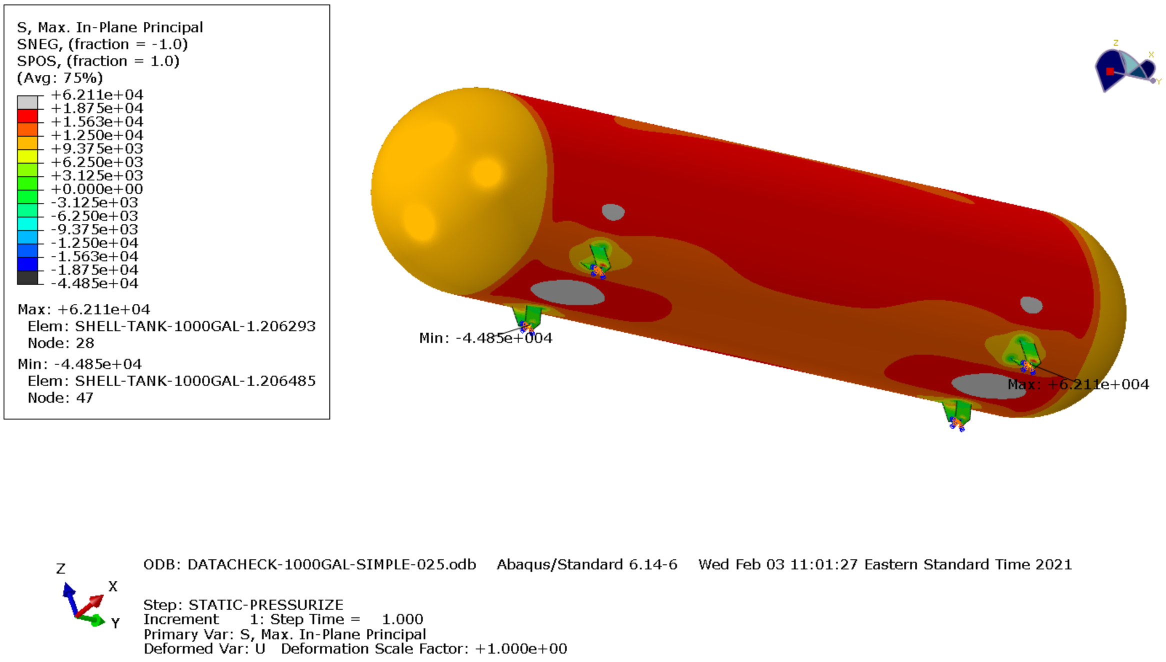

Figure 23. Maximum in-plane Principal Stresses in Simplified Tank and Feet, 1G + MAWP

Areas of gray in this image represent stresses in excess of the 18,750 psi upper limit of maximum principal stress. While stress concentrations at the simplified foot-to-tank attachment would be expected due to mesh discretization, the areas of high stress were found to be in the same cross-section of the tank as the feet but at a distance from the feet.

4.2.2 Legacy and modern thickness

The minimum thickness of a nurse tank's head and shell must be calculated in accordance with formulae given in the applicable version of Section VIII Division 1 of the ASME Code. The applicable version refers to the version of the ASME Code that is incorporated into the HMR at the time of the nurse tank's construction[1]. Different equations apply to the head, depending on the geometry (e.g., the formula to be used for a hemispherical head is different from the formula to be used for an ellipsoidal head). The minimum shell thickness of a cylindrical shell is governed by the hoop stress rather than the axial stress. The minimum thickness (t) can be calculated according to Mandatory Appendix 1 of Section VIII, Division 1 of the ASME Code[2] using the internal design pressure (P), the shell's outside radius (Ro), a joint efficiency factor (E), and the maximum allowable stress (S) of the material of construction as shown in Equation 1 [12]. Note that Section VIII, Division 1 of the ASME code contains additional calculations for minimum thickness that can be used as an alternative to this calculation that are defined in terms of the inner radius rather than the outer radius [12].

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[1] As of June, 2025, the 2017 edition of Section VIII, Division 1 is incorporated by reference at 49 CFR 171.7.

[2] This thickness equation was verified as unchanged for the 2013-2023 editions of Section VIII, Division 1.

Equation 1. Minimum Cylindrical Shell Thickness (ASME Section VIII, Division 1, Mandatory Appendix 1, 2013-2023 editions)

$$t = \frac{PR_o}{SE + 0.4P}$$

For a nurse tank the minimum value for MAWP, 250 psig, is defined in the regulations at 49 CFR 173.315(m). Values for joint efficiency are obtained from Section VIII, Division 1 of the ASME Code. The appropriate value for joint efficiency is based on the type of weld, the components the weld is attaching, and the level of radiography to be used on the weld. The diameter of the tank can be chosen by the manufacturer based on the desired capacity, overall tank length, and other practical limits (e.g., available plate size).

Finally, the value for allowable stress is dependent on the material of construction chosen. Materials used to construct pressure vessels according to Section VIII, Division 1 of the ASME Code must be listed in Section II of the ASME Code. Section II of the ASME Code contains values for the ultimate tensile strength (UTS) of each listed material, as well as the value of allowable stress to be used in Section VIII, Division 1 calculations. In general, the allowable stress of a material is based on the UTS divided by a reduction factor. Prior to 1998 (i.e., legacy tanks), this reduction factor was 4.0. After 1998 (i.e., modern tanks), this factor has been 3.5.

If the ultimate tensile strength of a material remained unchanged but the reduction factor decreased from 4.0 to 3.5, the allowable stress of that material would increase. If the design pressure (P), outside radius (Ro), and joint efficiency (E) of a nurse tank remained unchanged regardless of the year of construction, the effect of increasing the allowable stress (S) is to allow a thinner value for the minimum shell thickness (t) in a tank constructed in accordance with more recent versions of Section VIII Division 1.

Two tank capacities were included in the detailed FE modeling study, 1,000 gallon and 1,450 gallon. Legacy and modern head and shell thicknesses were calculated for both tank capacities. The values used for head and shell thickness of the four combinations of capacity and vintage are summarized in the following section.

4.2.3 1,000 and 1,450 gallon capacities

Volpe Center researchers developed models of both the 1,000 and 1,450 gallon capacity tanks. In addition to the volumes the two tanks had different shell diameters, head shapes, head thicknesses, and shell thicknesses. Based on observations made during a field visit, nurse tank manufacturer web sites, and online auction sites the two models were developed to represent typical, generalized examples of each capacity of nurse tank. In general, 1,000 gallon tanks were found to have a hemispherical head, while larger capacity tanks used an ellipsoidal tank. The 1,000 gallon tank model featured a hemispherical head and the 1,450 gallon tank featured a 2:1 ellipsoidal head. The geometry of the 1,000 gallon and 1,450 gallon tanks used in the FE model are shown in Figure 24.

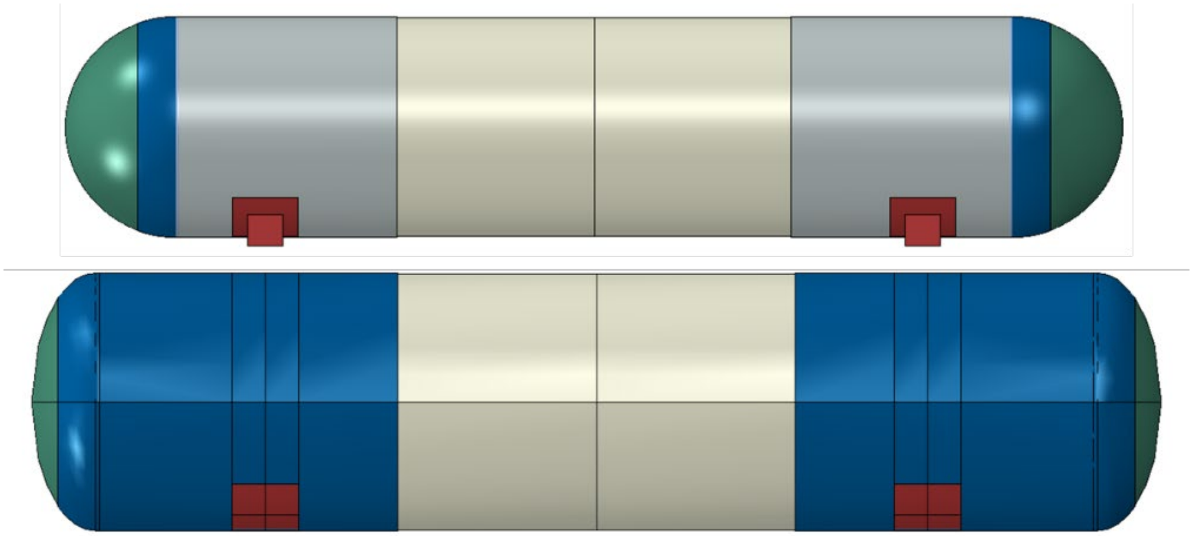


Figure 24. 1,000 gallon (top) and 1,450 gallon (bottom) FE Model Geometry

Additionally, the two different capacity tanks featured different head thicknesses and shell thicknesses. Each dimension also varied between the modern thickness tank and the legacy thickness tank of a given capacity. The dimensions are summarized in Table 3.

Table 3. Head Thickness, Shell Thickness, and Shell Outer Diameter of Modern and Legacy Tank Models

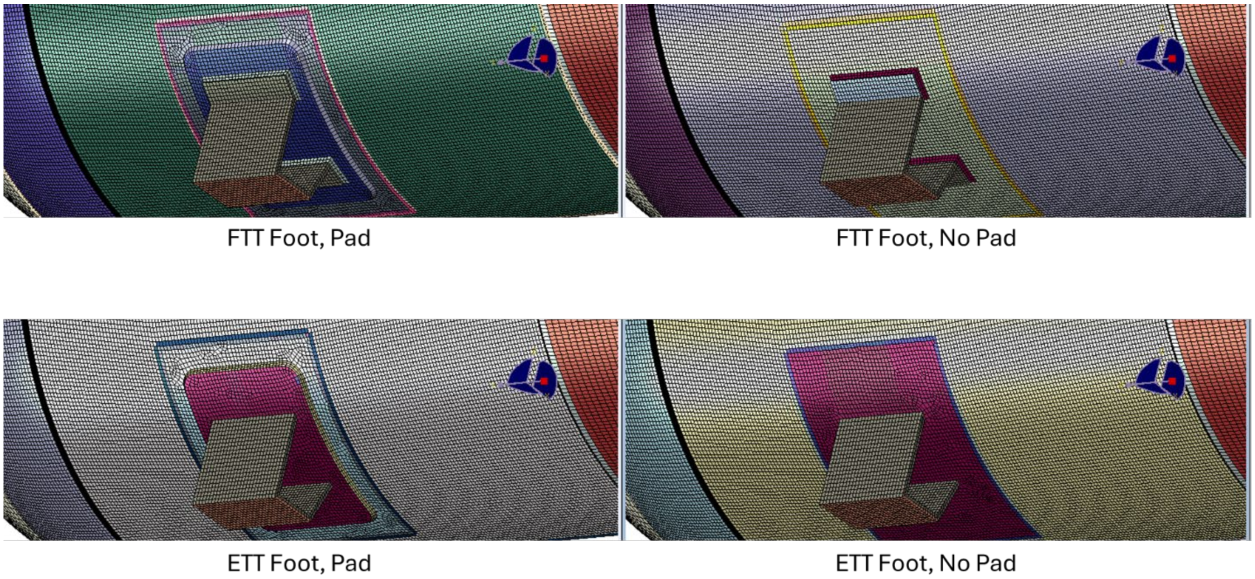
	Modern	**Legacy**	**Modern**	**Legacy**
	1,000 gal.	**1,000 gal.**	**1,450 gal.**	**1,450 gal.**
Head Thickness (in.)	0.203	0.231	0.273	0.362
Shell Thickness (in.)	0.239	0.321	0.273	0.375
Shell Outer Diameter (in.)	40.96	40.5	46.77	46.5

4.2.4 Foot and Pad Configurations

For all load cases and geometries, the feet and pads (if applicable) were modeled using brick elements. Additionally, fillet welds were modeled explicitly for any case involving an FTT foot, or for attaching a pad to the tank. A side-by-side comparison of an FTT foot attachment observed on a nurse tank and the FE mesh of that geometry is shown in Figure 25.

Figure 25. Example of FTT Foot Attached via Pad on Actual Tank (left) and FE Mesh (right)

For any load cases involving a pad the fillet weld surrounding the pad was modeled explicitly, with contact defined between the inside face of the pad and the outside face of the tank. For models using an FTT foot arrangement a similar approach was used, with the fillet weld around the outside of the face modeled explicitly. Contact was defined between the inner surface of the attachment face and the outer surface of the pad or tank, as appropriate. The ETT feet, having a smaller contact area with the pad or tank, were modeled as directly attached to the pad or tank without representation of the fillet welds. Example meshes of the four foot/pad combinations are shown in Figure 26.



FTT Foot, Pad

FTT Foot, No Pad

ETT Foot, Pad

ETT Foot, No Pad

Figure 26. Examples of Four Foot and Pad Combinations Modeled

4.2.5 Loads and boundary conditions

Four types of loads were applied to each FE model. These loads were applied sequentially to allow the effects of each load to be examined independently. Each tank had a simulated 250 psig internal pressure applied to the interior of the tank. This pressure is the minimum value for MAWP permitted for nurse tanks by 49 CFR 173.315(m).

An additional hydrostatic pressure, representing the weight of the NH3, was applied to the interior of the tank. The hydrostatic pressure varied linearly from its maximum value at the bottom of the tank to zero at the top of the tank. For simplicity and conservatism, the maximum value of hydrostatic pressure was simply added to the 250 psig internal pressure and applied to the entire interior surface of the tank. For the 1,000 gallon tank, the hydrostatic pressure at the bottom of the tank was 0.82 psig. For the 1,450 gallon tank, the hydrostatic pressure at the bottom of the tank was 0.93 psig. The hydrostatic pressure calculations are shown in Appendix A. Finally, each load case included a 1g downward gravity load. Together, the internal pressure, hydrostatic pressure, and gravity load represented a fully-loaded tank at its MAWP at rest.

Additional gravity load steps were used to represent the dynamic effects of a nurse tank in transportation. Individual static G-loads were applied in the longitudinal (forward or backward) direction, lateral (left or right) direction, and the vertical (upward and downward) directions. Due to symmetry only one longitudinal and one lateral direction was simulated. However, because a nurse tank in transportation could bounce upward (attempting to pull away from its feet) or downward (attempting to compress its feet), both vertical-up and vertical-down simulations were performed.

Symmetry boundary conditions were applied to the model, as appropriate for the direction of the G-load being applied. A longitudinal G-load required a full-length model, a lateral G-load required a full-width model, and a vertical G-load required only a quarter-tank model. A full-length, full-width model could also be used to represent any of these load cases, with a longer runtime. Examples of the three approaches to symmetry are shown in Figure 27. Areas of the tank modeled using shell elements required boundary conditions on both translational (i.e., U) and rotational (i.e., UR) degrees of freedom to enforce symmetry. Areas modeled using solid elements only required boundary conditions applicable to translational degrees of freedom as solid elements do not possess rotational degrees of freedom.

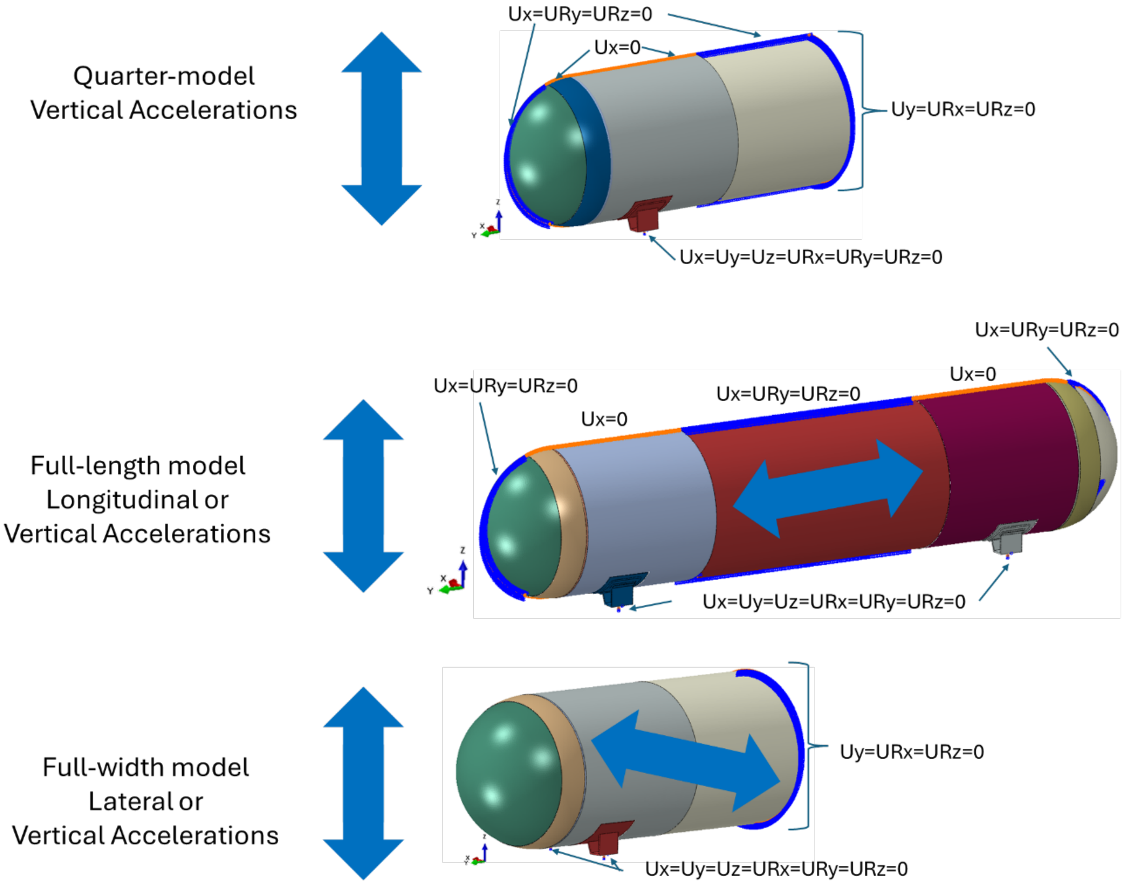


Figure 27. Exemplar Symmetric Models

In addition to the symmetry boundary conditions, the bottom surface of each foot (i.e., the location where the foot would contact the mounting surface on the running gear) was constrained in all degrees of freedom. This boundary condition represented the bolted attachment between the running gear and the nurse tank in a physical nurse tank. The boundary conditions at the foot in the FE model were effective for all force values, whereas a bolt on a physical nurse tank could fail if the load through the bolt exceeded its capacity.

4.3 FE Results Compared to Simplified Manual Calculations

Simplified hand calculations were used as a preliminary check on the FE model results. These calculations built off of preliminary calculations made in Phase 1 of this project. In Phase 1, manual calculations of the stresses in the tank under a combination of internal pressure and self-weight were performed by adapting the techniques given in an industry standard applicable to DOT 406/407/412 CTMVs, TTMA RP-96 [1]. These same manual calculations were repeated for a subset of the Phase II models to demonstrate that the more detailed FE models using solid elements for a portion of the tank and higher fidelity representation of the feet and pads (if applicable) continued to agree with theoretical calculations.

4.3.1 Pressure vessel calculations, remote from feet

As a check on the Phase II FE models the maximum principal stresses were obtained for the interior surface and exterior surface of the tank at multiple cross-sections. This study used a 1,000 gallon tank with modern thicknesses and FTT feet attached via pads. Figure 28 shows the FE model with the cross-sections identified. The cross-section taken furthest from the feet and pads was within the tank shell modeled with shell elements. This model used quarter-symmetry, so the results presented in the following figures have been mirrored to include a full 360-degree circumference of the tank. In the following figures the convention is to define 0-degrees at the bottom of the tank and 180 degrees at the top.

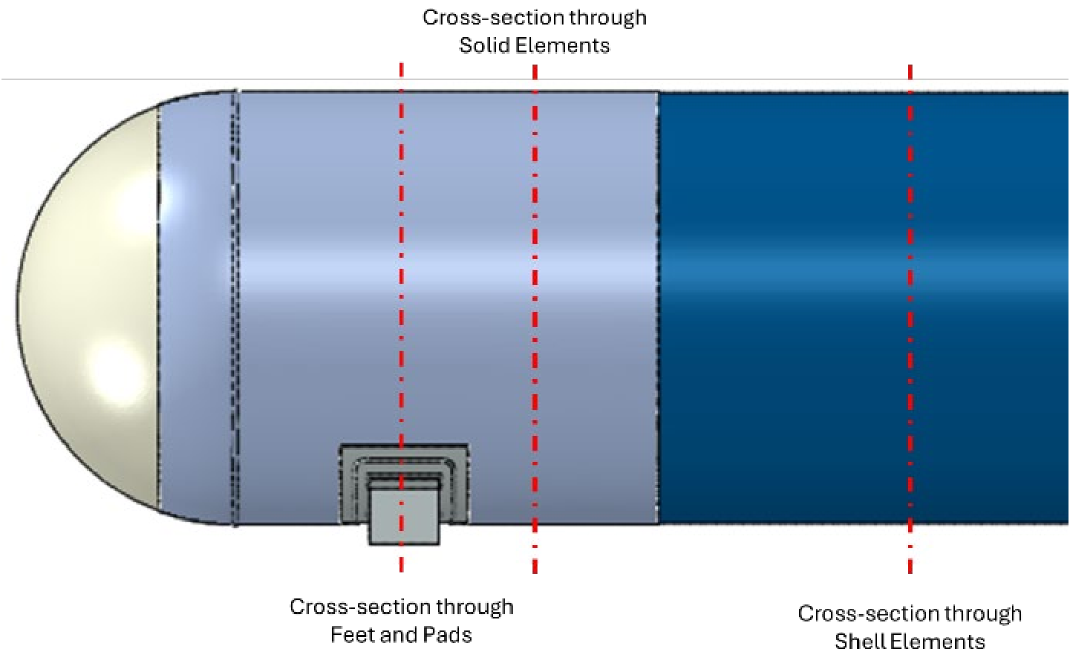


Figure 28. Cross-sections on 1,000 gal Modern Thickness, FTT Feet w/Pads

Figure 29 compares the maximum principal stress results from the FE model for the interior surface of the tank with the maximum principal stress calculated using the approach given in TTMA RP-96 [1]. Figure 30 contains a similar comparison for the exterior surface of the tank. The FE models exhibit some fluctuations above and below the manually-calculated values but are generally in agreement with the magnitudes.

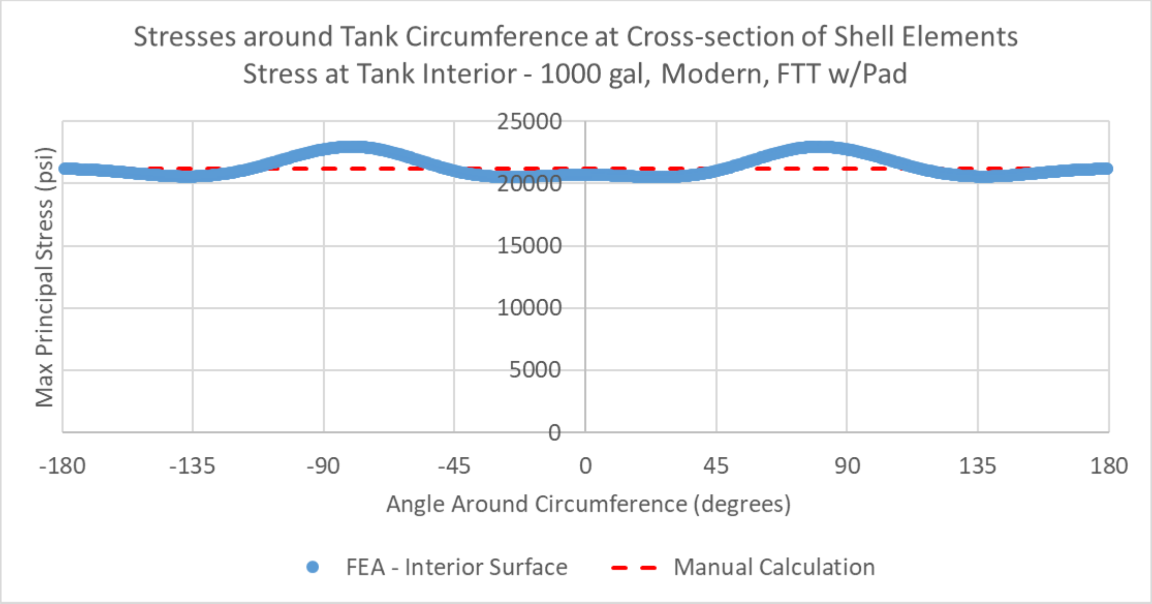


Figure 29. Interior Stress Results from FEA and Hand Calculations for Cross-section through Shell Elements

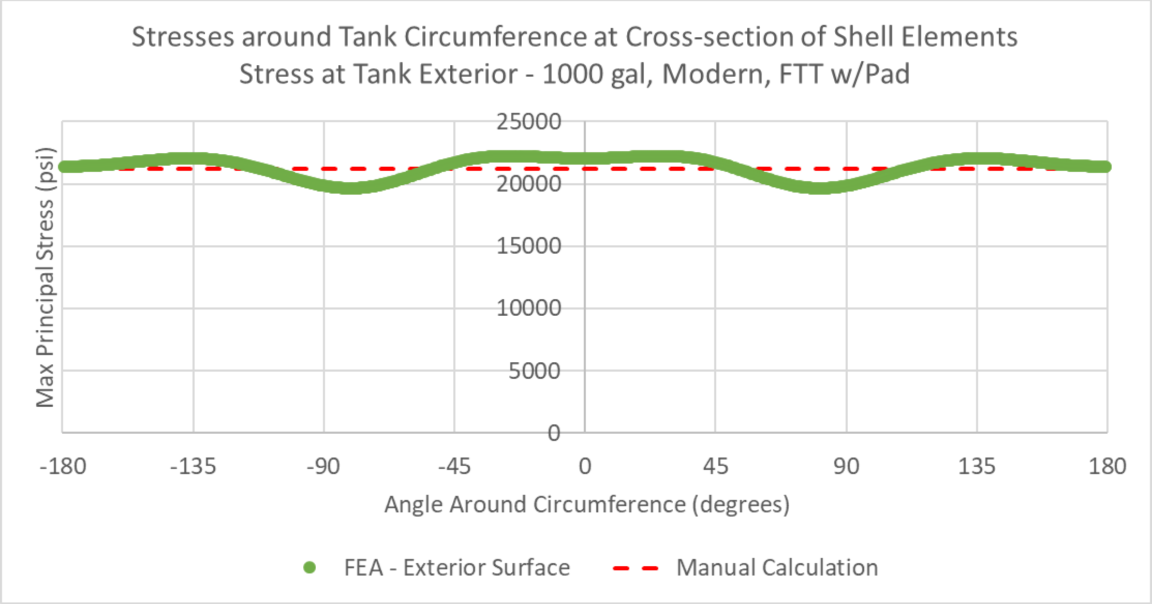


Figure 30. Exterior Stress Results from FEA and Hand Calculations for Cross-section through Shell Elements

4.3.2 Modified Hetényi calculations, in vicinity of feet

As the cross-section of the tank moves closer to the cross-section containing the feet (and pads, if applicable), the tank's mesh changes from shell elements to solid elements. It was important to verify that the solid elements produced reasonable agreement with the manual calculations, as solid and shell elements use different formulations. Figure 31 contains a plot of the maximum principal stresses on the

FE model's interior surface compared to the manual calculations. Figure 32 contains a similar comparison for the stresses on the exterior surface of the model at the same cross-section. While the manual calculations and FE model results are in good agreement beyond approximately 90 degrees in either direction (i.e., the top half of the tank), there are considerable variations from the manual calculation in the bottom half of the tank.

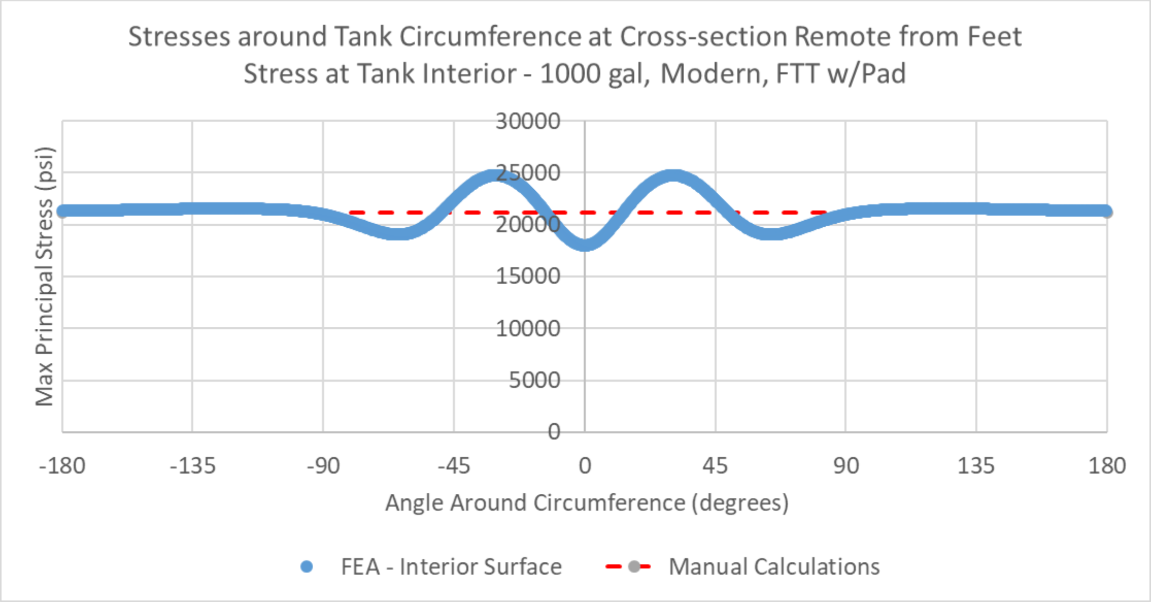


Figure 31. Interior Stress Results from FEA and Hand Calculations for Cross-section through Solid Elements Remote from Feet

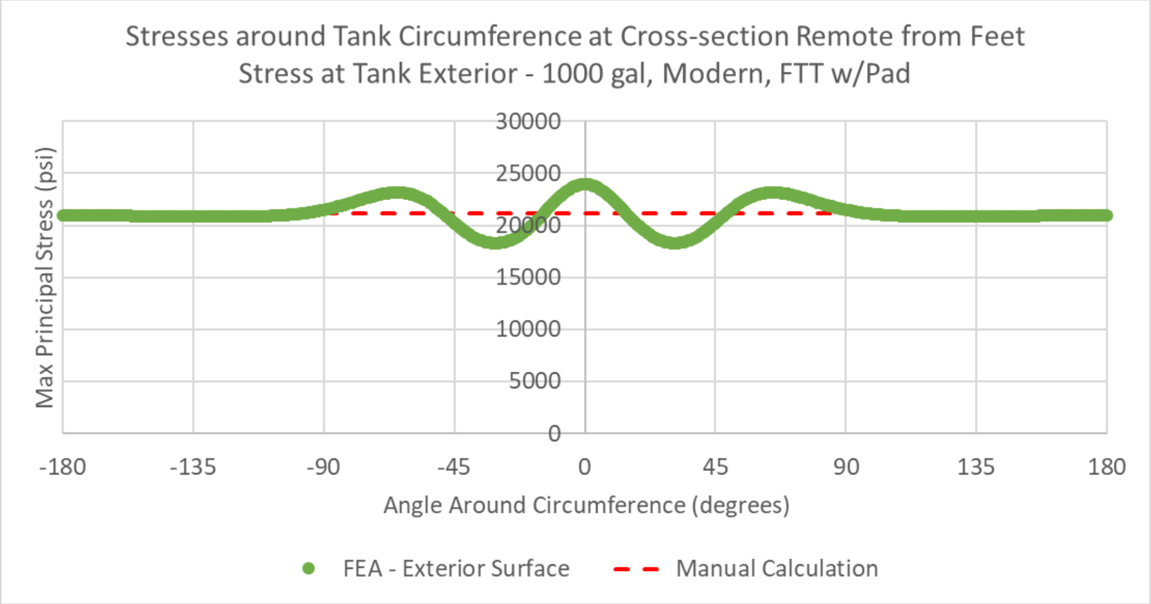
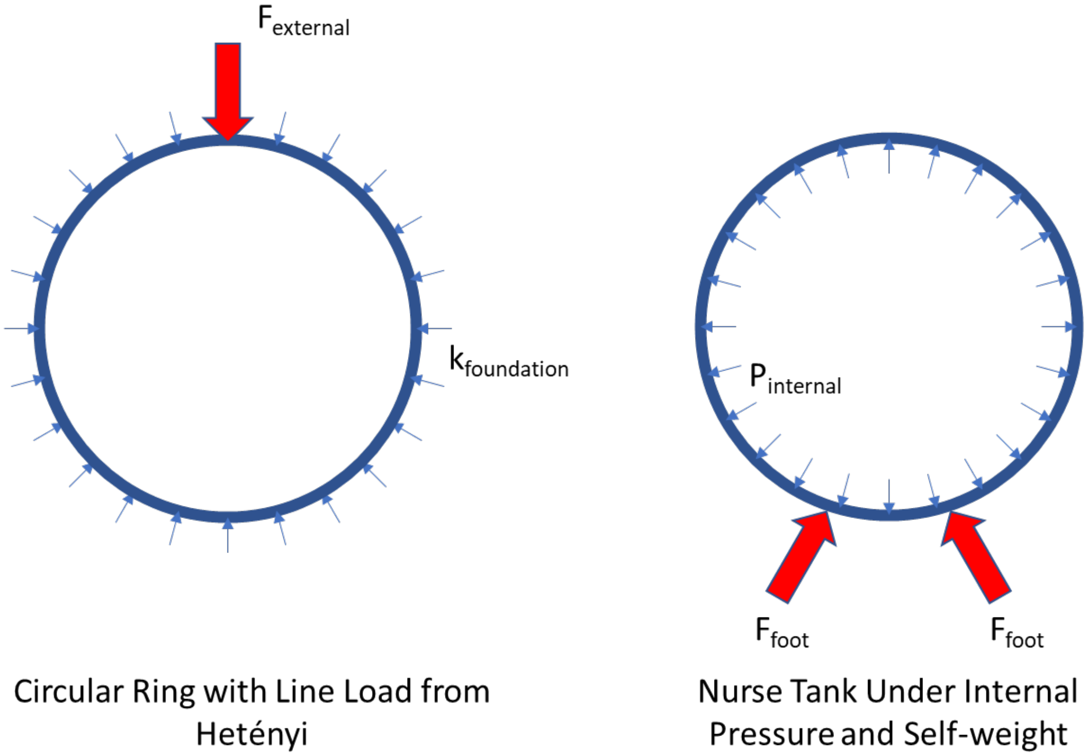


Figure 32. Exterior Stress Results from FEA and Hand Calculations for Cross-section through Solid Elements Remote from Feet

The simplified modeling during Phase 1 identified the potential for regions of increased stress in the tank at the cross-section containing the feet and pads at regions of the tank that were remote from the edges of the feet (see Figure 23). These areas of increased stress were thought to be real effects, rather than artifacts of mesh discretization since they did not occur at the points of foot attachment. A closed-form solution developed by Hetényi [13] was adapted in this work to approximate the stress distribution in the tank shell at the cross-section containing the feet and pads. The solution developed by Hetényi represented a point load applied to a circular ring on an elastic foundation [13]. This solution was originally developed for buried pipes subjected to an external load ($F_{external}$), where the surrounding earth forms an elastic foundation ($k_{foundation}$) as shown in the left side of Figure 33. The right side of this figure shows the internal pressure ($P_{internal}$) and foot support forces (F_{foot}) acting on the nurse tank at the cross-section containing the feet.



Circular Ring with Line Load from Hetényi

Nurse Tank Under Internal Pressure and Self-weight

Figure 33. Circular Ring with Line Load (adapted from Hetényi) and Nurse Tank Subject to Combined Internal Pressure and Self-weight

By treating the internal pressure of the nurse tank as an elastic foundation (essentially, reversing the sign) and repositioning and duplicating the external force from the circular ring load case to correspond with the foot loads of the nurse tank, the beam on elastic foundation approach from Hetényi can be applied to the nurse tank to estimate the stress distribution at a cross-section of the tank that passes through the feet. The force at each foot was adapted by first calculating the loaded weight of the NH3 nurse tank and dividing that by the four feet to obtain the weight carried by each foot. Because the external force in Hetényi represents a line load acting along the length of the pipe, the weight carried by each foot was divided by the length of each foot in the longitudinal (i.e., into the page) direction to obtain an approximation of the load per linear inch of foot (F_{foot}). The stress distribution calculated using the adapted method of Hetényi was combined with the maximum principal stress in the tank shell caused by internal pressure calculated using the method of TTMA RP-96. The stresses were calculated on both the interior and exterior surfaces of the nurse tank and plotted against the stresses from the respective surfaces in the FE model.

There are several limitations to the adaptation of Hetényi's formulation to a circular ring with a line load to represent the nurse tank under internal pressure and self-weight. In Hetényi, the line load is assumed to be constant along the entire length of the pipe (i.e., the cross-section shown in Figure 33 represents every cross-section along the length of the pipe). In contrast, the nurse tank's feet and pads only exist at discrete locations along the tank's length. The adaptation of Hetényi may be better suited to stresses through a cross-section in the center of the feet, rather than near the edges of the feet, as a cross-section through the center of the feet will be less affected by the edge effects near the front and back of the feet or pads.

Second, the formulation given in Hetényi was developed for a point load acting on the circular cross-section. For the nurse tank work, two separate point loads were superimposed on the circular cross-section of the tank to represent the two feet at each end of the nurse tank. However, while the feet and/or pads are small in comparison to the circumference of the tank, they are not truly point loads. Each foot and/or pad distributes loads around an arc on the circumference of the tank. Further, with tanks modeled using a pad between the foot and the tank shell the distribution of forces transmitted between foot and shell may be nonuniform as the pad is attached to the shell around its perimeter with a fillet weld but in contact with the tank shell toward its interior.

Figure 34 contains an image of a cross-section through the tank at the centerline of the feet for the FTT tank with pads. The angles shown on this image represent the angle around the circumference of the tank to the feature of interest: the bottom of the tank (0°), the inboard edge of the pad (11.7°), the inboard edge of the foot (17.1°), the outboard edge of the foot (40.0°), the outboard edge of the pad (45.3°), the side of the tank (90°), and the top of the tank (180°). Note that while the figure only contains a detailed view of one side's foot the model is symmetric, thus the angles to the features of interest on the opposite-side foot are the same as those shown in the figure.

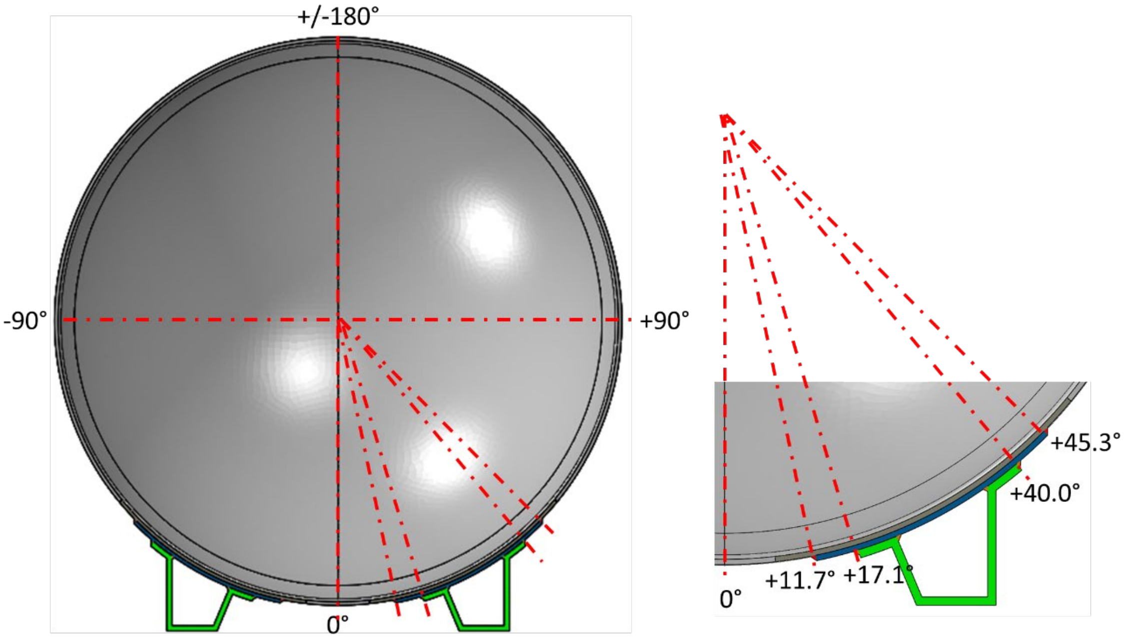


Figure 34. Angles from Center of Tank to Pad and Feet, FTT Tank with Pads

The stress distributions on the interior surface of the tank are shown in Figure 35 for both the FE model and the Hetényi adaptation. The stresses at the top of the tank (+/- 180 degrees) are in close agreement from both methods, indicating the effects of the feet and pads are localized to the bottom of the tank. Both the Hetényi adaptation and the FE model indicate a locally high stress on the interior of the tank in the regions where the pads are welded to the exterior of the tank. Additionally, both the Hetényi adaptation and the FE model indicate a region of relatively low stress on the interior surface of the tank near the bottom of the tank (i.e., at zero degrees).

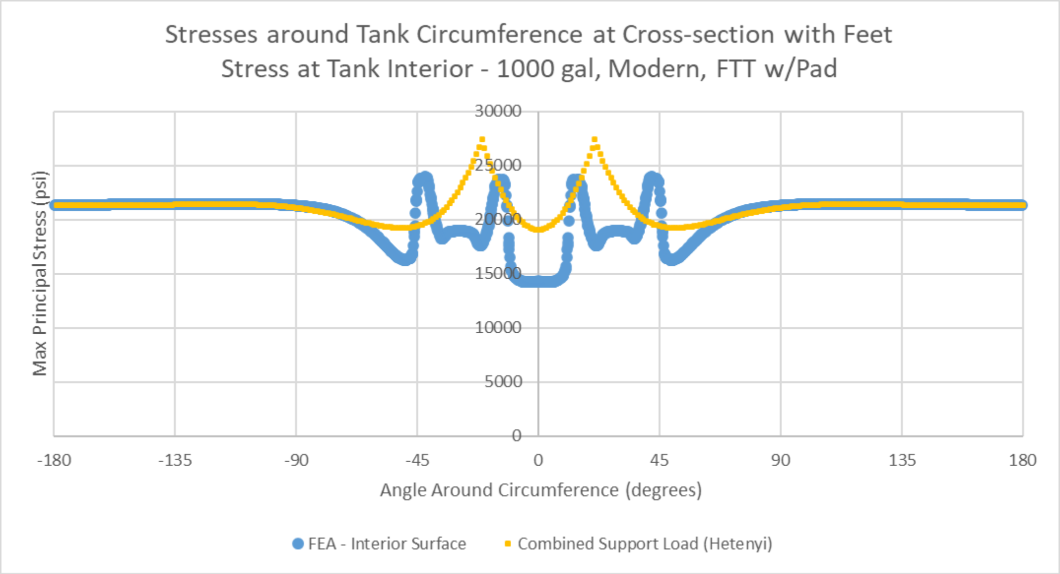


Figure 35. FEA and Hetényi Calculations of Stresses Around Interior of Tank Circumference at Cross-section Passing Through Feet (1,000 gal tank, Modern Thickness, FTT Feet with Pad)

The stress distributions on the exterior surface of the tank are shown in Figure 36 for both the FE model and the Hetényi adaptation. The stresses at the top of the tank (+/- 180 degrees) are in close agreement from both methods, indicating the effects of the feet and pads are localized to the bottom of the tank. Both the Hetényi adaptation and the FE model indicate a locally high stress on the exterior of the tank in the region at the very bottom of the tank (i.e., at zero degrees), between where the pads are welded to the exterior of the tank. Additionally, both the Hetényi adaptation and the FE model indicate a region of relatively low stress on the exterior surface of the tank near the bottom of the tank below the pads (i.e., between approximately 12 and 45 degrees).

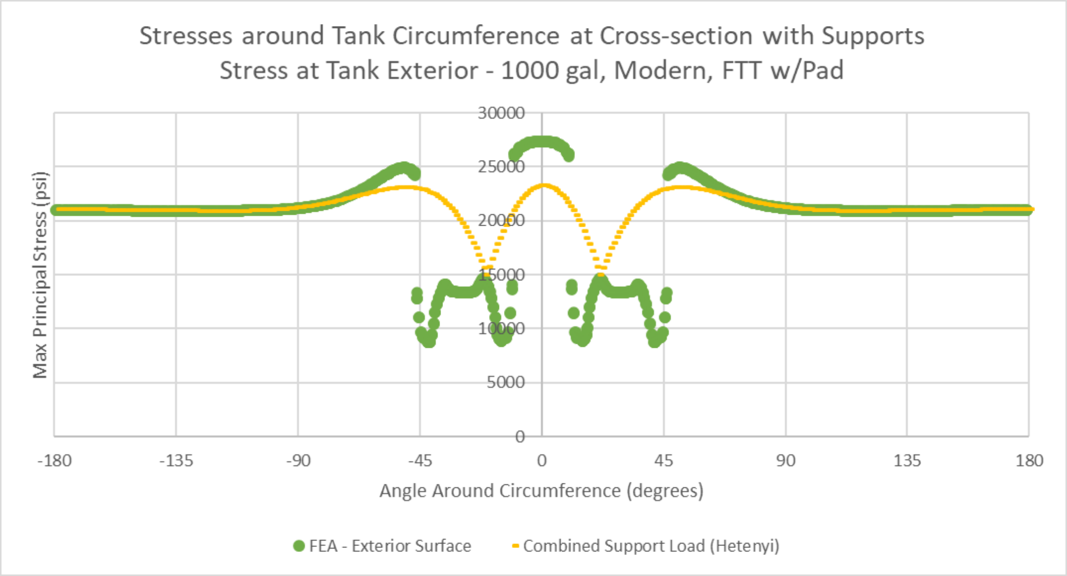


Figure 36. FEA and Hetényi Calculations of Stresses Around Exterior of Tank Circumference at Cross-section Passing Through

Feet (1,000 gal tank, Modern Thickness, FTT Feet with Pad) FEA and Hetényi Calculations

The principal stresses in the interior of the tank at the cross-section through the feet exhibit several behaviors of interest. At the top of the tank (+/-180 degrees) the stresses are consistent with the far-field stresses calculated according to TTMA RP-96. As the location approaches +/-45 degrees there is a local stress increase followed by a sharp decrease in stress as the angle crosses +/-45 degrees. This coincides with the outboard edge of the pads. In the areas under the pads (between approximately 12 and 45 degrees to each side of the centerline) the stresses are lower than the stresses higher up on the tank. Finally, in the region of the tank between the pads (angles between -5 and +5 degrees) the maximum principal stress reaches a local maximum.

The Hetényi adaptation is similar, but not identical to, the distribution of maximum principal stresses around the tank from the FE model. The detailed representation of the foot and pad introduce a more complex local stress distribution than was captured by the assumption in the Hetényi approximation of a point load representing the force applied by the foot and pad. A more complex adaptation of the Hetényi approximation could better capture the variation of stresses in the vicinity of the pads and feet, but the simplified adaptation does demonstrate that the local high stresses at the bottom surface of the tank's exterior are a real effect rather than an artifact of meshing.

4.4 FE Modeling Results & Takeaways

A full set of modeling results are presented in Appendix D, organized in various ways. For each tank design (e.g., capacity, vintage, feet, pads) static equivalent G-loads were applied separately in the vertical (up and down), lateral, and longitudinal directions. The key results from each model are the maximum principal stresses throughout the tank for each combination of load magnitude and direction.

This section summarizes the results of the FE modeling performed on the 1,000 gallon and 1,450 gallon nurse tanks. Key findings include:

- Regardless of capacity, vintage, or foot design, the highest stress for a given G-load corresponds to a lateral load, followed by a vertical-up load
- For nearly every capacity and vintage, feet attached with pads show lower *normalized* stresses than feet without pads at each G-load
    - The one exception was the 1,450 gallon legacy tank with a 1G upward acceleration

4.4.1 Foot and pad effects

The results for both the 1,000 gallon and 1,450 gallon nurse tanks have been color-coded by the foot and pad arrangement throughout this section of the report. The legend for the foot and pad arrangement is shown in Table 4. The schematic illustrations show an end-on view of the simplified foot and, as applicable, pad arrangement.

Table 4. Legend for Foot and Pad Arrangements

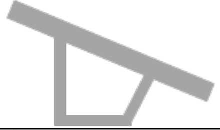
ETT feet, no pads	
FTT feet, no pads	
ETT feet, pads	
FTT feet, pads	

Figure 37 contains side-by-side plots of the peak value of maximum principal stress in the 1,000 gallon legacy tank using ETT feet. The left side shows the stress distribution for each load direction and magnitude for the tank with pads, and the right side shows the distribution for the tank without pads. The magnitudes of stress are different for the comparable legacy tanks, but the trends are the same. It should be noted that the FE simulations used an elastic model, with an assumed yield strength of 38,000 psi. Stresses in excess of this value correspond to permanent deformation and cannot be considered accurate stress values for an elastic model.

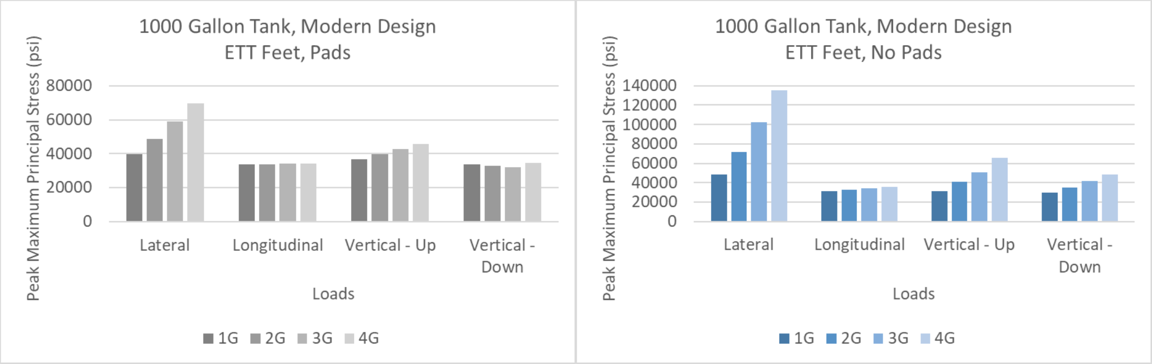
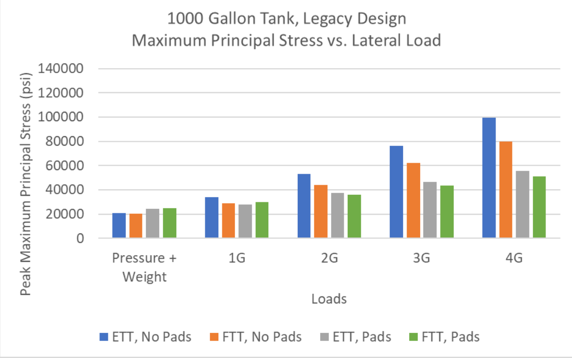
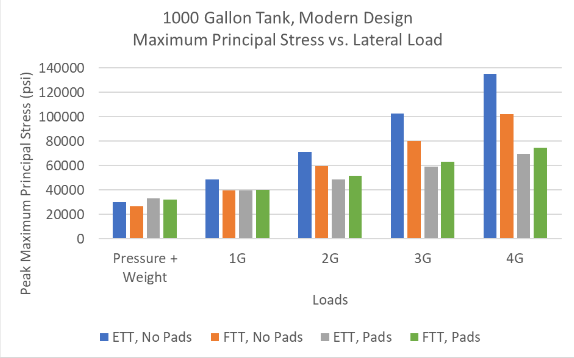
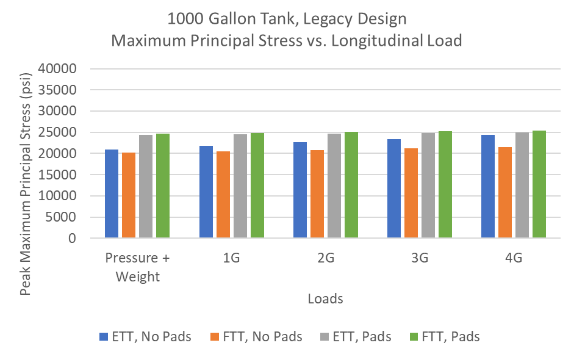
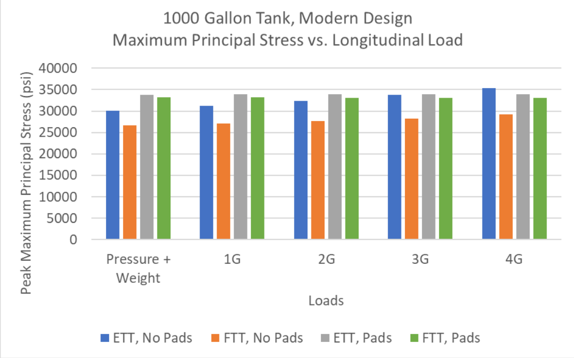
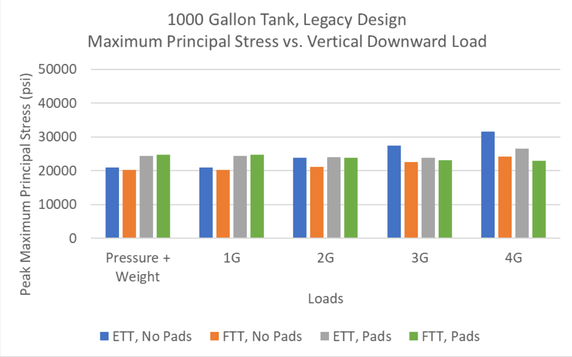
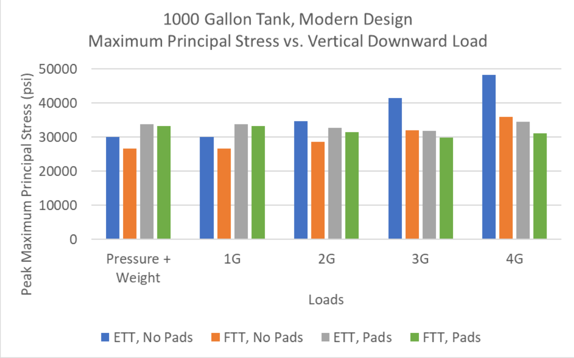


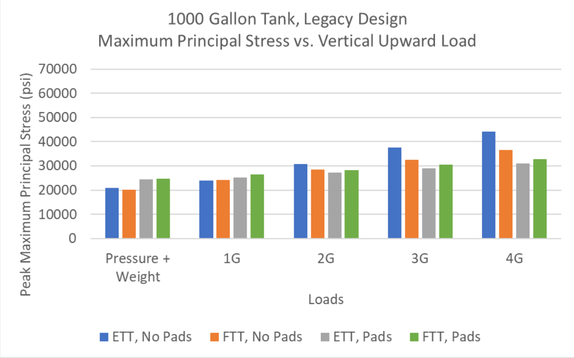
Figure 37. Peak Maximum Principal Stress in 1,000 gallon Modern Tank Shell, ETT Feet, Pads and No Pads

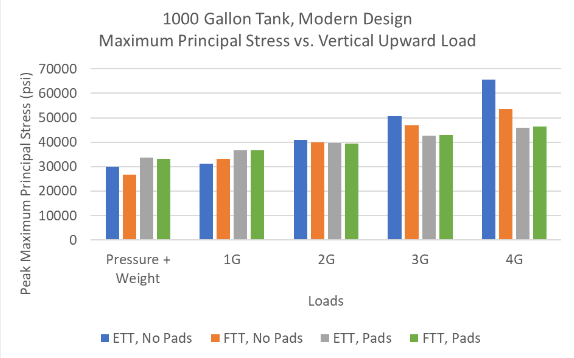
For the modern tank with ETT feet the peak value of maximum principal stress is least sensitive to longitudinal acceleration. The peak value of maximum principal stress is most sensitive to a G-load in the lateral direction.

Table 5 contains a summary of peak maximum principal stress results from the 1,000 gallon tank simulations. The left column contains results from tanks with a legacy thickness, and the right column contains results for modern thickness tanks. Each row of this table contains results from G-loads in a different orientation. Finally, each table contains results sorted by pad and foot arrangement for five load cases: tank standing under MAWP (250 psig) plus self-weight and 1- through 4-G loads acting in the respective direction for that row. An elastic material model was used for the steel in the FE model, with an assumed yield strength 38,000 psi. Stresses above this value cannot be considered accurate in an elastic model.

Table 5. Summary of Peak Maximum Principal Stresses from 1,000 gallon tanks

	Legacy Design	**Modern Design**
Lateral G-load		
Longitudinal G-load		
Vertical-down G-load		

<table>
<tr>
<td>Vertical-up G-load</td>
<td>

1000 Gallon Tank, Legacy Design
Maximum Principal Stress vs. Vertical Upward Load

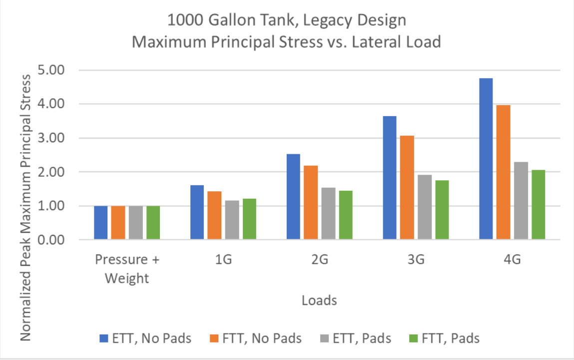
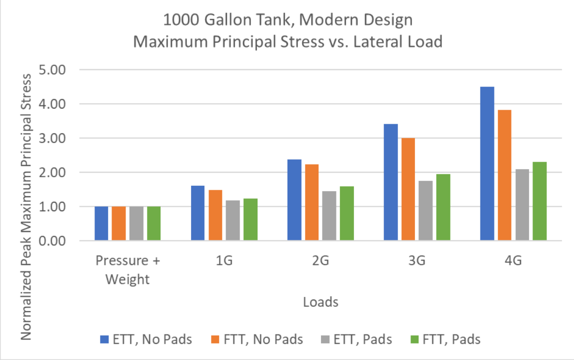
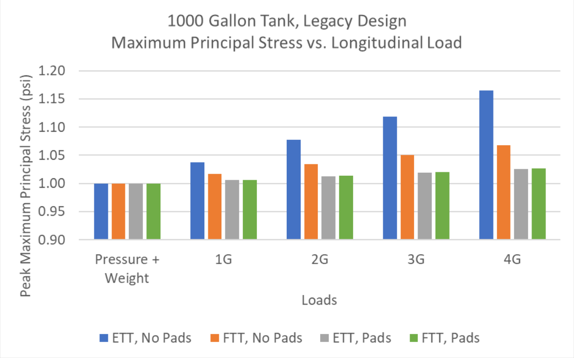
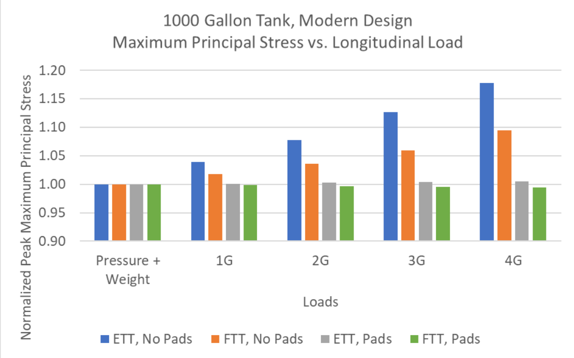
</td>
<td>

1000 Gallon Tank, Modern Design
Maximum Principal Stress vs. Vertical Upward Load

</td>
</tr>
</table>

Focusing on the Pressure + Weight load case the inclusion of pads produces peak stresses that are higher than the tanks modeled with feet attached directly to the tank. However, for loads in the vertical-up and lateral directions the models with pads resulted in lower peak values of maximum principal stress compared to the two cases without pads. Pads can increase the initial state of stress resulting from the tank's MAWP and self-weight but can be effective in some cases at reducing the maximum stress that occurs at higher G-loads.

The peak maximum principal stress results presented in Table 5 can be normalized by the respective peak maximum principal stress in each tank under the combination of MAWP and self-weight. This normalization allows the relative increase in peak maximum principal stress to be more easily identified from the G-loads alone. The normalized stress results are summarized in Table 6.

Table 6. Summary of Peak Maximum Principal Stresses from 1,000 gallon tanks Normalized by Pressure + Weight Results

<table>
<tr><th></th><th>Legacy Design</th><th>Modern Design</th></tr>
<tr><td>Lateral G-load</td><td>
</td><td>
</td></tr>
<tr><td>Longitudinal G-load</td><td>
</td><td>
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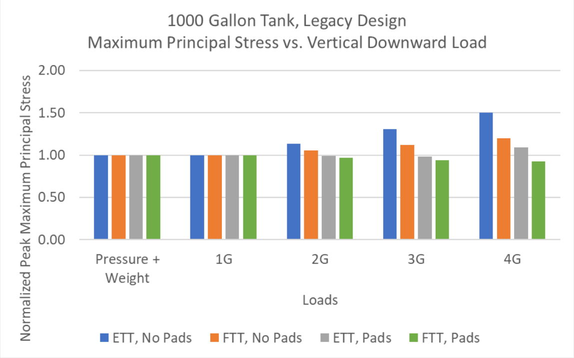
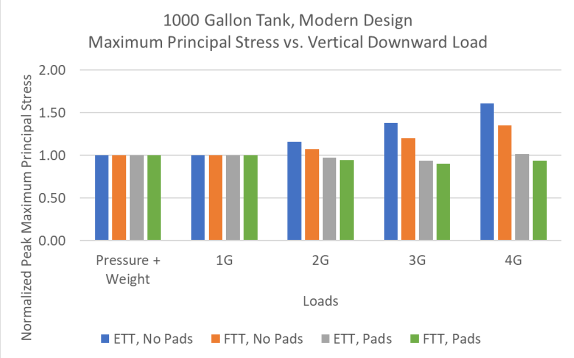
<tr><td>Vertical-down G-load</td><td>
</td><td>
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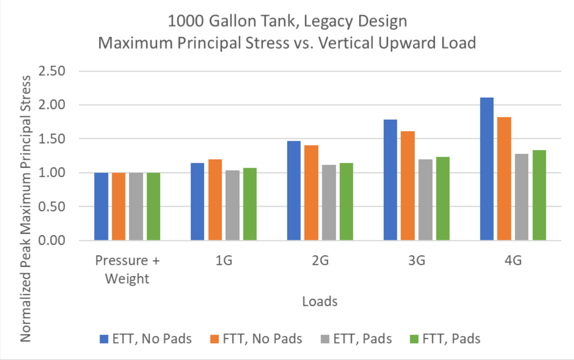
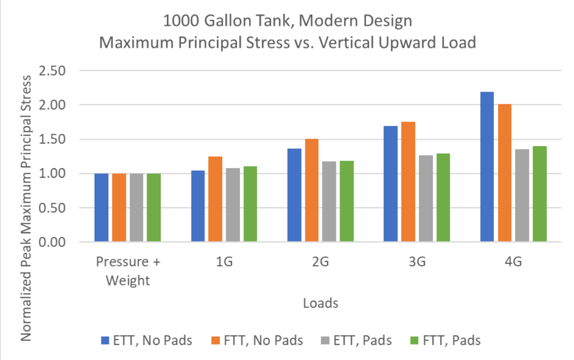
Vertical-up G-load

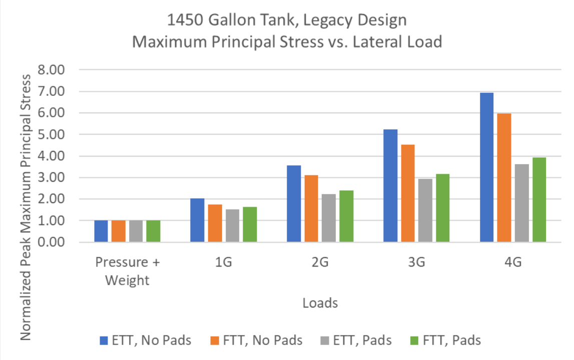
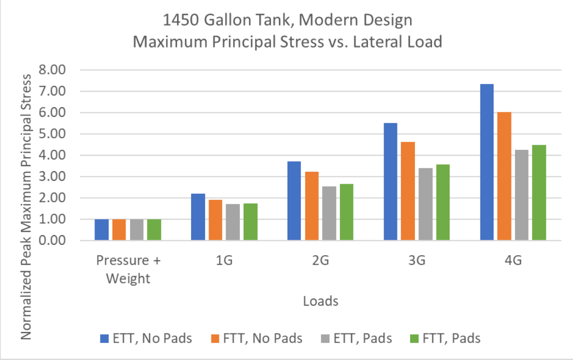
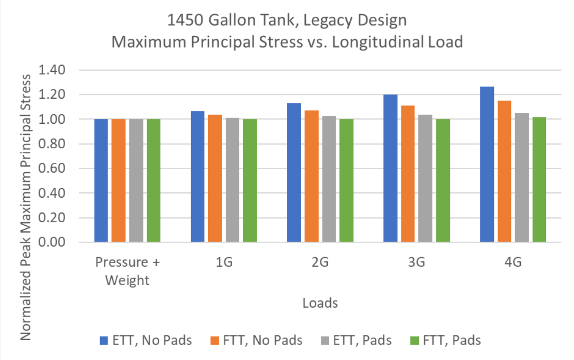
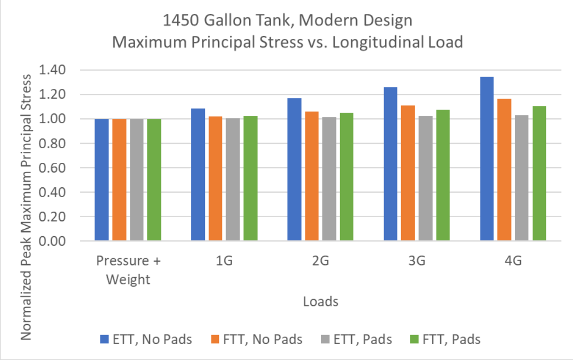
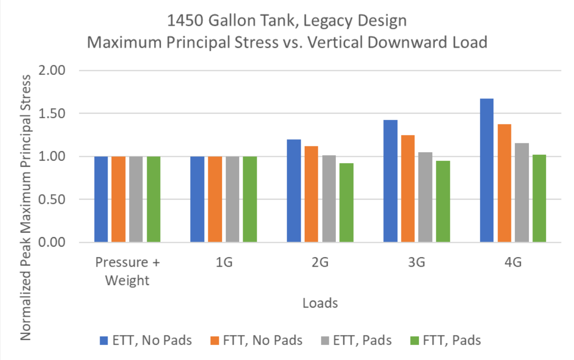
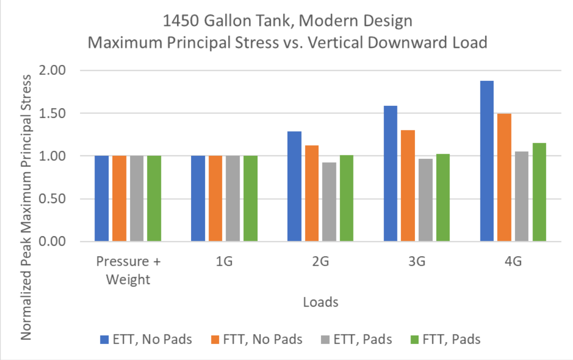
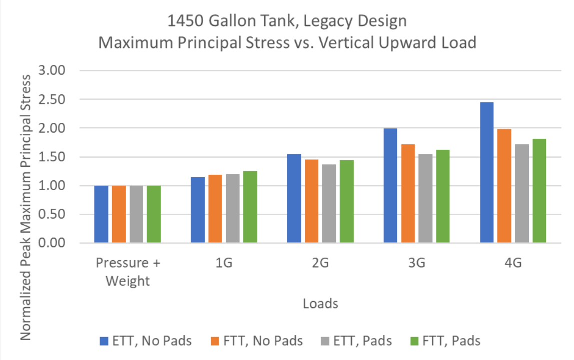
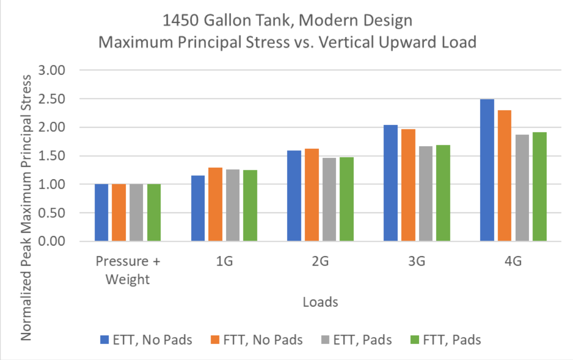




When the peak maximum principal stress value from each G-load is normalized by the peak maximum principal stress in the Pressure + Weight load case, the effects of the pads become more pronounced. For all G-load magnitudes and directions examined in this study the models with pads experience a smaller increase in maximum principal stress than the models without pads. Put another way, the use of pads may increase the peak value of maximum principal stress under the Pressure + Weight load case due to inhibiting the tank from freely expanding under pressure, but pads reduce the subsequent increase in peak maximum principal stress associated with G-loading.

For the 1,450 gallon tank the trends in normalized stress results are similar. The normalized peak maximum principal stress under a given load magnitude and direction is lower for the tank with a pad compared to the same foot shape mounted directly on the tank. One exception was noted, for the 1,450 gallon tank and a 1-G upward load. For the 1,450 gallon tank with a legacy thickness both the ETT and FTT foot shapes produced a higher normalized stress in the tank shell when mounted via a pad. For the 1,450 gallon tank with a modern thickness only the ETT foot shape had a higher normalized peak stress value when mounted via a pad.

Table 7. Summary of Peak Maximum Principal Stresses from 1,450 gallon tanks Normalized by Pressure + Weight Results

	Legacy Design	**Modern Design**
Lateral G-load	 1450 Gallon Tank, Legacy Design Maximum Principal Stress vs. Lateral Load	 1450 Gallon Tank, Modern Design Maximum Principal Stress vs. Lateral Load
Longitudinal G-load	 1450 Gallon Tank, Legacy Design Maximum Principal Stress vs. Longitudinal Load	 1450 Gallon Tank, Modern Design Maximum Principal Stress vs. Longitudinal Load
Vertical-down G-load	 1450 Gallon Tank, Legacy Design Maximum Principal Stress vs. Vertical Downward Load	 1450 Gallon Tank, Modern Design Maximum Principal Stress vs. Vertical Downward Load
Vertical-up G-load	 1450 Gallon Tank, Legacy Design Maximum Principal Stress vs. Vertical Upward Load	 1450 Gallon Tank, Modern Design Maximum Principal Stress vs. Vertical Upward Load

4.4.2 Legacy versus modern tanks

For a given tank capacity, pad and foot arrangement, load magnitude and load direction the legacy thickness tanks developed lower stresses than the modern thickness tanks. This result is expected, since the modern tanks have a higher allowable stress in Section VIII, Division 1 of the ASME Boiler and Pressure Vessel Code compared to legacy tanks.

4.4.3 Peak stress contributors

In general, the peak value of maximum principal stress in the tank occurs in the lower half of the tank. Typical locations for the peak value of maximum principal stress include the very bottom of the tank (consistent with the Hetényi calculations described in Section 4.3.2), under the foot, or at the pad-to-tank weld. Figure 38 contains an exemplar contour plot of the maximum principal stress distribution on a nurse tank standing under its own weight and 250 psig internal pressure. This particular tank is a 1,000 gallon tank of modern thickness with ETT feet attached directly to the tank. The peak value of stress in the tank is indicated in this figure and occurs on the exterior of the tank, adjacent to a foot. The maximum value of the contour plot has been limited to the maximum allowable stress value of 21,400 psi. Areas of locally-high stress above this limit appear as gray in the contour plot.

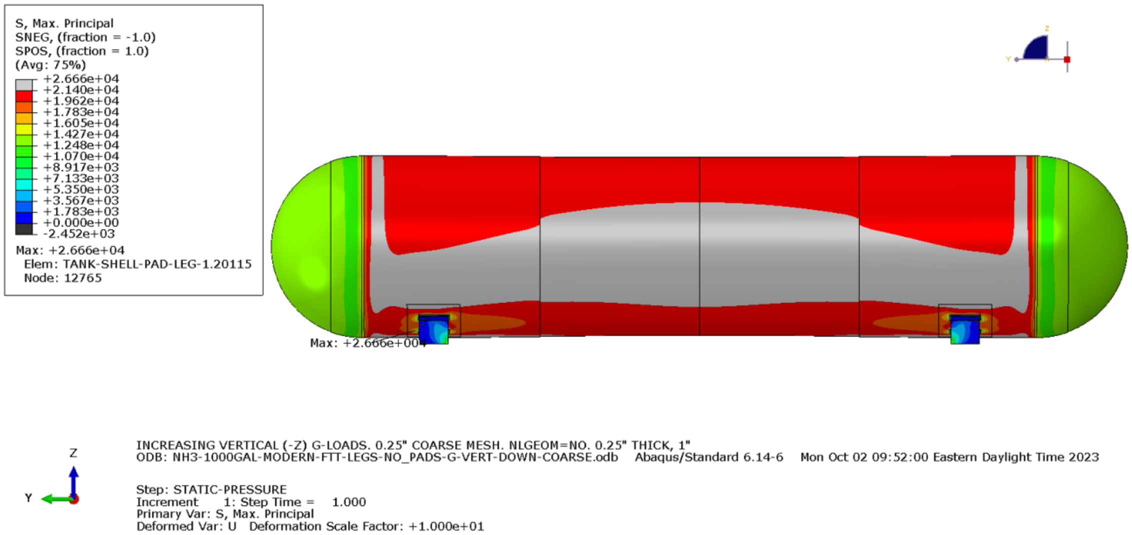


Figure 38. Maximum Principal Stress Distribution on 1,000 gallon Modern Tank, ETT Feet without Pads, MAWP + 1G

4.4.4 Practical limits

A significant limitation on the modeling is the use of elastic steel material for the tank, pads, and feet. The assumed yield strength of the material was 38,000 psi, which is consistent with the minimum yield strength of SA-455 steel. Stress results in excess of 38,000 psi cannot be considered accurate, since the material model does not include elastic-plastic behavior.

While the simulations were run for G-loads up to and including 4G, it may not be possible for these G-loads to be applied to a nurse tank on its running gear without causing another mode of failure. In the physical world the nurse tank and its running gear could overturn if a sufficiently-high lateral G-load were applied to the tank. The FE models did not include the ability of the nurse tank to overturn. While overturning introduces a new hazard of the nurse tank contacting the ground or a sharp surface and failing due to this load, overturning loads are not expected to occur more than once during the nurse tank's service life.

Sufficient G-loads in the lateral, longitudinal, or vertical-up directions could cause the bolts attaching the nurse tank's feet to the running gear to fail. The G-loads transmitted into the nurse tank from the running gear would be limited once the bolts failed, but the nurse tank could experience impact loads if it separated from the running gear completely.

Finally, the running gear itself may fail and limit the G-loads that can be introduced into the nurse tank. Due to the variety of running gear designs, vintages, and mounting arrangements for nurse tanks it was not practical to estimate the failure loads for running gear in this study. It is also expected that G-loads sufficient to fail the running gear would not occur multiple times during the nurse tank's service life.

4.4.4.1 Estimated Bolt Loads to Failure

Any acceleration or deceleration of the vehicle towing the running gear with the nurse tank on it will be transmitted into the nurse tank's feet via the bolts attaching them to the running gear (previously shown in Figure 9). If the towing vehicle's acceleration is severe enough the resulting inertial forces acting through the bolts could cause one or more bolts to fail. If the bolt fails for accelerations in most directions the load path between the tank and running gear is also broken, preventing further loads from being transmitted between the running gear and tank. One exception is a downward acceleration of the nurse tank (e.g., from running gear moving downward, such as into a dip in the road), as contact between the bottom of the nurse tank's foot and the top of the running gear support surface will still allow load transmission.

The strength of a bolt is governed both by its size and its grade, and dependent on whether the bolt is loaded in shear or in tension. Based on in-person measurements taken in December 2022, and review of manufacturer information [14], researchers used a 0.75-inch diameter bolt at each of the four feet. Bolts of Grade 2 through 8 were investigated for their tensile and shear strength, as researchers assumed that the bolts used to attach the nurse tank to the running gear could be relatively easily replaced with bolts of varied strength over the course of the nurse tank's life (e.g., nurse tank swapped to new running gear).

The tensile load was estimated by multiplying the tensile strength of a given grade of bolt by its cross-sectional area. The maximum shear load was estimated to be 57.7% of the tensile load, based on the shear yield strength predicted by the distortion energy theory [15]. The resulting estimates for the tensile and shear loading capacities of Grade 2-8 bolts are shown in Table 8.

Table 8. Estimated Tensile and Shear Load Capacities of 0.75 inch diameter Grade 2-8 Bolts

Bolt Grade	Tensile Strength	Diameter	Area	Tensile Load	Shear Load	Reference
-	psi	inches	in^2	lbf	lbf	-
2	74,000	0.75	0.442	32,692	18,864	[16]
5	120,000	0.75	0.442	53,014	30,589	[16]
8	120,000	0.75	0.442	66,268	38,237	[16]

The loaded weight of a 1,000 gallon nurse tank was estimated to be 6,464 lbf, and the 1,450 gallon nurse tank was estimated to weigh 9,429 lbf (see Appendix A – NH3 Filling Calculations). A vertical, upward load at the CG of the tank would load each bolt uniformly in tension. Assuming 4 bolts of equal strength attaching the nurse tank's feet to the running gear, the G-load to produce a tensile failure of the bolts can be estimated by dividing four times the load capacity of a single bolt, from Table 8, by the loaded weight of the tank. Similarly, a longitudinal or lateral G-load on the CG of the tank would load the four bolts in shear. The estimated G-loads to cause bolt failure are shown in Table 9.

Table 9. Estimated G-loads to Cause Bolt Failure, 1,000 and 1,450 gallon Nurse Tanks

	1000 gal			1450 gal		
Bolt Grade	Loaded Weight (lbf)	G-load to Tensile Failure	G-load to Shear Failure	Loaded Weight (lbf)	G-load to Tensile Failure	G-load to Shear Failure
2	6,464	20.2	11.7	9,429	13.9	8.0
5	6,464	32.8	18.9	9,429	22.5	13.0
8	6,464	41.0	23.7	9,429	28.1	16.2

A longitudinal or lateral G-load acting on the CG of the nurse tank will also develop a moment that tends to rotate the tank. This moment will tend to cause the feet on one side of the CG to push downward, increasing the load on the running gear through contact. The feet on the opposite side of the CG will tend to lift upward, increasing the tensile load on the bolts between the tank's feet and running gear. This situation is illustrated in Figure 39 for a longitudinal G-load.

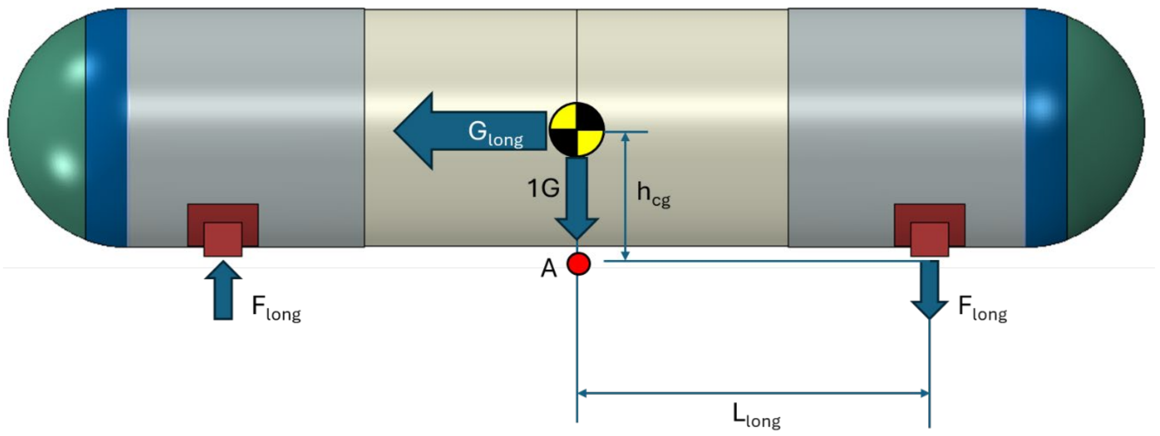


Figure 39. Free-body Diagram of Longitudinal Acceleration at Nurse Tank C.G.

The longitudinal G-load to reach the tensile strength of the bolts can be estimated by summing the moments about point A, as shown in Equation 2. The bolt is assumed to fail when the force at each foot, F_{long}, equals the tensile strength of the assumed bolt at each foot.

Equation 2. Longitudinal G-load to Reach Tensile Failure in Bolts from Moment About Tank's C.G.

$$\sum M_A = 0 = W_{tank} \cdot G_{long} \cdot h_{cg} - 4 \cdot F_{long} \cdot L_{long}$$

$$G_{long} = \frac{4 \cdot F_{long} \cdot L_{long}}{W_{tank} \cdot h_{cg}}$$

The results of Equation 2 for typical dimensions from the 1,000 and 1,450 gallon nurse tanks are shown in Table 10.

Table 10. Estimated Longitudinal G-loads to Cause Tensile Failure of Bolts

			1000 gal	1000 gal	1000 gal	1000 gal	1450 gal	1450 gal	1450 gal	1450 gal
Bolt Grade	**Tensile Load**	**Number of Bolts**	**Loaded Weight**	**h_{cg}**	**L_{long}**	**G-load to Tensile Failure**	**Loaded Weight**	**h_{cg}**	**L_{long}**	**G-load to Tensile Failure**
	lbf	**-**	**lbf**	**In.**	**In.**			**inches**	**inches**	
2	32,692	4	6,463.8	21.8	60	55.7	9,428.6	25.2	60	33.0
5	53,014	4	6,463.8	21.8	60	90.3	9,428.6	25.2	60	53.5
8	66,268	4	6,463.8	21.8	60	112.9	9,428.6	25.2	60	66.9

Similar calculations can be performed for the lateral acceleration illustrated in Figure 40 using Equation 3. The resulting lateral G-loads to reach the tensile load of the bolts are shown in Table 11.

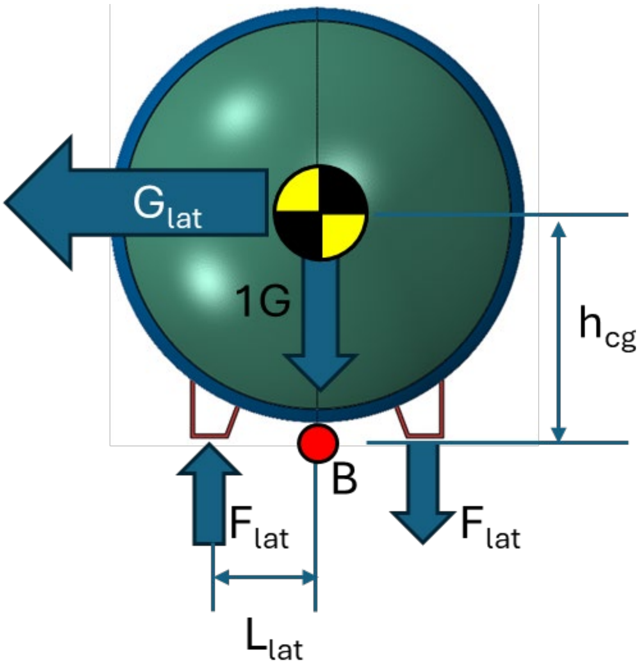


Figure 40. Free-body Diagram of Lateral Acceleration at Nurse Tank C.G.

Equation 3. Lateral G-load to Reach Tensile Failure in Bolts from Moment About Tank's C.G.

$$\sum M_B = 0 = W_{tank} \cdot G_{lat} \cdot h_{cg} - 4 \cdot F_{lat} \cdot L_{lat}$$

$$G_{lat} = \frac{4 \cdot F_{lat} \cdot L_{lat}}{W_{tank} \cdot h_{cg}}$$

Table 11. Estimated Lateral G-loads to Cause Tensile Failure of Bolts

			1000 gal	1000 gal	1000 gal	1000 gal	1450 gal	1450 gal	1450 gal	1450 gal
Bolt Grade	Tensile Load	Number of Bolts	Loaded Weight	h_{cg}	L_{lat}	G-load to Tensile Failure	Loaded Weight	h_{cg}	L_{lat}	G-load to Tensile Failure
	lbf	-	lbf	In.	In.			inches	inches	
2	32,692	4	6,463.8	21.8	10.5	9.7	9,428.6	25.2	10.5	5.8
5	53,014	4	6,463.8	21.8	10.5	15.8	9,428.6	25.2	10.5	9.4
8	66,268	4	6,463.8	21.8	10.5	19.8	9,428.6	25.2	10.5	11.7

These estimates are based on highly-simplified calculations, but the G-load magnitudes are significant. The authors did not pursue more detailed bolt strength calculations based on the high margins between the simplified estimates of the bolts' load-carrying capacities and the G-loads acting on the loaded tanks to produce loads that approached the capacities of the bolts. Other G-load practical limits were found to exist at lower G-loads than estimated for bolt failure, indicating other modes of failure were likely to serve as an effective G-load limit before the load to cause a bolt failure were reached.

4.4.4.2 Limits on Upward Vertical G-load

An upward G-load acting on the CG of the nurse tank will tend to lift the tank upward. If sufficient G-loads are applied in the vertical upward direction the nurse tank's feet will place the bolts attaching the feet to the running gear into tension. If the force transmitted through the bolts is not sufficient to cause a tensile failure (as discussed in the previous section), the G-load will cause the running gear to lift off the ground. Using an estimated light weight of 1,000 pounds for a single-tank running gear [17] , a G-load of slightly more than 1.1 G on the weight of the tank would be sufficient to initiate wheel lift for both the 1,000 gallon and 1,450 gallon nurse tanks. G-load estimates to lift the running gear are shown in Table 12.

Table 12. Estimated Upward Vertical G-loads to Lift Tank and Running Gear

Volume (gallons)	Loaded Tank Weight (lbf)	Estimated Running Gear Weight (lbf)	Combined Tank and Running Gear Weight (lbf)	G-load to Lift Running Gear (G)
1,000	6,464	1,000	7,464	1.15
1,450	9,429	1,000	10,429	1.11

4.4.4.3 Limits on Downward Vertical G-load

A downward vertical G-load on the CG of the nurse tank will not place the bolts under additional load, but can load the running gear directly via contact between the bottom of the foot and the mating surface on the running gear. As an estimate of the limit on the maximum downward vertical G-force that can act on the nurse tank, the gross vehicle weight rating (GVWR) of several nurse tank running gear were identified from published sources. If the vertical downward G-load is sufficient to reach the running gear's GVWR, it is plausible that damage to the running gear could occur. For a single-tank running gear, GVWRs in the range of 12,000 to 14,000 pounds were found to be typical [18] [19]. G-load estimates to reach each GVWR are shown in Table 13.

Table 13. Estimated Downward Vertical G-loads to Reach Running Gear GVWR

Volume (gallons)	Loaded Tank Weight (lbf)	Estimated Running Gear Weight (lbf)	Combined Tank and Running Gear Weight (lbf)	G-load to Reach 12,000 lbf GVWR (G)	G-load to Reach 14,000 lbf GVWR (G)
1,000	6464	1,000	7,464	1.6	1.9
1,450	9429	1,000	10,429	1.2	1.3

4.4.4.4 *Limits on Lateral G-load*

A practical limit on the maximum lateral G-load that can be applied to the nurse tank at its C.G. is the onset of wheel lift. If a sufficient lateral G-load is applied to the nurse tank the running gear will either slide sideway, or, if sufficient resistance is offered by the tire-ground interface, the far side wheels will begin to unload. Figure 41 contains a schematic illustration of the forces acting on the nurse tank and running gear for the situation where the lateral acceleration "G" is sufficient to initiate wheel lift (i.e., the far side wheel's vertical reaction force is zero).

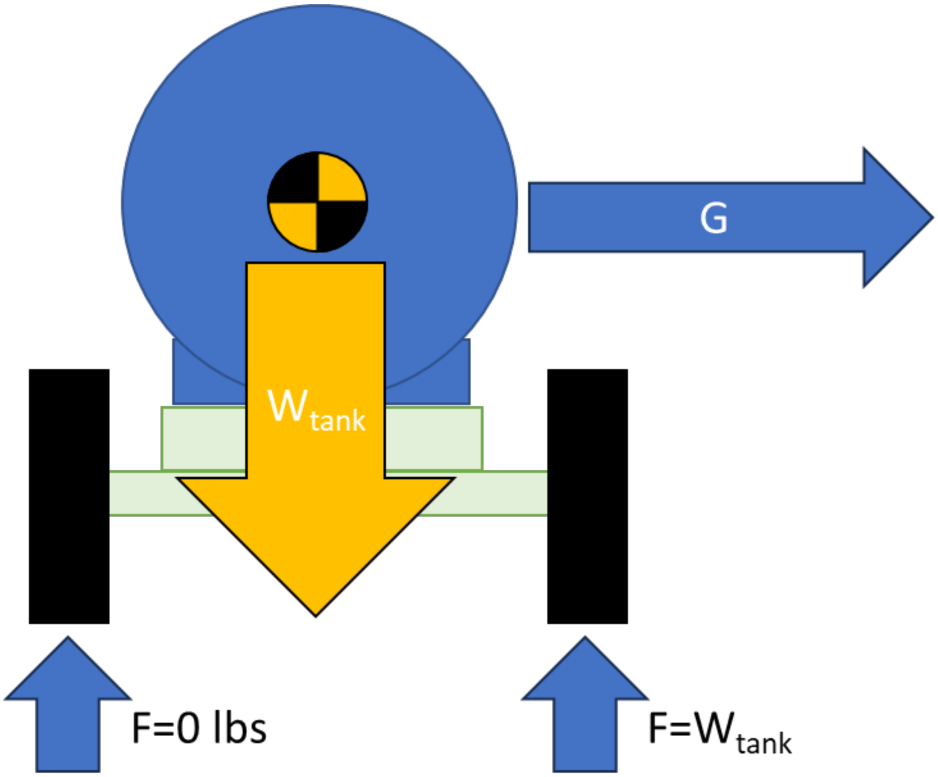


Figure 41. Schematic of Forces at Onset of Wheel Lift from Lateral G-load

The static stability factor (SSF) is a criterion used to estimate the likelihood of vehicle rollover, with a higher SSF corresponding to a decreased tendency for rollover [20]. The SSF is calculated according to Equation 4 as the ratio of one-half the track width (TW) divided by the height of the vehicle's center of gravity (H_{CG}). The SSF can also be thought of as the magnitude of the G-load multiplied by the weight of the tank (W_{tank}) that would cause the onset of wheel lift.

Equation 4. Calculation of SSF

$$SSF = \frac{TW}{2 \cdot H_{CG}}$$

Values for track width for typical running gear designed to carry a single 1,000 or 1,450 gallon nurse tank were obtained from a review of manufacturer websites [18], [19], [17]. Values for typical H_{CG} of nurse tanks were not readily available. However, during an in-person examination of nurse tanks undertaken as part of this project the center of the tank was measured to be between 61 and 63 inches above ground for several exemplar single-tank running gear. For comparison purposes, researchers assumed that no H_{CG} values of greater than 63 inches would be likely to occur, as the weight of the running gear would lower the height of the CG. A range of lateral G-loads were calculated for various track widths and assumed CG heights between 57 and 63 inches in Table 14.

Table 14. Summary of Lateral G-loads to Initiate Wheel Lift for Various Combinations of Track Width and Tank C.G. Heights

	Height of C.G.						
Track Width	**(inches)**						
(inches)	**57**	**58**	**59**	**60**	**61**	**62**	**63**
60	0.53	0.52	0.51	0.50	0.49	0.48	0.48
72	0.63	0.62	0.61	0.60	0.59	0.58	0.57
80	0.70	0.69	0.68	0.67	0.66	0.65	0.63

Over the range of track widths and CG heights examined the G-load to initiate wheel lift ranged from 0.48 to 0.7 G. This provides a reasonable estimate of the maximum lateral G-loads expected to occur during normal transportation, as a rollover event was assumed to be a very rare occurrence that would likely only happen once in the life of a tank. As will be subsequently discussed, these lateral G-loads to initiate wheel lift are below the 0.2 G and 0.4 G lateral accelerations used in the normal operating and extreme dynamic load cases required by 49 CFR 178 for the dynamic stress evaluation of specification tanks.

4.4.4.5 Limits on Longitudinal G-load

Longitudinal G-loads acting on the CG of the nurse tank will be affected by the acceleration or deceleration performance of the vehicle towing the nurse tank. The ability of the vehicle to accelerate the tank will be based on the power of the vehicle, while the ability of the vehicle to decelerate the nurse tank will be based on the braking ability of the vehicle. Due to the large variety of vehicles that could plausibly tow a nurse tank (e.g., pickup trucks, farm tractors), determining a limiting factor based on the acceleration and/or braking capabilities of these vehicles posed a significant challenge.

Current design regulations at 49 CFR 178.345-8(e), applicable to DOT-406, -407, and -412 CTMVs but not NH3 nurse tanks, require stress analysis to be performed on specification tanks against a 2G deceleration "…to account for stresses due to longitudinal impact in an accident." Since an accident load is presumed to be a non-recurring load (i.e., a load that only occurs at most once during the life of the tank), a 2G longitudinal limit for repeated longitudinal loads was assumed to be conservative.

5 Fatigue Screening Analysis

Per 49 CFR 173.315(m)(1)(i), nurse tanks must be constructed in accordance with ASME B&PVC, Section VIII, Division 1. This standard does not contain a specific requirement to conduct either fatigue screening or fatigue assessment. As a starting point for considering fatigue assessment of nurse tanks researchers consulted several additional sections of the ASME B&PVC that do include fatigue analysis procedures, but which are not used nor required to be used in the design of nurse tanks.

5.1 Fatigue Screening Methodologies

The research team investigated the applicability and requirements of different screening methods under Section VIII, Division 2 of the ASME B&PVC, under Section VIII, Division 3 of the ASME B&PVC, and the fatigue life calculations in Section XII of the ASME B&PVC that are applicable to certain specification CTMVs.

5.1.1 ASME Section VIII, Division 2

Section VIII, Division 2 of the ASME B&PVC is entitled “Alternative Rules” [21]. Section VIII, Division 2 is not (as of June 2025) IBR into the HMR for the design of NH3 nurse tanks.

A fatigue analysis may be required for a pressure vessel designed according to Section VIII, Division 2. Section 5.5.2 of Section VIII, Division 2 includes screening criteria to determine whether a fatigue analysis is required for a particular pressure vessel. Fatigue analysis may not be required for a vessel design either based on experience with “comparable equipment operating under similar conditions”, or by applying either of two analytical methods. While the specifics of the two analytical methods differ, in each case the designer must first determine a load history that the pressure vessel will experience during its service life, including such events as startups and shutdowns, the range of operating pressures to be encountered, and thermal gradients. The number of stress cycles that are included in the load history based on either analytical method are then compared against either a tabulated number of cycles or by using a fatigue curve based on the material of construction to determine whether a full fatigue analysis is required. Notably, if the number of cycles is greater than 1 million cycles further fatigue screening is not necessary, and the pressure vessel must undergo fatigue assessment.

Section VIII, Division 2 refers to both “operational cycles” and “stress cycles.” Section VIII, Division 2 defines an operational cycle as “the initiation and establishment of new conditions followed by a return to the conditions that prevailed at the beginning of the cycle” [21]. A stress cycle is defined as “a condition in which the alternating stress difference goes from an initial value through an algebraic maximum value and an algebraic minimum value and then returns to the initial value” [21]. Importantly, one operating cycle may include numerous stress cycles [21].

As an example, an operational cycle could consist of a loaded nurse tank being towed on a road from one location to another. The pressure, temperature, and weight of the NH3 in the nurse tank is the same at the start of the cycle as at the end of the cycle. While in-transit during a single operational cycle, the NH3 nurse tank could experience numerous stress cycles associated with vertical, lateral, and longitudinal G-loads.

5.1.2 ASME Section VIII, Division 3

Section VIII, Division 3 of the ASME B&PVC is entitled “Alternative Rules for Construction of High Pressure Vessels” [22]. Generally, Section VIII Division 3 is intended for pressure vessels with a design pressure above 10,000 psi but includes a statement that “it is not the intent of this Division to establish maximum pressure limits for either Section VIII, Division 1 or 2, nor minimum pressure limits for this Division” [22]. Section VIII, Division 3 is not (as of June 2025) IBR into the HMR for the design of NH3 nurse tanks.

A fatigue evaluation is required for vessels designed according to Section VIII, Division 3. This standard contains different methods that must be used to perform the fatigue evaluation based on whether the vessel being designed can be shown to have a “leak-before-burst” mode of failure. If a “leak-before-burst” mode of failure cannot be shown, then Section VIII, Division 3 requires a fracture mechanics evaluation following procedures given in Article KD-4 [22].

In addition to analytical methods, Section VIII, Division 3 contains procedures for determining the allowable number of operating cycles using testing. Similar to the approach used for fatigue analysis given in Section VIII, Division 2, the designer must determine a load history that the vessel is anticipated to experience during its service life. Notably, Section VIII, Division 3, includes discussion in Article KD-3 on the need to account for residual stresses due to certain manufacturing processes in the fatigue analysis [22].

5.1.3 ASME Section XII

Section XII of the ASME B&PVC is entitled “Rules for Construction and Continued Service of Transport Tanks” [23]. Section XII contains requirements specifically applicable to tanks used in transportation, including specification DOT 406, 407, 412, and MC 331 CTMVs. As of June 2025, Section XII is not IBR in the HMR, so it is not required to be used in the design of these CTMVs nor for NH3 nurse tanks.

Section XII contains many similar service load cases as can be found in the HMR in Subpart J to 49 CFR 178 for specification tanks. The scope of Section XII does not include NH3 nurse tanks. However, Section XII does contain design requirements for MC 331 CTMVs that are used in NH3 service. Beyond the design load requirements found in Subpart J to 49 CFR 178, Section XII includes requirements to analyze MC 331 Cargo Tanks against fatigue. These requirements were examined in the current research as a means of understanding the load magnitudes and number of cycles that may be appropriate to consider for NH3 nurse tanks.

Section XII requires fatigue analysis for two different types of cyclic loads, to be considered individually. The first category of cyclic loads are the static G-load equivalents (e.g., vertical acceleration, lateral acceleration, longitudinal acceleration/deceleration) that are required by both Section XII and Subpart J to 49 CFR 178. While the MC 331 designed according to Section XII must be designed to withstand the stresses that develop under a one-time G-loading, just like the CFR requirement, it must also be evaluated for 8 x 10^9 cycles of each G-load equivalent [23].

The G-load cases described in Section XII are substantially-similar to the G-load cases given in 49 CFR 178.337-3. The G-load cases from 49 CFR 178.337-3 are summarized in Table 15.

Table 15. Summary of G-load Cases Applicable to MC 331 Cargo Tanks in CFR

Load Case Description	CFR Citation	Internal Pressure	Static Weight (G)	Longitudinal Acceleration (G)	Vertical Acceleration (G)	Transverse Acceleration (G)	Notes
Normal Operating Loading	49 CFR 178.337-3(c)(1)	MAWP + Static Head	1	+/- 0.35	+/- 0.35	+/- 0.2	Tractor acceleration, tractor deceleration, trailer deceleration
Extreme Dynamic Loading (Longitudinal)	49 CFR 178.337-3(c)(2)	MAWP + Static Head	1	+/- 0.7	-	-	Tractor acceleration, tractor deceleration, trailer deceleration
Extreme Dynamic Loading (Vertical)	49 CFR 178.337-3(c)(2)	MAWP + Static Head	1	-	+/- 0.7	-	
Extreme Dynamic Loading (Transverse)	49 CFR 178.337-3(c)(2)	MAWP + Static Head	1	-	-	+/- 0.4	

Additionally, Section XII requires the MC 331 cargo tank to be evaluated against a pressure change of "20% of the sum of the value of the vessel's [MAWP] plus static liquid head of a vessel filled to its design weight of lading" [23]. This pressure variation is to be evaluated for 1 x 10^5 cycles. As discussed previously, the minimum MAWP for an NH3 nurse tank is set at 250 psig in 49 CFR 173.315(m)(i). The static head of NH3 adds less than 1 psi to the pressure in either a typical 1,000 gallon or 1,450 gallon NH3 nurse tank (see Appendix A – NH3 Filling Calculations). Thus, a 20% change in pressure relative to 251 psig is 50.2 psig. Notably, the change in pressure associated with lowering the liquid level of NH3 in the tank as the NH3 is supplied to the implement is not sufficient to reach the 20% threshold, as near-complete emptying of the tank would only reduce the static head by 1 psig.

For both the dynamic G-loads and the pressure variation cyclic loading the fatigue analyses under Section XII are to be performed according to Section VIII, Division 2, Part 5, 5.5 [23].

5.2 Events, Assumptions, and Limitations

When designing a vessel for fatigue analysis under Section VIII, Division 2, the desired number of design cycles is a part of the specification for the vessel. For an NH3 nurse tank designed according to Section VIII, Division 1, there is currently not a design life that is set for the vessels (e.g., number of loads, number of miles, years in service, etc.) Over the course of the nurse tank's operational life numerous loads may act on the tank over time and contribute to its overall fatigue life. Because these loads are not required to be set out as a part of the tank's design, the load history was estimated as a part of this research project.

Constructing the load history for NH3 nurse tanks was done by first considering the various events that a nurse tank would be subjected to during its life. For example, one event would be towing a loaded nurse tank over roads to a field. For each event in the nurse tank's life, researchers had to estimate the sources of stress on the tank, the number of stress cycles within a single occurrence of the event, and the number of times that event would be repeated over the nurse tank's life.

For each operation, the stresses that develop in the NH3 nurse tank are attributed to one or more of the following loads:

- Internal pressure
    - Pressure introduced during operation (e.g., hydrostatic test)
    - Pressure incident to temperature change during operation
- NH3 weight
    - NH3 introduced into tank, or
    - NH3 flowing out of tank
- Dynamic G-loads
    - Vertical
    - Lateral
    - Longitudinal
- Thermal Stresses in Tank
    - Atmospheric conditions (e.g., tank sitting in sun)
    - Lading conditions (e.g., filling tank with NH3 at a different temperature than tank temperature)

As discussed in Section 4.4.4, G-load limits for the dynamic loads acting on the NH3 nurse tanks were estimated based on practical limits for the tank, bolts, and running gear. The major events that are considered for fatigue life are illustrated, schematically, in Figure 42. This illustrates several major events and identifies a sequential relationship between events but does not account for all possible events that could occur. For example, nurse tanks may be swapped between different running gears during their services lives. This event is not explicitly represented as it is not expected to occur frequently and is not expected to produce unique stresses that would affect the fatigue life of the NH3 nurse tank. The shaded events contained within the dashed boundary indicate the events that would also be subject to atmospheric variation, as the tank contains NH3 during those events. Each event in Figure 42 is discussed in the following subsections.

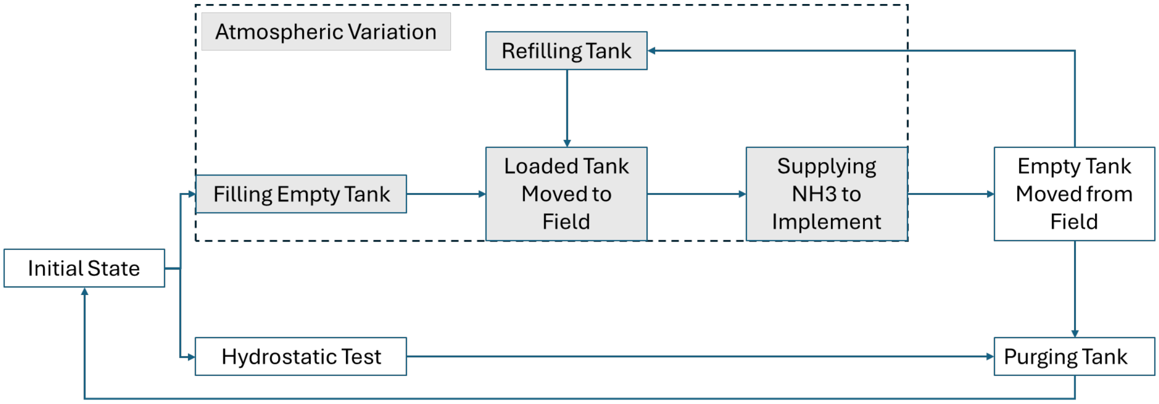


Figure 42. Nurse Tank Events

5.2.1 Initial State

The initial state of the tank represents both a new tank that has yet to be loaded, and a tank that has been purged, such as after a hydrostatic test. In the initial state the tank is assumed to be empty of NH3 and at atmospheric pressure and ambient temperature. The only G-load acting on the tank is normal gravity (i.e., -1G vertically) acting on the empty mass of the tank. The loads acting on the nurse tank during this event are summarized in Table 16. This event occurs once for each new tank, and once after each successful hydrostatic test.

Table 16. Summary of Loads on Nurse Tank for Initial State

Pressure		
Initial Pressure:	0	psig
Lading Weight		
Initial Weight of Lading:	0	lbf
Dynamic Load Amplitudes		
Vertical		
Min:	-1	G
Max:	-1	G
Lateral		
Min:	0	G
Max:	0	G
Longitudinal		
Min:	0	G
Max:	0	G
Dynamic Stress Cycles per Event		

Vertical:	1	cycles
Lateral:	0	cycles
Longitudinal:	0	cycles
Thermal Cycles		
Minimum Temperature:	Ambient	
Maximum Temperature:	Ambient	

5.2.2 Filling Empty Tank

This event represents filling the tank from its initial state to its ready-to-run state. The internal pressure of the tank increases during this event from an initial pressure of 0 psig to the saturation pressure (P_{sat}) of NH3 at the filling temperature (T_{sat}). The weight of the lading increases during this event from the empty tank (i.e., zero lading weight) to the maximum allowable filling density given in 49 CFR 173.315(m)(1)(v), 56% of the water weight for the tank's capacity. The loads acting on the nurse tank during this event are summarized in Table 17. Note that the values for minimum and maximum temperature may be reversed, depending on whether the T_{sat} for NH3 being introduced to the tank is above or below the initial temperature of the empty tank. This event occurs once for each new tank, and once after each successful hydrostatic test when a tank is being returned to service.

Table 17. Summary of Loads on Nurse Tank for Filling Empty Tank Event

Pressure		
Initial Pressure:	0	psig
Peak Pressure:	P_{sat}	psig
Final Pressure:	P_{sat}	psig
Lading Weight		
Initial Weight of Lading:	0	lbf
Peak Weight of Lading:	0.56 x V_{tank} x 8.3 lbf/gal	lbf
Final Weight of Lading:	0.56 x V_{tank} x 8.3 lbf/gal	lbf
Dynamic Load Amplitudes		
Vertical		
Min:	-1	G
Max:	-1	G
Lateral		
Min:	0	G
Max:	0	G
Longitudinal		
Min:	0	G
Max:	0	G
Dynamic Stress Cycles per Event		
Vertical:	1	cycles

Lateral:	0	cycles
Longitudinal:	0	cycles
Thermal Cycles		
Minimum Temperature:	Ambient	
Maximum Temperature:	T_{sat} for NH3	

5.2.3 Loaded Tank Moved to Field

This event represents a loaded NH3 tank being towed over the road to the field where NH3 is being applied. The weight of NH3 within the tank, the temperature of the tank, and the initial pressure within the tank are assumed to remain constant during this event. The dynamic loads on the tank are assumed to vary over the course of this event as the tank is in motion. The limits for G-loads are based on the estimated G-loads discussed in Section 4.4.4.

The magnitude of the dynamic G-load acting in each direction and the number of G-load cycles per mile need to be better quantified. Additionally, the distance that the nurse tank is towed over the road to a typical field needs to be defined. The loads acting on the nurse tank during this event are summarized in Table 18.

Table 18. Summary of Loads on Nurse Tank for Loaded Tank Moved to Field Event

Pressure		
Initial, Peak, and Final Pressures:	P_{sat}	psig
Lading Weight		
Initial and Final Weight of Lading:	0.56 x V_{tank} x 8.3 lbf/gal	lbf
Dynamic Load Amplitudes		
Vertical		
Min:	-1.88	G
Max:	+1.15	G
Lateral		
Max/Min:	+/-0.7	G
Longitudinal		
Max/Min:	+/-2	G
Dynamic Stress Cycles per Event		
Vertical:	See Section 5.3.4	cycles/mile
Lateral:	See Section 5.3.4	cycles/mile
Longitudinal:	See Section 5.3.4	cycles/mile
Thermal Cycles		
Max/Min Temperature:	Ambient	

This event is repeated each time a loaded tank is towed over the road, to a field. At a minimum this event occurs once per tankload. The event could occur more than once, if the nurse tank travels over the road between multiple fields before returning to be refilled. It is also assumed that the number of dynamic G-load cycles per event increases as the distance the nurse tank travels over roads increases.

5.2.4 Supplying NH3 to Implement

This event represents the NH3 nurse tank in operation, supplying NH3 to an implement in a field. The weight of NH3 within the tank decreases during this event as the NH3 flows out of the tank. The internal pressure is assumed to remain constant, as equilibrium between NH3 liquid and vapor is assumed to be maintained during the event. Dynamic loads act on the nurse tank as the tank travels through the field. The magnitude and number of cycles of each G-load during operations in a field are assumed to differ from the magnitude and number of cycles of G-loads that are typical of the nurse tank traveling on roads. However, typical G-loads for field operations and the number of cycles that occur for each load per linear mile of travel or per acre of NH3 application are uncertain. This event is repeated once per tankload. Even if the NH3 tank is towed between multiple fields over the road it is assumed that the tank will be emptied to the same level before being returned to the location where it will be filled. There are uncertainties within this event related to the distance the nurse tank will travel over a field before the supply of NH3 has been exhausted. As the application rate (i.e., pounds of NH3 per acre of field) increases, a single tankload will cover fewer acres before needing to be refilled. This correlates to fewer miles of in-field dynamic G-loads between refilling cycles. At the same time, a higher application rate will require more refills to cover a certain number of acres. The loads acting on the nurse tank during this event are summarized in Table 19. The limits for G-loads are based on the estimated G-loads discussed in Section 4.4.4.

Table 19. Summary of Loads on Nurse Tank for Supplying NH3 to Implement Event

Pressure		
Initial, Peak, and Final Pressures:	P_{sat}	psig
Lading Weight		
Initial Weight of Lading:	$0.56 \times V_{tank} \times 8.3$ lbf/gal	lbf
Final Weight of Lading:	0[3]	lbf
Dynamic Load Amplitudes		
Vertical		
Min:	-1.88	G
Max:	+1.15	G
Lateral		
Max/Min:	+/-0.7	G
Longitudinal		
Max/Min:	+/-2	G

---

[3] In practice, the tank is not expected to be emptied completely of NH3. Assuming complete unloading represents a worst case scenario for the change in weight during this event.

Dynamic Stress Cycles per Event		
Vertical:	See Section 5.3.4	cycles/acre
Lateral:	See Section 5.3.4	cycles/acre
Longitudinal:	See Section 5.3.4	cycles/acre
Thermal Cycles		
Max/Min Temperature:	Ambient	

5.2.5 Empty Tank Moved from Field

After supplying NH3 to the field(s) requiring application, the empty tank is assumed to be towed along roads back to the location where it was originally loaded with NH3. As discussed above, the dynamic G-loads imparted by travel over roads are assumed to differ from the G-loads that develop during travel through a field. The primary difference between this event and the “Loaded Tank Towed to Field” event is that the tank’s weight will be lower during this event, as the NH3 has been applied to the field. While in practice the tank is expected to contain some amount of NH3, for simplicity the tank is assumed to be empty of NH3 during this event. However, the internal pressure is assumed to remain constant at P_{sat}, as even a small volume of liquid within the tank would be held under pressure to remain in the liquid state. The loads acting on the nurse tank during this event are summarized in Table 20. The limits for G-loads are based on the estimated G-loads discussed in Section 4.4.4.

Table 20. Summary of Loads on Nurse Tank for Empty Tank Towed from Field Event

Pressure		
Initial, Peak, and Final Pressures:	P_{sat}	psig
Lading Weight		
Initial and Final Weight of Lading:	0	lbf
Dynamic Load Amplitudes		
Vertical		
Min:	-1.88	G
Max:	+1.15	G
Lateral		
Max/Min:	+/-0.7	G
Longitudinal		
Max/Min:	+/-2	G
Dynamic Stress Cycles per Event		
Vertical:	See Section 5.3.4	cycles/mile
Lateral:	See Section 5.3.4	cycles/mile
Longitudinal:	See Section 5.3.4	cycles/mile
Thermal Cycles		
Minimum Temperature:	Ambient	
Maximum Temperature:	Ambient	

This event is repeated each time an empty tank is towed over the road, from a field. At a minimum this event occurs once per tankload. It is also assumed that the number of dynamic G-load cycles per event increases as the distance the nurse tank travels over roads increases. For simplicity, it may be assumed that the mileage traveled by the empty nurse tank was the same as the mileage traveled by the loaded nurse tank in the "Loaded Tank Moved to Field" event.

5.2.6 Refilling Tank

An empty nurse tank will be refilled with fresh NH3 before it can be used again. During this event, the weight of NH3 in the tank will increase from the assumed light weight of zero pounds to the assumed maximum weight corresponding to a 56 percent filling density. The internal pressure is assumed to be constant during this event, but in practice the pressure may vary as NH3 is transferred from the supply tank to the nurse tank. Additionally, the temperature of the tank is assumed to remain constant during this event but may vary if the fresh NH3 being introduced into the tank is at a different temperature than the bulk temperature of the nurse tank being refilled. This event is similar to the "Filling Empty Tank" event, but with the important distinction that during a refill event the nurse tank is assumed to have an initial pressure due to a small amount of NH3 remaining in the tank. For the "Filling Empty Tank" event, the tank is initially at atmospheric pressure and experiences an increase in pressure as the NH3 is introduced. The loads acting on the nurse tank during this event are summarized in Table 21. This event is repeated once per tankload.

Table 21. Summary of Loads on Nurse Tank for Refilling Tank Event

Pressure		
Initial, Peak, and Final Pressure:	P_{sat}	psig
Lading Weight		
Initial Weight of Lading:	0	lbf
Final Weight of Lading:	0.56 x V_{tank} x 8.3 lbf/gal	lbf
Dynamic Load Amplitudes		
Vertical		
Min:	-1	G
Max:	-1	G
Lateral		
Min:	0	G
Max:	0	G
Longitudinal		
Min:	0	G
Max:	0	G
Dynamic Stress Cycles per Event		
Vertical:	1	cycles
Lateral:	0	cycles
Longitudinal:	0	cycles

Thermal Cycles		
Min/Max Temperature:	Ambient	

5.2.7 Atmospheric Variation

An NH3 nurse tank is exposed to variations in temperature due to atmospheric conditions. While a nurse tank must be painted white or aluminum to reduce tendency to heat up, the nurse tank will still absorb some heat from exposure to the sun. The tank itself will experience direct heating from exposure to the sun and will cool off at nights and during winter months. Additionally, for a nurse tank loaded with NH3 the change in temperature of the saturated NH3 (T_{sat}) will produce a corresponding change in P_{sat} (see Appendix A – NH3 Filling Calculations). The change in temperature and internal pressure will occur over the course of each day between the daily low and daily high temperature. The specific temperature cycles will be specific to the nurse tank's location. The loads acting on the nurse tank during this event are summarized in Table 22.

Table 22. Summary of Loads on Nurse Tank for Atmospheric Variation Event

Pressure		
Initial Pressure:	P_{sat} at Low T_{sat}	psig
Peak and Final Pressure:	P_{sat} at High T_{sat}	psig
Lading Weight		
Initial and Final Weight of Lading:	0.56 x V_{tank} x 8.3	lbf
Dynamic Load Amplitudes		
Vertical		
Min/Max:	-1	G
Lateral		
Min/Max:	0	G
Longitudinal		
Min/Max:	0	G
Dynamic Stress Cycles per Event		
Vertical:	1	cycles/day
Lateral:	0	cycles/day
Longitudinal:	0	cycles/day
Thermal Cycles		
Minimum Temperature:	Ambient Daily Low	
Maximum Temperature:	Ambient Daily High	

The tank is assumed to undergo one thermal cycle per day between the ambient daily low temperature and ambient daily high temperature typical of its location. The assumption that the tank and lading are both at an ambient temperature is overly simplified but thought to be conservative. In reality, it will take time for the steel of the tank to heat up through its thickness and to transfer heat into the NH3. A thermal gradient is likely to exist within the NH3, as the entire volume of the tank will not heat or cool instantaneously. At the same time, a metallic tank parked in the sun may have a surface temperature that is higher than the ambient air temperature. As historical data for normal and record daily temperature variations are widely available, ambient temperature was thought to be a relatively simply assumption to include this effect in the analysis.

5.2.8 Purging Tank

Currently, NH3 nurse tanks with present and legible ASME plates are not required to undergo any periodic hydrostatic testing per 49 CFR 173.315(m). However, the current HMR does not prevent an owner from proactively conducting such a test even if it is not required. If a hydrostatic test is to be performed on an NH3 nurse tank, the tank must first be purged of NH3. Independent of a hydrostatic test a tank may need to be purged prior to performing some maintenance on the tank, such as replacing a valve.

For this load event the tank is initially assumed to contain an insignificant weight of NH3 but remain under pressure. The tank's pressure is reduced to atmospheric pressure (i.e., 0 psig) prior to the remaining NH3 is purged. At the end of this event the NH3 nurse tank has returned to the same conditions as the "Initial State" when it was new. The loads acting on the nurse tank during this event are summarized in Table 23. This event is repeated each time the tank is purged prior to either maintenance or a hydrostatic test.

Table 23. Summary of Loads on Nurse Tank for Purging Tank Event

Pressure		
Initial Pressure:	P_{sat} at Tsat	psig
Peak Pressure:	P_{sat} at Tsat	psig
Final Pressure:	0	psig
Lading Weight		
Initial and Final Weight of Lading:	0	lbf
Dynamic Load Amplitudes		
Vertical		
Min/Max:	-1	G
Lateral		
Min/Max:	0	G
Longitudinal		
Min/Max:	0	G
Dynamic Load Cycles per Event		
Vertical:	1	cycle
Lateral:	0	cycles
Longitudinal:	0	cycles
Thermal Cycles		

Min/Max Temperature:	$T_{ambient}$	

5.2.9 Hydrostatic Test

Currently, NH3 nurse tanks with present and legible ASME plates are not required to undergo any periodic hydrostatic testing per 49 CFR 173.315(m). However, the current HMR does not prevent an owner from proactively conducting such a test even if it is not required. If a hydrostatic test is required because a nurse tank has a missing or illegible ASME plate, the minimum test pressure set by 49 CFR 173.315(m)(2)(iii) is 375 psig. In addition to this test pressure the tank will be loaded to its full volume with water during a hydrostatic test. The hydrostatic test event includes both the loading and unloading portions of the test, so that the initial and final states of the tank care both the same as the "Initial State" defined above. The temperature of the tank is assumed to remain constant during this event. The loads acting on the nurse tank during this event are summarized in Table 24.

Table 24. Summary of Loads on Nurse Tank for Hydrostatic Test

Pressure		
Initial Pressure:	0	psig
Peak Pressure:	375	psig
Final Pressure:	0	psig
Lading Weight		
Initial Weight of Lading:	0	lbf
Peak Weight of Lading:	$8.3 \times V_{tank}$	lbf
Final Weight of Lading:	0	lbf
Dynamic Load Amplitudes		
Vertical		
Min/Max:	-1	G
Lateral		
Min/Max:	0	G
Longitudinal		
Min/Max:	0	G
Dynamic Load Cycles per Scenario Cycle		
Vertical:	1	cycles/test
Lateral:	0	cycles/test
Longitudinal:	0	cycles/test
Thermal Cycles		
Min/Max Temperature:	$T_{ambient}$	

This event is repeated each time the tank undergoes a hydrostatic test. If hydrostatic testing is required, it must be repeated every five years following the initial testing, per 49 CFR 173.315(m)(2)(iv). A conservative estimate of the number of repeated events would assume that hydrostatic testing occurs every five years of the nurse tank's operational life.

5.3 Estimated Number of Operational and Stress Cycle Counts for Each Event

Each of the events described in the previous section are expected to occur multiple times over the course of the NH3 nurse tank's operational life. For the three events that involve the tank in motion (i.e., Loaded Tank Moved to Field, Supplying NH3 to Implement, and Empty Tank Moved from Field), a single event will also contain numerous stress cycles for the dynamic G-loads.

An additional challenge on estimating the number of stress cycles an NH3 nurse tank will encounter during its service life is the unknown duration of its expected service life. Additionally, some of the events described above repeat based only on time (e.g., Hydrostatic testing and atmospheric variation), while others vary with the number of tankloads of NH3 (e.g., Refilling Tank). Finally, the events that involve dynamic G-loads require an estimate of the number of vertical, lateral, and longitudinal acceleration cycles as a function of the distance traveled by the NH3 nurse tank bother over the road and through fields.

5.3.1 Estimated Number of Tankloads

The number of "Refiling Tank" events that occurs during the life of a nurse tank depends on how many tankloads of NH3 it transports each year and its expected service life. As an estimate, an upper limit estimate of the number of tankloads of NH3 that a 1,000 gallon NH3 nurse tank could transport in a single year was made using available data. In 2019, U.S. domestic consumption of anhydrous ammonia was approximately 15,182 million kg, or 16.7 million tons [24]. Approximately 88 percent of the anhydrous ammonia used in the U.S. in 2018 was used for fertilizer [24]. Conservatively[4] assuming all the anhydrous ammonia used as fertilizer was applied via nurse tanks gives an estimated 14.7 million tons of anhydrous ammonia carried in nurse tanks in 2019.

For conservatism, it is assumed that all NH3 moves in 1,000 gallon nurse tanks. Again, if a larger capacity nurse tank was used fewer tankloads would be needed to carry the same amount of NH3. A 1,000 gallon nurse tank filled to the maximum filling density of 56 percent can hold 4,670 pounds, or 2.3 tons, of NH3 per tank (see Appendix A – NH3 Filling Calculations). Thus, the 14.7 million tons of anhydrous ammonia used as fertilizer in 2018 would require 6.3 million tankloads if transported entirely using 1,000 gallon nurse tanks.

A previous report estimated the U.S. nurse tank fleet size as approximately 200,000 nurse tanks [5].

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[4] In this context, a conservative assumption is an assumption that will produce the largest number of loads a single tank will need to transport the commodity.

Further, this same report indicated that anhydrous ammonia became common as a fertilizer in the 1950s, and as of 2022 nurse tanks older than 50 years remained in the fleet [5]. On average, each 1,000 gallon nurse tank would need to transport 31.5 loads of anhydrous ammonia per year to equal the 6.3 million tankloads of NH3 calculated above.

Table 25 contains an estimate for the number of loads of NH3 an average 1,000 gallon nurse tank will transport over various service lives, based on the conservative assumptions described above. Note that this table assumes that both the demand for NH3 and the size of the fleet remains constant throughout the service lives.

Table 25. Estimated Number of Lifetime NH3 Loads for Various Assumed Service Lives

Service Life (years)	Estimated Number of Loads of NH3
30	945
40	1,261
50	1,576
60	1,891

5.3.2 Estimated Number of Hydrostatic Test Events

Nurse tanks with a missing or illegible ASME plate or nurse tanks mounted on field trucks (rather than running gear on a trailer) are required to be hydrostatic tested every 5 years per 49 CFR 173.315(m)(2). This same interval was assumed for all nurse tanks to estimate the number of "Purging Tank," "Hydrostatic Test," and "Filling Empty Tank[5]" events. The estimated number of hydrostatic test events for various service lives are shown in Table 26.

Table 26. Estimated Number of Hydrostatic Test Events for Various Assumed Service Lives

Service Life (years)	Number of Hydrostatic Test Events

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[5] One additional instance of the "Filling Empty Tank" event occurs for every nurse tank the first time a new tank is loaded, regardless of whether that tank will be subject to hydrostatic testing.

30	6
40	8
50	10
60	12

5.3.3 Estimated Number of Atmospheric Variations

When not being used to supply NH3 to agricultural implements nurse tanks may still be filled with NH3, serving as temporary storage. While a standing nurse tank is not subject to dynamic G-loads, the nurse tank will still be subject to changes in temperature and pressure associated with the tank heating and cooling due to changes in atmospheric conditions. Assuming the nurse tank undergoes a thermal cycle every day of its service life is conservative for several reasons. The nurse tank will not be full of NH3 every day, as there will be some days when the tank is purged for maintenance, a hydrostatic test, or simply not in use. Even if the nurse tank is filled with NH3, the pressure change associated with the daily temperature variation may not be a significant contributor to the fatigue life of the nurse tank. Table 27 contains the calculated number of daily temperature cycles that would occur if an NH3 nurse tank was loaded for various services lives.

Table 27. Number of Daily Temperature Cycles for Various Service Lives

Service Life (years)	Number of Daily Temperature Cycles
30	10,958
40	14,610
50	18,263
60	21,915

Historical temperature data for central Iowa (Des Moines) as of 2020 was used to approximate the change in NH3 pressure associated with daily temperature changes [25]. Figure 43 contains a plot of the average daily high, average daily low, record daily high, and record daily low for Des Moines, IA as of 2020 [25]. Additionally, the T_{sat} of 114.5 degrees, corresponding to saturated NH3 reaching the minimum nurse tank MAWP of 250 psig is shown, for reference. The data for T_{sat} and P_{sat} were obtained from NIST data [26], as shown in Appendix A – NH3 Filling Calculations.

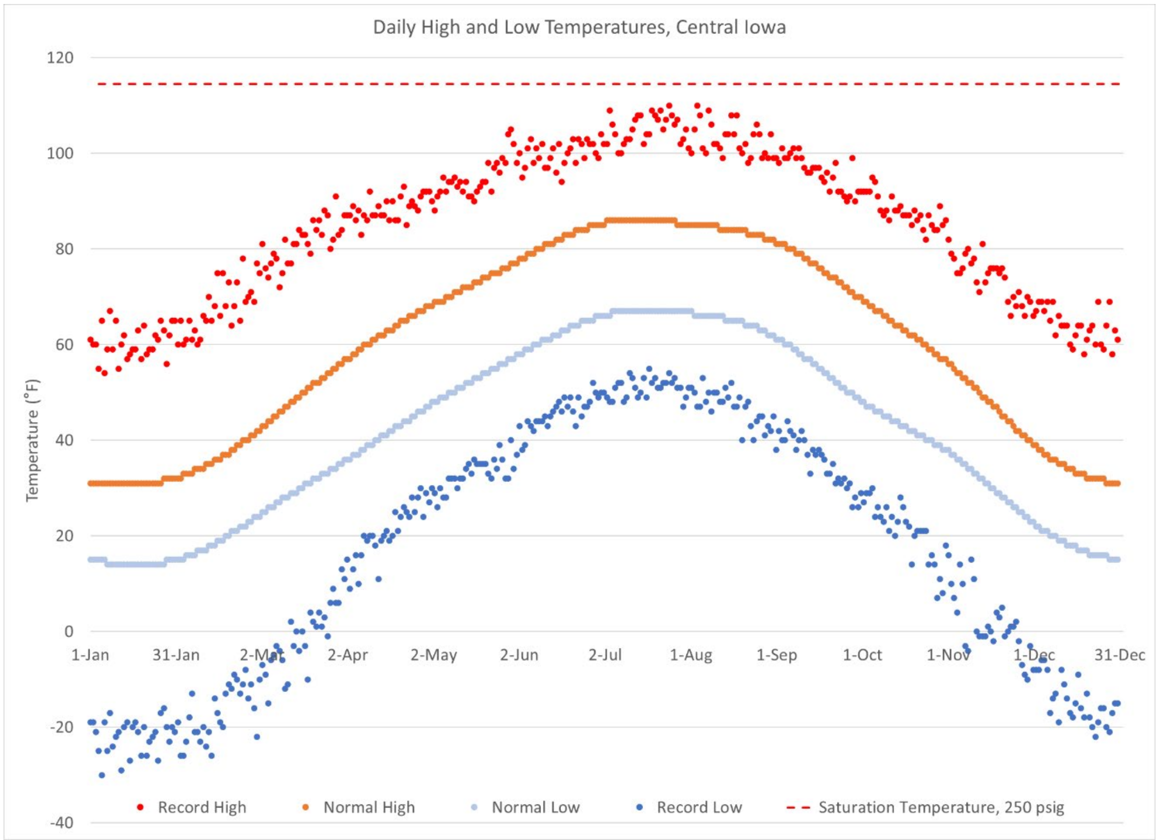


Figure 43. Daily and Record High and Low Temperatures for Central Iowa (Data from [25], as of 2020)

Assuming that the NH3 within a nurse tank is in a saturated state, a change in bulk temperature will produce a known change in the pressure of the NH3 vapor in the outage space. Conservatively assuming the temperature of the NH3 within the tank matches the external temperature, the saturation data from NIST [26] and the normal daily high and low temperature data can be combined to estimate the daily change in internal pressure for saturated NH3. The estimated daily changes in pressure are shown in Figure 44. Additionally, dashed lines representing a pressure change of 15 percent and 20 percent of the 250 psig minimum MAWP for an NH3 nurse tank are shown, for reference. Under Fatigue Screening method A in Section VIII, Division 2, pressure cycles caused by atmospheric variations are not counted toward the cycle count used to determine if a fatigue assessment is required, but pressure cycles of greater than 15 percent of the design pressure of a vessel of non-integral construction are included in the cycle count [21]. Separately, the fatigue analysis procedures applicable to MC 331 cargo tanks under Section XII consider any changes in pressure greater than or equal to 20 percent of the MAWP plus the static head of the liquid [23].

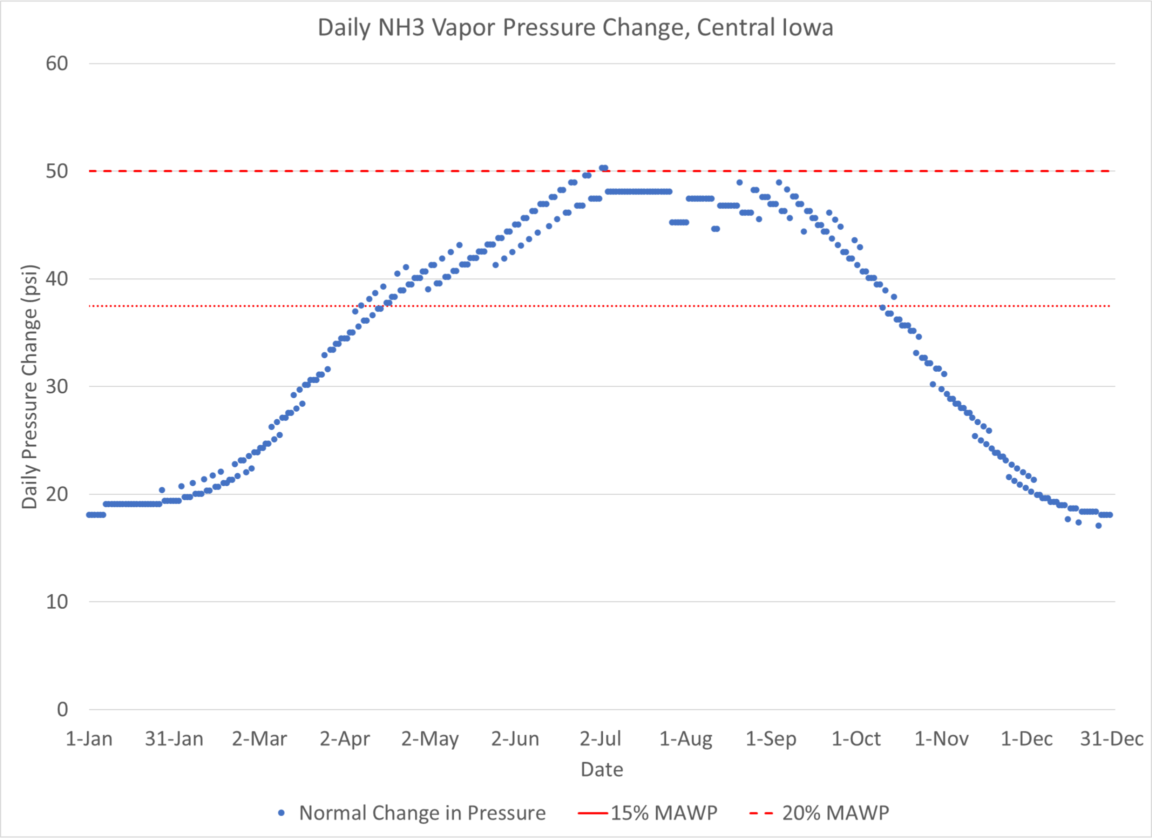


Figure 44. Vapor Pressure Change from Normal Daily Temperature Variation, Central Iowa

The resulting normal pressure changes show that very few daily temperature cycles based on normal, historical data for central Iowa would exceed the pressure change threshold of 20 percent of the MAWP used in Section XII for fatigue life assessment. Considerably more days would produce an estimated change in pressure of greater than 15 percent of the 250 psig MAWP.

Finally, the historical temperature data were used to estimate the change in NH3 vapor pressure associated with the record high and low temperatures recorded (as of 2020) for central Iowa [25]. Two different changes in pressure were calculated from the historical data. One pressure change was estimated using the daily average low temperature and the daily record high temperature for each day. The second pressure change was estimated using the daily average high temperature and the record low temperature for each day. Each of these assumptions are assumed to be conservative, as a day that experiences one extreme temperature (i.e., either a record high or record low) is unlikely to have an average value for the other extreme temperature. Put another way, a day with a record high temperature is likely to have a higher-than-average low temperature, and a day with a record low is likely to have a lower-than-average high temperature. The resulting vapor pressure changes for Central Iowa are shown in Figure 45.

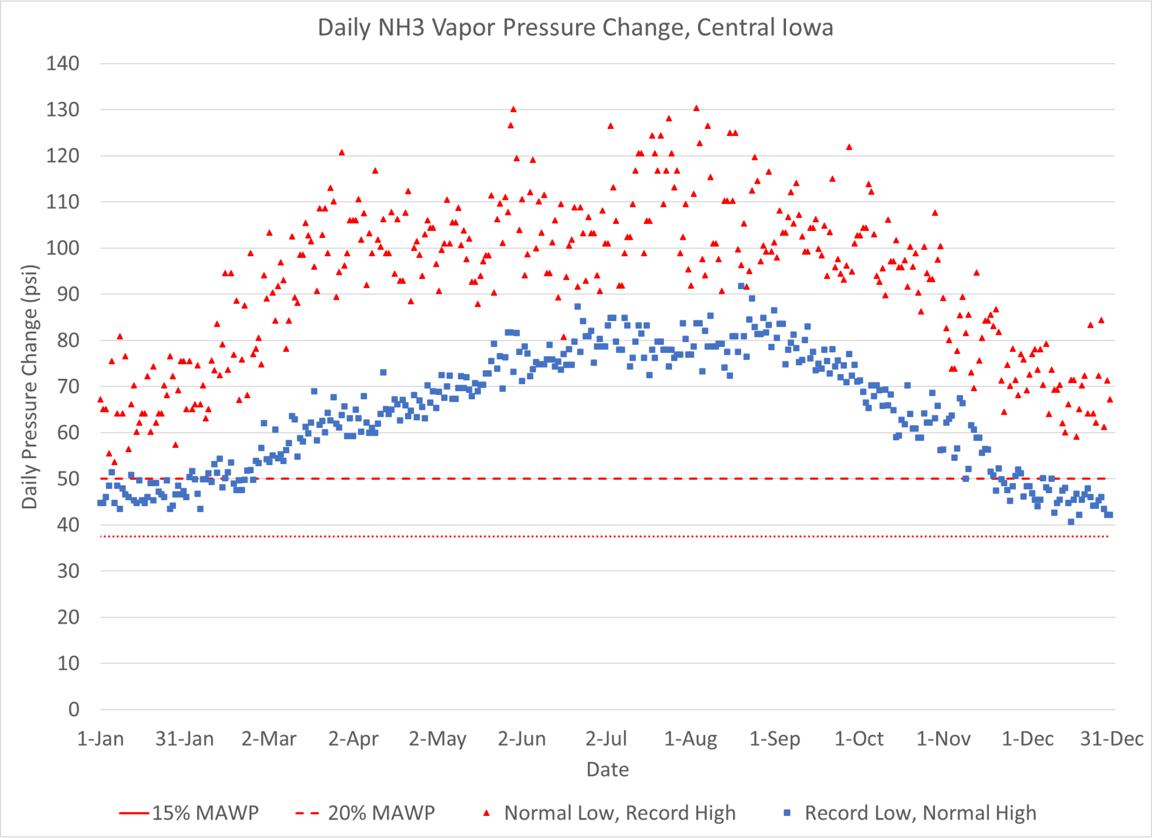


Figure 45. Vapor Pressure Change from Record Daily Temperature Variation, Central Iowa

Using one record value and one average value to estimate the change in saturated NH3 pressure results in every day having a daily pressure change in excess of 15 percent of the 250 psig MAWP of a nurse tank, and a majority of days outside of the winter months having a pressure change in excess of 20 percent. Assuming a daily record high temperature and an average low temperature results in every day having a pressure change in excess of 20 percent of the tank’s MAWP.

5.3.4 Estimated Number of G-loads

NH3 nurse tanks are subjected to inertial loads from transportation during multiple events during their operational lives. Similar to other cargo tanks, such as MC331 tanks used to transport NH3, nurse tanks experience over-the-road loads when in transit between application sites over public roadways. Additionally, NH3 nurse tanks operate over farm fields when supplying NH3 to an implement. A considerable challenge to this research is estimating both the on-road and in-field mileage traveled by an NH3 nurse tank and estimating the number of inertial loads in the vertical, lateral, and longitudinal directions experienced by the nurse tank for each mile of travel in each environment.

When traveling over public roadways the NH3 nurse tanks may be towed behind a farm tractor, or behind a vehicle such as a pickup truck. The current HMR does not impose a speed limit on NH3 nurse tanks when traveling over public roads. However, states may impose speed limits over nurse tank operations. For example, Minnesota limits loaded nurse tanks to 30 mph over public roads, and limits vehicles towing one or two empty nurse tanks to 35 mph [27]; North Dakota limits nurse tanks to 25 mph [28].

Generally, the HMR do not impose a limit on the distance that nurse tanks may travel over public roadways. However, field truck mounted nurse tanks are limited to “rural roads in areas within 50 miles of the fertilizer distribution point where the nurse tank is loaded,” per 49 CFR 173.315(m)(3)(iii). In general, it is also assumed that nurse tanks being towed on running gear would be limited to rural roads and have a relatively short distance over the road, either between distribution location and application location, or between application locations. As over-the-road travel distance (and therefore, travel time) increases the amount of time available in a day to apply NH3 is reduced.

Lacking better data, 50 miles of on-road travel is taken as an upper practical limit for the distance a nurse tank must travel for each load of NH3 that is applied. As a simplification this distance is taken to include both travel from filling site to application site, and between application sites between “Refilling Tank” events. Based on the rough estimate of 31.5 loads of NH3 per 1,000 gallon tank, per year (see Section 5.3.1), the average number of on-road miles for various service lives can be estimated as shown in Table 28.

Table 28. Estimated Number of On-road Miles for Various Assumed Service Lives and 31.5 Tankloads per Year

Service Life (years)	Estimated Number of Loaded On-road Miles
30	47,300
40	63,000
50	78,800
60	94,600

Section XII requires 8×10^9 cycles for each of the dynamic G-load scenarios (e.g., 0.4 G lateral acceleration, 0.7 G vertical acceleration) specified by 49 CFR 178.337 for evaluation of MC 331 cargo tanks [23]. Section XII was not written with nurse tanks in mind, nor is it currently applicable to nurse tanks. The 8×10^9 cycles required by Section XII appears to be a conservative fatigue life for nurse tanks, based on the estimated number of loaded on-road miles summarized above. A nurse tank would need to experience a disproportionately high number of G-load events per mile compared to other types of vehicles over the course of its service life to reach the 8×10^9 cycle fatigue life requirement in Section

XII. This value may be deliberately conservative, as not all load events, magnitudes, and cycle counts can be known for each type of vehicle that the fatigue calculations in Section XII are intended to apply to. Nurse tanks travel fairly low numbers of on-road miles, compared to vehicles primarily intended for on-road transportation of hazardous materials. Since nurse tanks travel fewer miles over their lives, they would have to experience more loads per mile to reach the same fatigue life as a tank that experiences more miles of loading.

Data on the accelerations experienced by nurse tanks per mile of road travel or per mile of field travel were not available to the researchers during this project.

The number of miles traveled in a field during application depends on the rate of application (pounds of nitrogen per acre), width of the toolbar used to apply NH3, and the geometry of the field (i.e., how many turns are necessary to exactly cover 1 acre of land).

The application rate of *nitrogen* per acre is highly variable based on the crop being grown and existing soil conditions at the specific site of application. As a starting point, a target rate of 150 pounds of nitrogen per acre was used to estimate the in-field mileage of a nurse tank [29]. This value represents the target value of nitrogen to be applied per acre of land, which is different from the target rate of NH3 application per acre. Since NH3 is 82 percent by weight nitrogen [30], a nitrogen application rate of 150 pounds/acre corresponds to 183 pounds/acre of NH3. As calculated in Appendix A, a 1000 gallon NH3 nurse tank filled to 56% of its water capacity, by weight, holds approximately 4670 pounds of NH3. Therefore, at a rate of 183 pounds of NH3 per acre a 1,000 gallon NH3 nurse tank can supply enough NH3 to cover approximately 25.5 acres per tankload.

How far the NH3 nurse tank has to travel in a field while supplying NH3 to an implement over the 25.5 acres estimated for a single tankload depends on both the width of the toolbar and the geometry of the field. Typical toolbar widths between 27 ½ and 62 ½ feet were found on manufacturer websites [31] [32]. As a rough estimate, researchers assumed a single toolbar width would be used with a nurse tank for its entire life. In practice, a single nurse tank may be used in conjunction with a variety of toolbars during its service life.

The geometry of the field will also affect the number of passes a toolbar of a given width must make to cover a fixed surface area. Oddly-shaped parcels of land could result in additional travel distance compared with square or rectangular fields. As a simplified estimate of in-field travel distances researchers assumed a square field having an area of 25.5 acres, the estimated area of coverage from a single 1,000 gallon NH3 nurse tank at a rate of 150 pounds nitrogen per acre. The resulting linear mileage of travel per acre of application and per tankload (i.e., per 25.5 acres) are shown in Table 29.

Table 29. Estimated Field Mileage per Acre and 1,000 gallon Tankload

Toolbar Width	Miles per Acre	Miles per Tankload

27.5 feet	0.31	7.8
45 feet	0.19	4.9
62.5 feet	0.14	3.6

Combining the estimated mileage per tankload calculated in Table 29 with the estimated 31.5 annual tankloads carried per 1,000 gallon NH3 nurse tank produces the estimates for field mileage for various assumed service lives shown in Table 30.

Table 30. Estimated Number of Field Miles for Various Assumed Service Lives and 31.5 Tankloads per Year

Service Life (years)	Estimated Number of Field Miles 27.5 Foot Toolbar Width	Estimated Number of Field Miles 45 Foot Toolbar Width	Estimated Number of Field Miles 62.5 Foot Toolbar Width
30	7,413	4,598	3,358
40	9,884	6,162	4,478
50	12,355	7,664	5,597
60	14,826	9,197	6,717

During NH3 application in a field the speed is expected to be much lower, but the terrain is expected to be rougher compared to on-road travel. The equivalent G-loads applied to the NH3 nurse tank may be higher in-field than on the road given the nonuniform surface of a field. Additionally, the braking and acceleration behaviors of a farm tractor as the towing vehicle are expected to differ significantly from the braking and acceleration behaviors of a pickup truck as the towing vehicle.

5.4 Fatigue Takeaways

The significant events expected to recur multiple times in the normal operating life of a nurse tank have been identified. For each event, the pressure, weight, and G-loads acting on the nurse tank and its NH3 lading have been estimated. The number of occurrence for each event have been estimated based on a conservative set of assumptions. The number of times each event was estimated to recur is summarized in

Table 31.

Table 31. Estimated Lifetime Count of Nurse Tank Events

Service Life (years)	Estimated Number of Loads of NH3	Number of Hydrostatic Test Events	Number of Daily Temperature Cycles	Estimated Number of Loaded On-road Miles	Estimated Number of Field Miles	Estimated Number of Field Miles	Estimated Number of Field Miles
					27.5 Foot Toolbar Width	45 Foot Toolbar Width	62.5 Foot Toolbar Width
30	945	6	10,958	47,300	7,413	4,598	3,358
40	1,261	8	14,610	63,000	9,884	6,162	4,478
50	1,576	10	18,263	78,800	12,355	7,664	5,597
60	1,891	12	21,915	94,600	14,826	9,197	6,717

Both ASME Code Section VIII, Division 2 and Division 3 require a load history to be constructed for the expecting operating environment of the pressure vessel undergoing evaluation. The estimated lifetime number of events shown in

Table 31 forms a portion of that load history. The magnitudes and counts for number of G-loads per on-road and field mile of nurse tank travel are significant pieces of information that are currently not accounted for. As discussed previously, the G-loads encountered by a nurse tank during on-road and in-field towing are expected to be different due to different ground conditions and towing speeds.

ASME Code Section XII includes a requirement to perform fatigue assessments of MC331 specification CTMVs, using the techniques given in Section VIII, Division 2. As of the 2023 edition of Section XII, an MC331 specification CTMV must have a fatigue life sufficient to withstand 8 x 10^9 cycles of the G-loads specified in 49 CFR 178.337-3, and 1 x 10^5 pressure cycles of at least 20% of the tank's MAWP. The 1 x 10^5 pressure cycle count given in Section XII appears conservative if applied to NH3 nurse tanks. Based on the highest service life of 60 years shown in

Table 31 the total number of daily temperature cycles, assuming the nurse tank is never empty, is less than one-quarter of the 1 x 10^5 pressure cycles required by Section XII. Further, the pressure change associated with daily temperature variation would not always be in excess of 20% of the tank's MAWP.

Researchers are unable to assess whether the 8 x 10^9 G-load cycles are conservative for nurse tank operations due to insufficient information. Without additional information on the number of actual vertical, lateral, and longitudinal accelerations experienced by a typical NH3 nurse tank for both on-road and in-field towing it is not possible to comment on whether 8 x 10^9 is sufficient over the course of a nurse tank's life. Additionally, Section XII uses the vertical, lateral, and longitudinal G-load magnitudes from 49 CFR 178.337-3, which are applicable to MC331 CTMVs. Researchers are not able to determine whether these G-load magnitudes are comparable to the G-load magnitudes that occur during in-field operations.

6 Findings and Conclusions

This section summarizes the Phase 2 findings and outlines considerations for potential future research and rulemaking.

6.1 Summary of Findings from Phase 2 Research

Due to changes in the allowable stress value used in Section VIII, Division 1 of the ASME Code nurse tanks built since 1998 tend to have thinner heads and shells than nurse tanks built prior to this change. The HMR do not require accident damage protection features on nurse tanks, but such features are required for specification tanks transporting anhydrous ammonia, and for nurse tanks operated in Canada. Nurse tanks are not required by the HMR to undergo a PWHT during manufacturing, nor are nurse tanks required by the HMR to be equipped with pads. As of the writing of this report, manufacturers can and do equip nurse tanks with accident damage protection features, perform PWHT, and install pads between the tank and welded attachments, such as feet, even though the HMR does not require them to.

Researchers reviewed the anonymized NTIP data. For the 1,000 gal and 1,450 tanks in the database, confirmed failures occurred most frequently at locations close to the head-shell junction, or on the head itself. Researchers noted the presence of tanks in the NTIP data with a measured thickness at every location that was below the minimum value set out in the HMR for nurse tanks with a missing or illegible data plate. Notably, these tanks with all measured locations having a thickness below the minimum were 1,000 gallon capacity modern (i.e., post-1998) nurse tanks. This finding supports the concern that if modern nurse tanks are constructed of steel that is at or slightly above the minimum value in the HMR, those tanks may be removed from service due to perceived thinning at a rate above the legacy tanks that were constructed of thicker steel.

There was agreement between the location distributions of relative thickness change rates for dated 1,000 and 1,450 tanks with the areas of high principal stress found in the FE modeling performed in this study. In both the NTIP data and FE model the areas of most concern were along the head-shell junction and bottom of the tank, as well as on the heads of modern 1,450 gal tanks. There was relatively weak correlation between the location distributions of relative thickness change rates and confirmed failures.

FE modeling results and simplified hand calculations were both performed in Phase 2 of this study. Under a combination of internal pressure and gravity the nurse tanks experienced locally-high stresses around the area of foot attachment, whether or not a pad was used between foot and tank. Using an adapted version of a calculation developed by Hetényi for buried pipes subjected to line loads, researchers demonstrated that the localized effect of the feet and pads was a real effect on the stress distribution and not a modeling artifact. Both the FE simulation results and the Hetényi calculations showed that on the interior surface of the tank localized areas of high tensile stress occurred in the vicinity of the pad/foot attachment under a combination of MAWP and gravity. On the exterior surface of the tank locally high tensile stresses occurred at the bottom of the tank, in the area between the two feet. While a tensile stress on either the interior or exterior of the tank's shell can cause a crack to propagate, a tensile stress on the interior surface is in contact with NH3 and therefore also an area that may be susceptible to SCC. The exterior of the tank is not typically exposed to NH3, so SCC is not of concern for areas of tensile stress on the exterior of the tank.

Researchers performed FE simulations of lateral, vertical, and longitudinal G-loads between 1 and 4 G in each direction. Both vertical-down and vertical-up loads were simulated, as a downward G-load will encourage contact between foot/pad and tank, while an upward G-load will pull the foot/pad away from the tank, with only the welds in the load path. Regardless of capacity, vintage, or foot design, the highest stress for a given G-load occurred from a lateral G-load, followed by a vertical-up load. The stresses results from each G-load magnitude and direction were also normalized by the stresses that develop from the combination of MAWP and 1G down. For nearly every capacity and vintage, feet attached with pads showed lower normalized stresses than feet without pads at each G-load. The one exception was the 1,450 gallon legacy tank with a 1G upward acceleration.

Researchers estimated a lifetime nurse tank load history based on typical events, such as filling the nurse tank or towing the nurse tank on roads. Developing the load history is one step in typical fatigue life calculations. For many events the number of occurrences over various service lives could only be estimated as data were not found. One significant knowledge gap that remained at the end of Phase 2 was the dynamic load conditions (e.g., G-load magnitude and frequency) for both on-road travel and in-field travel. Researchers expect the G-load environment to differ between on-road and in-field travel but were unable to quantify the number or severity of the vertical, lateral, and longitudinal G-loads that are typical of nurse tank travel in each environment.

In analyzing fatigue screening methodologies, researchers compared the estimated load history of nurse tanks to the fatigue requirements for MC331 specification tanks under ASME Code Section XII. The Section XII requirement to withstand 100,000 pressure cycles of at least 20 percent of the tank's MAWP appears highly conservative for nurse tanks. Even over an estimated 60-year service life, the number of daily temperature cycles is less than one-quarter of this 1×10^5cycle threshold. Additionally, normal daily temperature variations would not always produce a pressure change exceeding 20 percent of the MAWP. However, researchers could not determine if Section XII's requirement to withstand 8×10^9 G-load cycles is conservative for nurse tanks, as there is insufficient data regarding both the magnitude and count for actual dynamic G-loads experienced during on-road and in-field travel over the course of a nurse tank's service life.

As an attempt to bound the limits of the practical G-loads that a nurse tank could be encountered, researchers made several assumptions and calculations based on the physical constraints of the nurse tank and its running gear. The G-load limits are summarized in Table 32.

Table 32. Summary of Practical G-load Limits

Load Direction	Practical Limit
Lateral	Researchers estimated wheel lift to initiate at lateral G-loads ranging from 0.48 to 0.7 G, depending on the running gear's track width and the height of the mounted nurse tank's C.G.
Vertical Upward	A vertical upward load of slightly more than 1.1 G was estimated to initiate wheel lift for both 1,000 gallon and 1,450 gallon nurse tanks when mounted to typical running gear.
Vertical Downward	Downward G-loads that reach the running gear's GVWR—typically between 12,000 and 14,000 pounds for a single-tank setup—could cause damage to the running gear.
Longitudinal	An estimated 2 G limit for repeated longitudinal loads is assumed conservative, as it aligns with the deceleration loads intended to simulate a non-recurring accident impact for specification tanks.

6.2 Considerations for Potential Future Research and Rulemaking

Nurse tanks with attached and legible data plates that are mounted on running gear are not required to undergo any periodic inspection under the current HMR. Nurse tanks with missing or illegible data plates, or nurse tanks with present and legible data plates that are mounted to farm trucks instead of running gear must undergo the same periodic inspections and tests as are required for MC331 specification CTMVs. The presence of a data plate provides an inspector useful information on the age of the tank, its manufacturer, and the original thickness. However, the presence of this information exempts the tank from any periodic inspection requirement. USDOT also does not impose either a life limit (e.g., removed from service after X years in service) or a requalification period (e.g., tested and requalified after Y years) on nurse tanks.

Based on discussions held with nurse tank users during this project, it is apparent that some nurse tanks that are not required to be periodically inspected are proactively inspected and/or hydrostatically tested. However, the full scope of how many nurse tanks are proactively inspected and/or tested is not known. Additionally, it is not apparent whether proactive inspections are occurring across all fleet sizes or are more likely to occur among owners of larger fleets. Understanding the scope of proactive inspection practices would be an important aspect to consider prior to any potential future actions that would expand the current inspection requirements in the CFR to encompass the entire nurse tank fleet. Additionally, the limitations of personnel who are qualified to perform periodic testing and inspections, as well as the available time periods for additional testing and inspections during the normal annual usage cycle for nurse tanks should be considered as practical limits on expanding the nurse tank inspection requirements.

Modern, 1,000 gallon tanks have a thickness when new that is very close to the minimum thickness required by the CFR for 1,000 gallon nurse tanks with missing/illegible data plates. Those tanks are likely to fail the thickness test with only minor thinning, while the legacy 1,000 gallon tanks with missing or illegible data plates would have to experience more significant thinning before reaching the minimum value defined in the CFR. This could create a situation in the future where younger 1,000 gallon tanks with missing/illegible data plates are failing the thickness test, while older tanks continue in service for much longer due to the greater amount of thinning needed to fail when the tank started off thicker.

Similarly, both legacy and modern 1,450 gallon tanks were found to typically have manufactured head and shell thicknesses that are greatly in excess of the minimum thickness required by the CFR for missing/illegible data plates. While not studied in-depth in this research project, nominal thicknesses of both 2,000 and 3,000 gallon nurse tanks were also found to be higher than the minimum thickness required by the CFR for nurse tanks with missing/illegible data plates to remain in service. The implication of these higher values is that 1,450 gallon, 2,000 gallon, and 3,000 gallon nurse tanks of typical thicknesses would have to undergo significant thinning before reaching the threshold value in the CFR to fail the thickness test in the absence of a legible data plate.

Currently, the CFR does not require nurse tanks to be equipped with any specific accident damage protection, such as a structure surrounding top fittings or rear-end protection. While it is typical industry practice for such structures to be installed on nurse tanks, these structures are not required to be present, nor are they required by the CFR to be designed to withstand prescribed accident loads. This practice is inconsistent with U.S. practice for specification CTMVs (e.g., DOT-406, -407, and -412 and MC-331). For example, an MC-331 CTMV used to transport anhydrous ammonia must protect all valves, fittings, pressure relief devices, and other accessories to the tank proper against damage that could result from collision, jack-knifing, or overturning, per 49 CFR 178.337-10. This regulation further states that the accident damage protection must be designed to withstand, without failure, a load equal to twice the loaded weight of the CTMV applied to the protective device from any direction. Finally, under this load, the stresses may not exceed one-fourth of the ultimate tensile strength of the material of construction.

Additionally, the practice of not requiring a prescribed level of accident damage protection on nurse tanks is inconsistent with Canadian practice for nurse tanks as specified by CSA B620-20 and CSA B622-22. New nurse tanks constructed to the CSA standards must be mounted with prescribed rear-end protection and must be mounted in such a way that the nurse tank is entirely within the extents of the vehicle's frame.

Estimating the fatigue life of any pressure vessel using the techniques given in ASME B&PVC Section VIII, Division 2 or 3, requires a comprehensive understanding of the loading cycles the vessel is expected to experience over the course of its life. This presents several challenges to be applicable to nurse tanks.

Currently, nurse tanks do not have a lifespan limit, and comprehensive data were not found on the expected lifespan of nurse tanks. Thus, the service life (in years) of a nurse tank is not known with certainty. Additionally, data on the number of loads carried per year, the number of days the nurse tank is used as a static storage vessel subject to temperature fluctuations, and the on- and off-road mileage a typical nurse tank experiences in a typical year were not available. Finally, dynamic load (e.g., vertical, lateral, and longitudinal G-loads) magnitudes and cycles for on- and off-road travel were not measured.

If fatigue life calculations are to be performed in the future for nurse tanks, better data on the cyclic loads should be gathered to use as inputs to the calculations. Consideration should also be given to the potential ranges of values that could be reasonably expected to occur. For example, different running gear configurations could impart different dynamic loads to the nurse tanks. Similarly, different towing vehicles could produce different accelerations to the running gear that would in turn affect the loads imparted to the nurse tanks.

Additionally, any fatigue life calculated for a nurse tank must be translated into both an evaluation period (e.g., inspection every X years) and the actions that must be taken at that evaluation period. The evaluation period could be informed by future fracture mechanics work, such as fatigue crack growth studies. Fracture mechanics evaluation could include environmental testing on typical nurse tank steel alloys in the presence of NH3 (both with and without added water) to establish the crack grown curve for portions of the tank exposed to both the liquid and vapor phases of NH3. Various sizes of flaws, their shapes, and depth through the thickness of the tank wall could be considered. The crack growth rate could be calculated under various conditions of steel, lading, and initial flaw size, leading to an estimate of the period of time taken to reach a critical size (e.g., crack propagates through 90 percent of the wall thickness). This period would then be used to set an inspection interval that would ensure a flaw is detected before it reaches a critical size.

The actions that must be taken once the evaluation period has been reached could include both inspecting the tank and/or performing testing on the tank. The inspection techniques that are most effective at detecting a potential flaw before it reaches a size that compromises the structural integrity of the tank must be determined based on the outcome of the fatigue life calculations. A visual inspection, a hydrostatic test, and a thickness test can each identify different types of flaws. Each inspection technique will also have different limitations to its capabilities, and different challenges if being applied across the entire U.S. nurse tank fleet.

Technical Appendices

Appendix A – NH3 Filling Calculations

This appendix presents calculations that were used to determine the weight and approximate filling volume of NH3 that could be filled in a tank within the filling density limits set out in the regulations. Throughout this report the nominal capacity of the tanks (e.g., 1,000 gallon) has been used to differentiate between tanks of different capacities. However, no nurse tank can be filled to 100% of its nominal volume with NH3, as there must be outage (i.e., vapor) space left above the liquid NH3 to allow for thermal expansion of the NH3 within the tank.

Nurse tanks are limited to a filling density of no greater than 56% of the weight of water that the tank can contain, per 49 CFR 173.315(m)(1)(v). Note 1 to the table of filling densities given in 49 CFR 173.315(a)(2) gives the density of water to be used in the filling density calculations as 8.32828 lbf/gal. Equation A1 is used to calculate the weight capacity of water for a nurse tank of a given volume. Equation A2 is used to calculate the weight capacity of NH3 that may be carried in a nurse tank in compliance with the filling density limit. The results of both calculations for several tank capacities are shown in Table A1.

Equation A1. Calculation of Water Capacity, by Weight

$$W_{water} = Capacity_{tank} \cdot 8.32828 \frac{lbf}{gal}$$

Equation A2. Calculation of NH3 Capacity, by Weight

$$W_{NH3} = W_{water} \cdot 0.56$$

Table A1. Weight Capacities of Water and NH3 for Several Nominal Nurse Tank Capacities

Nominal Capacity	Weight of Water	Weight of NH3
Gallons	lbf	lbf
1,000	8,328.3	4,663.8
1,450	12,076.0	6,762.6
2,000	16,656.6	9,327.7
3,000	24,984.8	13,991.5

Figure A1 shows a saturation curve for NH3 that was constructed using data from NIST [26] for anhydrous ammonia. The vertical axis shows the absolute pressure, and the horizontal axis shows the temperature of the NH3. For combinations of pressure and temperature above the curve, NH3 can exist in a liquid state. For combinations of temperature and pressure below the curve NH3 can exist as a vapor. The curve itself represents the saturation or boiling conditions of NH3, where the liquid and vapor states can simultaneously exist at those temperatures and pressures. The dashed horizontal line represents an absolute pressure of 264.7 psia, which is equivalent to a 250 psig pressure inside a tank that is surrounded by atmospheric air at 14.7 psia. A value of 250 psig is the minimum design pressure that can be used for a nurse tank, as given in 49 CFR 173.315(m)(1)(i). Finally, the vertical dashed line corresponds to the saturation temperature for NH3 at a pressure of 264.7 psia, which is approximately 114.5 °F. Put another way, if the full volume of NH3 within the tank reached a temperature of 114.5°F the internal pressure would reach the design pressure of the nurse tank.

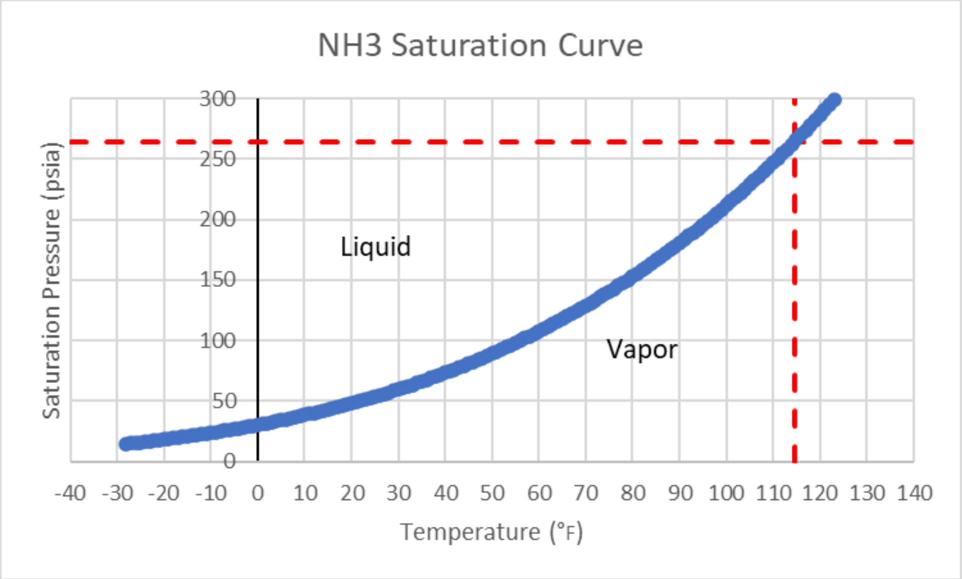


Figure A1. Saturation Curve for NH3

The weight of NH3 in the tank will remain constant unless NH3 leaves the vessel either through normal operations (e.g., supplying NH3 to an implement) or through emergency conditions (e.g., venting through the pressure relief valve). However, the volume of NH3 within the tank and its resulting pressure will vary based on the temperature of the NH3. As the temperature of saturated NH3 is increased the density of the liquid decreases. Using saturated density data from NIST [26], Figure A2. Volume of Tank Occupied by NH3 as a function of Saturation Temperature shows the volume of the tank that would be occupied by saturated NH3 at various temperatures, assuming the tank is filled by weight to the value shown in Table A1. Note that the filling volume versus saturation temperature relationship would be the same regardless of the nominal capacity of the tank, since tanks of all volumes are limited to the same 56-percent filling density by weight.

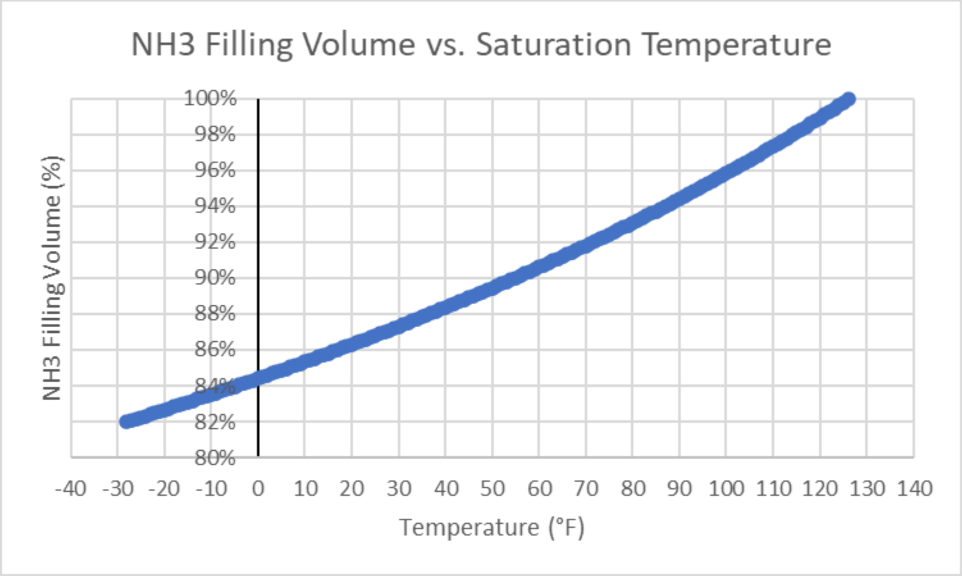


Figure A2. Volume of Tank Occupied by NH3 as a function of Saturation Temperature

The static head (P_{head}) is the additional pressure at the bottom of a column of liquid caused by the weight of that liquid. The peak value of static head occurs where the column of liquid is the highest, which is the bottom of the nurse tank. Static head is calculated as the product of the mass density of saturated liquid (ρ_{sat}), acceleration due to gravity (g), and height (h) of the column of liquid. Values of ρ_{sat} were previously identified in literature [26]. The height of the column of liquid in the nurse tank (h) was approximated as the product of the tank's diameter (D_{tank}) and filling volume at a given temperature (*%Fill*). The filling volume at a given saturation temperature was shown in Figure A2. The expression used to approximate P_{head} is shown in Equation A3. The resulting values of static head for the 1,000 and 1,450 gallon nurse tanks used in the simulations are shown in

Table A2.

Equation A3. Calculation of Static Head of NH3

$$P_{head} = \rho_{sat} \cdot g \cdot (D_{tank} \cdot \%Fill)$$

Table A2. Static Head of NH3 in 1,000 and 1,450 gal Tanks

Nominal Capacity	**P_{head}**
Gallons	**psi**
1,000	0.82
1,450	0.93

The empty weights of 1,000 gal and 1,450 gal NH3 tanks were estimated from manufacturer product literature [33] [34]. Combining the typical empty weights of each NH3 nurse tank capacity with the maximum weight of NH3 calculated in Table A1 produced the estimated loaded nurse tank weights shown in Table A3.

Table A3. Estimated Loaded Weights of 1000 and 1450 gallon NH3 Nurse Tanks

Tank Capacity	Empty Weight (lbf)	Loaded Weight (lbf)
1,000 gal	1,800	6,464
1,450 gal	2,666	9,429

Appendix B – Tank Thickness

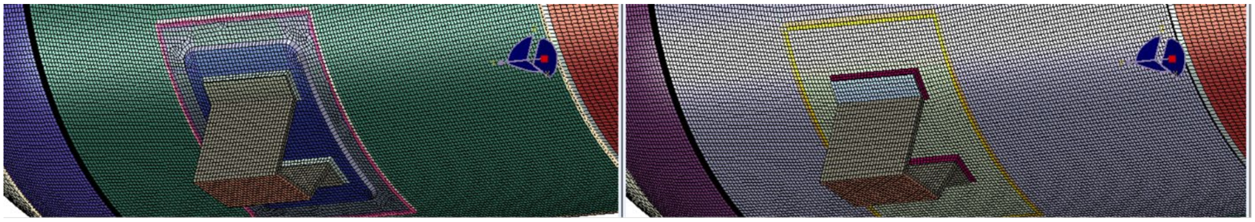
Tank thickness calculations were performed for four tank geometries. Table 1 contained a matrix of 16 tank design variations that were considered for the FE modeling portion of this study. Two variations, the foot shape and the use of a pad between the tank and the foot, do not have an influence on the thickness of the tank's head or shell. The remaining two variables, the capacity of the tank and the use of modern versus legacy allowable stress values do have an effect on the head and shell thickness. Four different combinations of tank head and shell thickness were calculated: legacy and modern thicknesses of 1,000 and 1,450 gallon tanks. Table B1 summarizes the head thickness, shell thickness, and shell outer diameter used in each of the four modeled tank variants.

Table B1. Summary of Head Thickness, Shell Thickness, and Shell Outer Diameter for Modeled Tanks

	Modern	**Legacy**	**Modern**	**Legacy**
	1,000 gal.	**1,000 gal.**	**1,450 gal.**	**1,450 gal.**
Head Thickness (in.)	0.203	0.231	0.273	0.362
Shell Thickness (in.)	0.239	0.321	0.273	0.375
Shell Outer Diameter (in.)	40.96	40.5	46.77	46.5

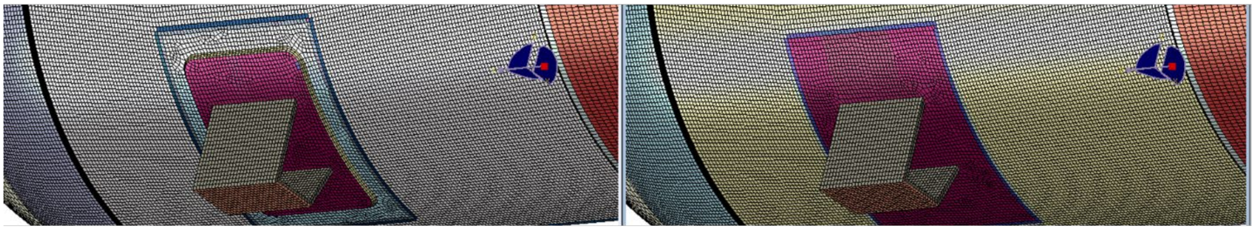
Appendix C – FE Model Development

Researchers developed FE models of 1,000 and 1,450 gallon NH3 nurse tanks in Phase 2. Four different combinations of foot shape and pad presence were modeled for each capacity. These foot and pad combinations are illustrated in Figure C1.



FTT Foot, Pad

FTT Foot, No Pad



ETT Foot, Pad

ETT Foot, No Pad

Figure C1. Examples of Four Foot and Pad Combinations Modeled

Figure C2 contains an annotated FE image of the 1,000 gallon nurse tank FE model with features of interest indicated. This image shows a side view of a quarter model, which would be suitable for vertical loads. Different planes of symmetry were used for different load conditions, as appropriate, but similar modeling techniques were used in all models. In all variations the nurse tank was modeled using solid hexahedral (“brick”) elements for areas of interest, with shell elements used to model the tank in areas away from features of interest. Shell elements and solid elements were attached to one another via a shell-solid coupling (SSC), a type of constraint available in the Abaqus/Standard solver [11]. Features of interest included the feet, the pads (if equipped), and the tank head and shell spanning from inboard of the feet to outboard of the head-shell junction.

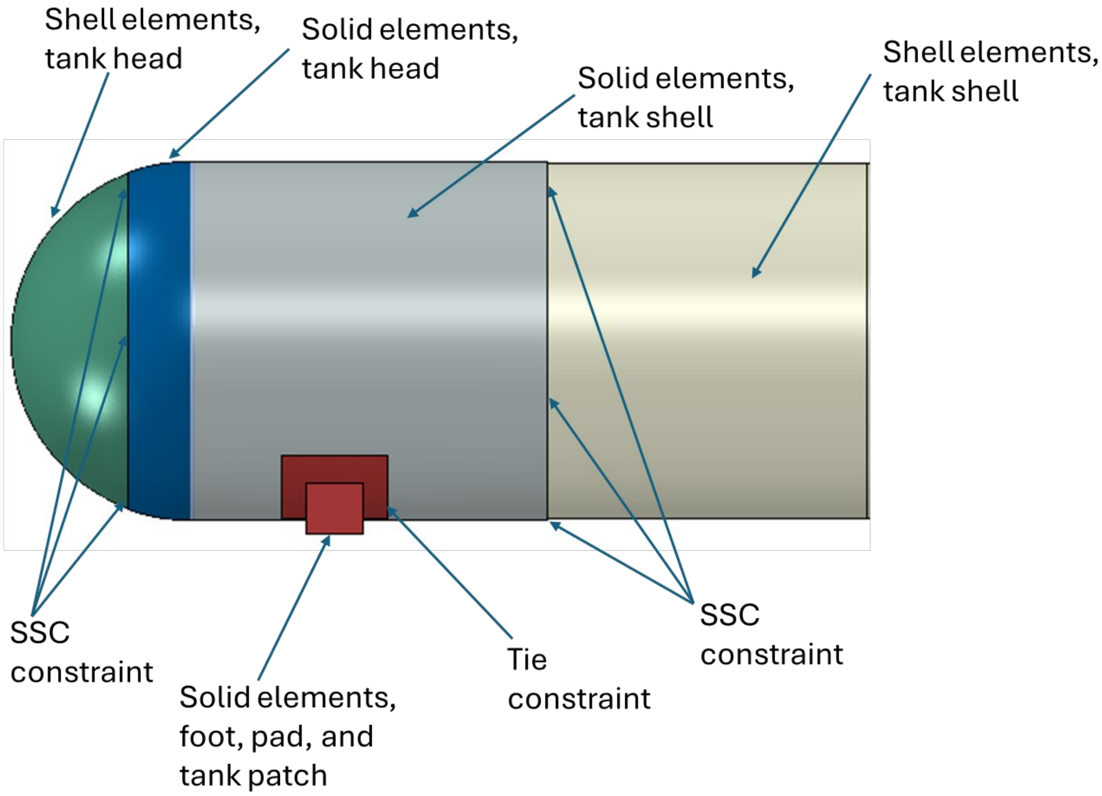


Figure C2. Annotated FE Model Geometry Showing Regions of Solid and Shell Elements and Constraints

A separate part was created for each foot and pad, if equipped, and a small “patch” of tank shell of appropriate thickness and diameter for each tank capacity and vintage (i.e., modern or legacy). Each tank model featured a square hole in the area of solid elements in the tank shell of the same dimension as the patch of tank associated with each foot and pad arrangement. The patch of tank shell with the foot and pad geometry was attached to the remainder of the tank shell using a tie constraint. Researchers ensured that the mesh on the edges of the hole in the tank was conformal with the mesh on the outside of the tank patch with the foot and pad, ensuring a 1:1 tie between nodes. This approach allowed for efficient model modification to consider the numerous combinations of tank shell thickness, foot geometry, and presence of a pad without remeshing the entire tank model. The mesh of the patch and the tank without the patch are both shown in Figure C3. While not done in this study, this approach could also be used to locally refine the mesh around the foot or pads without remeshing the entire tank.

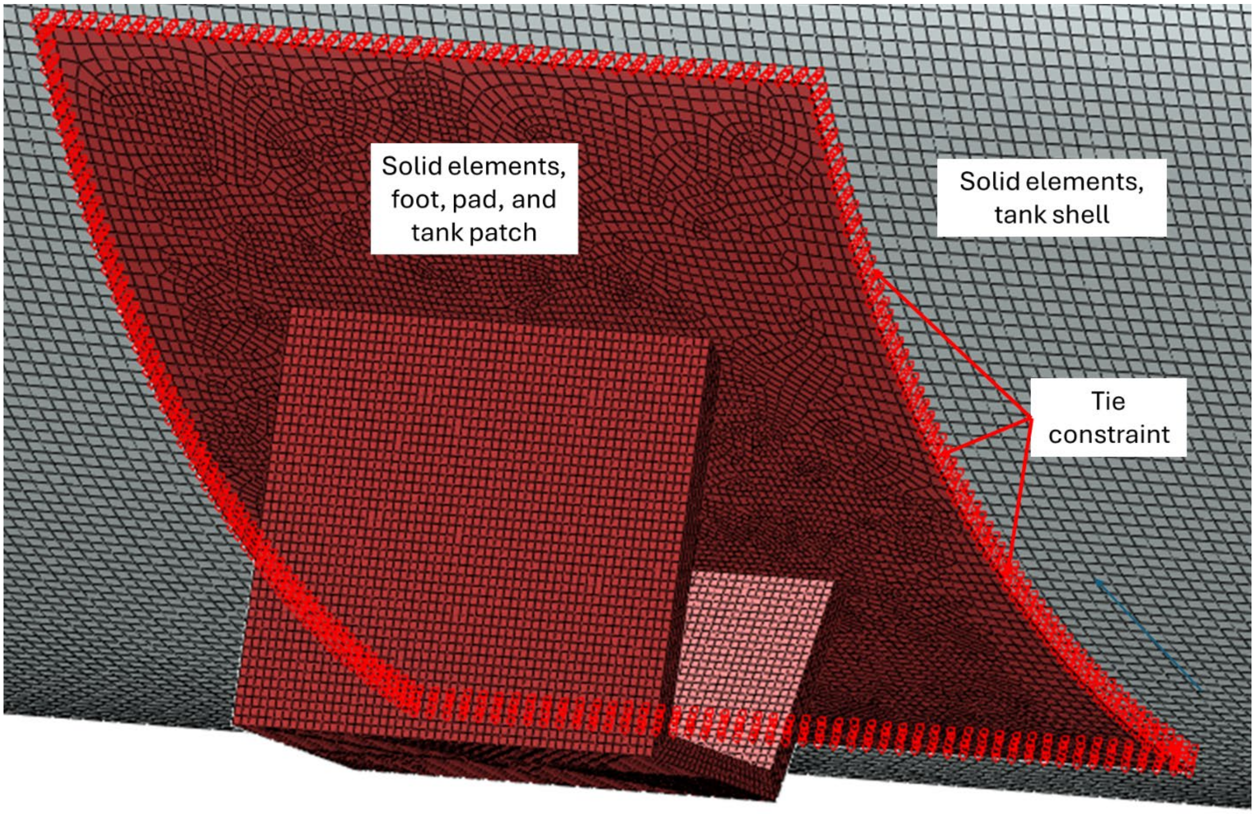


Figure C3. Detail of Mesh on Foot Patch (ETT Foot, No Pad Variation Shown)

For tanks modeled with FTT feet or pads, researchers defined a contact interaction between components that could experience face-to-face contact. A friction coefficient of 0.3 was used in the contact definition for steel-on-steel contact. This value was chosen as an engineering assumption, representing a reasonable coefficient of friction between two steel plates. However, this value was not experimentally derived and should be considered a source of uncertainty in the model results. The primary purpose in defining contact between the components that could experience face-to-face contact was to prevent contact penetration in the normal direction (i.e., to prevent faces from passing through one another). Tangential contact (i.e., slipping or sticking) was expected to be minimal based on the anticipated small deformations in the simulation between faces in contact.

Fillet welds were explicitly defined around the perimeter of the pad or of the FTT foot, providing a continuous load path between components. For tanks equipped with FTT feet or pads a “seam” was defined between the interior surface of foot or pad and the exterior surface of the component it was attached to. This modeling technique creates duplicate nodes within a mesh, allowing the two surfaces to separate from one another if the forces and moments acting on them try to pull them apart. Contact was defined for the surfaces modeled as a seam, allowing the surfaces to separate but preventing them from passing through one another. The use of fillet welds and contact to define pad-to-tank interactions is shown for an exemplar foot in Figure C4. This image is a cross-section through the middle of the foot with the fillet welds, pad, and tank given distinct colors to distinguish them from one another.

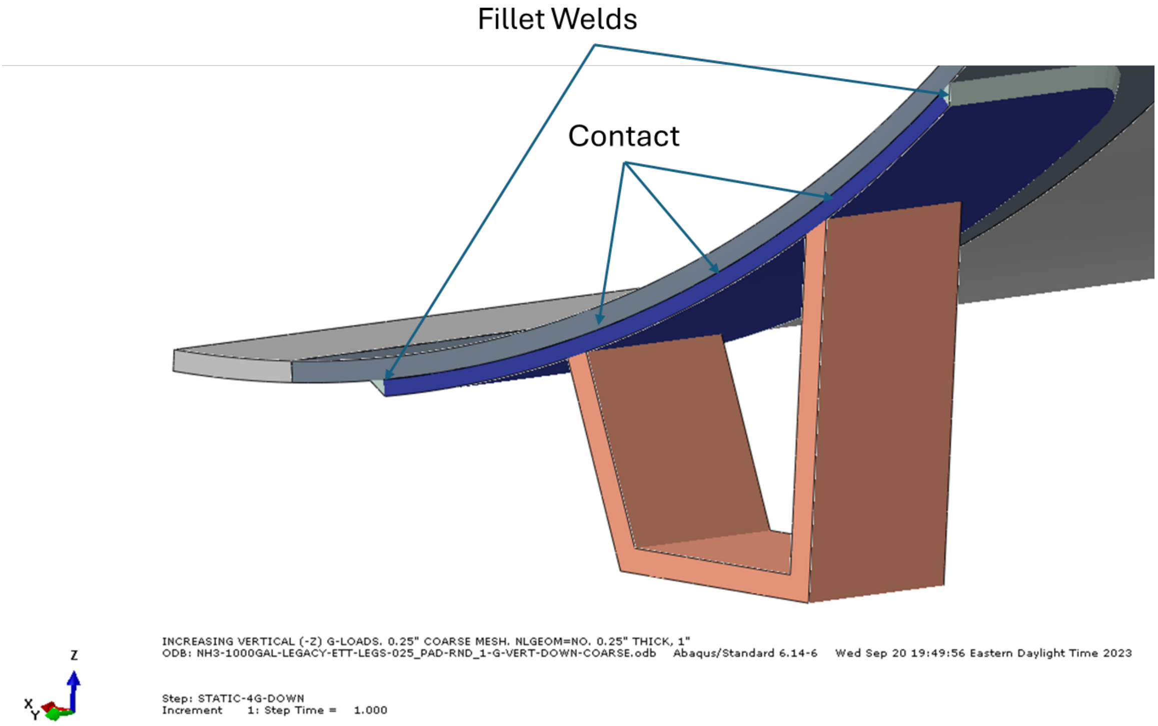


Figure C4. Section View through Foot and Pad Showing Areas of Fillet Weld and Contact Between Pad and Tank

The “joggle” joint between the head and shell was explicitly modeled, along with the head-to-shell attachment weld. The geometry of the joggle joint and weld are shown in Figure C5. In this image the tank’s shell is on the left side of the figure and the tank’s head is on the right side. As seen in this image both the tank shell and tank head used 4 elements through the thickness.

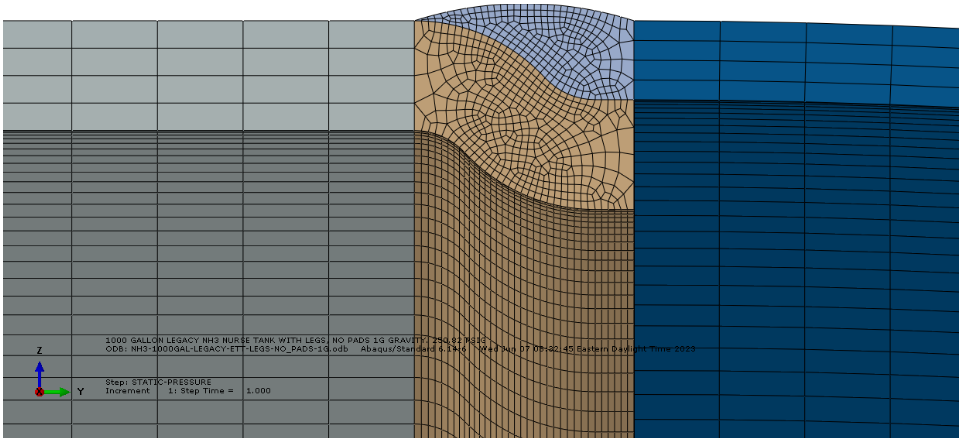


Figure C5. Tank Shell-to-head Attachment Weld

Figure C6 shows a detail of the mesh at the region of shell-solid attachment for the tank shell. The reference surface of the shell elements was aligned with the midplane diameter of the tank shell (i.e., the diameter halfway between the tank’s inner diameter and outer diameter). The SSC constraint is visualized between the faces of the solid elements and the edges of the shell elements. Similar modeling techniques were also used on the tank's head, outboard of the joggle joint.

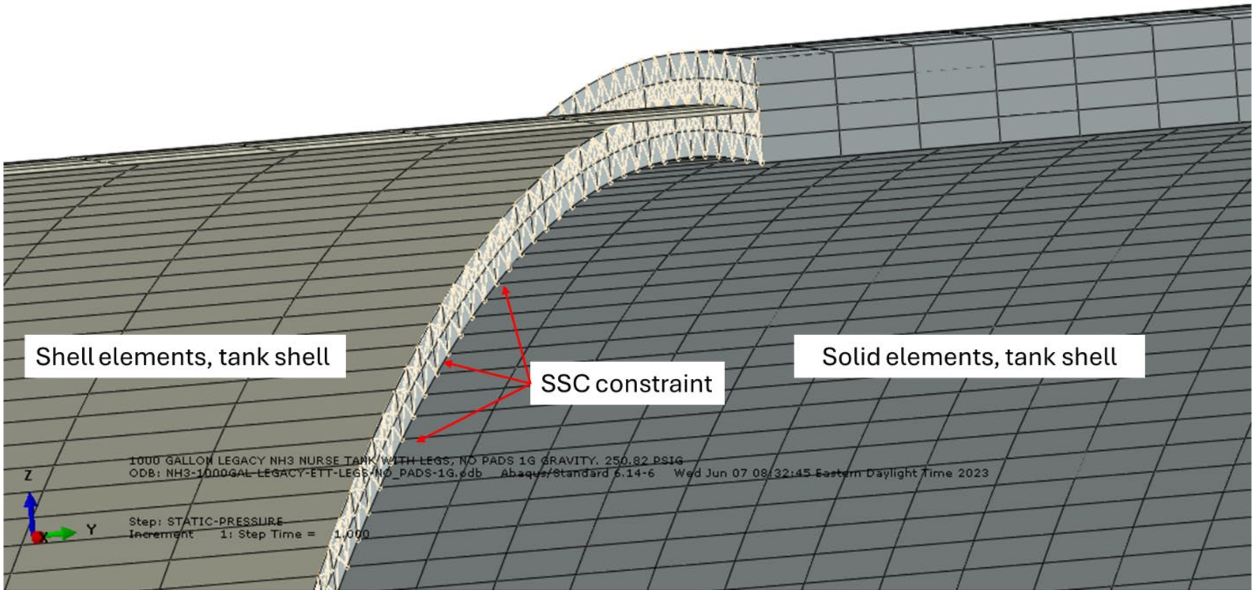


Figure C6. Detail of Shell-solid Attachment, Tank Shell

Appendix D – FE Model Results

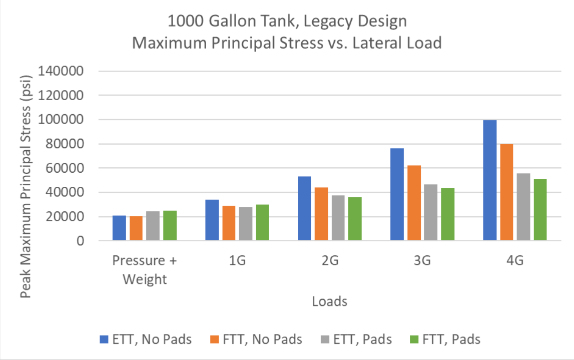
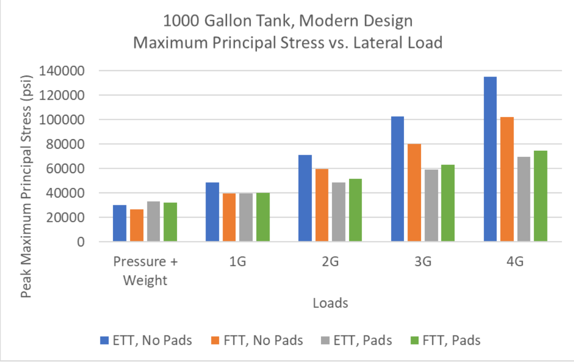
For each model the maximum principal stress within the tank itself (excluding stresses in the pads or feet) was obtained for five states: the tank standing under its own weight and internal pressure, 1G, 2G, 3G, and 4G accelerations in the direction of interest (e.g., longitudinal). The maximum principal stress was chosen for comparison as this is the design stress required to evaluate DOT-400 series CTMVs against combined G-loads (see 49 CFR 178.345-3(c)(1)). While nurse tanks are not required to meet this requirement, a similar methodology was chosen to evaluate nurse tanks as other specification tanks are already required to meet.

D1 Peak Stress Organized by Foot and Pad Arrangement

The maximum principal stress results from each combination of foot and pad configuration have been compiled in the results in this section. For a given tank capacity and design (i.e., modern or legacy) the maximum principal stress results for each pad and foot arrangement are organized by load magnitude. Organizing the results in this way allows for the influence of pad and foot arrangement on the peak maximum principal stress to be examined. In addition to the four G-load magnitudes the peak value of maximum principal stress in the tank under only internal pressure and 1-G downward (self-weight) are included. This baseline level of stress provides a useful point of reference to understand the magnitude of the peak stress that is not associated with any G-loads but would be present in a stationary vessel with internal pressure.

D1.1 1,000 gallon Tank

The assumed yield stress of the tank shell’s material was 38,000 psi; higher stress results from an elastic simulation are not considered accurate.

	Legacy Design	**Modern Design**
Lateral G-load		

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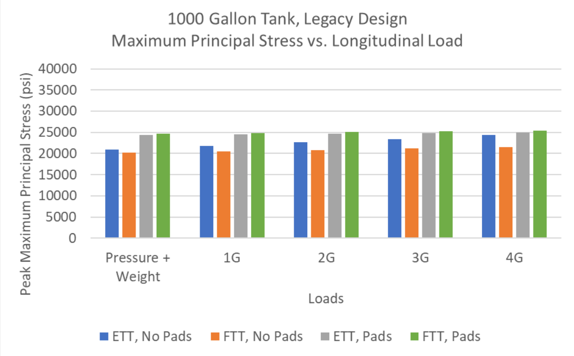
<td>
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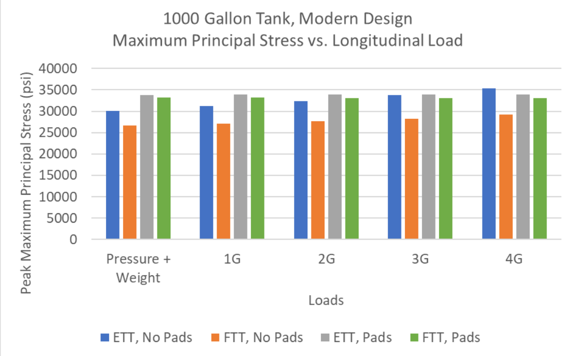
<td>
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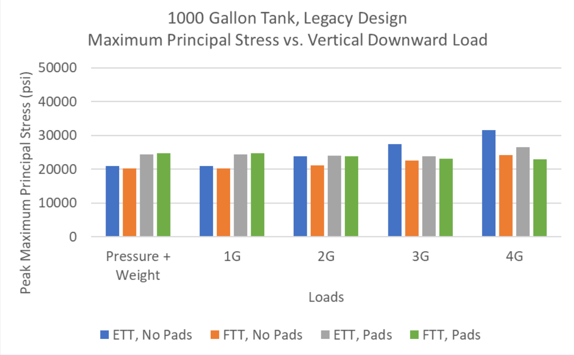
</tr>
<tr>
<td>Vertical-down G-load</td>
<td>
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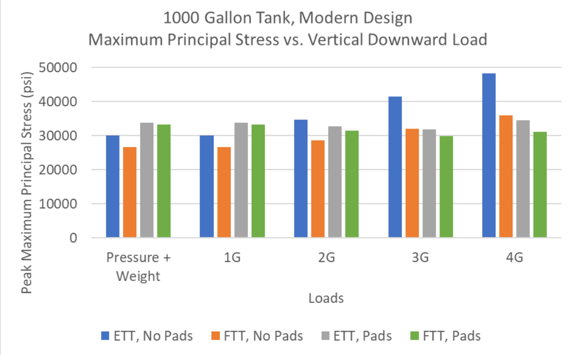
<td>
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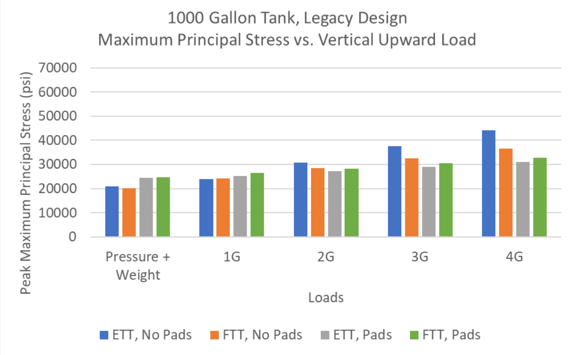
<td>
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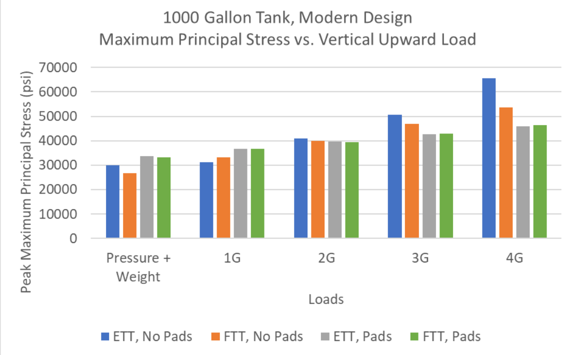
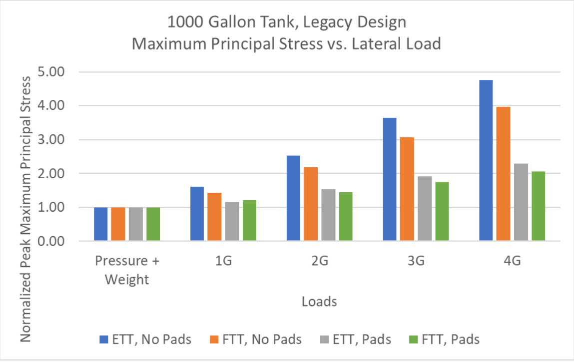
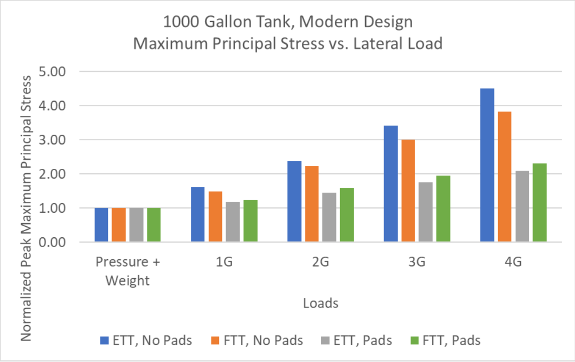
<td>
</td>
</tr>
</table>

The following figures present the peak value of maximum principal stress for each G-load magnitude and direction normalized to the peak maximum principal stress in that tank design under internal pressure and self-weight. This approach allows for the effects of the G-loads to be easily distinguished from the stress present in the tank at rest.

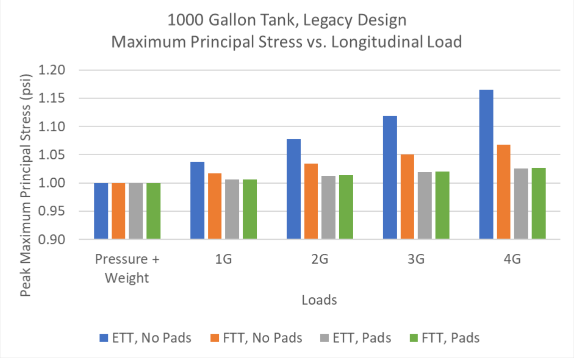
	Legacy Design	**Modern Design**

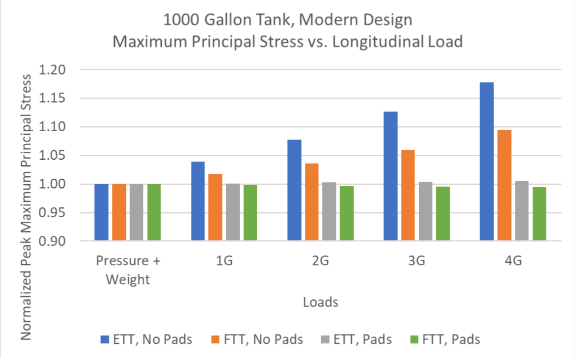
Lateral G-load


1000 Gallon Tank, Legacy Design
Maximum Principal Stress vs. Lateral Load

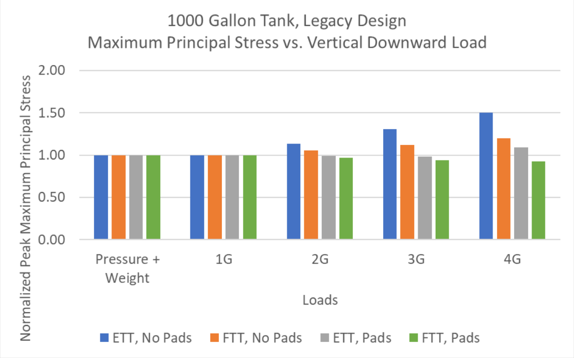

1000 Gallon Tank, Modern Design
Maximum Principal Stress vs. Lateral Load

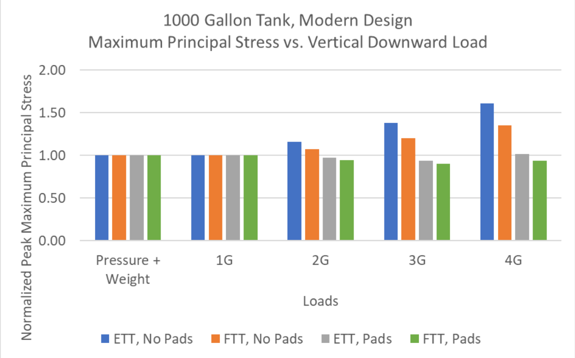
Longitudinal G-load


1000 Gallon Tank, Legacy Design
Maximum Principal Stress vs. Longitudinal Load

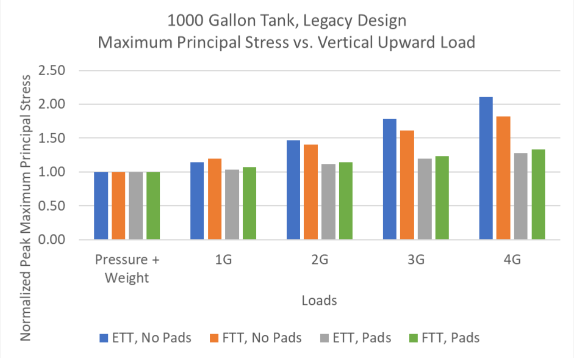

1000 Gallon Tank, Modern Design
Maximum Principal Stress vs. Longitudinal Load

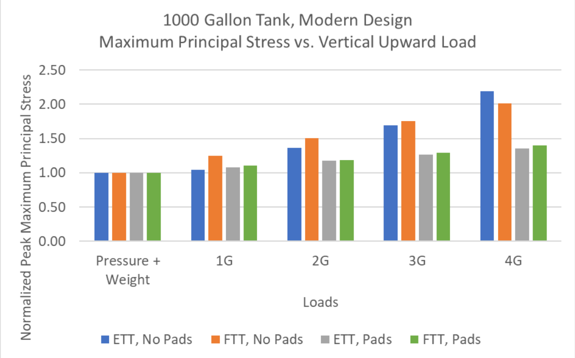
Vertical-down G-load


1000 Gallon Tank, Legacy Design
Maximum Principal Stress vs. Vertical Downward Load


1000 Gallon Tank, Modern Design
Maximum Principal Stress vs. Vertical Downward Load

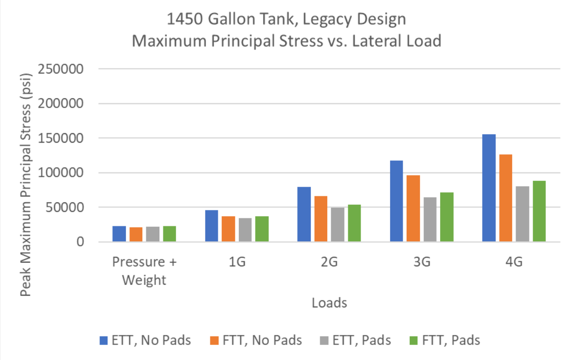
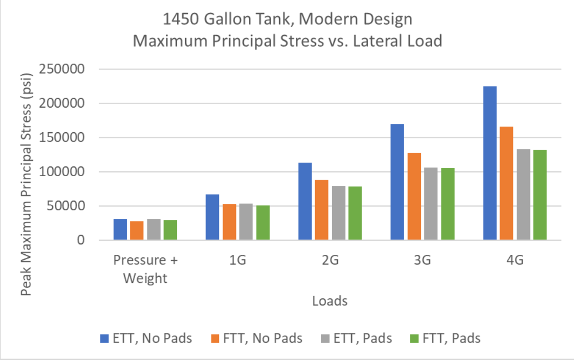
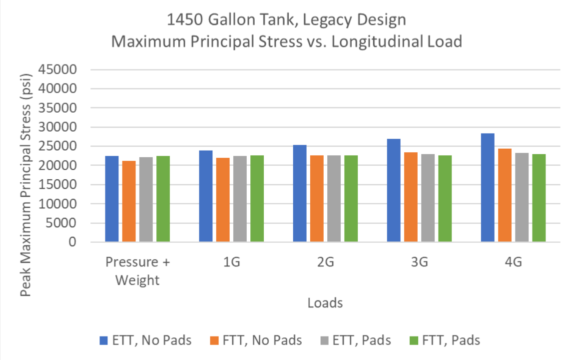
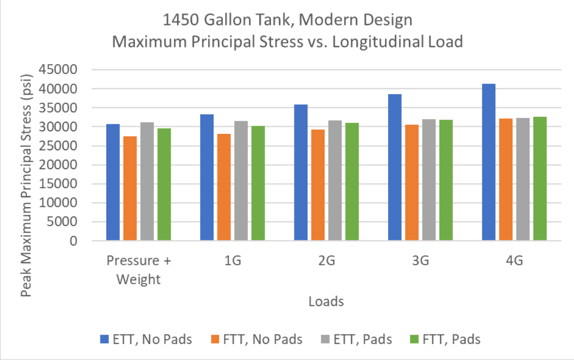
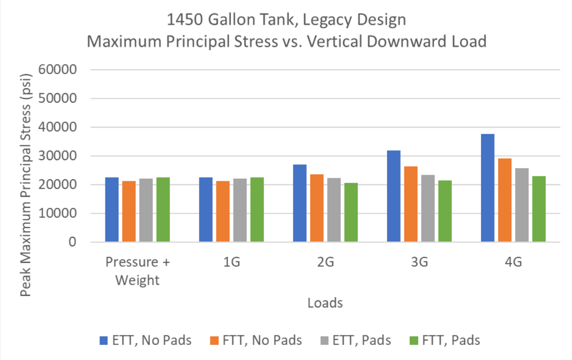
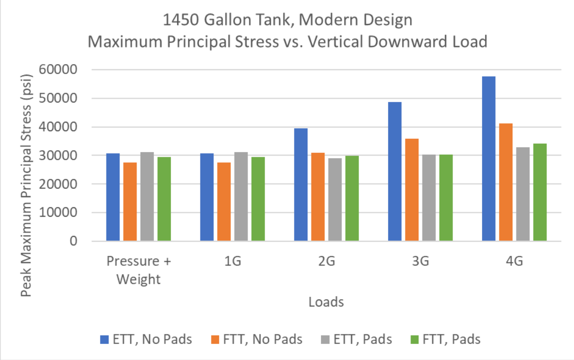
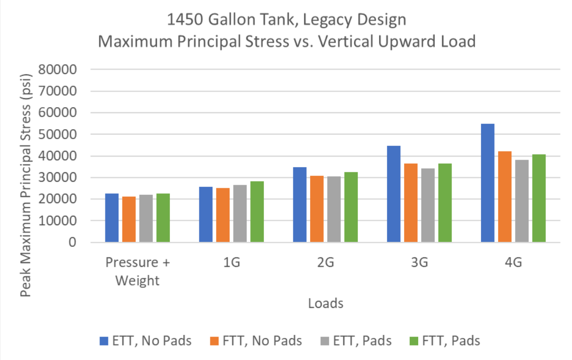
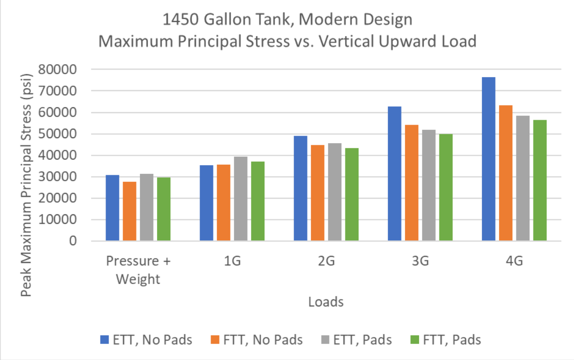
Vertical-up G-load


1000 Gallon Tank, Legacy Design
Maximum Principal Stress vs. Vertical Upward Load

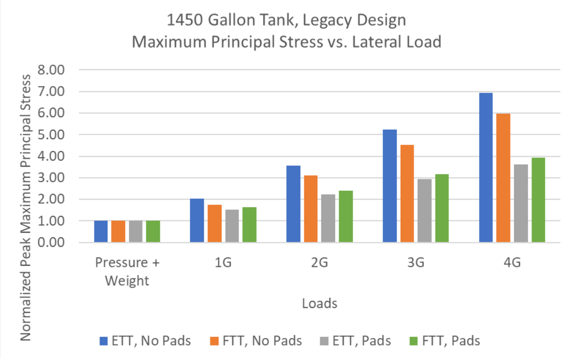
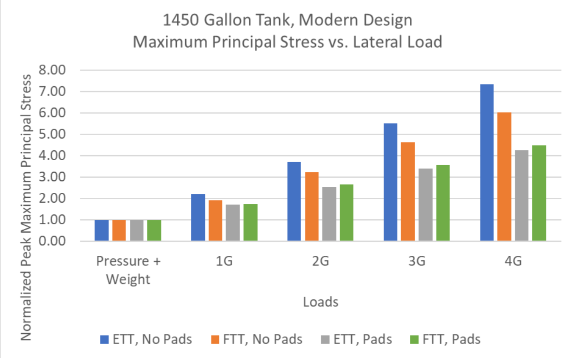
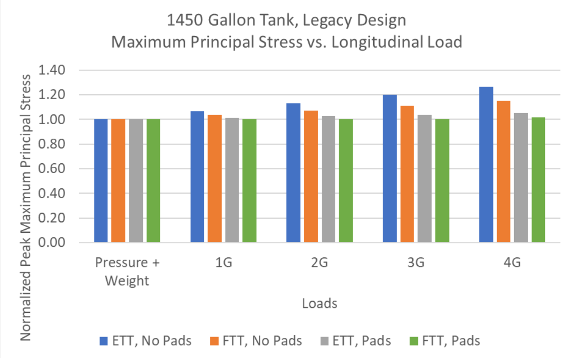
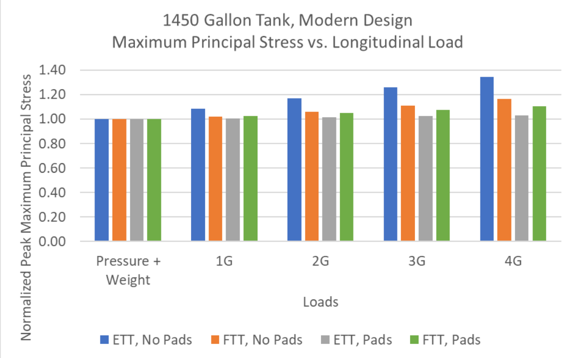
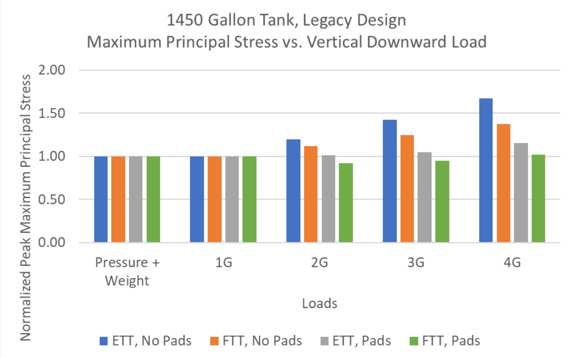
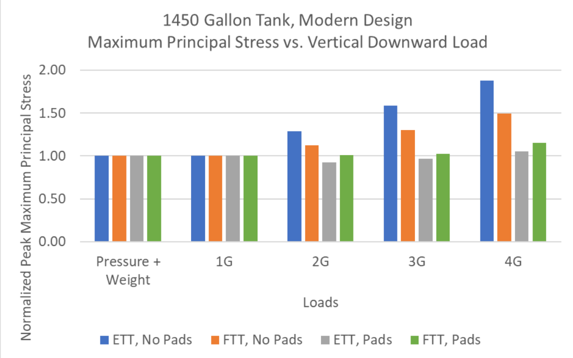
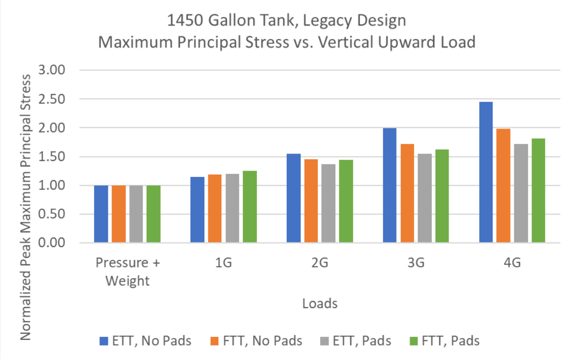
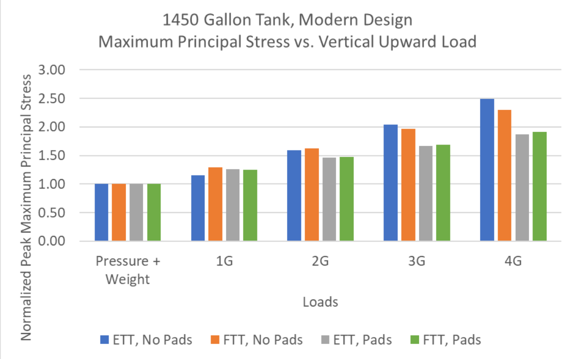

1000 Gallon Tank, Modern Design
Maximum Principal Stress vs. Vertical Upward Load

D1.2 1,450 gallon Tank

The assumed yield stress of the tank shell's material was 38,000 psi; higher stress results from an elastic simulation are not considered accurate.

	Legacy Design	Modern Design
Lateral G-load		
Longitudinal G-load		
Vertical-down G-load		
Vertical-up G-load		

The following figures present the peak value of maximum principal stress for each G-load magnitude and direction normalized to the peak maximum principal stress in that tank design under internal pressure and self-weight. This approach allows for the effects of the G-loads to be easily distinguished from the stress present in the tank at rest.

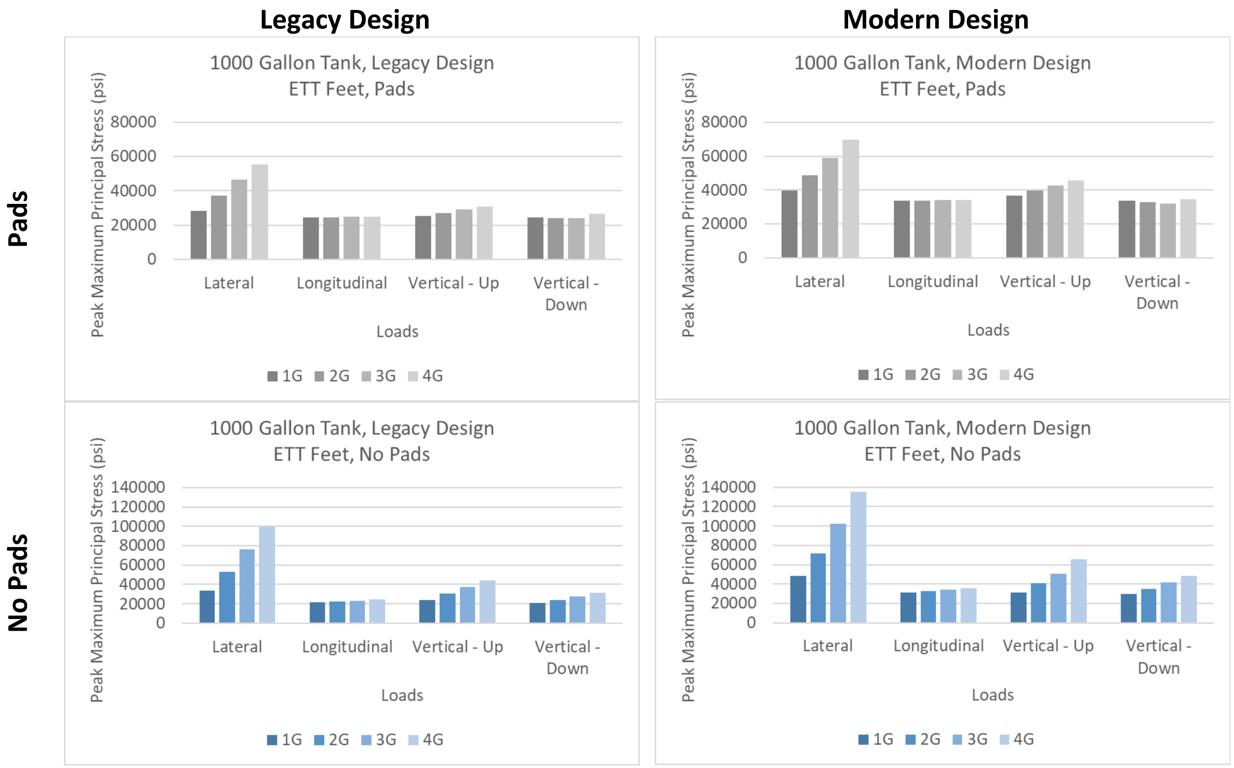
	Legacy Design	**Modern Design**
Lateral G-load	 1450 Gallon Tank, Legacy Design Maximum Principal Stress vs. Lateral Load 	 1450 Gallon Tank, Modern Design Maximum Principal Stress vs. Lateral Load
Longitudinal G-load	 1450 Gallon Tank, Legacy Design Maximum Principal Stress vs. Longitudinal Load 	 1450 Gallon Tank, Modern Design Maximum Principal Stress vs. Longitudinal Load
Vertical-down G-load	 1450 Gallon Tank, Legacy Design Maximum Principal Stress vs. Vertical Downward Load 	 1450 Gallon Tank, Modern Design Maximum Principal Stress vs. Vertical Downward Load
Vertical-up G-load	 1450 Gallon Tank, Legacy Design Maximum Principal Stress vs. Vertical Upward Load 	 1450 Gallon Tank, Modern Design Maximum Principal Stress vs. Vertical Upward Load

D2 Peak Stress Organized by Load Magnitude

The peak value of maximum principal stress from each simulation has been organized by load magnitude in this section. For a given load direction (lateral, longitudinal, vertical-up and vertical-down) the max principal stress under a 1, 2, 3, and 4 G acceleration in that direction has been plotted in the following figures. Data have been organized by tank capacity, modern or legacy thickness, and absence or presence of pads. Organizing the data in this manner allows comparison of both the increasing G-loads in a given direction, and evaluation of the sensitivity of the maximum stress to the direction of load application.

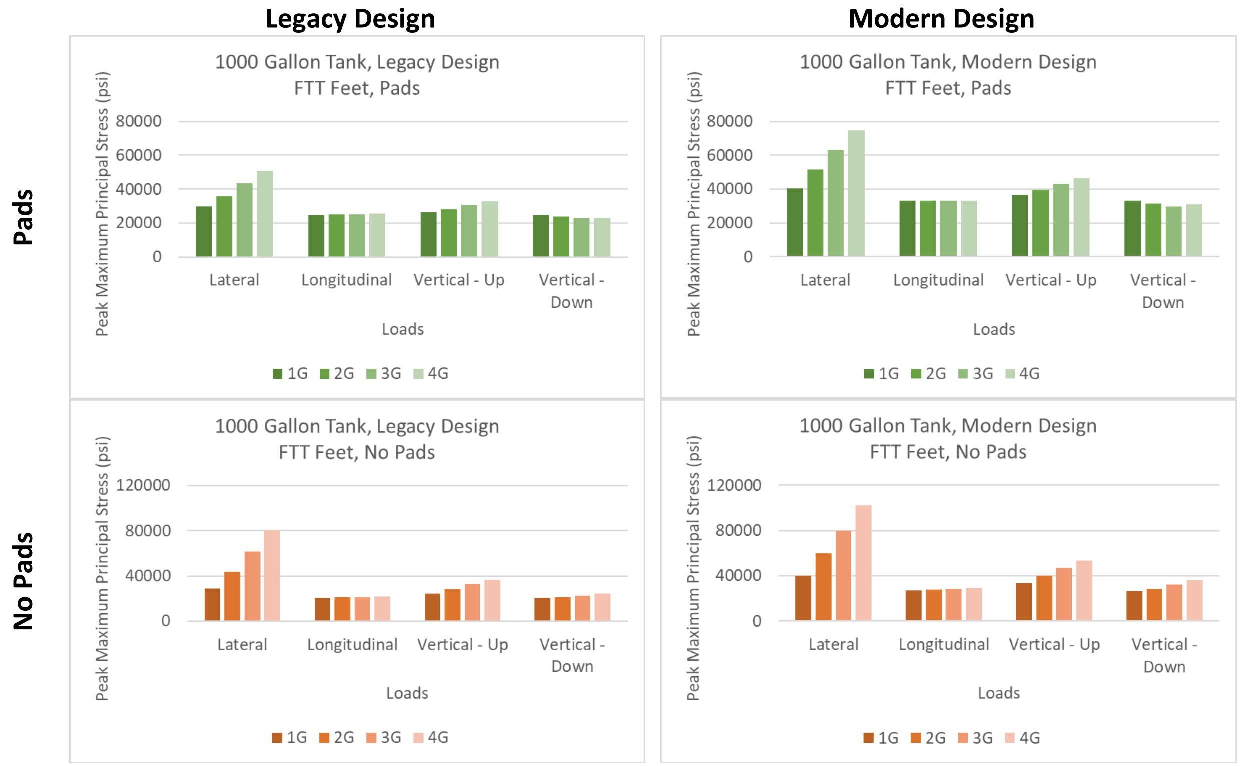
D2.1 1,000 gallon tank, ETT Feet

For a given load magnitude, direction and pad status the 1,000 gallon tank made to a modern thickness generally had a higher stress than the same conditions on a tank made with legacy thickness. The lateral loading showed the highest sensitivity, meaning that the increase in peak stress was the greatest for a given increase in G-load when that acceleration was in the lateral direction. The stresses in the longitudinal direction appeared fairly insensitive to the magnitude of the G-load. The stress results for the vertical-down G-load exhibited different trends for the simulations with and without the pads. With the pads, the peak maximum principal stress decreased slightly at moderate G-loads, whereas without pads the peak maximum principal stress increased with increasing G-loads. The assumed yield stress of the tank shell’s material was 38,000 psi; higher stress results from an elastic simulation are not considered accurate.



D2.2 1,000 gallon tank, FTT Feet

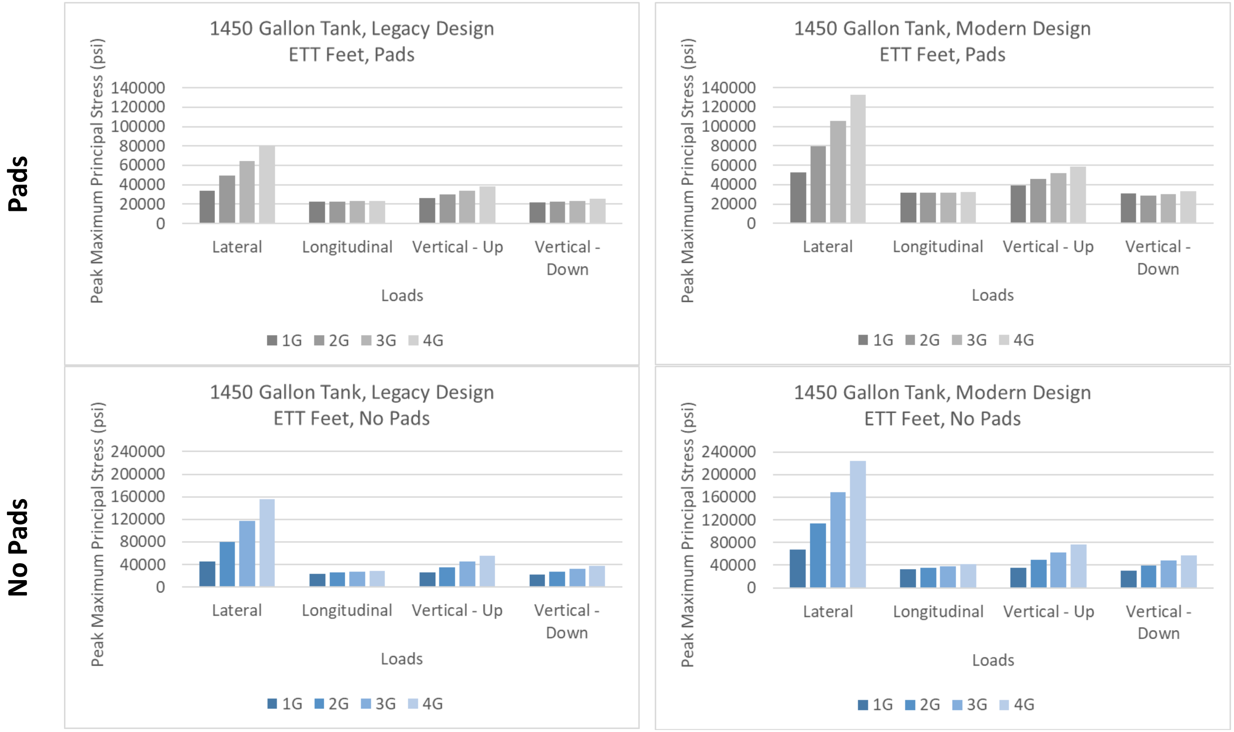
For a given load magnitude, direction and pad status the 1,000 gallon tank made to a modern thickness generally had a higher stress than the same conditions on a tank made with legacy thickness. The lateral loading showed the highest sensitivity, meaning that the increase in peak stress was the greatest for a given increase in G-load when that acceleration was in the lateral direction. The stresses in the longitudinal direction appeared fairly insensitive to the magnitude of the G-load. The stress results for the vertical-down G-load exhibited different trends for the simulations with and without the pads. With the pads, the peak maximum principal stress decreased slightly at moderate G-loads, whereas without pads the peak maximum principal stress increased with increasing G-loads. The assumed yield stress of the tank shell’s material was 38,000 psi; higher stress results from an elastic simulation are not considered accurate.



D2.3 1,450 gallon tank, ETT Feet

For a given load magnitude, direction and pad status the 1,450 gallon tank made to a modern thickness generally had a higher stress than the same conditions on a tank made with legacy thickness. The lateral loading showed the highest sensitivity, meaning that the increase in peak stress was the greatest for a given increase in G-load when that acceleration was in the lateral direction. The stresses in the longitudinal direction appeared fairly insensitive to the magnitude of the G-load. The stress results for the vertical-down G-load exhibited different trends for the simulations with and without the pads and for modern and legacy thicknesses. With the pads, the peak maximum principal stress in a modern tank decreased slightly at moderate G-loads, whereas without pads the peak maximum principal stress increased with increasing G-loads. For a legacy tank both with and without pads the peak stress increased with increasing G-load. The assumed yield stress of the tank shell’s material was 38,000 psi; higher stress results from an elastic simulation are not considered accurate.

Legacy Design **Modern Design**

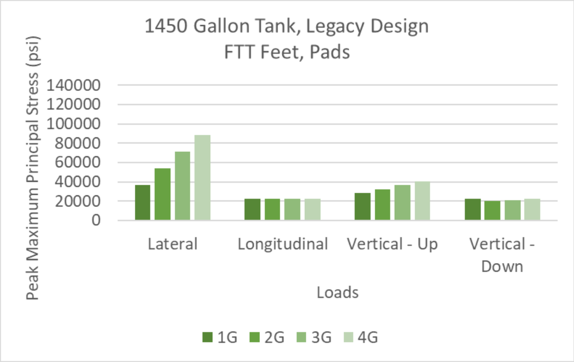


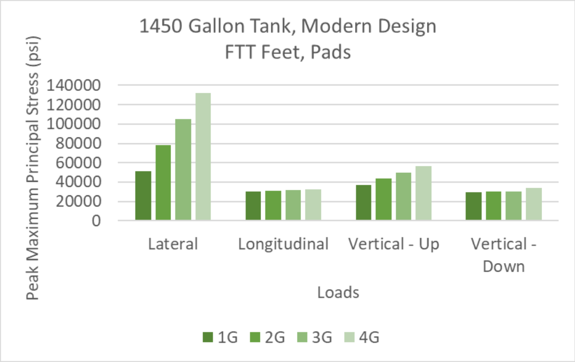
D2.4 1,450 gallon tank, FTT Feet

For a given load magnitude, direction and pad status the 1,450 gallon tank made to a modern thickness generally had a higher stress than the same conditions on a tank made with legacy thickness. The lateral loading showed the highest sensitivity, meaning that the increase in peak stress was the greatest for a given increase in G-load when that acceleration was in the lateral direction. The stresses in the longitudinal direction appeared fairly insensitive to the magnitude of the G-load. The stress results for the vertical-down G-load exhibited different trends for the simulations with and without the pads and for modern and legacy thicknesses. With and without pads the peak maximum principal stress in a modern tank increased slightly at moderate G-loads. For a legacy tank without pads the peak stress increased with increasing G-load but decreased slightly for moderate G-loads in a tank with pads. The assumed yield stress of the tank shell’s material was 38,000 psi; higher stress results from an elastic simulation are not considered accurate.

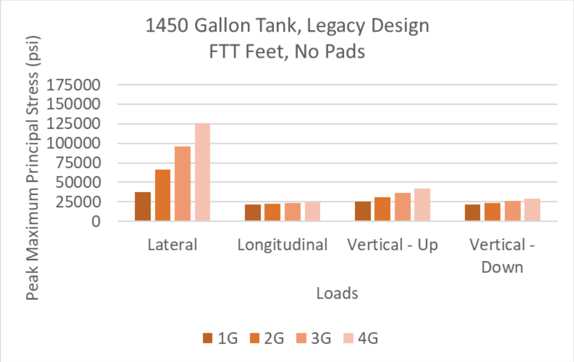
Legacy Design **Modern Design**

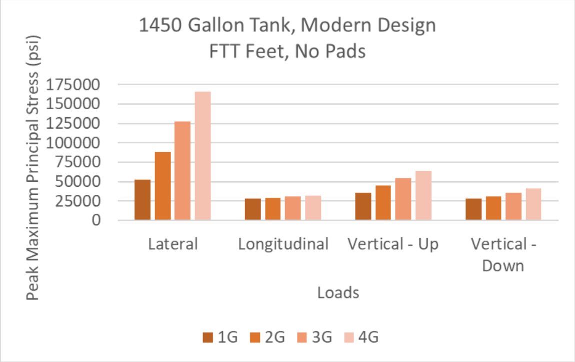
Pads





No Pads





D3 Peak Stress Organized by Load Direction

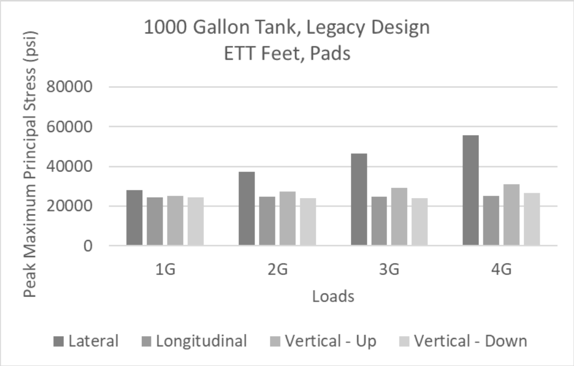
D3.1 1,000 gallon tank, ETT Feet

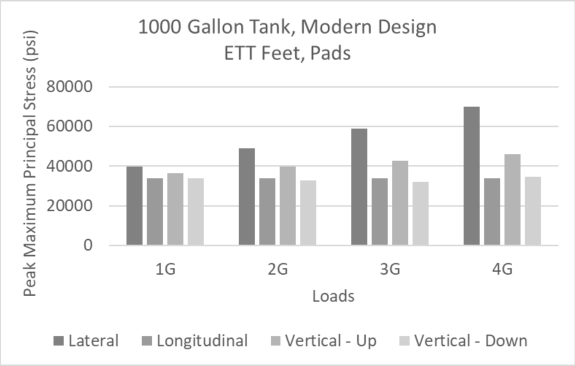
For a given G-load magnitude the highest stress develops from the lateral load direction, followed by the vertical-up load direction. The assumed yield stress of the tank shell's material was 38,000 psi; higher stress results from an elastic simulation are not considered accurate.

Legacy Design

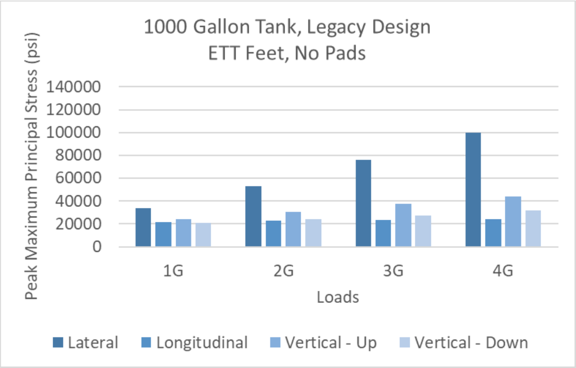
Modern Design

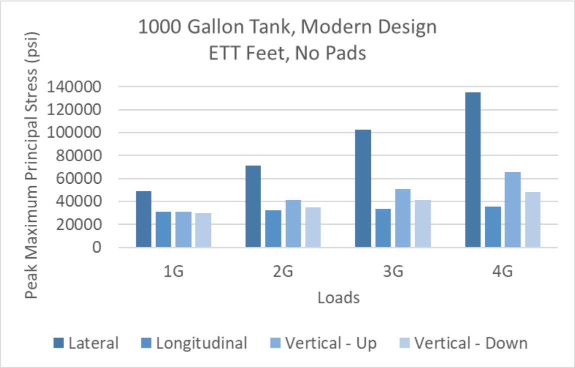
Pads





No Pads





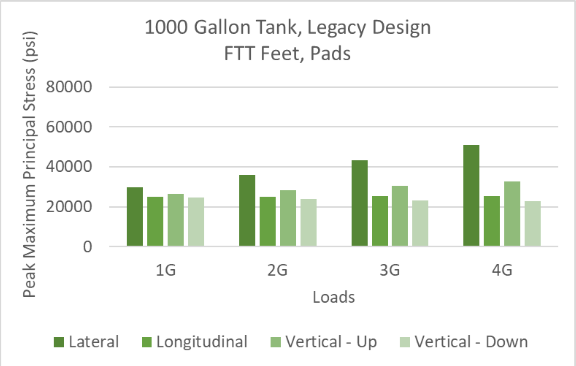
D3.2 1,000 gallon tank, FTT Feet

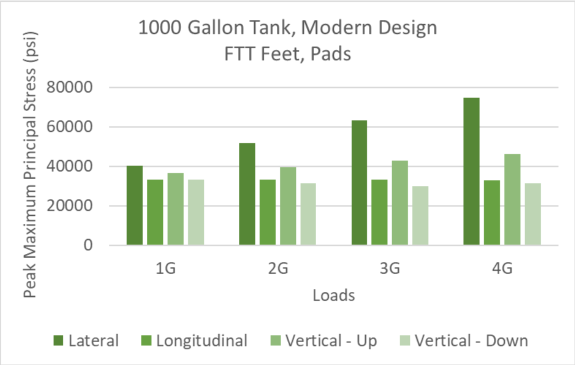
The assumed yield stress of the tank shell's material was 38,000 psi; higher stress results from an elastic simulation are not considered accurate.

Legacy Design

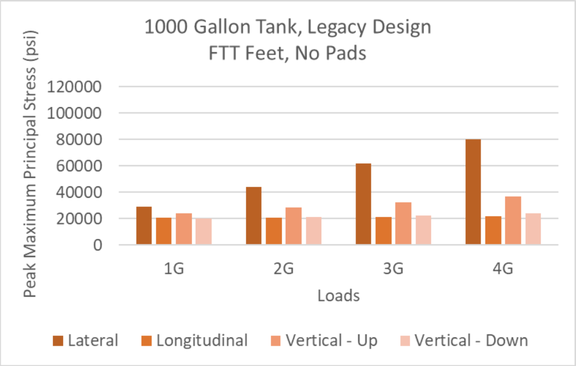
Modern Design

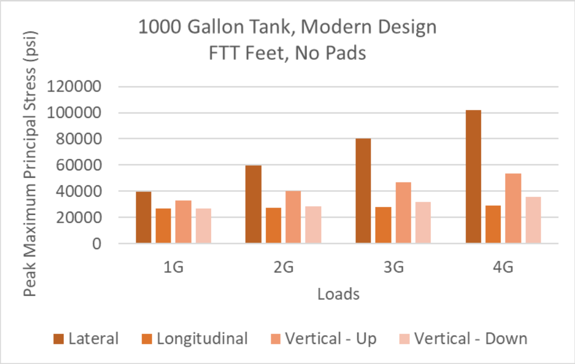
Pads





No Pads



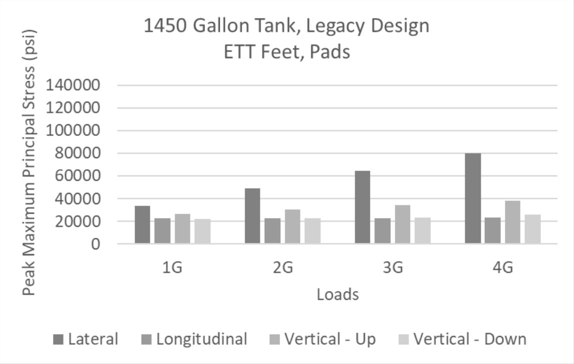


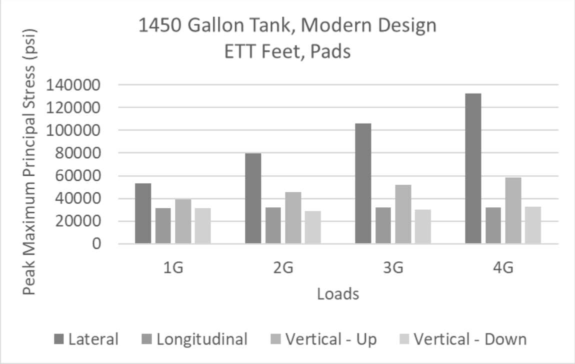
D3.3 1,450 gallon tank, ETT Feet

The assumed yield stress of the tank shell's material was 38,000 psi; higher stress results from an elastic simulation are not considered accurate.

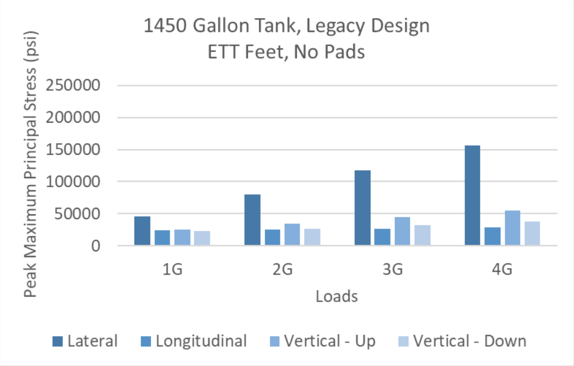
Legacy Design **Modern Design**

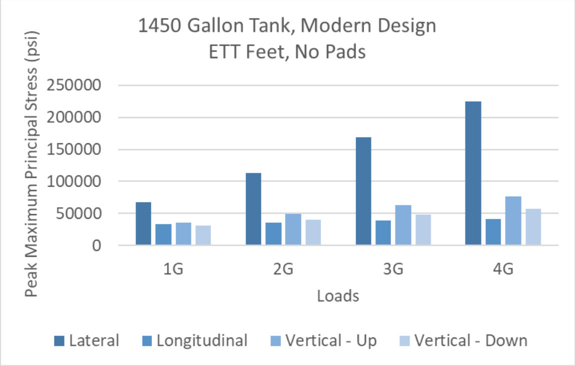
Pads





No Pads



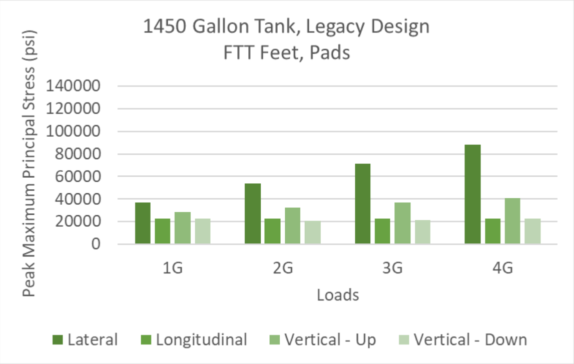


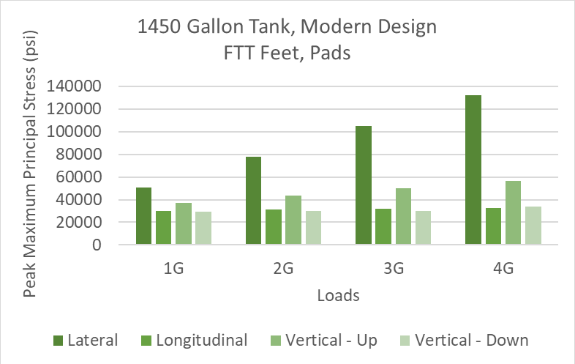
D3.4 1,450 gallon tank, FTT Feet

The assumed yield stress of the tank shell's material was 38,000 psi; higher stress results from an elastic simulation are not considered accurate.

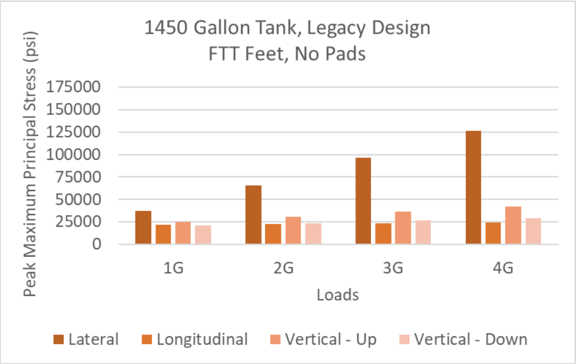
Legacy Design **Modern Design**

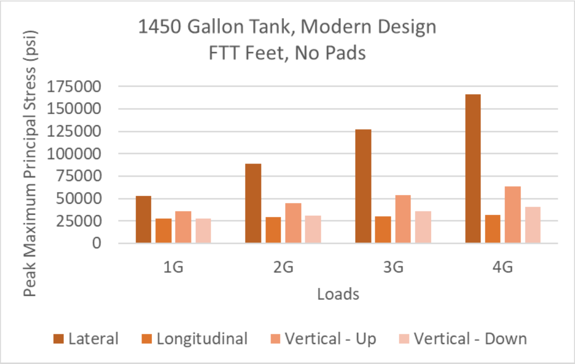
Pads





No Pads


1450 Gallon Tank, Legacy Design
FTT Feet, No Pads
Peak Maximum Principal Stress (psi)
175000
150000
125000
100000
75000
50000
25000
0
1G
2G
3G
4G
Loads
Lateral
Longitudinal
Vertical - Up
Vertical - Down


1450 Gallon Tank, Modern Design
FTT Feet, No Pads
Peak Maximum Principal Stress (psi)
175000
150000
125000
100000
75000
50000
25000
0
1G
2G
3G
4G
Loads
Lateral
Longitudinal
Vertical - Up
Vertical - Down

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U.S. Department of Transportation
John A. Volpe National Transportation Systems Center
220 Binney St.
Cambridge, MA 02142-1093

617-494-2000
www.volpe.dot.gov

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