Rupture of a DOT-105 Rail Tank Car and Subsequent Chlorine Release at Axiall Corporation New Martinsville, West Virginia August 27, 2016

Accident Report

NTSB/HZM-19/01
PB2019-100294

National
Transportation
Safety Board

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Hazardous Materials Accident Report

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490 L'Enfant Plaza, S.W.
Washington, D.C. 20594

National Transportation Safety Board. 2019. ***Rupture of a DOT-105 Rail Tank Car and Subsequent Chlorine Release at Axiall Corporation, New Martinsville, West Virginia, August 27, 2016.*** **NTSB/HZM-19/01. Washington, DC.**

Abstract: On August 27, 2016, about 8:26 a.m., a railroad tank car sustained a 42-inch long crack in its tank shell shortly after being loaded with 178,400 pounds of liquefied compressed chlorine at the Axiall Corporation Natrium plant in New Martinsville, West Virginia. Over the next 2.5 hours, the entire 178,400-pound load of chlorine was released and formed a large vapor cloud that migrated south along the Ohio River valley.

The investigation focused on these safety issues: continued use of pre-1989 tank cars constructed of nonnormalized steel in chlorine and other poison inhalation hazard/toxic inhalation hazard service, tank car manufacturer's maintenance and repair instructions, postweld heat treating procedures, and qualification and maintenance intervals.

As a result of this investigation, the National Transportation Safety Board (NTSB) makes new safety recommendations to the Pipeline and Hazardous Materials Safety Administration, the Association of American Railroads, and the American Railcar Industries, Inc.

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Abbreviations and Acronyms

AAR	Association of American Railroads
AAR TC	Association of American Railroads Tank Car
ARI	American Railcar Industries, Inc.
ARL	American Railcar Leasing
ASTM	American Society for Testing and Materials
ATCCRP	Advanced Tank Car Collaborative Research Program
Axiall	Axiall Corporation
CFR	*Code of Federal Regulations*
CI	The Chlorine Institute
CPC	Casualty Prevention Circular
CSX	CSX Transportation
DOT	Department of Transportation
ERG	Emergency Response Guidebook
FRA	Federal Railroad Administration
ft-lb	foot-pound
HM	hazardous materials
HRB	Rockwell B scale
HSER	Homeland Security and Environmental Response Group
IDLH	immediately dangerous to life and health
LPWHT	local postweld heat treatment
MSRP	*Manual of Standards and Recommended Practices*
NIOSH	National Institute for Occupational Safety and Health
NPRM	notice of proposed rulemaking

NRC	National Research Council of the National Academies
NTSB	National Transportation Safety Board
OES	Office of Emergency Services
OSHA	Occupational Safety and Health Administration
PHMSA	Pipeline and Hazardous Materials Safety Administration
PIH	poison inhalation hazard
PPM	parts per million
PRD	pressure-relief device
psig	parts per square inch, gauge
Rescar	Rescar Companies
RSPA	Research and Special Programs Administration
Superheat	Superheat FGH Services, Inc.
TC	Transport Canada
TCID	Tank Car Integrated Database
TIH	toxic inhalation hazard
UMLER	Railinc Corporation Universal Machine Language Equipment Register
WV DEP	West Virginia Department of Environmental Protection

Executive Summary

On August 27, 2016, about 8:26 a.m. eastern daylight time, a railroad tank car sustained a 42-inch long crack in its tank shell shortly after being loaded with 178,400 pounds of liquefied compressed chlorine at the Axiall Corporation Natrium plant in New Martinsville, West Virginia. Over the next 2.5 hours, the entire 178,400-pound load of chlorine was released and formed a large vapor cloud that migrated south along the Ohio River valley. The railroad tank car, AXLX1702, built in June 1979 by ACF Industries, Incorporated, was a 17,388-gallon US Department of Transportation specification-105J500W tank car, also known as a class DOT-105 tank car, with a stenciled load limit of 178,400 pounds and a maximum gross rail load of 263,000 pounds.

The tank car was equipped with an ACF Industries, Incorporated ACF-200 stub sill underframe design, which the Federal Railroad Administration has previously noted in a 2006 safety advisory as being prone to defects such as tank head cracks, pad-to-tank cracks, sill web cracks, and tank shell buckling that in some instances has led to release of hazardous materials.

Rescar Companies received the tank car in January 2016 to conduct a 5-year interior inspection required on chlorine tank cars in accordance with Axiall Corporation maintenance instructions. Inspectors revealed many corrosion pits across the bottom of the tank shell. AllTranstek (Axiall Corporation's maintenance administration contractor) approved repairs that were made at that time. The tank shell crack and chlorine release occurred following its first postrepair loading.

The National Transportation Safety Board initiated this investigation to examine the performance and structural failure of the DOT-105 tank car. The shell failure was consistent with crack propagation from a preexisting, undetected crack, and the presence of stresses induced by uncontrolled postweld heat treating, shell buckling, and low temperature lading. This report focuses on the following safety issues:

- **Continued use of pre-1989 tank cars constructed of nonnormalized steel in chlorine and other poison inhalation hazard/toxic inhalation hazard service:** According to the general requirements for pressure tank cars outlined in the Association of American Railroads *Manual of Standards and Recommended Practices, Specifications for Tank Cars*, Section C, Part III, all class DOT-105 tank cars built after January 1, 1989, must have heads and shells constructed of normalized steel plate material to reduce the possibility of brittle and low-energy fracture propagation. The Association of American Railroads estimated there were about 942 nonnormalized steel tank cars in use as of the second quarter 2018, and about 697 were being used to transport chlorine.
- **Tank car manufacturer's maintenance and repair instructions**: Available industry guidance for inspecting and repairing ACF-200 stub sill attachments and cradle pad welds is only applicable to nonpressure tank cars. There is a need for a similar guidance document applicable to pressure tank cars equipped with ACF-200 underframes.

- **Postweld heat treating procedures**: The tank car shop records show that following extensive corrosion repairs made to the interior surfaces of the tank shell, technicians made multiple attempts to stress relieve the repaired surfaces with local postweld heat treating. National Transportation Safety Board investigators found tank shell scaling, decarburization, and microstructure differences near the area of a preexisting crack that propagated and caused the chlorine release, suggesting a significantly overheated region and uncontrolled heat treatment processes.
- **Qualification and maintenance intervals:** Safe operation of a tank car throughout its service life is contingent upon periodic inspections and testing to identify and repair cracks in critical structures before tank car integrity is compromised. Axiall Corporation based its inspection regime on the federally required maximum 10-year interval, which was too infrequent. The Axiall, Rescar, and AllTranstek failures to examine widely recognized, damage-prone inboard cradle pad weld terminations on AXLX1702 following the 2016 repairs, when the tank car was in a facility capable of conducting such inspections, was a missed opportunity to avoid the chlorine release.

Probable Cause

The National Transportation Safety Board determines that the probable cause of the chlorine release was an undetected preexisting crack near the inboard end of the stub sill cradle pad, that propagated to failure with the changing tank shell stresses during the thermal equalization of the car after loading with low temperature chlorine. Contributing to the failure was Axiall Corporation's insufficiently frequent stub sill inspection interval that did not detect the crack, the low fracture resistance of the nonnormalized steel used in the tank car construction, and the presence of residual stresses associated with Rescar Companies' tank wall corrosion repairs and uncontrolled local postweld heat treatment.

1. The Incident

On August 27, 2016, about 8:26 a.m. eastern daylight time, a railroad tank car sustained a sudden 42-inch long crack in its tank shell shortly after being loaded with 178,400 pounds of liquefied compressed chlorine at the Axiall Corporation (Axiall) Natrium plant in New Martinsville, West Virginia.[1] The incident occurred on Axiall plant property outside of a tank car loading shed. Over the next 2.5 hours, the entire 178,400-pound load of chlorine was released and formed a large vapor cloud that migrated south along the Ohio River valley. The railroad tank car, AXLX1702, built in June 1979 by ACF Industries, Incorporated, was a 17,388-gallon US Department of Transportation (DOT) specification-105J500W tank car, also known as a class 105 tank car, with a stenciled load limit of 178,400 pounds and a maximum gross rail load of 263,000 pounds.

The tank car was equipped with an ACF Industries, Incorporated ACF-200 stub sill underframe design.[2]

Rescar Companies (Rescar) received the tank car in January 2016 for a 5-year interior inspection required on chlorine tank cars in accordance with Axiall maintenance instructions. The inspection revealed many corrosion pits across the bottom of the tank shell. The work included interior cleaning, ultrasonic thickness testing, removing internal corrosion, weld buildup to restore the shell thickness in corroded locations, and postweld stress-relief heat treating.[3] Rescar returned the tank car to Axiall in June 2016 after completing the repairs. The tank shell crack and chlorine release occurred shortly after its first postrepair loading.

Between 2:00 a.m. and 3:00 a.m. on the day of the incident, two Axiall employees began loading tank car AXLX1702 with liquefied compressed chlorine at the Axiall Natrium plant railcar loading shed. The Natrium plant produces chlorine, hydrochloric acid, calcium hypochlorite, sodium hydroxide pellets, and caustic soda at a 500-acre chemical manufacturing facility. The plant is located on the Ohio River at the southern end of Marshall County, about 5 miles north of New Martinsville. Figure 1 shows the incident location, which lies on the northern panhandle of West Virginia, along the Ohio River, south of the city of Wheeling.

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[1] (a) All times in this document are eastern daylight savings time. (b) On August 31, 2016, Westlake Chemical Corporation completed its acquisition of, and acquired all remaining interest in, Axiall.

[2] A *stub sill tank car* (or a tank car without continuous center sill) has draft sills at each end of the tank instead of a continuous center sill and uses its tank as a part of the car structure.

[3] The Association of American Railroads (AAR) *Manual of Standards and Recommended Practices (MSRP) Section C-III Specification M-1002*, defines *weld buildup* as the application by welding of a layer, or layers, of material to a surface to obtain desired dimensions or properties, as opposed to making a joint (AAR 2014).

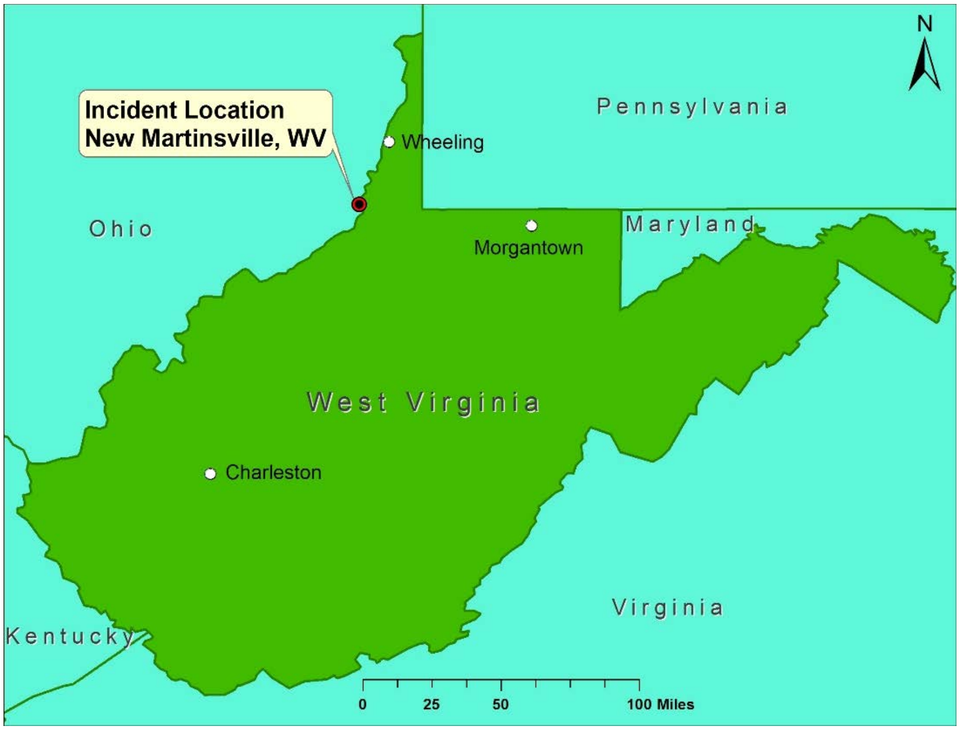

Figure 1. Map showing the location of New Martinsville, West Virginia.

By 8:15 a.m., the tank car was filled with its maximum authorized load of 178,400 pounds. After Axiall personnel removed the loading lines and sealed the valves and fittings, they used a Trackmobile® railcar mover to move the tank car forward at a walking pace about 30 to 40 yards north of the loading shed on track 10.[4] The Axiall personnel set the handbrake and chocked the wheels. At 8:26 a.m., loading personnel heard a loud bang as AXLX1702 experienced a 42-inch long crack in the lower portion of the tank shell. Plant surveillance video showed a yellow-green chlorine vapor cloud quickly growing in the vicinity of the tank car. The tank car had not been offered into transportation at the time nor was it coupled to other railcars.

As the gas cloud grew, one chlorine-loading employee notified the guard station to initiate a chlorine release alarm. Both chlorine-loading employees shut down other railcar-loading equipment and evacuated the area. All nonessential employees and contractors immediately evacuated to the guard station or the dispensary for exposure treatment. Figure 2 shows where the chlorine release occurred north of the Axiall railcar loading shed on track 10.

[4] A *Trackmobile® railcar* is a slow-moving vehicle fitted with couplers used to move small numbers of railroad cars around and conduct switching on the Axiall plant property.

Figure 2. Chlorine release incident location, September 1, 2016.

Chlorine gas sensors positioned at several locations within the plant first detected the release and alarmed about 8:28 a.m.[5] Between about 8:29 a.m. and 11:07 a.m., several in-plant gas sensors near the point of release and downwind of the release (south), near the plant's southern perimeter, recorded chlorine concentrations above the level the National Institute for Occupational Safety and Health (NIOSH) has identified as immediately dangerous to life and health (IDLH) concentration. The perimeter gas sensors also measured chlorine concentrations that exceeded the US Environmental Protection Agency Acute Exposure Guideline Level 3; thus, chlorine concentrations at the plant perimeter were above that at which it is predicted the general population could experience life-threatening health effects or death (NRC 2004). The entire 178,400-pound load of chlorine was released from the tank car and migrated south toward the town of New Martinsville, along the Ohio River valley. Figure 3 shows the visual evidence of the chlorine release beyond Axiall's property line.[6] The photographs show the view near the Axiall south perimeter fence looking south toward a wooded area before and after the arrival of the chlorine vapor cloud. The wooded area is about 6,100 feet southeast of the incident site. The Ohio River is on the right side of the photographs.

[5] The Axiall Natrium plant is monitored by 51 chlorine gas sensors that are set to alarm at 1.0 part per million, which is the Occupational Health and Safety Administration (OSHA) short-term exposure limit, or the average concentration above which a worker should not be exposed over a 15-minute time period.

[6] Most gas sensors were stationed around the plant perimeter. One of the gas sensors near the point of release recorded intermittent IDLH levels until about 12:51 p.m.

Figure 3. Axiall security camera views, August 27. 2016. (Photographs courtesy of Axiall.)

Five Axiall and three contractor employees were treated for chlorine exposure injuries and released. Significant vegetation damage occurred downwind (south) from the release.

The neighboring Covestro industrial facility, directly south of the Natrium plant, reported damage to stainless-steel piping, tanks, and operating equipment. In addition, some Covestro employees filed claims for damage to their vehicles that were in the parking lot at the time of the release. Total monetary damages have not been determined as of the date of this report.

At the time of the incident, fog was lifting after sunrise; the temperature was 72°F, and there was light wind from the north at 1 mph.

The National Transportation Safety Board (NTSB) investigation into this incident focused on the condition and performance of the tank car. While examining these matters, NTSB investigators also discovered issues with the qualification and maintenance of the tank car and continued use of pre-1989 specification DOT-105 pressure tank cars constructed of nonnormalized steel to transport materials that are poisonous inhalation hazard (PIH) or toxic inhalation hazard (TIH).[7]

This investigation was initiated to examine the performance and structural failure of the AXLX1702 tank car. The shell failure was consistent with crack propagation from a preexisting, undetected crack and the presence of stresses induced by uncontrolled postweld heat treating, shell buckling, and low temperature lading.

1.1 Emergency Response

The state of West Virginia, Department of Environmental Protection (WV DEP) reported that the Marshall County, West Virginia, Office of Emergency Services (OES), Wetzel County,

[7] The Pipeline and Hazardous Materials Safety Administration (PHMSA) promulgates hazardous materials regulations in the United States, including those pertaining to the manufacture, fabrication, maintenance, reconditioning, and testing of containers used in the transportation of hazardous materials in commerce. DOT-105 refers to the specific set of requirements that the tank car is required to meet. See Title 49 *Code of Federal Regulations* (*CFR*) Part 179, Subpart C.

West Virginia, OES, and Monroe County, Ohio, OES activated their respective incident command posts. The Marshall County OES command post was about 4 miles north of the Axiall facility on State Route 2.

WV DEP reported that the communities of Kent (Marshall County), Proctor (Wetzel County), Clarington (Monroe County), and the northern portion of New Martinsville were ordered to evacuate via the reverse 911 system or by door-to-door notification by public safety personnel. A total of 1,864 households were located within a 5-mile radius of the Axiall facility.

Adjacent industrial facilities, including Covestro and Blue Racer Midstream Natural Gas activated shelter-in-place procedures. Traffic was halted on State Route 2, State Route 7, and the CSX Transportation (CSX) rail line, all running parallel to the Ohio River. Additionally, the US Coast Guard halted commercial river traffic on the Ohio River.

Between 1:37 p.m. and 2:19 p.m., Axiall personnel used portable air monitoring devices to test several intersections and business locations along State Route 2, extending about 4 miles south of the Axiall plant. The chlorine plume had dissipated, and Axiall personnel measured no airborne concentrations during that time.

Additionally, between 1:40 p.m. and 2:15 p.m., the WV DEP Homeland Security and Environmental Response Group (HSER) conducted air monitoring for chlorine at several stations along State Route 2 from New Martinsville, south of the Axiall plant, to the Marshall County command post north of the facility. HSER found no detectable chlorine concentrations. Similarly, between 3:40 p.m. and 4:14 p.m., HSER personnel checked several locations along Route 7 on the Ohio side of the river, finding no detectable chlorine levels. These air monitoring results prompted emergency management officials to lift the community evacuations.

1.2 Facility Information

Axiall produces chlorine, hydrochloric acid, calcium hypochlorite, sodium hydroxide pellets, and caustic soda at a 500-acre chemical manufacturing facility, known as the "Natrium plant," in New Martinsville. The facility is located on the Ohio River at the southern end of Marshall County about 5 miles north of the town of New Martinsville and has a workforce of about 500 employees.

Natrium plant chlorine products are shipped by water and rail transportation. At the time of this incident, Axiall operated a fleet of 1,027 owned or leased pressure tank cars used in chlorine transportation. The company's tank car chlorine-loading rack consisted of three tracks within an enclosure that was situated near the center of the manufacturing facility on the west side of the property, near the Ohio River.

1.3 Hazardous Materials Information

1.3.1 Health and Safety Guidance

Chlorine is a Division 2.3 poison gas and is PIH/TIH in Hazard Zone B.[8] Chlorine also exhibits subsidiary hazard classes 5.1 (oxidizer) and 8 (corrosive). Chlorine is a gas at normal temperature and pressure and presents a toxic inhalation hazard. It may be fatal if inhaled or absorbed through the skin. Chlorine gas appears green-yellow, is highly reactive, and has a pungent and suffocating odor. It rapidly combines with both organic and inorganic substances. Reaction with moist surfaces produces hydrochloric and hypochlorous acids. When released, liquid chlorine evaporates quickly and forms a vapor cloud that is heavier than air. At 32°F and standard atmospheric pressure, chlorine has a liquid-to-gas expansion ratio of about 460, so one volume of liquid forms about 460 volumes of gas when released.

For occupational exposures, the Occupational Safety and Health Administration (OSHA) ceiling exposure limit for chlorine is 1 part per million (ppm). The NIOSH-established IDLH value for chlorine is 10 ppm.[9] NIOSH recommends that first responders use a self-contained breathing apparatus with a fully encapsulating chemical protective suit when entering an area where the concentration exceeds the IDLH.

The Emergency Response Guidebook (ERG) recommends that in the event of a chlorine release from a railcar, the initial isolation distance should be 3,000 feet in all directions. Isolation and protection guidance provided by the ERG further recommends that in wind speed of less than 6 mph during daylight hours, persons downwind should be protected for a distance of 6.2 miles.

1.3.2 Chlorine Effects on Mechanical Integrity

Moisture reacts with chlorine to form hydrochloric and hypochlorous acids, which can cause corrosion to tank car equipment and to piping and handling systems. At temperatures below 250°F, equipment fabricated from carbon steel is not aggressively attacked when chlorine is dry. However, dry chlorine has an extremely high affinity for moisture, and very small amounts of moisture entering chlorine handling systems can create an environment conducive to rapid corrosion in carbon steel tank cars.

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[8] A *hazard zone* is one of four levels of hazard (A-D) assigned to gases and liquids that are PIH. Hazard zones are based on the acute inhalation toxicity of gases and vapors, with Hazard Zone B having an LC50 of greater than 200 ppm and less than or equal to 1,000 ppm. The Department of Transportation Classification System identifies nine classes of hazardous materials, each with subgroups known as divisions. Class 2 is gases and Division 2.3 is gases poisonous by inhalation. LC stands for "lethal concentration," and LC50 refers to the chemical concentration in the air, which if inhaled by test animals over a specific period of time, kills half of them. For additional information, see 49 *CFR* 173.115(c).

[9] OSHA regulations at 29 *CFR* 1910.134(b) define an IDLH atmosphere as posing an immediate threat to life, causing irreversible adverse health effects, or impairing an individual's ability to escape.

1.4 Tank Car Information

1.4.1 Design and Specifications

Tank car AXLX1702 was a DOT Specification-105J500W that was built in June 1979 by ACF Industries, Incorporated – AMCAR Division, Milton, Pennsylvania.[10] AXLX1702 had a full-water capacity of 17,388 gallons (144,812 pounds), a stenciled load limit of 178,400 pounds, and a maximum gross rail load of 263,000 pounds. The interior diameter was about 100.4 inches, and the interior length was 43 feet 8 3/4 inches between tank heads. The material of construction was Association of American Railroads Tank Car (AAR TC)-128 grade B nonnormalized carbon steel.[11] The tank was constructed with two elliptically shaped tank heads and five barrel-shaped shell sections, or rings, all joined by submerged arc welding.[12] The elliptically shaped tank heads had an original thickness of 13/16 inch (0.8125 inch) and were protected with a 0.5-inch thick full headshields. The original tank shell thickness was 0.7751 inch for each of the five ring sections. The minimum allowable shell thickness was 0.7438 inch (AllTranstek 2014). The tank car was equipped with a safety relief valve with a set pressure of 360 pounds per square inch, gauge (psig), rated at 4,935 standard cubic feet per minute air at 375 psig. The tank car was originally built with an 11-gauge (0.1196-inch) jacket and 4 inches of urethane foam insulation. Texana Tank Car Manufacturing performed a conversion in July 2010 that replaced the urethane foam with a combination of 2 inches of ceramic wool and 2 inches of fiberglass insulation over the ceramic wool. The tank car had been qualified for a 50-year service-life limit.[13] Figure 4 shows an August 27, 2016, postincident view of the tank car near the incident location on the Axiall track.

Current special commodity requirements for tank cars in chlorine service include fabrication from normalized carbon steel with ASTM Specification A516, Grade 70, or AAR TC-128 Grade A or B. In accordance with Title 49 *Code of Federal Regulations* (*CFR*) 173.314(c), chlorine tank cars built on or after March 16, 2009, must meet the interim specification designated as 105J600I.[14]

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[10] In 1994, American Railcar Industries, Inc. was formed from the acquisition of railcar component manufacturing and railcar maintenance assets from ACF Industries, Incorporated.

[11] *Normalized steel* has undergone a heat treatment process that refines the steel's microstructure to enhance mechanical properties. Since 1989, pressure tank car shells have been required to be fabricated from normalized steel.

[12] *Submerged arc welding* is typically a mechanized welding process where the arc from a consumable electrode is submerged in flux to protect the deposition process from atmospheric contamination. Submerged arc welds have the advantage of producing long, deeply penetrating welds that are ideal where work pieces are joined with long straight welds.

[13] AAR *MSRP Section C-III Specification M-1002*, paragraph 1.3.10 states there is no life limit on a tank car tank if the tank conforms to both the federal regulations and AAR requirements. Underframes built prior to July 1, 1974, had an AAR life limit of 40 years unless rebuilt or granted extended service status (AAR 2014).

[14] The delimiter "I" in the specification signifies the tank car has been built to interim performance standards to meet the requirements of 49 *CFR* 173.244(a)(2) or (3) or 173.314(c) or (d).

Figure 4. Tank Car AXLX1702, postincident. (Photograph courtesy of Axiall.)

1.4.2 ACF-200 Stub Sill Underframe

The ACF-200 stub sill underframe of the tank car was originally manufactured by ACF Industries, Incorporated. Figure 5 shows the ACF-200 underframe layout with cradle pad and bolster components and weld identification numbers from the AAR Data Collection template. At the inboard end of the cradle pad, A6 designates fillet welds.[15] Figure 6 provides a three-dimensional view of the tank car and underframe showing the cradle pad and inboard fillet weld and terminations and attached underframe components.

While both general service and pressure tank cars have employed the ACF-200 stub sill underframe design, about 2,186 DOT-105 pressure tank cars were equipped with this underframe.[16] The design used cradle pads welded to the tank to transfer running loads from the stub sills through the tank.[17] The ACF-200 underframe layout position of the cradle pad and bolster pad is shown in figure 5. The pads are highlighted in green and fillet welds designated A6 at the inboard end of the cradle pad are highlighted in red.

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[15] (a) The *bolster* cradles the tank ends and is attached to truck assemblies, which support ends of the tank car on the railway tracks. (b) A *fillet weld* is a weld deposit of a triangular cross section joining two surfaces at about near right angles to each other, in a lap, tee, or corner joint.

[16] Source: Umler® (is an acronym for the Railinc's Universal Machine Language Equipment Register), an equipment management and information system and the industry's central repository for registered rail and intermodal equipment in North America.

[17] The *cradle pad* is a reinforcing plate welded directly to the tank to which the stub sill is attached. The pad protects the tank from damage caused by fatigue, overstressing, denting, puncturing, or tearing. In tank cars with stub sills, the tank is used as the primary structural component to carry longitudinal train loads. Couplers are attached to the outer end of the stub sills at each end of the tank.

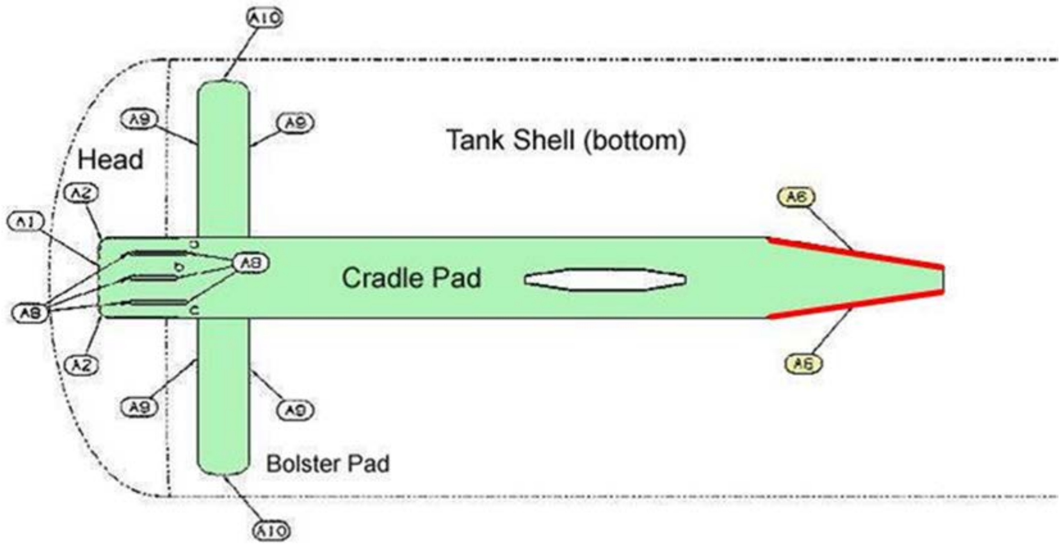

Figure 5. ACF-200 underframe general layout and weld identification numbers.

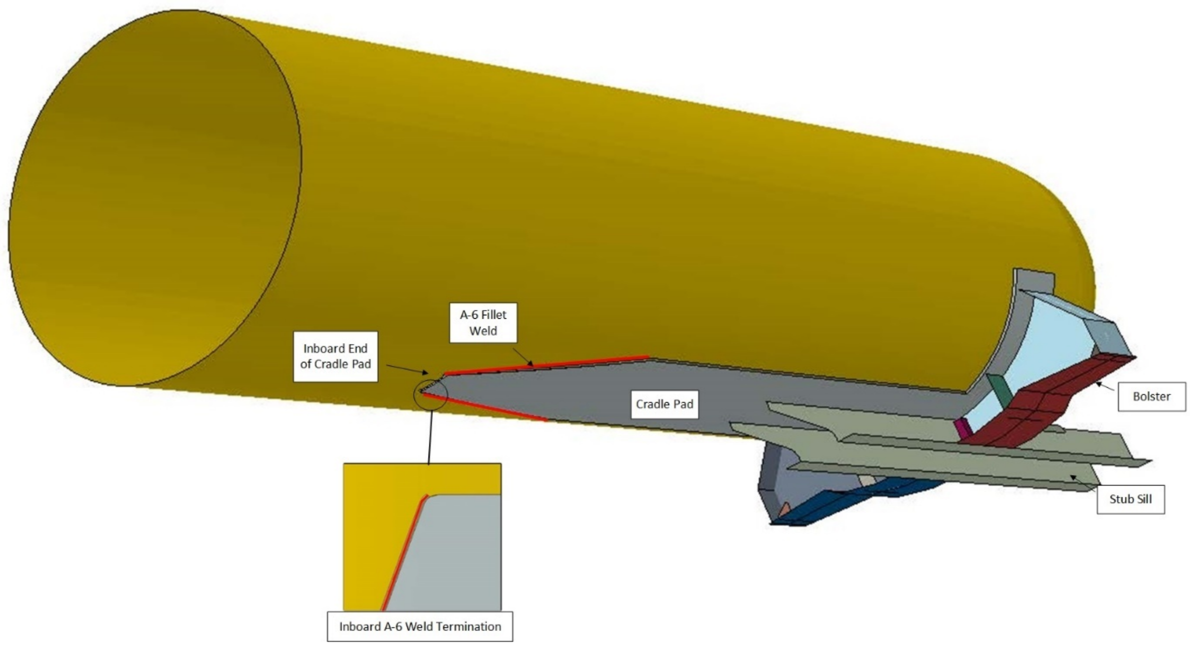

Figure 6. Three-dimensional image of the tank car and underframe.

Axiall's written qualification program to comply with federal regulations in Subpart F of 49 *CFR* Part 180 for qualification and maintenance of tank cars, included specific maintenance instructions applicable to tank cars equipped with ACF-200 underframes (Axiall 2015). These instructions stated that tank cars with ACF-200 underframes must have a stub sill inspection outboard of the body bolster every 5 years, in accordance with AAR requirements.[18] This inspection requirement did not include examining the inboard cradle pad weld terminations, which Axiall established on a 10-year federal maximum inspection cycle under AAR Rule 88B2.

The Federal Railroad Administration (FRA) noted in a 2006 safety advisory that this stub sill underframe design was prone to defects such as tank head cracks, pad-to-tank cracks, sill web cracks, and tank shell buckling, which in some instances have led to hazardous materials incidents (FRA 2006).[19]

1.4.3 Service History

Tank car AXLX1702 was used for chlorine transportation its entire service life. It was originally owned by PPG Industries, at which time the car was stenciled PPGX1702. The tank car was part of the Axiall fleet since 2013, and there was no record that the car sustained any railroad damage or had any defective equipment.

1.4.4 Previous Repairs

In 2010, AXLX1702 (PPGX1702 at that time) was subjected to a hazardous materials (HM)-201 tank car qualification inspection at the Rescar DuBois, Pennsylvania, tank car facility.[20] The shop records indicated that Rescar cleaned and inspected the interior of the tank car and found no indications of interior corrosion or mechanical damage at that time. Rescar technicians recorded ultrasonic thickness measurements and noted no evidence of shell thickness below minimum requirements.[21]

During the 2010 servicing, Rescar technicians conducted stub sill and structural integrity inspections using visual inspection techniques to inspect for weld defects.[22] The inspection documents reported that each of the four A-end and B-end longitudinal cradle pad-to-tank fillet weld terminations exhibited 3-inch crack indications and, therefore, failed the inspection.[23] Technicians also inspected the bottom 4 feet of tank girth welds (a circumferential weld that is made around the tank to join two ring sections) by ultrasonic angle beam (shear), finding no

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[18] The Axiall *Rail Fleet Maintenance Manual* states that until a tank car with an ACF-200 stub sill has been modified to include a head brace, the stub sill shall have a stub sill inspection (SS-3) performed every 5 years. A head brace is typically welded to the top plate of the stub sill and to the head to help avoid potential stress concentrations at the connection between the stub sill and the tank. Axiall states that this inspection requirement is intended for general service tank cars in sodium hydroxide service and not pressure tank cars in chlorine service. The SS-3 inspection is limited to the structural integrity of underframe components outboard from the body bolster web (AAR 2001).

[19] A *pad* is an attachment welded directly to the tank under a bracket or light structure for the purpose of preventing damage to the tank through fatigue, overstressing, denting, puncturing, or tearing.

[20] HM-201 refers to the requirements of a Research and Special Programs Administration (RSPA) final rule that requires tank car qualification inspections (RSPA 1995).

[21] *Ultrasonic thickness testing* is a nondestructive test method that transmits ultrasonic energy through the test material to detect internal and surface discontinuities and thickness measurements.

[22] *Visual inspection* is a nondestructive test method using aided or unaided vision to detect surface imperfections in materials (including welds).

[23] For orientation reference, the *B end* of a rail freight car is always the end where the hand brake is located. The *A end* is the opposite end from where the hand brake is mounted.

reportable indications. The Rescar repair work order reflected that the defective cradle pad termination welds were removed by grinding and rewelded. Shop records indicate that postrepair visual and dye-penetrant inspections found the longitudinal pad-to-tank fillet welds in acceptable condition.

Between January and July 2016, AXLX1702 remained at the Rescar Dubois, Pennsylvania, tank car facility as part of Axiall's fleet maintenance program that included a 5-year interim inspection to check for interior corrosion and shell thickness in accordance with Axiall's fleet-specific requirements. The qualification stencil indicated the tank car was not yet due for its 10-year HM-201 inspection, which would have occurred in 2020. Therefore, the Axiall service request did not include all items covered by HM-201 inspections, such as an evaluation of the structural integrity of the stub sill underframe weld terminations.

Rescar technicians noted the presence of heavy rust and corrosion damage on the interior surfaces of each of the five tank shell rings that resulted in tank shell thickness below Axiall's designated minimum for AXLX1702 of 0.7438 inch. The technicians collected ultrasonic thickness measurements in a 32-location grid pattern within each tank shell ring section, 24 inches to each side of the bottom center line, finding 25 percent of the locations below Axiall minimum tank shell thickness requirements. The thickness of the most severely corroded tank shell location measured 0.712-inch. Technicians completed a structural integrity defect record and reported that the tank car failed inspection. On April 19, 2016, Axiall's maintenance administration contractor, AllTranstek, LLC, approved Rescar's proposal to repair the tank car using a weld buildup procedure to increase tank shell thickness in the corroded locations.[24]

Rescar reported that it repaired 6,912 square inches of internal tank shell surface by grinding away the corrosion and restoring tank thickness with weld buildup.[25] Rescar technicians blended the repaired spots into adjacent parent metal using handheld grinders. On May 24, 2016, Rescar performed ultrasonic thickness testing to confirm minimum thickness at each repair spot. Technicians did not identify any exceptions. Technicians also used magnetic particle inspection methods to examine areas with weld buildup repairs for evidence of cracks, finding no exceptions.[26] Technicians did not examine the external cradle pad fillet welds because these welds were not required to be inspected nor were they repaired during this time in the shop.

Between May 24 and June 9, 2016, Rescar technicians attempted to conduct local postweld heat treating (LPWHT) in accordance with shop procedures for electrically controlled heating pads.[27] The procedure called for using ceramic fiber insulation over the heating elements, as well as insulating the opposite surface of the material to be treated to ensure balanced heating of the entire treatment region.

[24] *Weld buildup* is the application by welding of a layer, or layers, of material to a surface to obtain desired dimensions or properties, as opposed to making a joint.

[25] FRA investigators collected additional measurements from the tank car on September 29, 2016, and estimated the total amount of weld overlay repair to be 405 square inches.

[26] *Magnetic particle inspection* is a nondestructive test using magnetic fields, along with magnetic powders or fluids, to detect discontinuities at or slightly below the surface.

[27] *LPWHT* reduces residual stresses and ensures material strength after welding. Requirements for LPWHT are found in AAR *MSRP*, Appendix R, Table R.2, and temperature and time requirements are found in Appendix W, paragraph 16.2. (AAR 2014).

Rescar subcontracted Superheat FGH Services Inc. (Superheat) of Aston Mills, Pennsylvania, to provide internet-based remote LPWHT operations and monitoring. Superheat supplied Rescar with a general layout plan indicating the locations for placing the matrix of 26 ceramic heating-pad circuits, along with the thermocouple attachment points. The heating pads and thermocouple leads were attached to heater control units that allowed Superheat to remotely regulate the rate, intensity, and duration of the heating process. Superheat also provided Rescar technicians with a map of the locations for exterior insulation to control work-piece temperature. The heat treatment occurred on six different dates between May 27, 2016, and June 7, 2016, because equipment problems led to several of the heat treatment cycles being aborted and rerun. Figure 7 depicts the shell repair locations and the chronological order of the successful LPWHT runs. The area where the shell crack developed is circled in red near heating elements 7 and 8.

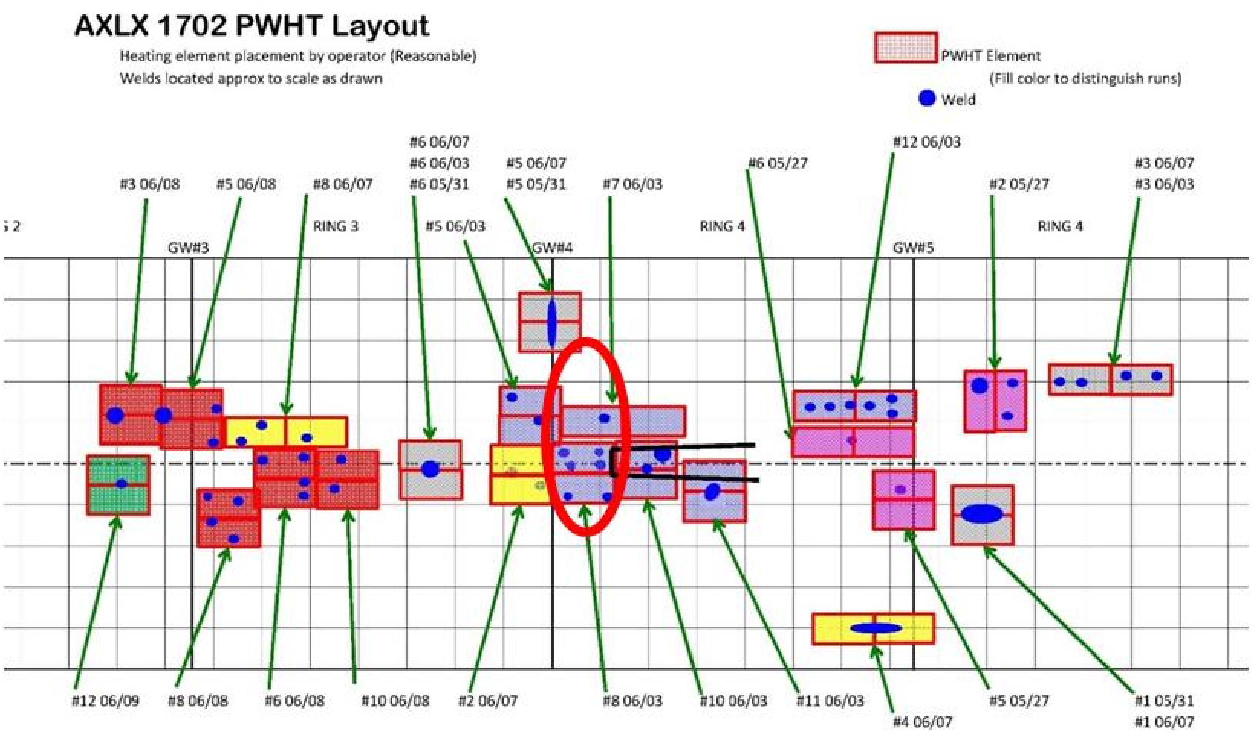

Figure 7. AXLX1702 LPWHT layout. (Courtesy of Rescar Companies.)

The stress-relieving heat treatment temperature and time was 1,012°F ± 12°F for a minimum hold time of 3 hours in accordance with AAR LPWHT temperature requirements for carbon steel tanks.[28] The remote monitoring facility was supposed to control the temperature of each heating element to ensure that temperature ramp-up limits, soak temperature and time, and cool-down rates were within the limits of the procedure and complied with AAR requirements. The remote monitoring facility was capable of aborting heat treatment cycles if communication is lost with thermocouples or heating pads that do not reach or maintain the target temperature.

[28] Permissible postweld heat treatment time-temperature combinations are found in *MSRP*, Appendix W, Table W16 (AAR 2014).

Superheat records indicated that the area of the tank car where the shell crack occurred received LPWHT as part of a six-circuit run on May 31, 2016, but the run was aborted. Superheat records indicate that LPWHT was successfully completed on this same area of the tank on June 3, 2016.

On June 20, 2016, Rescar inspectors conducted direct visual inspection and magnetic particle examination of the tank interior following the LPWHT procedure. No exterior inspection was conducted. The inspectors did not note any exceptions.

On July 20, 2016, an AllTranstek inspector reviewed the applicable documentation for tank car AXLX1702, inspected the service equipment and mechanical repairs that Rescar performed, and witnessed the final bubble leak test.[29] The inspector noted that all repairs were done with "good quality," and he observed no visual defects.

The incident occurred after the AXLX1702 received its first chlorine load following the corrosion repairs.

1.5 Tank Car Loading

On July 28, 2016, about 9:31 p.m., AXLX1702, pressurized to about 30 psig with nitrogen to preclude introduction of oxygen and moisture during shipment, departed the Rescar tank car facility in DuBois, Pennsylvania, destined for the Axiall Corporation facility in New Martinsville, West Virginia. The initial transporting railroad was Buffalo and Pittsburgh Railroad. The tank car was interchanged to CSX in Newcastle, Pennsylvania, on July 30, 2016. No transportation incidents were recorded during this movement. The tank car arrived at the Axiall Natrium facility on August 6, 2016, at 4:37 p.m.

1.5.1 Tank Car Loading Process

Axiall's procedure for filling AXLX1702 began with inspecting it for signs of defects or damage and confirming that the tank was of proper specification to load with chlorine. Because AXLX1702 was returned pressurized with about 30 psig of nitrogen, it was not necessary to purge the tank. Chlorine-loading personnel opened a liquid valve and vented some gas to test the tank for the presence of moisture. Finding no moisture in the tank, the loader left the liquid valve open to release the nitrogen until the pressure was about 10 psig. The tank car was moved onto a track scale, and loading lines were connected to load with liquefied compressed chlorine.

On August 27, 2016, about 2:00 a.m., chlorine-loading personnel monitored scale readings and product flow rates as they began filling the tank car. By 8:15 a.m., the tank car was filled to its maximum authorized load of 178,400 pounds, yielding a gross weight for the railcar of 261,950 pounds. The tank car was loaded to an internal pressure of 65 psig, which was typical for the chlorine-loading rack and below the tank car test pressure of 500 psig and its rated

[29] *AAR MSRP*, Appendix T, Chapter 3.0 specifies bubble leak testing criteria. *Bubble leak testing* is conducted at tank test pressure with a solution that produces bubbles in the presence of a leak in the region being examined. Continuous bubble growth on the surface of the object being tested indicates leakage.

bursting pressure of 1,250 psig.[30] The temperature of the chlorine product loaded into the tank car was - 9°F, which was typical for the loading facility and within the facility's parameters. The Chlorine Institute (CI) recommends that tank car loading facilities consider the increase in vapor pressure as the temperature increases, such that the chlorine pressure in the tank should be maintained below about 80 percent of the pressure-relief device (PRD) start-to-discharge setting of 375 psig (CI 2015). The tank car-loading pressure was consistent with CI guidance and would have been appropriate for a loading temperature as high as 0°F. Quality control testing showed the chlorine was within Axiall's production specification and contained traces of other halogens, halogenated hydrocarbons, and moisture.

Loading personnel tested valves and fittings for leaks with ammonia solution spray and found none.[31] The network of chlorine gas sensors and alarms near the loading shed and throughout the plant also did not detect any chlorine during and immediately following the loading process. Three chlorine-loading technicians who handled the tank car told NTSB investigators they observed no leaks or unusual events during the loading process.[32]

1.6 Postincident Tank Car Examination

NTSB investigators conducted postincident examinations of the AXLX1702 tank car on September 1, 2016, and removed shell samples for further testing at the NTSB Materials Laboratory, beginning on September 20, 2016.

The tank shell sustained a 42-inch-long, mostly circumferential crack across the bottom of the fourth ring of the tank, about 0.25 to 0.5 inch from the inboard end of the A-end stub sill cradle pad, as shown in figure 8, which is a postincident photograph of the bottom of the tank with the jacket removed and showing the shell crack inboard of the cradle pad.[33] The crack ended near the right corner of the cradle pad and showed local yielding of the tank material to the left; the crack ran partially up the side of the tank and bifurcated into two branches. One branch continued circumferentially about 13 inches before arresting, and the other branch turned horizontally toward the B end. This branch terminated at the girth weld between the third and fourth tank section rings. The crack faces were gapped apart at about 0.25 inch at the bottom of the tank. However, the only visible yielding deformation was at the right termination of the crack.

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[30] Title 49 *CFR* 173.31(c) requires the tank car test pressure to be at least 133 percent of the maximum loading pressure and at least 300 psig for materials that are PIH. Loading personnel told NTSB investigators that typical chlorine tank car loading pressures are between 50 and 108 psig.

[31] Ammonia mist reacts with a chlorine leak to produce a visible white cloud. This technique is used by chlorine-loading personnel to trace and remediate leaks.

[32] Transcripts of interviews conducted by NTSB can be found in the docket for this investigation: DCA16SH002.

[33] All orientations noted in this report are as viewed looking from the B end (brake wheel end) of the tank car toward the A end.

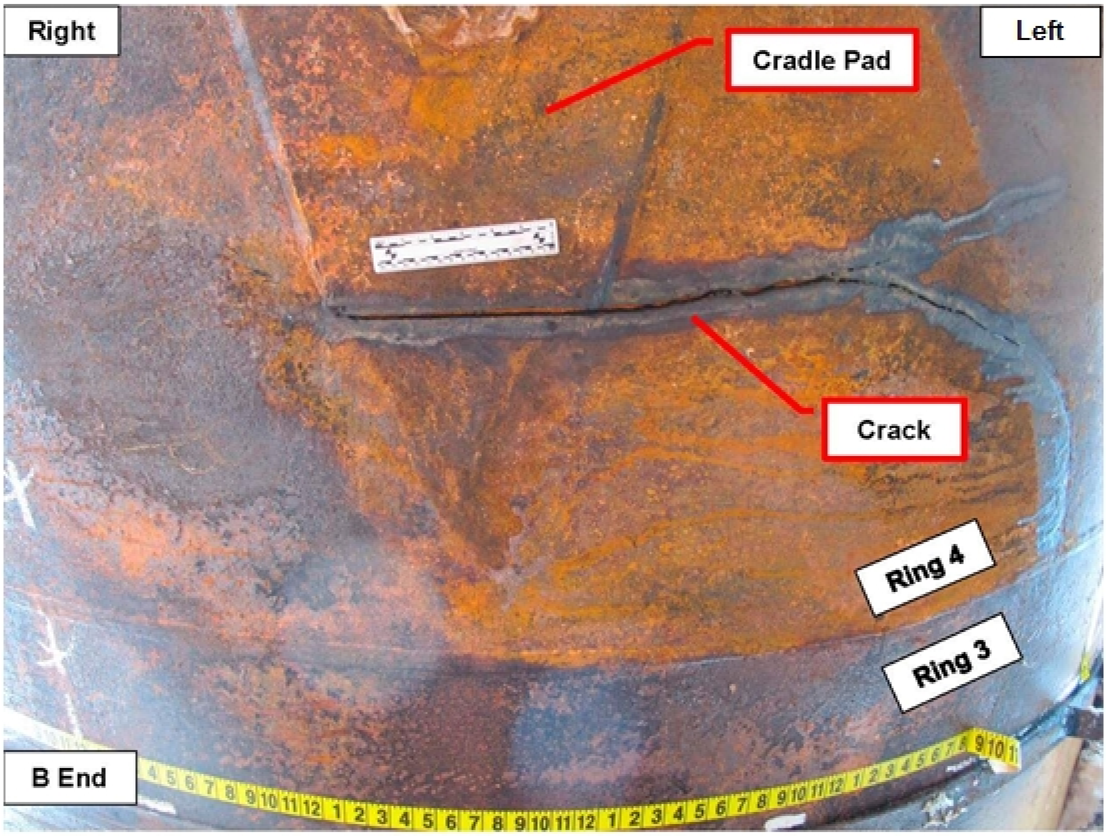

Figure 8. Exterior surface of tank car bottom showing circumferential crack inboard of cradle pad.

Differences in the welds were apparent at the inboard terminations of both right and left cradle pad-to-tank fillet welds. The different welds were consistent with manually applied repair welds, as documented in the Rescar 2010 weld crack repairs. The cradle pad repair weld was about 2.5 inches long on the right side and about 2 inches long on the left side.

The tank outer surface surrounding the crack displayed general corrosion and many pits. The corrosion and pitting were also noted in locations remote to the crack. Some of the corrosion appeared as deep pitting.

Multiple weld buildup repairs were found on internal tank shell surfaces, along with locations where the surface had been abrasively ground. Postincident inspections found no evidence of corrosion pitting on the interior surfaces. A portion of the third and fourth tank ring shell material that encompassed the entire crack area was removed for further examination. It had 13 visible weld buildup repairs. Of these, 8 weld buildups and 11 ground spots were noted in tank ring 4, and 5 weld buildups and 2 ground spots were found in ring 3. Two weld buildup repair areas were just inboard of, but did not intersect, the crack. Figure 9 shows the interior surface of the tank shell coupon showing the shell crack (red line), corrosion weld buildup repairs (yellow circles), thermal scaling, inboard cradle pad termination on the exterior/opposite surface (dashed blue line), and girth weld between tank ring 3 and tank ring 4 (orange line).[34] The purple oval on the left of the cradle pad indicates the area with visible interior surface scaling. Ground spots are identified with a green + mark.

The shell material in tank ring 4 buckled between the crack at the cradle pad plate and the tank ring 3 to 4 girth weld joint. Over this 11-inch distance, the interior surface was deformed downward about 1/2 inch. The circumferential extent of the deformation could not be measured because of the size of the sample.

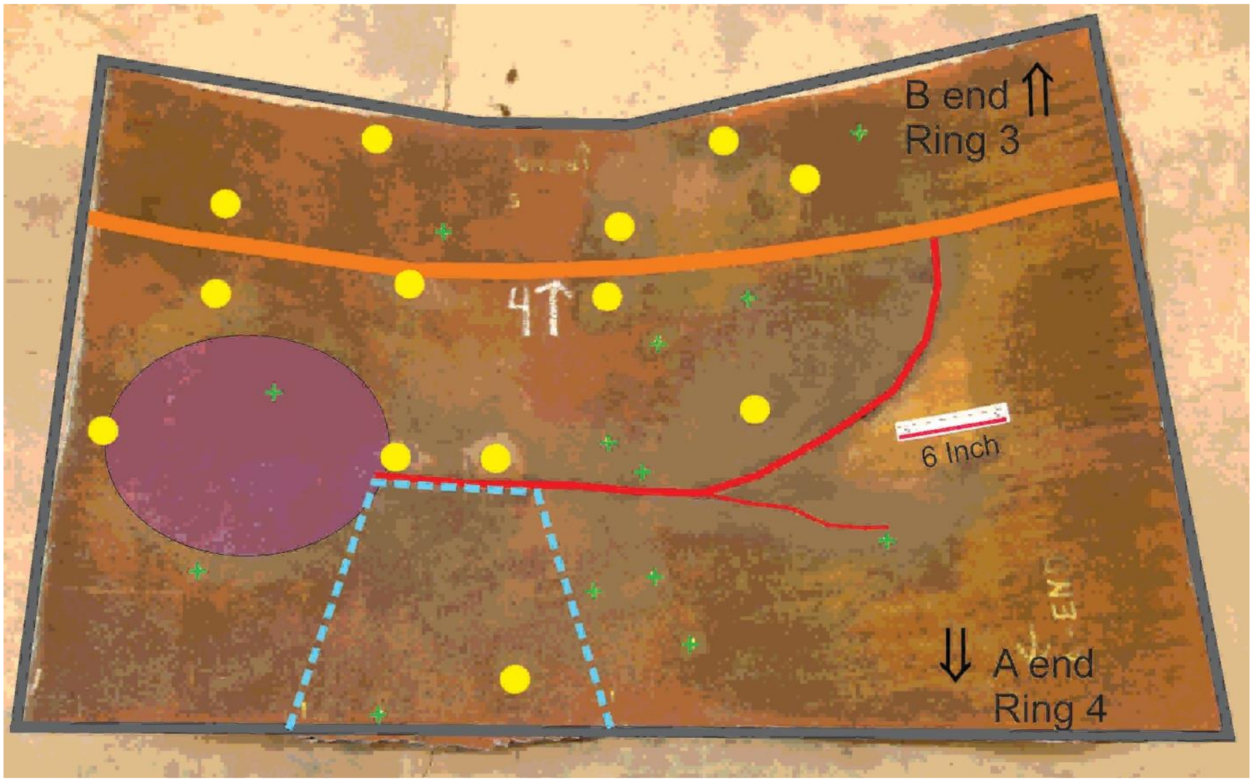

Figure 9. Annotated view of the interior side of the tank shell coupon.

An area of surface oxidization (scale) that measured 0.03-inch thick was found on the interior tank surface near the right corner of the cradle pad. The scaling boundaries were indistinct, but the area was estimated to be at least 12 inches in diameter and included the right-side termination of the crack. Shell thickness measurements within the scaled area with the scale removed were below the minimum allowed.[35] A metallographic section from the scaled area also showed decarburization 0.006-inch deep and scaling on both the interior and exterior surfaces. The scaled area material surface hardness measured somewhat softer than the

[34] A *tank shell coupon* is the section of the tank shell that has been cut out of the tank car for examination in a laboratory setting.

[35] The measured thickness ranged from 0.705 inch to 0.725 inch, while the minimum allowable thickness for AXLX1702 tank shell bottom is 0.7438 inch, as specified in AllTranstek's technical requirements (AllTranstek 2014).

surrounding material, with an abrupt transition in hardness over a distance of about 1 inch, indicating a variation in postweld heat treatment in this region.[36]

The crack was consistent with brittle fracture propagation for its entire length. Chevron markings on the crack faces demonstrated that the crack initiated near the toe of the left-hand repair weld bead. Propagation was circumferentially away from the left weld as shown in the lower image of figure 10. The upper image in figure 10 provides an interior view of the tank shell coupon showing the crack initiation site, crack propagation (red arrows), and NTSB investigator saw cuts to open the region of the rupture (purple brackets). Dashed blue lines indicate the location of the cradle pad on the exterior side of the shell. Red arrows indicate the direction of crack progression to the right-hand side, where the crack arrested near the right cradle pad repair weld but did not intersect the weld or its apparent heat-affected zone.[37] The left-hand side of the crack continued to propagate circumferentially before splitting into two legs with the longer portion turning toward the B end of the car and arresting in the fusion weld connecting tank rings 3 and 4. The shorter leg of the crack continued for a distance and arrested in the middle of the plate.

[36] Steel hardness measurements were taken on the Rockwell B scale (HRB), a designation of metallic material hardness measured by pressing a specific indenter against a prepared surface with a specific force.

[37] The place where a crack stops is the point where it arrested.

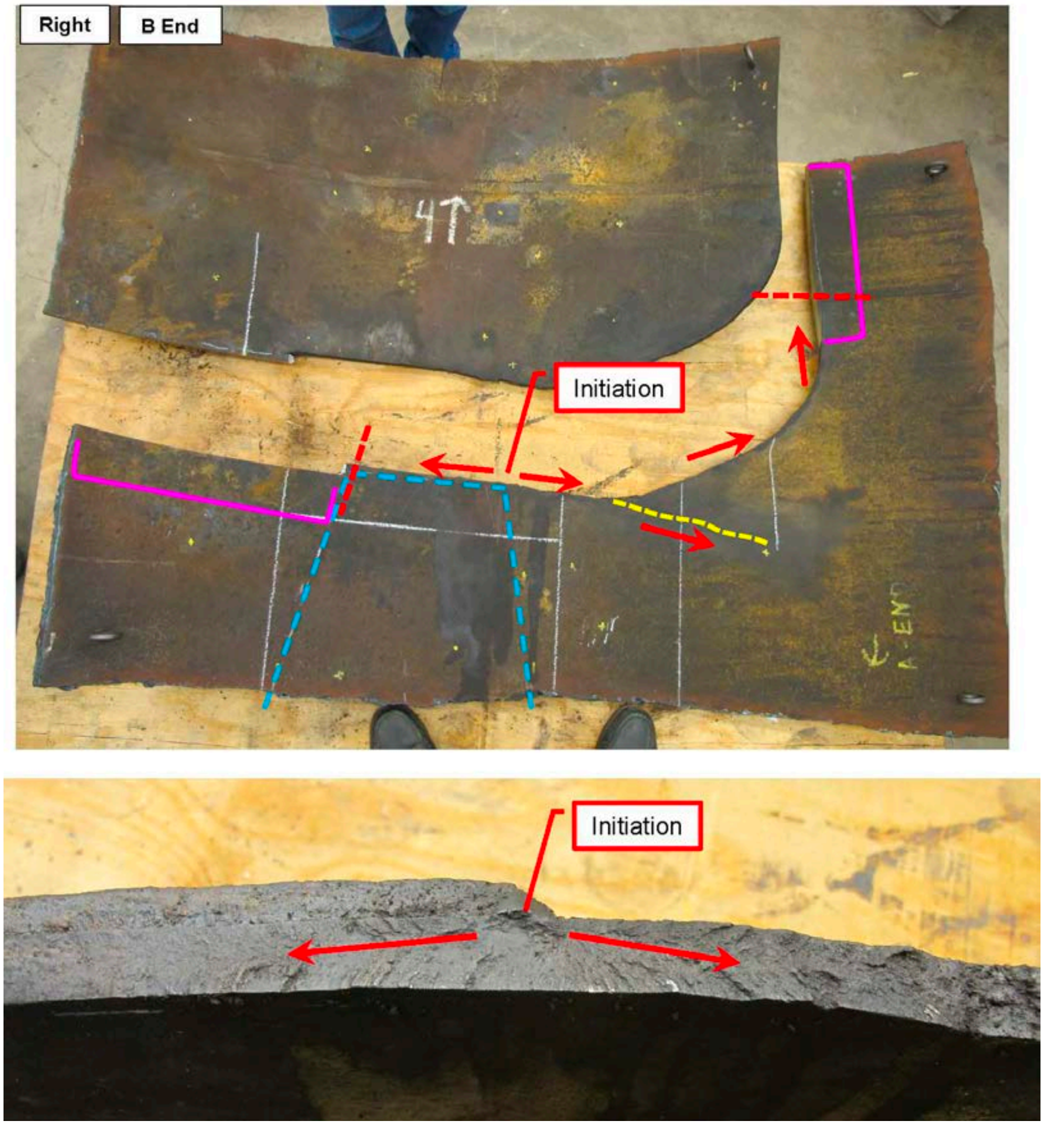

Figure 10. Interior view of the tank shell coupon.

A darker-colored elliptically shaped region at the repair weld toe that appeared consistent with an oxide layer identified the crack initiation area. NTSB investigators estimated the dark region to be about 0.7-inch wide by about 0.2-inch deep. The crack initiation region roughly followed the curved shape of the repair weld toe, which projected past the inboard end of the cradle pad by almost 0.3 inch. Three additional cracks found under the repair weld bead measured 0.037 inch, 0.094 inch, and 0.109 inch.[38]

The right-side fillet weld repair partially wrapped around the inboard corner of the cradle pad, and its configuration was not symmetric with the termination of the left-side fillet weld. The right terminus of the shell crack arrested further inboard and did not intersect the cradle pad fillet weld. The right weld was undercut and was made of several beads that did not blend smoothly

[38] The cross section of the weld material is referred to as a "bead." We are referring here to the section of the A-6 fillet weld that was gouged out and replaced in 2010.

together. The examination also identified an oxide-covered preexisting crack in the tank material at the right-side repaired weld that measured 0.6-inch wide and 0.3-inch deep.

Mechanical testing of tank ring 4 material (sampled from an area away from any repairs) showed the material met the minimum requirements for AAR TC-128 grade B steel for ultimate and yield strengths and elongation (AAR 2014).[39] Chemical analysis of the material identified minor deviations in the percentages of sulfur, aluminum, and boron compared with the current requirements for AAR TC-128 grade B steel (AAR 2014).[40]

Charpy impact tests of the tank material from tank ring 4 were conducted at variety of temperatures between -100°F and +200°F.[41] These tests were not required at the time the tank car was manufactured. For a shell temperature equal to the loading temperature of -9°F, as was the case in this incident, the interpolated Charpy impact value transverse to the rolling direction was about 8 foot-pound (ft-lb) and in the longitudinal direction was about 12 ft-lb, indicating the material was relatively brittle.

On September 8, 2016, Midland Manufacturing examined and tested the Emerson Crosby-style JQ PRD removed from AXLX1702. The PRD had an internal rupture disc that did not burst and, therefore, showed the PRD did not activate. Testing revealed that the rupture disc activated at a pressure of 410 psig, or about 35 psig higher than its rated pressure of 375 psig.

On September 29, 2016, FRA investigators collected additional ultrasonic tank shell thickness measurements from AXLX1702. The FRA investigators found seven areas in tank rings 3 and 4 that were below the minimum shell thickness of 0.7438 inch. Investigators noted that the below-minimum readings were in the grinding regions at the edges of the weld deposits where the repair technicians attempted to blend the toe of the welds into the shell.

[39] AAR *MSRP*, Table M.3.

[40] AAR *MSRP*, Table M.2.

[41] A *Charpy impact test* provides a relative measure of material toughness by impacting a swinging pendulum into a notched sample of material. Tests may be conducted at various temperatures.

2. Safety Issues

The NTSB found that the crack in the tank car shell occurred immediately following the first loading after the tank car was returned to the owner following extensive corrosion repairs. Investigators found evidence of several preexisting conditions that could have weakened or otherwise compromised the tank. These factors, taken together, combined to cause the tank failure and release of chlorine gas in this incident. NTSB investigators discovered issues with the use of nonnormalized steel tank cars to transport PIH materials and the repair, inspection, and testing of the tank car. These issues pose a substantial risk to the public and those who handle or may come into contact with hazardous materials in rail transportation.

2.1 Tank Car Steel Fracture Toughness

AAR statistics from September 2016 through August 2017 indicated there were about 75,400 annual shipments of PIH/TIH materials in a pressure tank car fleet of about 11,900 cars.[42] According to AAR standards, all class DOT-105 tank cars built after January 1, 1989, must have heads and shells constructed of normalized steel plate material (AAR 2014).[43] The standards further provided that for pressure tank cars ordered after August 1, 2005, each plate of steel used for pressure tank car heads and shells must be Charpy impact tested transverse to the rolling direction in accordance with ASTM A20 and must meet the minimum average for three specimens of 15 ft-lb at -30°F, with no single value below 10 ft-lb and no two below 15 ft-lb (ASTM 1993). There are currently no corresponding federal regulations that require the use of tank cars fabricated from normalized steel or that establish fracture toughness criteria for tank cars used to transport PIH/TIH commodities.

The majority of pressure tank cars that were constructed before 1989 were fabricated from nonnormalized steel. The Pipeline and Hazardous Materials Safety Administration (PHMSA) estimated there were about 3,000 chlorine tank cars built prior to 1989 from nonnormalized steel (*Federal Register*, 2008, 20006). The AAR reported that as of the second quarter of 2018, about 942 of these nonnormalized steel tank cars are still in PIH/TIH service; a 24 percent reduction from the previous year.[44] At the time of this incident, Axiall operated a fleet of 1,027 owned or leased pressure tank cars in chlorine transportation. The Axiall fleet included 350 chlorine tank cars constructed before 1989, of which 250 had shells manufactured from nonnormalized steel.

Normalizing is a heat-treating process typically employed in making steel plate whereby the steel is briefly heated just above the Ac_3 critical temperature and then allowed to cool in quiescent air to ambient conditions.[45] This process is employed in steelmaking practices to control the steel grain size and the morphology and distribution of carbides. Variables that

[42] E-mail from the AAR to NTSB, December 8, 2016.

[43] AAR *MSRP*, Chapter 2.2.1, General Requirements for Pressure Tank Cars.

[44] This number was reported during the AAR "Status of North American TIH Fleet as of June 30, 2018." Presentation to the Association of American Railroads Tank Car Committee, Dallas, Texas, October 17, 2018.

[45] The *Ac_3 critical temperature* is the temperature at which the transformation of ferrite to austenite is completed during heating.

control tank car shell material fracture toughness include the chemical composition of the steel, the ingot or continuous casting process and conditioning, the thermomechanical rolling processes used to develop the final plate thickness, and the incorporation of a finishing heat treatment such as normalizing. In general, nonnormalized TC128B steel plate can have lower fracture toughness and Charpy impact toughness compared with normalized steel.

In its report of the January 18, 2002, tank car derailment and release of anhydrous ammonia in Minot, North Dakota, the NTSB noted that brittle metals are more likely to result in complete fracture of the tank and instantaneous release of cargo (NTSB 2004). The NTSB further noted that in an incident scenario, nonnormalized steel in cold temperatures may form brittle cracks that grow rapidly because very little energy is required to propagate this type of failure. In brittle fracture, no apparent ductile deformation takes place before fracture. Alternatively, ductile material requires the continuous application of energy to propagate fracture. Because of the crack-arresting properties of ductile steel, a damaged tank above the ductile-to-brittle transition temperature frequently remains intact with lading losses taking place gradually over an extended period.

The mechanical properties of the steel tested from AXLX1702 met the requirements for the tank car at the time of manufacture in 1979 and were typical of nonnormalized TC-128 grade B steel of pre-1989 vintage, including those tank cars involved in the Minot, North Dakota, accident (McKeighan, Jeong, and Cardinal 2009). The Charpy V-notch impact energy value for the shell material, inferred from a curve fitted to test data at 30°F, was about 7 ft-lb in the transverse to the rolling direction and about 8 ft-lb in the longitudinal direction. Therefore, the material would not have met the present requirements of 15 ft-lb at -30ºF transverse to the rolling direction for pressure tank cars ordered after August 1, 2005 (AAR 2014).[46]

The crack in AXLX1702 exhibited a macroscopically brittle fracture from the point of origin through its entire length, indicating that the steel shell material had low fracture toughness. The NTSB concludes that the low fracture toughness of the nonnormalized steel shell material, along with the low temperature of the lading, contributed to the propagation of a preexisting crack and release of the chlorine.

The chemical composition of the tank shell steel was within AAR specifications except for sulfur being slightly over the specified limit of 0.015 weight percent (0.016 weight percent measured) and aluminum being under the specified range of 0.015–0.060 weight percent (0.01 weight percent measured).[47] The measured amount of sulfur would not be acceptable by present standards that limit sulfur to a maximum of 0.009 weight percent. However, comparing the chemical composition of AXLX1702 with the fracture-prone tank cars that were involved in the Minot, North Dakota, accident, the sulfur content was significantly lower than the 0.040 weight percent limit for TC 128B steel that was in effect at the time the tank cars involved in the Minot accident were built. While these results are out of specification, they are not believed to be causal or contributory to the release (Anderson and Kirkpatrick 2006).

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[46] AAR *MSRP*, Section 2.2.1.2 states that the test coupons tested transverse to the rolling direction must meet the minimum requirement of a 15 ft-lb average for three specimens at -30°F, with no single value below 10 ft-lb and no two values below 15 ft-lb.

[47] AAR *MSRP*, Appendix M, Table M.2, Chemical Requirements for AAR TC128 Grade B Steel.

The NTSB also addressed problems with pre-1989 pressure tank cars in the investigation of the Minot accident (NTSB 2004). NTSB investigators conducted metallurgical examinations of nonnormalized steel from five pre-1989 specification DOT-105 tank cars involved in that accident. The NTSB concluded "the low fracture toughness of the nonnormalized steels used for the tank shells of five tank cars that catastrophically failed in the accident contributed to their complete fracture and separation." Consequently, the NTSB expressed concern about safely transporting liquefied compressed gases in pressure tank cars constructed before 1989, given the high volume of hazardous materials transported in these tank cars and their lengthy service lives. As a result, the NTSB issued the following safety recommendations to the FRA:

> Conduct a comprehensive analysis to determine the impact resistance of the steels in the shells of pressure tank cars constructed before 1989. At a minimum, the safety analysis should include the results of dynamic fracture toughness tests and/or the results of nondestructive testing techniques that provide information on material ductility and fracture toughness. The data should come from samples of steel from the tank shells from original manufacturing or from a statistically representative sampling of the shells of the pre-1989 pressure tank car fleet. (R-04-4)
>
> This recommendation is classified *Closed—Unacceptable Action*.
>
> Based on the results of the Federal Railroad Administration's comprehensive analysis to determine the impact resistance of the steels in the shells of pressure tank cars constructed before 1989, as addressed in Safety Recommendation R-04-4, establish a program to rank those cars according to their risk of catastrophic fracture and separation and implement measures to eliminate or mitigate this risk. This ranking should take into consideration operating temperatures, pressures, and maximum train speeds. (R-04-5)
>
> This recommendation is classified *Closed—Unacceptable Action*.
>
> Develop and implement tank car design-specific fracture toughness standards, such as a minimum average Charpy value, for steels and other materials of construction for pressure tank cars used for the transportation of U.S. Department of Transportation Class 2 hazardous materials, including those in low-temperature service. The performance criteria must apply to the material orientation with the minimum impact resistance and take into account the entire range of operating temperatures of the tank car. (R-04-7)
>
> This recommendation is classified *Open——Acceptable Response.*

On January 13, 2009, PHMSA published final rule HM-246, which included a new provision in 49 *CFR* 173.31(e)(2)(v) that required a tank car owner, when retiring or removing tank cars transporting PIH/TIH materials, to select a tank car constructed of nonnormalized steel (pre-1989 construction) over a tank car constructed of normalized steel (*Federal Register* 2009, 1770). PHMSA stated in the preamble to this rule that although it considered the rule responsive to the NTSB, the rule did not directly implement Safety Recommendations R-04-4 or -5. On

August 19, 2010, the NTSB responded to the FRA that even though the new provision may result in pre-1989 tank cars that transport PIH/TIH materials being retired somewhat earlier than other pre-1989 tank cars, this was not an acceptable alternative to the recommended actions.

In response to Safety Recommendation R-04-7, on May 16, 2016, the FRA notified the NTSB that it had developed a list of regulated Class 2 hazardous materials and would obtain data related to their actual shipment conditions (e.g., temperature of the material at loading and the pressure in the tank car at loading). FRA stated that, based on this analysis, it will develop a list of Class 2 materials with shipping temperatures above the cryogenic temperature (-90°C or -130°F) and below the ambient temperature. FRA stated it will use this list to ensure that pressure cars carrying Class 2 hazardous materials within this temperature range and at elevated pressures will be required to have the tank car steels conform to the requirements of AAR's *Manual of Standards and Recommended Practices (MSRP)*, Section 2.2.1.2. AAR's specification requires steel used for both the shell and the heads of pressure tank cars be tested with a Charpy impact test at -30°F (-36.4°C) for steel coupons with the rolling direction normal to the test direction. AAR's specification also requires the test to be conducted at -50°F (-45.6°C) with coupons rolled in the direction of the test. The FRA stated that in a future rulemaking, it and PHMSA will incorporate provisions into the Hazardous Materials Regulations referencing the 2014 edition of the AAR's *MSRP* and identifying the "low-temperature" commodities.[48]

2.1.1 PIH/TIH Tank Car Regulatory and Industry Initiatives

The North American chlorine fleet consists of about 5,990 tank cars, of which 1,875 cars are compliant with federal interim PIH/TIH tank car design standards that were established by PHMSA final rule HM-246 pending completion of advanced tank car design research and the development of a new crashworthiness performance standard—Advanced Tank Car Collaborative Research Program 2016 (ATCCRP 2016). In its final rule, PHMSA stated that adoption of this interim standard for PIH/TIH tank cars would ensure the availability of tank cars that were intended to make immediate safety improvements in tank car construction while FRA and PHMSA completed and validated the research toward developing an enhanced performance standard (*Federal Register* 2009, 1770).

The interim design requirements include commodity-specific enhancements, such as increased shell and/or jacket thickness, full head shields where not already required, enhanced top fittings protection systems, and nozzle arrangements. The interim specification 105J600I PIH/TIH tank cars built after March 16, 2009, are all constructed of normalized steel.

Railroad freight cars, including tank cars constructed after July 1, 1974, have a federally mandated service-life limit of 50 years from the date of construction as long as the tank meets qualification requirements.[49] In the case of AXLX1702, the tank car could have remained in revenue service until 2029. At the time of the incident, federal regulations in 49 *CFR* 173.31(e)(2)(iii) mandated that tank cars constructed to interim performance specifications were authorized for transporting PIH/TIH materials for a period of 20 years after the date of original construction. PHMSA stated that it intended the 20-year authorized service-life limit to

[48] Letter from FRA Administrator to NTSB, May 16, 2016.
[49] Title 49 *CFR* 215.203.

guarantee tank car owners a reasonable period of useful service, even if a new tank car standard were developed in the years immediately following the 2009 rule. In the rule HM-246 preamble, PHMSA stated that it would not require a phaseout schedule for legacy PIH/TIH tank cars until after research had concluded and a final rule incorporating a new specification had been adopted.

The following organizations submitted petitions for rulemaking related to this issue after PHMSA established interim PIH/TIH tank car specifications:

- P-1636 – The Chlorine Institute (June 2014) to increase the service life of HM-246-compliant interim PIH/TIH tank cars from 20 to 50 years.
- P-1646 – AAR (February 2015) to prohibit the use of railroad tank cars constructed of nonnormalized steel for transporting PIH/TIH materials.
- P-1691 – The Chlorine Institute, American Chemistry Council, The Fertilizer Institute, AAR, and the Railway Supply Institute, in cooperation with ATCCRP (December 2016), to make the HM-246 PIH/TIH tank car interim standard the final standard for PIH/TIH tank cars.[50]
- P-1692 – AAR (December 2016) to phase out over a 6-year period all PIH/TIH tank cars that do not meet the HM-246 interim specification standard (ATCCRP 2016).

PHMSA published a November 7, 2018, final rule under docket PHMSA-2015-0102 (HM-219A) titled *Hazardous Materials: Response to Petitions From Industry to Modify, Clarify, or Eliminate Regulations* (*Federal Register* 2018, 55792). The final rule addressed CI's petition (P-1636) by extending the service life of interim-compliant PIH/TIH tank cars to the full 50-year service life of all other tank cars allowed under FRA regulations at 49 *CFR* 215.203. To date, PHMSA has not implemented regulatory proposals to address final PIH/TIH tank car construction standards or to phase out the use of tank cars fabricated of nonnormalized steels with poor fracture toughness performance.

In the industry coalition petition P-1691, the ATCCRP stated that for the previous 7 years it commissioned projects to study impact scenarios and performance of various tank car design concepts and materials, concluding that "no design feature or material was identified that would provide a significantly greater level of improvement, or would be a reasonable alternative, from an economic and manufacturability standpoint." The petition cited modeling and service experience of 14 derailed HM-246–compliant tank cars in which no PIH/TIH materials were released, to support its conclusion that the interim design standard provides significant improvement in incident survivability over former legacy specifications. The ATCCRP work in this area concluded at the end of 2016 with a recommendation that PHMSA accept the HM-246 interim tank car specification as the final PIH/TIH tank car specification (ATCCRP 2016). In its November 7, 2018, final rule HM-219A, PHMSA noted that if a future NPRM is developed, PHMSA will address the issue in that rulemaking.

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[50] ATCCRP is a joint effort of industry and government to develop a new generation tank car for PIH commodities. ATCCRP participants include the FRA, Transportation Security Administration, Department of Homeland Security, Transport Canada, AAR, The Chlorine Institute, The Fertilizer Institute, and the American Chemistry Council.

The AAR 6-year legacy tank car phase-out petition (P-1692) was followed up with an April 7, 2017, AAR Tank Car Committee Casualty Prevention Circular CPC-1325 titled *Final Action, Revision to MSRP Section C Part III, M-1002, Specifications for Tank Cars, Chapter 2*. Like the AAR regulatory proposal, CPC-1325 provided the following interchange requirements for tank cars used to transport TIH/PIH materials (AAR 2017):

- After July 1, 2023, remove from service tank cars used to transport TIH/PIH materials unless they comply with the requirements for tank cars built on or after March 16, 2009, as provided in 49 *CFR* 173.244a(2), 173.314c (Note 12), 179.16c(1), and 179.102-3 for cars marked DOT, or TP-14877 section 10.5.1.2 for cars marked TC; and
- After July 1, 2019, remove from service tank cars used to transport TIH/PIH materials unless tank heads and shells are constructed of normalized carbon steel.

In the meantime, in January 2018, Transport Canada (TC) published an update to regulatory standard TP14877E, *Containers for Transport of Dangerous Goods by Rail*. The updated tank car standard includes provisions to—

- Extend the service life of tank cars designed to interim PIH/TIH standards to the full 50-year maximum service life.
- Phase out over a 2-year period from the date of publication all pressure tank cars in PIH/TIH service fabricated of nonnormalized steel (TC 2018).

The updated standard is subject to a 60-day comment period, after which it will become effective once published in the *Canada Gazette*, Part II, currently projected for the spring of 2019.

Finally, on July 27, 2018, the AAR issued CPC-1336 for final revisions to Chapter 2 of the *MSRP* that revises the July 1, 2023, implementation date for phasing out non-HM-246-compliant tank cars in PIH/TIH service to December 31, 2027 (AAR 2018).[51] CPC-1336 retained July 1, 2019, as the date for requiring all tank cars transporting PIH/TIH materials to have heads and shells manufactured from normalized steel.

After 7 years of study to develop safer tank cars for PIH/TIH service, the ATCCRP concluded its work, having identified no better alternative than the existing HM-246–compliant interim tank car. Despite PHMSA's statement in its June 2016 NPRM that it continued to seek an enhanced PIH/TIH tank car design and permanent standard to replace the interim PIH/TIH requirements, AAR interchange requirement CPC-1336 imposed the HM-246 interim tank car as the final PIH/TIH tank car standard. According to the AAR's most recent PIH/TIH fleet statistics, CPC-1336 would phase out about 942 nonnormalized steel tank cars by July 1, 2019, and about 5,717 non-HM-246 compliant tank cars by December 31, 2027 (AAR 2018). The NTSB believes that PHMSA must exercise its rulemaking authority to establish appropriate fracture toughness and other design criteria that minimize the loss of lading from tank cars

[51] AAR *MSRP*, Chapter 2.8, Section C, Part III, Specifications for Tank Cars (M-1002).

transporting PIH/TIH liquefied gases in incidents and accidents and includes a timely risk-based implementation schedule. The current path forward, which relies on industry action for sweeping reconstitution of a safer tank car fleet, circumvents federal rulemaking and assumes that existing HM-246 standards and the industry-specified tank car replacements provide an acceptable level of safety. Furthermore, the NTSB is concerned that factors for selecting the 2027 date imposed by AAR CPC-1336 were largely influenced by a desire to maximize equipment investment rather than mitigating the risk of transporting highly toxic materials in tank cars with lesser lading protection and greater release potential in incidents.

An industry consortium petitioned PHMSA to develop a final standard for PIH/TIH tank cars, arguing that regulatory uncertainty about final technical specifications and the short useable service life for the interim HM-246-compliant PIH/TIH tank cars, compared to the 50-year service-life limit of older tank cars, created a significant financial disincentive for fleet investments that undermined the federal requirement to prioritize retirement of PIH/TIH tank cars constructed of nonnormalized steel (ATCCRP 2016). In the case of AXLX1702, Axiall decided to conduct extensive corrosion repairs on the 37-year-old nonnormalized steel tank car. At the time of the incident, some tank car owners and shippers of PIH/TIH materials may have found the expense of repairing a damaged tank car like AXLX1702 justified to avoid purchasing short-lived replacement interim specification HM-246-compliant tank cars that might be subject to uncertain additional retrofit requirements should a future permanent specification be adopted. However, final rule HM-219A extending the service life of these interim tank cars to the full service life of other rail cars only partially addresses this disincentive for fleet modernization. Because PHMSA has not developed a permanent PIH/TIH tank car specification, HM-246-compliant tank cars might still be subject to uncertain additional retrofit or replacement requirements should a more protective future permanent specification be adopted. Such regulatory uncertainty has encouraged the continued use of damage-prone tank cars such as AXLX1702 in the Axiall fleet.

The NTSB concludes that PHMSA’s failure to establish a final tank car specification for PIH/TIH tank cars and an aggressive schedule for removing nonconforming tank cars from service creates a disincentive to timely fleet modernization. Therefore, the NTSB recommends that PHMSA promulgate a final standard for pressure tank cars used to transport PIH/TIH materials that includes enhanced fracture toughness requirements for tank heads and shells. This new safety recommendation supersedes Safety Recommendation R-04-7 to the FRA. Therefore, Safety Recommendation R-04-7, classified *Open—Acceptable Response* under previous NTSB actions in this report (Safety Issues section) is reclassified *Closed—Acceptable Action/Superseded*.

Further, the NTSB recommends that PHMSA prohibit the use of those tank cars transporting PIH/TIH materials that are constructed of nonnormalized steels and not constructed of steels meeting the highest available fracture toughness specifications, as developed from Safety Recommendation R-19-01.

2.2 Tank Car Repair Procedures

Following extensive weld buildup corrosion repair work to the AXLX1702 tank shell between January and May 2016 at the Rescar DuBois, Pennsylvania, tank car facility, Rescar technicians tested using ultrasonic techniques to confirm minimum shell thickness at each repair spot. The technicians did not identify any exceptions. Rescar technicians also used magnetic particle inspection methods to examine areas with weld buildup repairs for evidence of cracks (AllTranstek 2015). The surfaces examined met the acceptance criteria and the technicians noted no exceptions. This examination did not include testing the structural integrity of any exterior surface cradle pad welds, which were not reworked as part of these repairs. Rescar told NTSB investigators that the cradle pad welds were not examined because all corrosion repairs were only to the interior of the railcar.

2.2.1 Control of Local Postweld Heat Treating

According to the Rescar procedure for LPWHT, ceramic fiber insulation must be placed over the heating elements, as well as the opposite shell surface, to ensure balanced heating of the entire treatment region. Additionally, heat sinks such as pads, brackets, and flanges in the heating area must be heavily insulated to prevent false temperature readings to the controller. In such cases, tank jacket cutouts are necessary to provide access to the external shell surfaces to be insulated. Rescar technicians made five tank jacket cutouts along the bottom center line of AXLX1702 rendering it difficult to sufficiently insulate the exterior shell surfaces of all repaired locations.

Rescar Shop Procedure RSP-014 cautioned that multiple heat treatments in the same area should be avoided because repetitive treatments could damage tank shell material and compromise tank integrity. However, Rescar experienced LPWHT equipment control problems that caused them to abort and rerun several heat treatment cycles on the same tank areas. AAR requirements for local postweld heat treatment stated that no portion of the tank shall exceed a temperature of 1,250°F (AAR 2014). However, scaling, decarburization, and microstructure differences in the area of the B-end right repair weld buildup indicated that this area was locally overheated between critical temperatures A_{C1} (1,330°F) and A_{C3} (1,570°F) for the material.[52] The NTSB concludes the presence of tank shell scaling and overheating on AXLX1702 indicated the LPWHT operations were not adequately controlled and exceeded the maximum allowable temperature of 1,250°F during stress relief operations following the weld buildup corrosion repair.

The scaling damage reduced the tank thickness below the minimum allowed. While the postweld heat treatment overheating may have increased local fracture toughness, causing the propagating crack to arrest, it could also have contributed to the tank shell failure by superposing additional residual stresses in the tank shell. Although the shape and location of the overheated region corresponded to one of the heating element locations, according to Superheat's Web-based monitoring records that relied on electronic communication with thermocouples attached to the tank, this heat-damaged tank shell region did not exceed 1,200°F. The NTSB concludes the tank shell overheating during LPWHT procedures reveals that processes relying on remote third-party Web-based monitoring require more rigorous in-shop quality control and recordkeeping procedures.

[52] A_{c1} is the temperature at which ferrite steel begins to transform to austenite upon heating.

Since this incident, the AAR Tank Car Committee has proposed modifications to Appendices R and W of its *MSRP* to address remote monitoring of LPWHT from satellite facilities (AAR 2017).[53] The proposed revisions would require written procedures for LPWHT equipment calibration, thermocouple placement, heating pad and insulation placement, process-monitoring requirements, and AAR temperature limits. The proposals also called for including LPWHT process-monitoring requirements in heat-treating technician training programs. The NTSB concludes that tank car integrity can be severely impacted by uncontrolled local postweld heat treating that causes thermal damage to tank car shells, including decarburization, scaling, thinning, microstructural changes, buckling, and accumulating stress in critical tank structures. Therefore, the NTSB recommends that AAR implement revisions to the AAR *MSRP Specifications for Tank Cars*, M-1002 to ensure that LPWHT processes are sufficiently monitored to avoid damage to tank car materials from uncontrolled heat treatment following welding and repairs.

2.2.2 Tank Shell Buckling

AAR *Maintenance Advisory* MA-0123 (CPC-1218), October 1, 2010, asked owners, repair shops, and railroads to inspect the bottom of the tank at the inboard end of the cradle pad for buckling in excess of 1/2 inch among other items during routine maintenance or inspection events. The maintenance advisory stated that the tank car owner is to be informed of the buckling (AAR 2010). AXLX1702 displayed a 1/2-inch buckle between the crack location and the nearby girth weld. The source of the buckle is unknown, but it may have been the result of the 2016 repairs, LPWHT or a previous event, and its presence could have affected local stress on the cracked cradle pad weld terminations. The maintenance advisory specifically identified the area where AXLX1702 was buckled as a critical location on tank cars that should be visually inspected whenever a tank car is shopped. However, technicians did not check for or report any buckling damage.

2.2.3 Repair Weld Configuration

The original manufacturing drawings specified an 8-inch no-weld zone on the inboard ends of the stub sill cradle pads. Other conflicting manufacturer drawings showed that the cradle pad was 9-inches wide at this location, therefore implying that the original welds could wrap the corners by 1/2 inch. This would further imply that repair welds could also wrap the corners to repair the car to its original condition.

The repair welds on the cracked A end of this car complied with the weld spacing requirements of the original drawings while the welds on the uncracked B end did not. While the A-end cradle pad fillet weld terminations conformed to the spacing requirement, their specific configuration was not symmetric from right to left, with the left-side weld projected further inboard than the right-side weld.

NTSB investigators conducted finite element modeling to examine local stresses in the tank near the inboard end of the cradle pad caused by the asymmetrical geometry of the 2010-repaired cradle pad fillet welds. Finite element models were used to investigate weld

[53] AAR Tank Car Committee Docket T80.2.4, “Welding Task Force Proposals,” October 18, 2017.

terminations in various configurations, including symmetrical and asymmetrical cases of wraparound welding (transverse and longitudinal weld terminations), and the models revealed stress concentrations in the same general tank location at the inboard edge of the cradle pad. However, the different weld termination geometries, including the actual asymmetrical case, resulted in local stresses of similar magnitudes and locations. (See figure 11.) Therefore, the asymmetrical weld geometry and wraparound welding were not likely significant factors in the tank shell failure. Nevertheless, the finite element modeling showed a stress concentration at the location where shell cracking initiated, which was the same location where investigators detected a preexisting crack immediately adjacent to thermal shell damage from uncontrolled LPWHT.

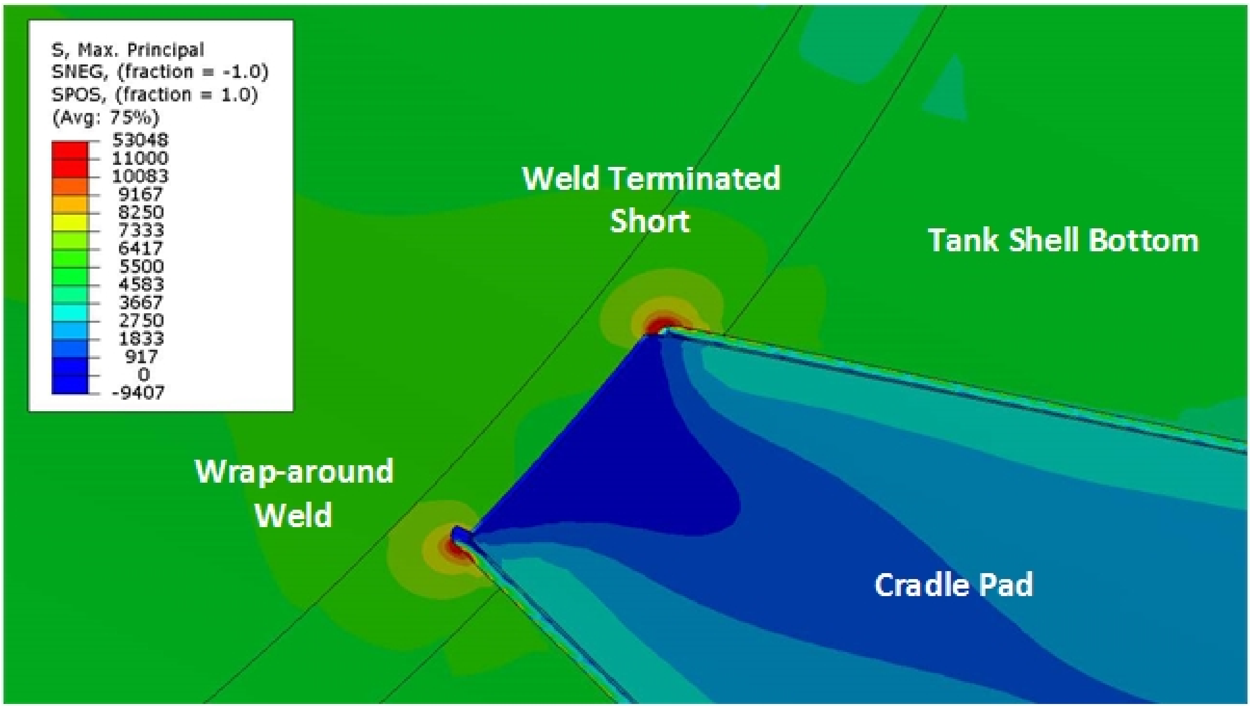

Figure 11. Maximum principal stress distribution at inboard end of cradle pad (asymmetric fillet weld).

The manufacturer, American Railcar Industries, Inc. (ARI), under its subsidiary American Railcar Leasing (ARL), issued additional instructions that detailed the inspection and defect repairs needed on nonpressure tank cars equipped with ACF-200 underframes (ARL 2006).[54] The bulletin stated that although most defects are located in welds, some start near welds and slowly progress in the parent metal. While much of the bulletin dealt with different areas of the tank car, one inspection step directly addressed the inboard cradle pad weld terminations and stated that any cracks found should be repaired in accordance with bulletin instructions.

On October 5, 2006, the FRA published *Safety Advisory 2006-04*, Notice No. 2 to announce the availability of the revised ACF maintenance bulletin. The FRA recommended that

[54] At the time the instructions were issued, ARI was the parent company and ARL was the subsidiary. ARI manufactured the car but ARL issued the guidance. However, on June 1, 2017, Sumitomo Mitsui Banking Corporation completed the acquisition of ARL.

tank car owners, in consultation with the manufacturer, inspect and modify as necessary ACF-200 tank cars at the earliest requalification or other maintenance event (FRA 2006). Because the bulletin specifically excluded relevance of the document to pressure tank cars, Axiall did not consider this guidance applicable to its chlorine tank car fleet and, therefore, did not order the inspection of cradle pad weld terminations in connection with the 2016 repairs of AXLX1702. The NTSB concludes that if the incident tank had been inspected in accordance with a maintenance plan similar to the guidance in the ARL bulletin for nonpressure tank cars at the time of the internal corrosion repairs, the preexisting cracks may have been detected and the chlorine release could have been averted.

Following this incident, on October 5, 2016, Axiall issued enhanced inspection instructions for its company-owned chlorine tank cars equipped with ACF-200 stub sills that were either in a shop or arriving in a shop for maintenance.[55] Tank car shops were instructed to perform complete stub sill inspections of the tank car inboard and outboard of the body bolster in accordance with AllTranstek procedures. The procedure required a complete cut down of the jacket to allow a direct visual and magnetic particle inspection of the welds. This procedure also required a magnetic particle inspection of the inboard weld termination of the sill pad, as well as magnetic particle inspection beyond the weld terminations. Shops were further instructed that if any tank car required weld buildup or other weld repairs (internal or external) within a 1-foot radius of the inboard terminations of the longitudinal sill pad welds, the shop was to notify AllTranstek and await further instruction and approval prior to proceeding with the work.

As of January 26, 2018, 79 of the Axiall-owned tank cars with the ACF 200-stub sill design had been delivered to tank car shops for the enhanced inspection procedure. The inspections found 29 tank cars with cradle pad fillet weld defects, of which 23 had crack lengths of greater than or equal to 0.5 inch. Therefore, the NTSB concludes that because weld cracks were found in all cradle pad weld terminations of AXLX1702 and the same locations on many other similarly equipped chlorine tank cars, the established inspection and repair protocols did not sufficiently account for the service conditions and stub sill weld attachment damage tolerance in pressure tank cars equipped with ACF-200 stub sill underframes.

Therefore, the NTSB recommends that ARI develop inspection and maintenance procedures to address cracks in cradle pad weld attachments applicable to pressure tank cars equipped with ACF-200 stub sill underframes.

2.3 Qualification and Maintenance Intervals and Acceptance Criteria

When Axiall scheduled AXLX1702 for a 5-year interim inspection to check for interior corrosion and shell thickness in accordance with its fleet-specific requirements, the tank car was not yet due for its 10-year HM-201, Rule 88.B2, and stub sill (SS-3) inspections (AAR 2001).[56] Therefore, AXLX1702 did not receive a structural integrity inspection of the stub sill underframe

[55] These inspection instructions were proprietary instructions that Axiall Corporation issued on October 5, 2016, and added to the Axiall Company Specific Requirements, AllTranstek Fleet Maintenance Procedure FM-214 (February 16, 2017, revision).

[56] The SS-3 inspection is limited to the structural integrity of underframe components outboard from the body bolster web.

weld terminations while in the Rescar shop. Both the AllTranstek tank car final inspection and test report dated July 25, 2016, and the Rescar service request form indicated "n/a" for Rule 88.B2 and SS-3 inspections. The service request form did not report any preexisting railroad damage. The car mileage report indicated AXLX1702 logged about 55,000 miles since its 2010 qualification inspection and repair; about 24,400 of these were loaded miles.

In the 1992 Special Investigation Report, *Inspection and Testing of Railroad Tank Cars*, the NTSB addressed stub sill failures on various types of tank cars that resulted from undetected cracks at welds (NTSB 1992). The NTSB concluded, among other things, that "tests and visual inspections at arbitrary intervals are not effective to detect defects at high-stress areas where stub sills or other components are attached to tanks before sudden and complete failure" (NTSB 1992). As a result of this special investigation, the NTSB issued the following safety recommendation to the FRA:

> Develop and promulgate, with the Research and Special Programs Administration, requirements for the periodic testing and inspection of rail tank cars that help to ensure the detection of cracks before they propagate to critical length by establishing inspection intervals that are based on defect size detectable by the inspection method used, the stress level, and the crack propagation characteristics of the structural component (requirements based on a damage-tolerance approach). (R-92-22)[57]
>
> This recommendation is classified *Closed—Unacceptable Action.*

The NTSB also issued companion recommendation R-92-23 to the Research and Special Programs Administration.

In 2013, the NTSB classified Safety Recommendation R-92-23 as closed with acceptable action after PHMSA published final rule HM-216B (*Federal Register*, 2012, 37961). The rule amended the hazardous materials regulations to incorporate provisions contained in widely used or longstanding special permits, as well as amending 49 *CFR* Part 180 to require tank car owners to develop written procedures for a qualification program with inspection procedures, intervals, and acceptance criteria. The acceptance criteria must be based on service reliability data or analytical evaluation of the tank car and its components. The program allows an owner to develop an alternative qualification program suited to the tank car design and use, contingent on FRA approval, by permitting an alternative inspection and test program or interval based on a damage-tolerance analysis. Qualification and maintenance intervals must be included in such a program to ensure that any cracks that develop in tank shell steels are detected and repaired before tank integrity is compromised. For establishing alternative inspection and test procedures or intervals, a damage-tolerance analysis must include a determination of the probable locations and modes of damage due to fatigue, corrosion, and accidental damage. If the procedures are

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[57] The Research and Special Programs Administration (RSPA) was established in 1992 as a DOT sub-agency focused on improving hazardous materials and pipeline safety, coordinating and advancing transportation research, promoting innovative transportation solutions, and managing the Department's transportation-related emergency response and recovery responsibilities. RSPA was abolished on November 30, 2004, and some of its duties and responsibilities were transferred to PHMSA.

based on a service reliability assessment, it must be supported by analysis of systematically collected data.[58]

Tank car facilities must incorporate the owner's qualification programs into their AAR-approved quality assurance programs.[59] The required elements of the program include procedures for evaluating the sensitivity and reliability of the inspection and testing techniques, identification of the minimum detectable crack length, and acceptance criteria. Tank cars must be subjected to structural inspections and tests at the specified interval or whenever they show evidence of abrasion, corrosion, cracks, dents, distortions, defects in welds, or any other condition that may make the tank car unsafe for transportation.[60] Federal regulations at 49 *CFR* 180.509 require that at a maximum interval of 10 years the owner must ensure the tank car receives an internal and external visual inspection for the above-mentioned defects, a structural integrity inspection and tests, and material thickness tests.[61]

Under normal operating conditions, pressure tank cars should not fail catastrophically from the presence of small cracks in welds or shell material. Given the propensity for defects in tank cars equipped with ACF-200 stub sills—as documented in FRA safety advisories 2006-04 and 2006-04, Notice No. 2—the inboard cradle pad-to-tank welds should have been inspected on a more frequent cycle. A more appropriate alternative inspection regime could have been established based on a damage-tolerance analysis or other analytic tool. Furthermore, avoiding the inspection of the failure-prone stub sill structure, particularly considering the extensive amount of corrosion repair and shop dwell time invested in refurbishing AXLX1702, was an unsound decision and missed opportunity that could have prevented this incident.[62] The presence and repair of such extensive corrosion, coupled with the stub sill underframe design service history, should have prompted a comprehensive structural integrity assessment that included the full spectrum of inspections and tests. The NTSB concludes that had the inboard end of the stub sill and cradle pad been inspected for weld cracks more frequently, based on damage-tolerance criteria rather than the 10-year federal maximum interval, the preexisting crack might have been identified before it failed.

Following this incident, Axiall conducted enhanced inspections of its 264 tank cars equipped with the ACF-200 stub sill underframes that could potentially have remained in service. As of January 26, 2018, after inspecting and/or repairing 82 of these tank cars, 56 had been returned to service, while 16 were in the process of inspection, repair, or scrapping. An additional 59 of these 264 tank cars had been scrapped. As a result of the AAR interchange rule that only allows tank cars with normalized steel tanks to transport PIH/TIH materials after July 1, 2019, Axiall plans to scrap about 131 nonnormalized steel chlorine tank cars that had not been through its enhanced inspection process. Meanwhile, Axiall continues to evaluate options

[58] See 49 *CFR* 180.509(l).

[59] Title 49 *CFR* 180.501(b) establishes the requirement for the associate administrator for railroad safety to approve alternative inspection and test procedures.

[60] See 49 *CFR* 180.509.

[61] Thickness testing may be required more frequently if the tank car is used to transport a material that is corrosive or reactive to the tank, or if the shell thickness has been reduced from as-built but still exceeds the minimum allowable thickness.

[62] *Dwell time* is the length of time the car was out of service and present in the shop.

regarding its 20 ACF-200 normalized steel tank cars, as well the potential for repurposing its nonnormalized ACF-200 series tank cars that had been inspected and returned to service.

Axiall's actions may ultimately remove about 12 percent of the 2,186 similarly constructed DOT-105 tank cars transporting chlorine and other PIH/TIH hazardous materials in the national fleet. While AAR interchange rules and proposed federal rulemaking may address the remainder of this fleet, as recommended by Safety Recommendations R-19-001 and R-19-002, many of these tank cars may be repurposed to other hazardous materials service and may continue to pose an unacceptable risk of catastrophic failure. While under the provisions of PHMSA final rule HM-216B, tank car owners are responsible for ensuring that their tank car qualification programs and inspection procedures have appropriate acceptance criteria based on service reliability analysis, but this investigation revealed that some fleet owners may not have developed sufficiently robust maintenance programs. Instead, as was initially the case with Axiall, fleet owners are more likely to rely on federal maximum qualification intervals and are unlikely to have developed tank qualification criteria based on damage tolerances suitable for their operations.

To provide the FRA assurances about the safety of its tank car fleet for continued operations, Axiall and its maintenance advisory contractor initiated a review of historical maintenance data to determine the appropriate inspection intervals for its tank cars equipped with ACF-200 stub sills. In developing an enhanced tank car inspection regime following this incident, Axiall argued that as a fleet owner and not a tank car manufacturer, it lacked the expertise to determine damage-tolerance parameters applicable to specific tank car designs. Because Axiall did not have access to design criteria, detailed service history data, or the loads applied to various locations of the tank car, it was unable to determine an actionable critical flaw size and likely crack growth rate. In consultation with FRA, Axiall ultimately proposed to select as its critical flaw size half of the crack size of 0.7 inch, which NTSB investigators found for the preexisting crack that propagated to failure in this instance. To facilitate timely fleet inspections, Axiall established its critical flaw size as 0.35 inch, although not based on any damage-tolerance approach other than empirical evidence from the performance of one tank car, AXLX1702. Furthermore, Axiall was only able to identify a single radiographic testing method with an acceptable probability of detecting a crack this size. While the recent availability of the Tank Car Integrated Database (TCID) will facilitate future damage-tolerance analysis, this illustrates the difficulty that even the larger fleet owners have in developing appropriate damage tolerance-based criteria.[63]

Although the preexisting cracks in each of the 2010 repair welds may have existed for some time, shop records indicated that postrepair and post-LPWHT visual and dye-penetrant inspections found the longitudinal pad-to-tank fillet welds in acceptable condition. With available nondestructive testing techniques, the probability of detecting cracks the size of the one that initiated the shell failure in AXLX1702 with a large degree of confidence is far from certain. NTSB investigators conducted several experimental nondestructive tests on the B-end left inboard A-6 weld termination. Two magnetic particle tests detected a crack that was later confirmed by sectioning. It should also be noted that the tank surfaces had to be cleaned by grit

[63] The TCID is a system managed jointly by the Railway Supply Institute and AAR. The system became mandatory in 2014 for tank car owners to report alterations, modifications, conversions, and damage to tank cars.

blasting prior to nondestructive testing. Therefore, obscured crack surfaces may render confirmation by visual inspection methods impractical without substantial surface preparation.

On October 1, 2010, in response to an increasing number of stub sill-related defects found on tank cars in transportation, AAR issued *Maintenance Advisory* MA-0123 advising tank car owners, repair shops, and railroads to inspect stub sills when personnel are performing maintenance or during normal inspection events (AAR 2010). Among several items, railroad operations and mechanical personnel were asked to visually inspect critical locations, including the bottom of the tank at the inboard end of the cradle pad, for buckling in excess of 1/2 inch. These employees should communicate the detection of any defects to tank car owners for a maintenance determination. The maintenance advisory also stated that repair shops should communicate any defects found on the stub sill structure or at the termination of stub sill reinforcing pads to ensure that tank car owners can address the required maintenance. The advisory further encouraged tank car owners to consider the sensitivity of inspection methods used for stub sill inspections and consider shortening inspection cycles when necessary (AAR 2010). The corrosion repair postweld heat treating jacket cutouts for AXLX1702 exposed the region of the tank at the inboard cradle pad weld terminations where an inspection could have revealed the shell bulge and weld cracks that contributed to the shell failure. However, because the tank was not scheduled for a qualification inspection, the opportunity to inspect for these defects was ignored. The NTSB concludes that the AXLX1702 tank shell failure and chlorine release might have been avoided had the tank car been inspected and repaired in accordance with the AAR *Maintenance Advisory* MA-0123.

The circumstances of this incident warrants reinforcing and elevating the urgency of implementing the suggested inspections contained in *Maintenance Advisory* MA-0123. The advisory should identify circumstances under which full stub sill inspections should be performed, such as when work necessitates jacket cutouts that expose critical locations on a stub sill that should be inspected. Therefore, the NTSB recommends that PHMSA issue maintenance guidance to owners of DOT-105 pressure tank cars transporting PIH/TIH hazardous materials with risk factors such as nonnormalized steel shell material and repairs or postweld heat treating near stub sill attachments and other high stress locations to (1) establish structural integrity inspection frequency, (2) provide guidance for defining critical flaw size and repair and acceptance criteria for indications in fracture-sensitive locations, and (3) provide guidance for selecting nondestructive testing methods to identify cracks with a sufficient probability of detection.

2.4 Shell Crack

Physical evidence showed the shell crack in AXLX1702 was the result of loads placed on it with a preexisting crack at a critical location, coupled with the inadequate fracture toughness of the steel. NTSB investigators did not directly determine the cause of the preexisting crack, but the initial portion most likely resulted from a weld crack at the toe of the left cradle pad fillet weld that was repaired in 2010. Oxidation suggested this crack may have been present and undetected for some time. The orientation and elliptical shape of the crack and oxidation pattern suggested that the majority of the preexisting crack propagation resulted from fatigue due to in-service loads. Further identification of the tank failure details was precluded by damage to fine fracture features caused by initial preexisting crack oxidation and the corrosive-erosive nature of the liquid chlorine being released through the crack.

NTSB investigators found through visual examinations that all four of the 2010 cradle pad fillet weld termination repair welds had poor workmanship, including undercutting, unevenness, slag inclusions, and porosity.[64] The poor-quality welds reveal insufficient control of the repair weld process and quality control steps in 2010. NTSB investigators determined the initiating weld probably had the best visual quality. Metallographic cross sections found preexisting cracks in all repairs to cradle pad fillet weld terminations. However, in the case of the three welds not associated with the tank failure, the cracks were small and confined to the heat-affected zone of the welds. Since other weld cracks did not cause the tank car to fail, other factors such as fatigue or damage from previous repairs may have caused the A-end cradle pad weld crack. Finite element modeling showed that the termination of the welds caused elevated stresses in the tank such that a crack near that location would propagate in the circumferential direction as observed. However, the modeling found that static loads alone from filling and pressuring the tank were unlikely to initiate failure without a preexisting crack. Therefore, the crack likely propagated under fatigue until it reached a critical size for unstable (rapid) crack growth. The NTSB concludes that the presence of the preexisting crack at the toe of the A-end left cradle pad fillet weld led to the tank car shell failure; however, the cause of the preexisting crack could not be determined because of fracture surface damage caused by oxidation and by erosion-corrosion from the liquid chlorine released through the crack.

NTSB investigators examined the PRD and found that it did not activate, and the pressure in the tank car could not have exceeded 410 psig when the crack initiated. Even though the PRD rupture disc did not meet AAR specifications for permissible burst pressure tolerances, the PRD would have activated significantly below the 500 psig-specified test pressure and 1,250 psig-rated burst pressure for the tank car (AAR 2014).[65] The tank car was loaded to 65 psig, which is the lower end of normal operating pressure for loaded chlorine cars. Thus, there was no evidence the tank had been subjected to internal overpressure. The NTSB concludes that the orientation and path of the crack in AXLX1702 indicated that the shell failure was the result of bending loads produced by the dead weight of the tank car and its contents in combination with its internal pressure. The ambient temperature at the time of the incident was about 72°F, while the loading temperature of the chlorine product was -9°F. Therefore, the NTSB concludes that the fracture timing was the likely result of changing stresses in the tank shell during thermal equalization of the car after loading.

[64] *Slag inclusion* is an internal particle of solidified flux and other oxidized material entrained in the weld deposit.

[65] According to AAR *MSRP*, Appendix A, Tank Car Valves and Fittings, Section 4.2.2, the permissible tolerance for the burst pressure of a rupture disc must be 0 percent to -15 percent.

3. Conclusions

3.1 Findings

1. The low fracture toughness of the nonnormalized steel shell material, along with the low temperature of the lading, contributed to the propagation of a preexisting crack and release of the chlorine.

2. The Pipeline and Hazardous Materials Safety Administration's failure to establish a final tank car specification for poison inhalation hazard/toxic inhalation hazard tank cars and an aggressive schedule for removing nonconforming tank cars from service creates a disincentive to timely fleet modernization.

3. The presence of tank shell scaling and overheating on AXLX1702 indicated the local postweld heat treatment operations were not adequately controlled and exceeded the maximum allowable temperature of 1,250°F during stress relief operations following the weld buildup corrosion repair.

4. The tank shell overheating during local postweld heat treatment procedures revealed that processes relying on remote third-party Web-based monitoring require more rigorous in-shop quality control and recordkeeping procedures.

5. Tank car integrity can be severely impacted by uncontrolled local postweld heat treating that causes thermal damage to tank car shells, including decarburization, scaling, thinning, microstructural changes, buckling, and accumulating stress in critical tank structures.

6. If the incident tank had been inspected in accordance with a maintenance plan similar to the guidance in the American Railcar Leasing bulletin for nonpressure tank cars at the time of the internal corrosion repairs, the preexisting cracks may have been detected and the chlorine release could have been averted.

7. Because weld cracks were found in all cradle pad weld terminations of AXLX1702 and the same locations on many other similarly equipped chlorine tank cars, the established inspection and repair protocols did not sufficiently account for the service conditions and stub sill weld attachment damage tolerance in pressure tank cars equipped with US Department of Transportation-Specification ACF-200 stub sill underframes.

8. Had the inboard end of the stub sill and cradle pad been inspected for weld cracks more frequently, based on damage-tolerance criteria rather than the 10-year federal maximum interval, the preexisting crack might have been identified before it failed.

9. The AXLX1702 tank shell failure and chlorine release might have been avoided had the tank car been inspected and repaired in accordance with the Association of American Railroads *Maintenance Advisory* MA-0123.

10. The presence of the preexisting crack at the toe of the A-end left cradle pad fillet weld led to the tank car shell failure; however, the cause of the preexisting crack could not be determined because of fracture surface damage caused by oxidation and by erosion-corrosion from the liquid chlorine released through the crack.

11. The orientation and path of the crack in AXLX1702 indicated that the shell failure was the result of bending loads produced by the dead weight of the tank car and its contents in combination with its internal pressure.

12. The fracture timing was the likely result of changing stresses in the tank shell during thermal equalization of the car after loading.

3.2 Probable Cause

The National Transportation Safety Board determines that the probable cause of the chlorine release was an undetected preexisting crack near the inboard end of the stub sill cradle pad, that propagated to failure with the changing tank shell stresses during the thermal equalization of the car after loading with low temperature chlorine. Contributing to the failure was Axiall Corporation's insufficiently frequent stub sill inspection interval that did not detect the crack, the low fracture resistance of the nonnormalized steel used in the tank car construction, and the presence of residual stresses associated with Rescar Companies' tank wall corrosion repairs and uncontrolled local postweld heat treatment.

4. Recommendations

4.1 New Recommendations

As a result of this investigation, the National Transportation Safety Board makes the following new safety recommendations:

To the Pipeline and Hazardous Materials Safety Administration:

> Promulgate a final standard for pressure tank cars used to transport poison inhalation hazard/toxic inhalation hazard materials that includes enhanced fracture toughness requirements for tank heads and shells. (R-19-001)
>
> Prohibit the use of those tank cars transporting poison inhalation hazard/toxic inhalation hazard materials that are constructed of nonnormalized steels and not constructed of steels meeting the highest available fracture toughness specifications, as developed from Safety Recommendation R-19-001. (R-19-002)
>
> Issue maintenance guidance to owners of US Department of Transportation Specification-105 pressure tank cars transporting poison inhalation hazard/toxic inhalation hazard hazardous materials with risk factors such as nonnormalized steel shell material and repairs or postweld heat treating near stub sill attachments and other high stress locations to (1) establish structural integrity inspection frequency, (2) provide guidance for defining critical flaw size and repair and acceptance criteria for indications in fracture-sensitive locations, and (3) provide guidance for selecting nondestructive testing methods to identify cracks with a sufficient probability of detection. (R-19-003)

To the Association of American Railroads:

> Implement revisions to the American Association of Railroads *Manual of Standards and Recommended Practices Specifications for Tank Cars*, M-1002 to ensure that local postweld heat treatment processes are sufficiently monitored to avoid damage to tank car materials from uncontrolled heat treatment following welding and repairs. (R-19-004)

To American Railcar Industries, Inc.:

> Develop inspection and maintenance procedures to address cracks in cradle pad weld attachments applicable to pressure tank cars equipped with ACF-200 stub sill underframes. (R-19-005)

4.2 Recommendations Reclassified in This Report

As a result of this accident investigation, the National Transportation Safety Board reclassifies Safety Recommendation R-04-7 to the Federal Railroad Administration from "Open—Acceptable Response" to "Closed—Acceptable Action/Superseded," by Safety Recommendation R-19-001 to the Pipeline and Hazardous Materials Safety Administration.

BY THE NATIONAL TRANSPORTATION SAFETY BOARD

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Adopted: February 11, 2019

Appendix

The National Transportation Safety Board (NTSB) was notified on August 27, 2016, that a US Department of Transportation Specification-105 tank car sustained a crack in its tank shell shortly after being loaded with liquefied compressed chlorine at the Axiall Corporation Natrium plant in New Martinsville, West Virginia. The NTSB launched a team consisting of an investigator-in-charge and two investigators on August 30, 2016, to investigate the performance, qualification, and maintenance of the tank car.

The parties to the investigation include the Federal Railroad Administration, Axiall Corporation, Rescar Companies, and AllTranstek LLC.

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