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Factual Investigative Update

Loy-Lange Box Company Catastrophic Pressure Vessel Failure

Contents

This is a Factual Investigative Update of a CSB investigation into a multi-fatality incident resulting from the catastrophic failure of a pressure vessel.[1] It provides the facts and findings established by the investigation team to date, which is subject to revision and updates as the investigation proceeds. This document identifies a path forward for a number of potential investigative areas of inquiry that may yield lessons for safety improvements.

Incident Overview

At approximately 7:20 a.m. on April 3, 2017, the bottom of a steam condensate (hot water) storage tank catastrophically failed at the Loy-Lange Box Company (LLBC), located at 222 Russell Boulevard in St. Louis, Missouri. The 1952-pound[2], 30-inch diameter by 17-½-feet long steel tank,[3] called a Semi-Closed Receiver (SCR)[4] contained about 510 gallons condensed steam (water at about 330 °F and 100 psig.[5]) Condensate from the vertically-mounted SCR was normally sent to two associated steam generators.[6]

As the pressure in the tank suddenly dropped due to the failure of the tank bottom, a portion of the water in the SCR instantaneously exploded into steam, resulting in an increase in volume of about 75 times the volume of the SCR.[7] A steam explosion of this type is extremely hazardous. The energy released was equivalent to about 350 pounds of TNT.[8] Some of that energy dissipated when the escaping steam condensed to water, but the surveillance video from a nearby custom work truck shop clearly shows the power of the explosion and the effect on the building (Figure 1), as does the damage evident after the event.

Figure 1. *Before and after photos for the explosion - Kranz video*

The force of the steam explosion exiting the bottom of the SCR destroyed a large portion of the LLBC facility, and launched the storage tank like a rocket through the roof (Figure 2, A). One LLBC employee was fatally injured, and a second was left in critical condition.

Even after pulling loose from all of the piping and floor attachments, and crashing up through the structure of the building and out through the roof, the 1952-pound SCR was still traveling at about 120 mph. It rose to about 425 feet above street level and traveled laterally across about 520 feet. It remained airborne for over 10 seconds.

As it fell, the SCR crashed through the roof of Faultless Healthcare Linen's[9] property at 2030 S. Broadway, fatally injuring three individuals (Figure 2, B).

Various pieces of piping and debris from the explosion also crashed into the surrounding areas. A third building at 400 Russell Boulevard, owned by Pioneer Industrial Group, suffered significant mechanical and water damage when a large piece of pipe from the Loy-Lange site punctured the roof and ruptured a portion of its water sprinkler system (Figure 2, C and Figure 3). No injuries occurred at this third site. An approximately 7 foot long section of about 1.5 inch pipe also speared down through the windshield of a truck parked adjacent to the Faultless property and embedded into the dashboard and floorboard (Figure 2, D and Figure 3).

1 http://www.csb.gov/csb-investigators-deploying-to-explosion-at-the-loy-lange-box-company-in-saint-louis-missouri/

2 The investigation team originally estimated the weight at 3000 pounds.

3 Overall length, including the support skirt, is 20 feet. The investigation team originally estimated the tank at 36 inches in diameter by 20 to 25 feet long.

4 It was called a Semi-Closed Receiver (SCR), because it received condensed steam (hot, high pressure water) from the LLBC steam system. "Semi-closed" refers to an open vent from the tank that vents any air in the system (and a small amount of steam from the hot water) to the atmosphere.

5 psig: pounds per square inch gauge.

6 A steam generator is a device similar to a steam boiler that turns water into steam. At Loy-Lange, the steam heated equipment that was used to make corrugated cardboard.

7 Investigation team calculation.

8 Investigation team calculation. Energy difference between 510 gal of water in the tank and water at ambient conditions is about 700,000 BTU. 1 pound of TNT releases about 1800 BTU.

9 http://www.faultlesslinen.com

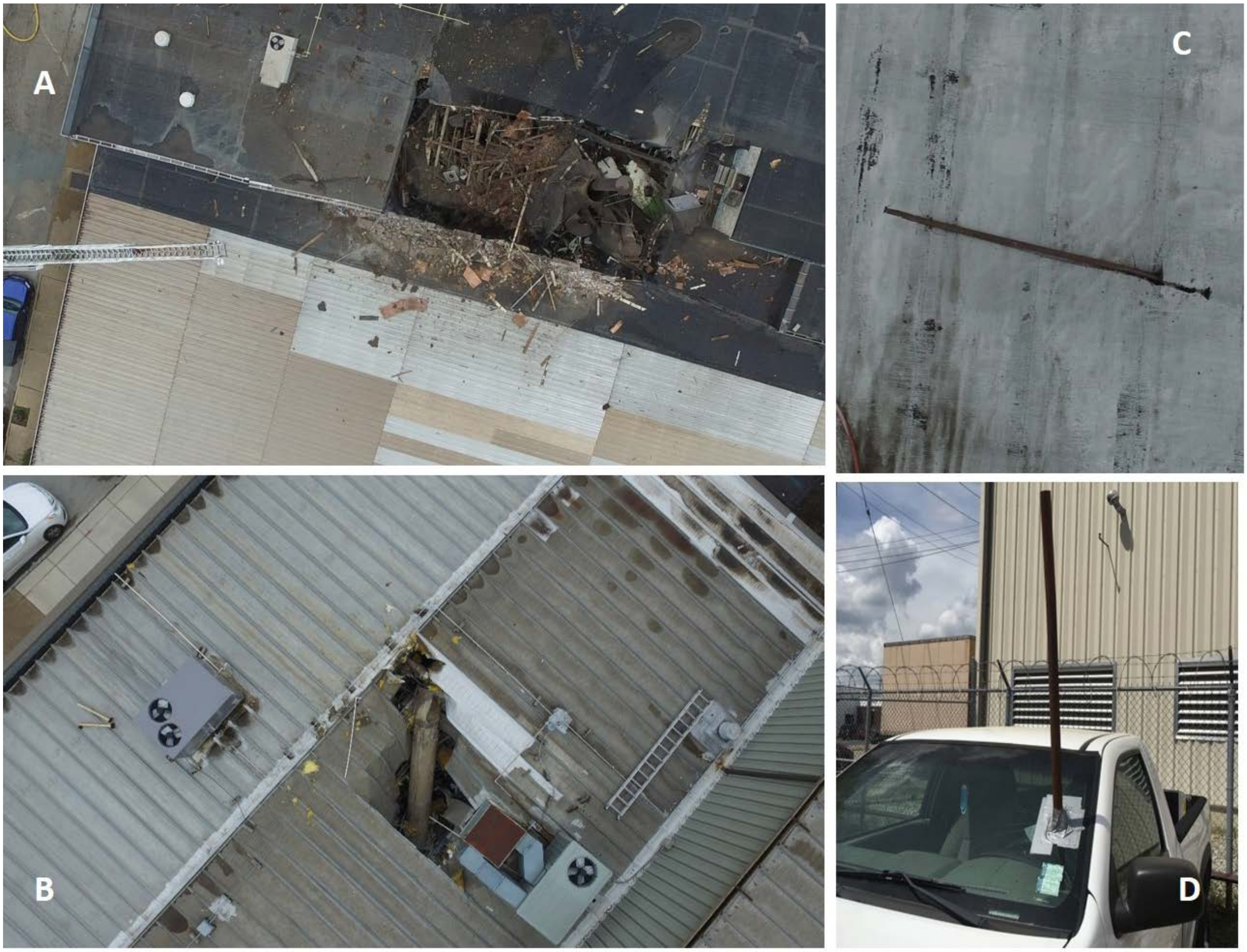

Figure 2. *Damage as a result of the incident*

Figure 3. *Debris map*

Process Description

Loy-Lange Box Company designs and manufactures many packaging products, including corrugated products.[10] Steam heat is crucial in the production of high-quality corrugated board.[11] To produce the steam required, LLBC alternates between using one of two steam generators, manufactured by Clayton Industries.[12] A flow diagram of a typical Clayton system with an SCR, (though with just one steam generator) is shown in Figure 4.

The steam generator (Figure 4, lower left) is a vertical cylinder filled with insulation and a tightly wound coil of tubing. Water from the SCR enters the top of the generator and flows down

10 http://www.loylangebox.com/about_loy_lange_box_company.html

11 http://www.pmengineer.com/articles/84670-web-exclusive-case-study-steam-system-refinements-improve-reliability-and-efficiency-for-corrugators

12 https://www.claytonindustries.com/clayton_d1_design_features.html

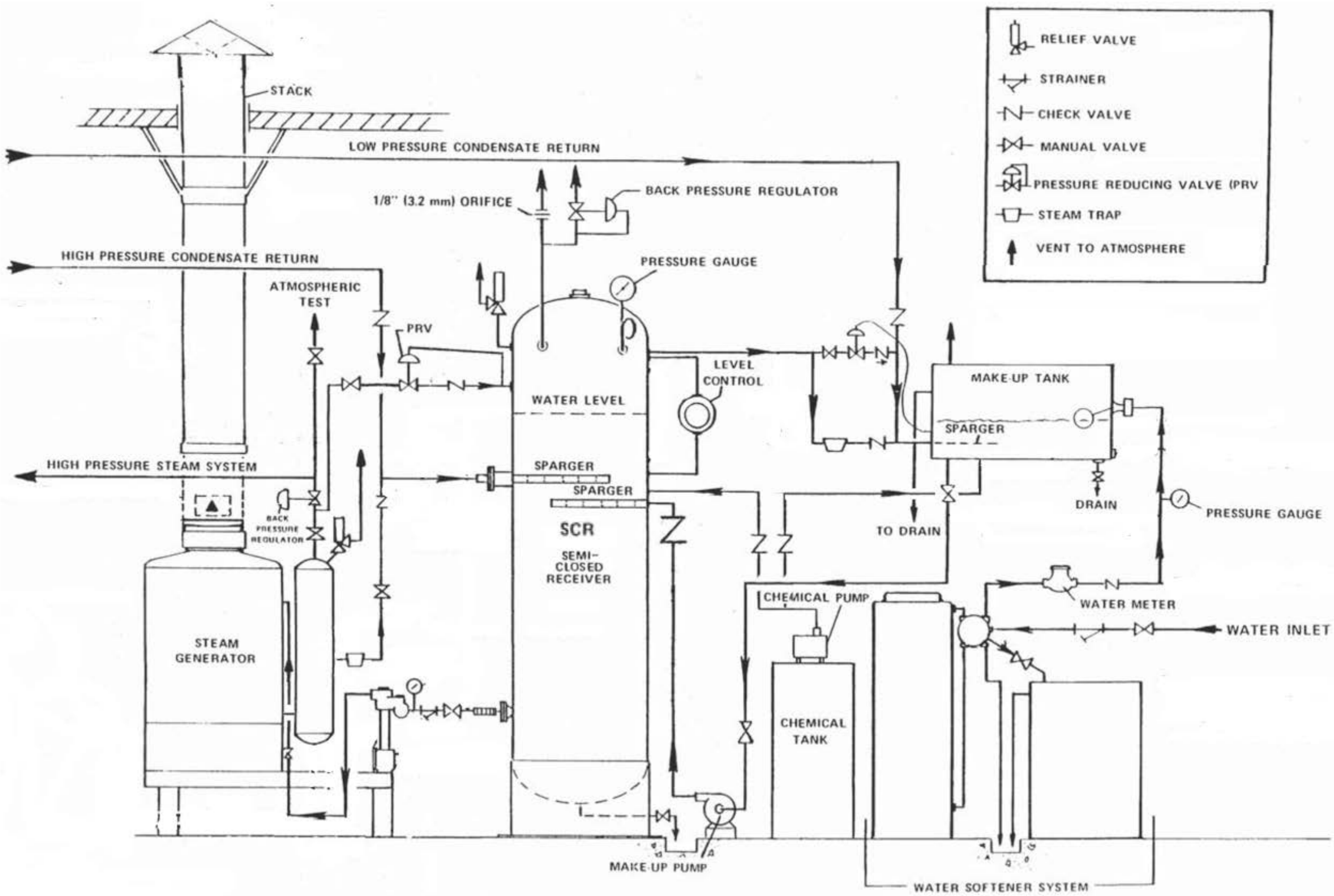

Figure 4. *Clayton Steam Generator with Semi-Closed Receiver*[13]

13 Generic SCR-system drawing provided by Clayton Industries, modified by the CSB to more closely represent the LLBC system.

through the tubing. Heat from natural gas burner[14] travels up and heats the water. Steam and water flash into the adjacent vertical separator, and steam for the corrugation process exits the top. Any water in the separator is sent back to the SCR. At LLBC, the steam system runs at 175 psig and 375 °F.

After being used in the process, the steam condenses to water, but it is still at a relatively high pressure. To conserve energy, the hot condensate is stored in the SCR and kept at 100 psig and about 330 °F. This hot water from the SCR is then recirculated to the steam generator, where it provides a head start to the heating done by the natural gas.

The SCR is physically mounted to the floor via a cylindrical "skirt" that is welded to the bottom edge of the cylindrical portion of the vessel. The skirt acts as a stand, and allows room for a bottom drain line (shown with dashed lines in Figure 4). This drain is used periodically (weekly at LLBC) to flush condensate to the sewer, with the intention of removing any sediments or contaminants that might collect there.

During the process, some water is lost. For example, there is a vent to the atmosphere from the top of the SCR to remove any air in the system, and steam continuously vents as well. There are also leaks and losses in the corrugation process. To maintain water inventory, St. Louis city water is brought in as make-up (Figure 4, right side). The raw city water runs through a water softener[15] and then into a stainless steel make-up tank. The tank is heated and vented to the

14 LLBC uses natural gas. Clayton systems can also be designed to use other gas and liquid fuels

15 The water softener is analogous to units used for private residences, just at a larger scale. A sodium salt-based resin converts magnesium carbonate and calcium carbonate in the raw water stream to "softer" sodium carbonate. When the resin becomes fully loaded with calcium and magnesium, it is regenerated using a sodium salt mixture. The sodium replaces the magnesium and calcium on the resin, with the resulting waste regen-water being dumped to the city sewer.

atmosphere to drive off dissolved oxygen. The make-up water is then added to the SCR as needed to hold the level near the top of the tank.

Chemicals are added from the chemical tank (Figure 4, bottom center) to both the make-up tank and the SCR to control corrosion. The stationary engineer analyzes water samples daily from the make-up tank and the water returned to the SCR from the steam separator.[16] Once a week, a water treatment specialist also analyzes samples from the boiler feed water, condensate from the steam header, and make-up water system. The specialist reviews the record of weekly samples for consistency and makes any adjustments or recommendations to improve the system and its operation.

Steam Generator History

The original Clayton steam generators at LLBC were 175-HP[17] units, and were installed in 1966 and 1968. However, the system was rebuilt using a 300-HP-generator (1999) and a 200-HP generator (2001). In June, 2012 the 200 HP-generator was upgraded by Clayton to 250-HP. In December 2016, the coil of the 250-HP unit was replaced by LLBC employees because it had developed a leak.

Semi-Closed Receiver History

The SCR was manufactured by Chicago Boiler Company to Clayton's design per ASME[18] Section VIII Div. 1 Rules for Construction of Pressure Vessels. The SCR was inspected and registered with the National Board of Boiler and Pressure Vessel Inspectors (NBBI) in February 1997. The entire vessel, shell and both heads, were manufactured of SA-516-70 carbon steel, a typical grade of steel for this service.[19]

2012 Leak Repair

The SCR was repaired during November 2012. The stationary engineers noticed water leaking from under the skirt of the SCR. One of the engineers torch-cut a large hole in the skirt[20] so that they could inspect for the source of the leak. Subsequently, in what was termed an "emergency repair[21]," Kickham Boiler and Engineering was contracted to repair the bottom head.[22]

The entire 30" diameter 2:1 elliptical bottom head was not replaced. Instead, a 24" center section of the head was removed and replaced with a custom-formed 24" diameter piece. The work sequence was:

- Kickham supported the SCR on three temporary legs welded to the SCR shell.
- The bottom head and skirt were cut off by cutting through the head-to-shell circumferential weld for easier access to make the repair. The head-to-skirt weld remained intact.
- A 24" diameter circular section cut out of the middle of the head was replaced with what Kickham described as a "tank circle." This is not standard pressure vessel terminology. Kickham custom manufactured this piece as a patch to the existing head.
- After cutting the 24" disk from the original head, there was an approximately 6" ring of the original head left behind.[23] The new 24" tank circle was welded inside this 6" ring of the original head.
- A drain hole was cut, and a new drain connection was welded into the center to the tank circle. New bottom drain piping was welded in place.
- The skirt/piping/head assembly (with the new center section and ring from the original head) was then welded back onto the SCR using a Kickham-created 1" by ¼" steel "backer ring" behind the weld. Kickham reported this as a replacement in kind, calling it "same as original."[24]
- The temporary legs were cut off and removed from the shell, and any remaining portions of the attachment points were ground down to the original shell steel.

The stationary engineers kept the removed center section of the original head around for several years as kind of a memento. They

16 The Loy-Lange facility employed three stationary engineers to operate and maintain the steam generation system, including the SCR. St. Louis City requires a certified stationary engineer on-site while this system is in operation. The initial stationary engineer certification requires one year of technical education, (e.g., Rankin Technical College) and a passing grade on both oral and written tests by the City of St. Louis. The stationary engineer must renew this certification annually by paying a fee; there is no further testing after initial certification is achieved.

17 Steam generators are rated by horsepower. Each horsepower represents the ability to generate about 33.5 lb/hr of steam at standard Clayton design conditions.

18 American Society of Mechanical Engineers.

19 http://www.macsteel.co.za/files/macsteel_vrn_-_pressure_vessel_steels_-_astm_a516.pdf

20 The hole cut into the skirt is apparent after the incident. It is large enough for a person to get their head and shoulders through. It was not an engineered modification. There was no analysis of the effect of cutting this hole on the structural integrity of the skirt or on the skirt's ability to subsequently still support the SCR.

21 Kickham Boiler and Engineering records.

22 A vessel like the SCR is manufactured from three basic parts. The center cylindrical section is welded from sections of rolled steel plate. At each end, the cylinder is closed by welding on a cap, or head. The head is a single piece of steel. For the SCR, these are a common 2:1 elliptical shape, with the vessel radius (15" in this case) nominally being twice the height (7.5"). There is 2" of straight wall height as well to make the attachment to the vessel shell. So for the SCR, the head diameter would be 30" and the height 9.5".

23 Investigation team calculation, assuming a 24" net diameter for the new section.

24 Use of a backer ring is not uncommon when making a weld from one side. It's the easiest way to ensure full penetration. The ring is not structural, but is intended to support the bottom of the weld–to be a floor for full penetration.

described the inside surface as severely pockmarked, looking like "the surface of the moon."

The remaining 6" ring of the original head—left behind during the repair on the SCR—connected the new tank circle to the original SCR shell.

Twenty-five days after the repair was completed, Kickham submitted a two-part proposal to Loy-Lange involving the fabrication and entire replacement of the bottom four feet of the shell, including a new 2:1 elliptical bottom head. The new steel would be 50 percent thicker than the original as a "corrosion allowance."[25] This replacement did not occur.

Following the repair, a weekly draining program was implemented. The bottom of the SCR was "blown down" weekly with the intent to remove any material that might be collecting there and contributing to corrosion.

The bottom of the SCR below the outlet nozzle to the steam generator is a "dead leg." A dead leg is a path, or leg, that is open for fluid to fill, but which has no normal flow—a non-flowing, or dead, path. Condensate entered at the top of the SCR, slowly dropped down through the vessel (about 5 to 7 inches per minute) and was then fed to the steam generators via an outlet located on the lower side of the vessel. Below this outlet, in the bottom of the SCR, there was no normal flow. Any sediment or solid material returning to the SCR from the corrugation process would fall down through the slowly flowing condensate in the SCR, and more likely than not, miss being drawn out with the steam generator feed. Instead, it would fall to the bottom and collect there.

Stationary engineers reported that when conducting blowdowns, they did not see chunks or solids in the drained water, but that at times it was opaque. The procedure was to blow down the bottoms until it ran clear. No sampling of the bottoms for conductivity or other parameters was carried out. With a focus on the steam system, the water specialist did not look at this drain water, nor become involved with determining SCR bottoms blowdown requirements.

Leaking Again, Right Before The Incident

On Friday, March 31, 2017, three days prior to the incident and 4.5 years after the 2012 leak repair, stationary engineers again noticed a leak from the bottom of the SCR. With consent from site management, they used a cell phone to photograph the leak (Figure 5). The phone was extended in through the large hole in the skirt that was cut in 2012; the camera is looking straight up at the SCR bottom tank circle and drain line inside the skirt. The weld line can also be seen between the 6"-wide ring of original bottom head and the tank circle installed in 2012.

Figure 5. *Photograph of SCR bottom head leak, taken March 31, 2017*

Figure 5 indicates that leaks are coming from at least two distinct and significant sections of the circumference of the SCR. Further, the wet area, most apparent on the left, is originating from the 6" ring of the original head left behind by the 2012 repair.

The steam generation system was shut down after the photograph was taken, and Loy-Lange contacted a repair service provider. Plans were made for the repair technician to arrive in the afternoon on the next business day, Monday, April 3.

On Monday morning, Loy-Lange started up the steam generation system. Based on the start-up schedule typically followed by the engineers and the time of the incident, it appears that the catastrophic failure occurred near the end of the start-up process.

Immediate Cause[26] of the Incident

The investigation team has determined that the vessel failed due to corrosion of the 6" ring of the original bottom head, resulting in the circumferential split of the ring and subsequent separation of the entire tank circle from the SCR.

The thinness of the corroded 6" ring of original head material provided an inherent circumferential weakness that allowed the

25 A Corrosion Allowance is an extra thickness of metal provided to account for metal loss due to corrosion during the lifespan of the equipment. Based on the U-1 National Board registration document, the SCR was originally specified by Clayton, and so manufactured, by Chicago Boiler without any corrosion allowance.

26 Immediate causes are the events or conditions that lead directly or indirectly to an incident, such as mechanical failure. (CCPS, *Guidelines for Investigating Chemical Process Incidents,* AIChE)

entire 24" diameter tank circle repair piece to separate from the SCR at one moment. This large opening, occurring so quickly, caused a rapid conversion of a portion of the 330 °F, 100 psig water in the tank to steam: a steam explosion.[27] The force of this explosion from the bottom of the tank is what caused it to break free, launch out through the building, and fly 520 feet before crashing down through the Faultless Linen building.

In addition to the photo of the leak, two additional pieces of evidence support his assignment of cause.

First, the inspection of the bottom of the SCR after the incident revealed that the entire bottom tank circle was gone, but that a significant portion of the 6" ring remained, hanging down around the entire circumference. See Figure 6 and Figure 7.

Figure 6. *Photo showing 3-4" highly damaged section of the original bottom head remaining in SCR*

Evident from this photo is the extreme difference between the clean condition of the steel that makes up the shell (above the weld) versus the extremely corroded steel of the remnant of the original bottom head (below the weld). The investigation team found that this extreme line of demarcation between good metal above and damaged metal below extended consistently around the entire circumference of the SCR. The clean condition of the inside of the shell can also be seen in Figure 8.

The original National Board certification document states that the shell and heads were manufactured from the same SA-516-70 grade of steel. Metallurgical test reports from the original manufacturing process confirm that both the shell and the heads conformed to SA-516-70 specifications.[28] The team will be pursuing further metallurgical testing and analysis in order to understand the corrosion damage mechanism indicated in the bottom head.

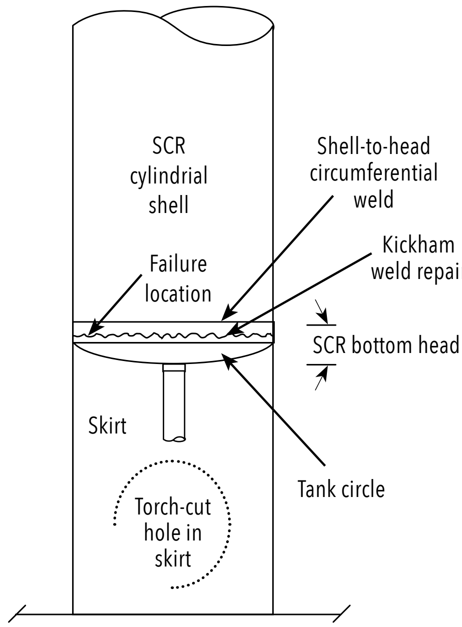

Figure 7. *Drawing of various parts of the SCR*

The second piece of evidence supporting the assignment of cause is based on an examination of two metal artifacts found within the upper portion of the SCR lodged at the spargers (Figure 8)[29]

Figure 7 is a drawing that illustrates the various parts of the SCR, the failure location, and the pieces depicted in the photographs.

When the artifacts were removed, they were determined to be the entire tank circle that had been added during the 2012 repair and a portion of the bottom piping, Figure 9. The entire weld is intact, and around the outside edge of the weld is a portion of the 6" ring that mates with the portion that is still attached at the bottom edge of the vessel shell. Initial measurements of the remnants of this ring were as thin as 0.08". The metal of the tank circle, installed in 2012 and in service for 4.5 years, also displayed "surface of the moon" corrosion characteristics, and has thinned from the original 0.25" to about 0.2" (Figure 9). If the corrosion rate is assumed to be linear with time, this rate of corrosion of the tank circle is consistent with the rate on the original bottom head, as evidenced by the remaining ring material.[30] The corrosion in the bottom of the SCR was still occurring, as it did before the 2012 repair. Again, the team will rely on metallurgical testing and analysis in order to develop a further understanding of the corrosion damage.

27 Imre, A. R., et. al., *Estimation of the Thermodynamic Limit of Overheating for Bulk Water from Interfacial Properties,* International Journal of Thermophysics, September, 2013

28 SA-516-70 specification: http://www.matweb.com/search/datasheet.aspx?matguid=9ccee2d0841a404ca504620085056e14.

29 There are two spargers, consisting of horizontal pieces of pipe with holes drilled in them. Return condensate and make-up fresh water enter the SCR from opposite sides of the SCR through these spargers, whose purpose is to enhance mixing and reduce thermal imbalances inside the SCR.

30 Based on rough measurements by the CSB following the incident:
Original head material: 0.22" to 0.08" in 18 years: 0.008 in/yr.
Tank circle: 0.25" to 0.2"in 5 years: 0.010 in/yr.

Figure 8. *Close-up of bottom tank circle and portion of bottom piping showing weld seam and, outside of the seam, the thinned original bottom head "ring" material*

Figure 9. *Interior "surface of the moon" condition of the tank circle that separated from the SCR vessel during its catastrophic failure on April 3, 2017. The tank circle was installed in 2012*

Figure 10. *Piece of bottom drain piping and a section of the bottom head*

SCR Inspection and Repair Certification Requirements

Repairs to National Board code unfired process vessels, such as the SCR, can be governed by various jurisdictions, such as Cities or States. The State of Missouri requires repairs to be compliant to National Board standards.[31] The City of St. Louis, however, has opted out of the state requirement. Instead, the City manages inspections and repairs of code unfired process vessels by requiring compliance with the Mechanical Code of the City of St. Louis, a city-specific ordinance.[32]

For inspection, the Mechanical Code requires:

> All […] pressure vessels […] shall be inspected annually by the code official or representative. The inspection shall be as thorough as circumstances permit.[33]

The City of St. Louis has not provided the CSB with any evidence of inspections of the SCR.

For repair, the Mechanical Code requires:

> Welded repairs to […] pressure vessels […] shall be performed only by those organizations which possess the appropriate ASME Certificate of Authority with extension to field work or an "R" Certificate of Authority issued by the National Board of Boiler and Pressure Vessel Inspectors. A permit shall be required for such work.[34]

Kickham did hold "R" Certificate Authority from the National Board of Boiler and Pressure Vessel Inspectors (NBBI) and thus could award an R-Stamp to pressure vessels it repaired that satisfied the ASME and Mechanical Code requirements. In 2012, Kickham filled out a Form R-1, and a certified NBBI inspector signed off on the repair. Filing the R-1 with the National Board is not required by the National Board Inspection Code,[35] but can be mandated by the jurisdiction. The City of St. Louis does not require filing for R-1s. If voluntarily submitted by the repair company, the National Board will file an R-1, however, NBBI has no record of receiving the Form R-1 for the 2012 SCR repair.

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31 National Board Inspection Code (NBIC) Part 3 – Repairs and Alterations.

32 City of Saint Louis Ordinance #68639, Mechanical Code of the City of Saint Louis, based on the International Mechanical Code, 2009 Edition, as published by the International Code Council, Inc., approved April 10, 2010, located at: https://www.stlouis-mo.gov/internal-apps/legislative/upload/Ordinances/BOAPdf/68639x00.pdf.

33 City of Saint Louis Ordinance #68639, Section 1001.2 Periodic inspections.

34 City of Saint Louis Ordinance #68639, Section 1001.4 Major Repairs.

35 NBBI NB-23 (NBIC) Part 3 Repairs and Alteration | 2007 2009 addenda, Section 6.

The Mechanical Code of the City of Saint Louis has a general provision stating that all mechanical systems shall be maintained in a safe condition.[36] This responsibility falls on the owner of the building that houses the mechanical system.

Inspections are managed by the "Mechanical Equipment Inspection Supervisor" (code official), appointed by the building commissioner. The code official is tasked with hiring enough inspectors to accomplish all inspections and enforce all ordinances. Yet, the code also specifically provides the caveat that the number of inspectors can be constrained to a number less than required, subject to the city's budget.[37]

Further, and more importantly, the section specific to pressure vessels states: "the inspection shall be as thorough as circumstances permit,"[38] leaving the determination of thoroughness at the discretion of the inspector. Inspections within the jurisdiction of the State of Missouri are not left to the discretion of the inspector. Inspectors hold commissions from the NBBI and must conduct inspections compliant with the National Board Inspection Code.[39,40,41] As mentioned previously, records provided by the City of St. Louis contain no evidence that the SCR was ever inspected.

After 2012, if any City inspections of the SCR had been carried out, the large, irregular, torch-cut hole in the side of the SCR skirt would have been a visible alteration to the vessel.

An alternative group that might have made inspections of the SCR is the underwriter, FM Global; however, FM Global stated that they do not do inspections in the City of St. Louis because they have no jurisdictional authority. That authority is reserved to the City code officials.

Per the City's mechanical code, the 2012 repair made to the bottom head of the SCR required a permit from the City,[42] but the CSB has found no evidence indicating that LLBC requested a permit for the repair or that the city issued a permit.

Summary and Proposed Further Work

The immediate cause of this incident is the mechanical integrity failure of the material of the original bottom head that remained in service following the 2012 repair.

The SCR was uniquely vulnerable to catastrophic failure because the severe corrosion of the 6" ring left it much thinner than the tank circle. The entire ring failed suddenly. The tank circle blew away in one piece from the SCR, creating the conditions for the steam explosion.

The City of St. Louis, who has jurisdictional authority, is required to inspect the SCR by its ordinance. The City provided no evidence of inspection.

The investigation team will be working with a metallurgist to classify the corrosion damage mechanism in the bottom of the SCR.

The issues of corrosion, mechanical integrity, and inspection will continue to be of interest. A final written product on the investigation will be forthcoming.

36 City of Saint Louis Ordinance #68639, Section 102.3 Maintenance.

37 City of Saint Louis Ordinance #68639, Section 103.3 Deputies.

38 City of Saint Louis Ordinance #68639, Section 1001.2 Periodic Inspections.

39 The National Board of Boiler and Pressure Vessel Inspectors, http://www.nationalboard.org

40 Boiler and Pressure Vessel Safety FAQ, Missouri Department of Public Safety, Office of the State Fire Marshal, http://dfs.dps.mo.gov/about/faqs.php#boiler-pressure-vessel-inspections

41 Application for Inspector's Certificate of Competency in the State of Missouri, http://dfs.dps.mo.gov/documents/forms/MO_815-F0010.pdf

42 City of Saint Louis Ordinance #68639, Section 1001.4 Major Repairs.