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Failure Evaluation of Savannah River Site High-Level Waste Evaporator 242-25H – Part II – 17353

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ABSTRACT

The Department of Energy's Savannah River Site evaporators are essential to the site actively managing and reducing its liquid high level waste inventory. Since 1951, a series of dedicated evaporators have reduced the liquid waste inventory from 600 ML (160 Mgal) by about a factor of four. The evaporators predominantly have experienced steam tube bundle failures, due to corrosion or fatigue, within about a decade of entering service. To extend service life, recent evaporators have used nickel-based alloys, such as Alloy G-3 (UNS N06030), and have improved operational controls to prevent corrosion. In spite of this, the 242-25H Evaporator recently developed a slow shell leak (0.4 L/min) after sixteen years. An evaporator shell leak is unique in the site's operating history. Finding and characterizing the leak has been challenging because of conflicting information from leak rate data and the locations of externally visible waste. The approaches used to evaluate possible failure modes are described. Failure modes considered include but are not limited to: pressure, temperature, materials, corrosion, fatigue, erosion, and wear.

INTRODUCTION

Since 1951, the Tank Farms at the Department of Energy's Savannah River Site (SRS) have received more than 600 ML (160 Mgal) of liquid high level waste (HLW). SRS has used a series of dedicated evaporators to manage the liquid waste and has reduced the volume by about a factor of four. Evaporation still has an essential role in SRS actively managing its liquid waste. While the waste vitrification processes reduce the total radioactive inventory, they also generate about 6 ML additional liquid waste volume per year [1].

Currently, the site is evaluating repair or replacement of the 242-25H HLW Evaporator (25H), which was designed in the early 1990s, put into service in January 2000, and discovered to be leaking in February 2016, after sixteen years of service. The maximum leak rate was about 0.4 L/min (0.1 gpm). The leakage was contained within a cell, preventing a hazard to personnel and a release to the environment. Since 1961, SRS has operated nine evaporators [2]. The steam tube bundle or its tubes have predominantly failed from hot-wall corrosion or thermally-induced fatigue within a decade, limiting service life. The 25H Evaporator is the first to fail by another mechanism, a vessel shell failure, making it unique in the site's history.

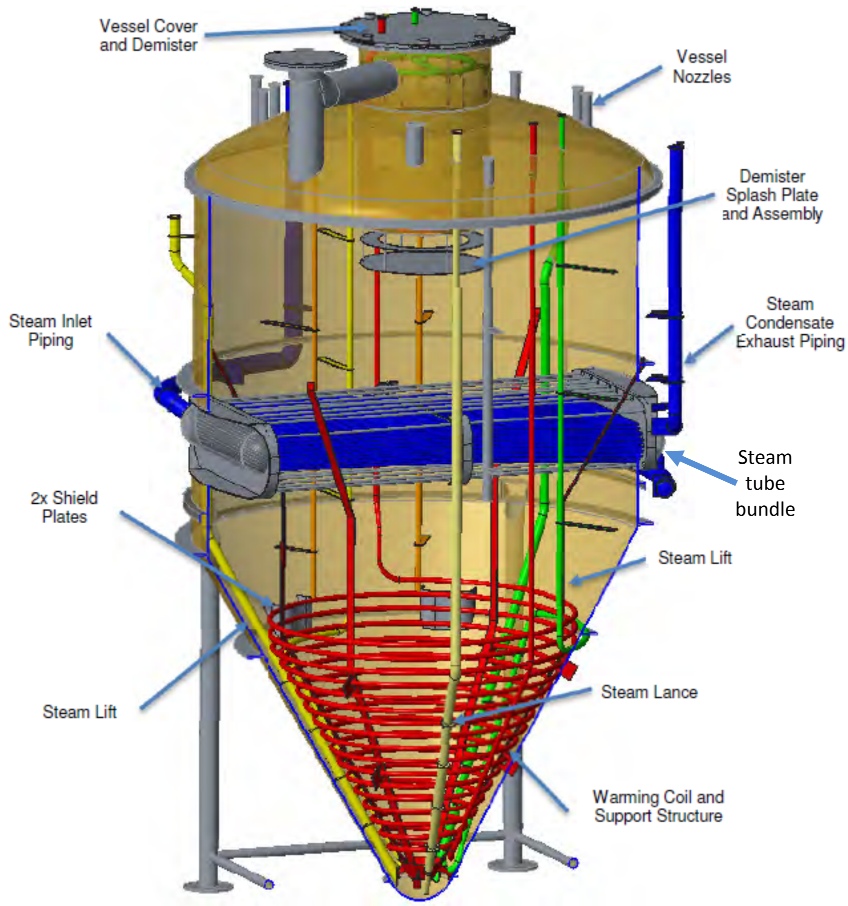

Fig.1. Major components of the 25H Evaporator (figure is from [3]).

The 25H Evaporator is a single-stage "pot" evaporator, as shown in Figure 1, and is about 8 meters tall by 4 meters in diameter. It is functionally identical to earlier SRS evaporators but about four times larger in volume and made from a more corrosion-resistant material (i.e., nickel-based Alloy G-3 instead of 304L stainless steel). The vessel consists of a lower conical section supported by four legs; an upper cylindrical section with a horizontal steam tube bundle; and a vessel head. The tube-bundle has hundreds of slightly curved tubes running between two thick vertical tube-sheets on opposite sides of the vessel. A steam lance injects steam into the vessel bottom and keeps the waste mobilized. Two steam and two lift lines also run to the bottom of the vessel cone to remove concentrated waste.

Normally, the vessel is at near-atmospheric pressure and holds highly caustic liquid waste, which is concentrated by heat from the tube bundle. Periodically, operators rapidly cycle steam to the tubes, causing the tubes to rapidly expand and contract and thereby remove scale. These thermal shocking transients improve heat transfer and corrosion resistance but introduce the possibility of fatigue, complicating the design.

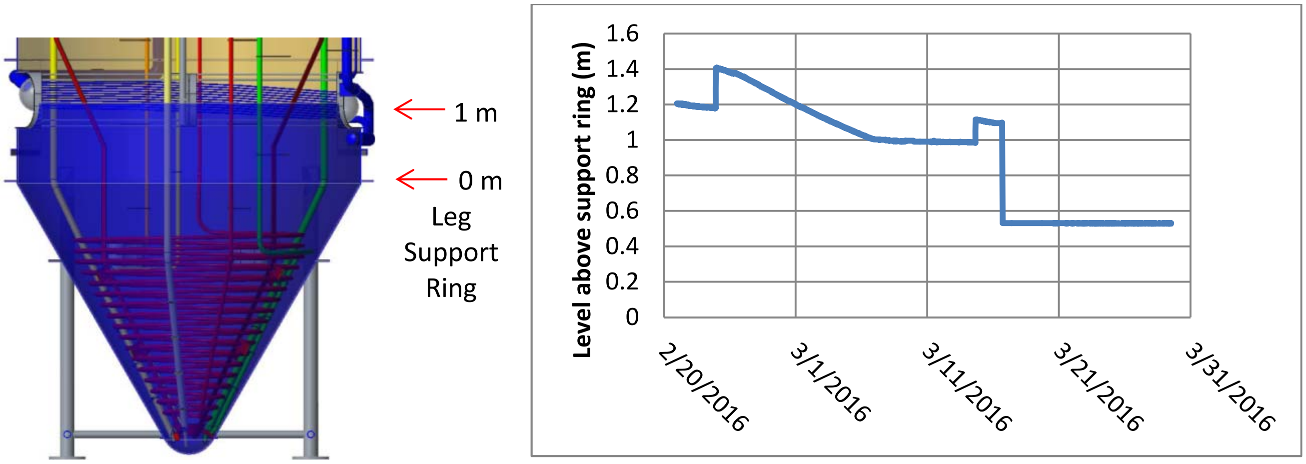

Fig.2. Leak rate data (evaporator figure is from [3]). Level dimensions are relative to the support ring where the legs are attached and where the shell transitions from a cone below to a cylinder above (i.e., 0 m).

Fig.3. Figure on the left shows visible salt deposits, emanating from where the legs penetrate the vessel insulation. Salt deposits are not visible on or above the support ring (0 m level). Figure on right shows the leg support ring during fabrication before installing vessel interior components, shipping to the site, and installing insulation.

At this time (October 2016), the location and nature of the 25H Evaporator leak are still being determined. Leak rate data and stress analyses favor a leak location near the tube bundle (Figure 2). However, visible salt deposits were found only on the lower cone (Figure 3). The evaporator drawings show no clear pathway for waste to flow from the tube bundle area to the cone without being visible on the upper cylindrical section, favoring a leak location in the cone. The vessel thickness is 9.5 mm (3/8 inch) in the cone and 14.3 mm (9/16 inch) in the cylindrical section.

Part I separately discusses the physical investigation to determine the nature and location of the leak site. This paper discusses the work to evaluate the most plausible failure modes.

DISCUSSION

The 25H failure investigation estimated the leak size, considered prior evaporator failures, and evaluated failure modes including but not limited to operations, materials, corrosion, fatigue, erosion, and wear, as discussed below.

Estimating the Defect Size and Location

Two alternate leak-site locations were considered: (1) in the conical shell and (2) within the elevation of the tube-bundle.

In early March 2016, to help find the leak-site, the leak was permitted to flow unimpeded until level stabilized, which occurred at about mid-elevation of the tube-bundle, 1.0 m above the support ring for the leg attachments (Figure 2). Level was raised and allowed again to fall unimpeded, this time falling more slowly and stabilizing at 1.1 m above the support ring, still within the height of the tube-bundle. Level was then lowered below the tube-sheets but above the support ring; it remained steady for the next two weeks, supporting a scenario that the leak-site was within the tube-bundle elevation.

The leak-rate data during this period was analyzed and is consistent with a crack about 25 mm long by 0.5 mm wide at the tube bundle elevation.[1] An attempt to re-activate the leak in early May 2016 was unsuccessful, indicating that the leak has somehow sealed.

After the leak's discovery, remote inspections of the vessel exterior showed salt deposits where the leg supports penetrate the vessel's insulation and insulation sheathing (Figure 3). Salt was not observed on the upper cylindrical portion of the vessel, supporting that the leak-site is in the cone below the support ring and not at the tube bundle elevation.

For the cone failure scenario, an equivalent hole diameter of 2 mm to 4 mm would be consistent with the maximum leak-rate (which occurred on February 28, 2016) and assuming the leak is located in the cone, fills the insulation annulus, and exits out the leg penetrations.

Evaporator Failure History

Since 1961, SRS has operated nine HLW evaporators [2].

- Six evaporators had tube or tube bundle failures after a median life of nine years. Three of these were investigated, repaired, and reused. Of these, two had a second tube bundle failure, and the third was retired before failure.
- One other evaporator was retired without failure.
- The eighth evaporator (242-16H) remains operational after 21 years but is about four times smaller in volume; evaporates a different waste stream; and operates at lower temperatures and about half the steam demand of the 25H Evaporator.
- The ninth evaporator is 25H, which has the site's first evaporator shell failure.

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[1] Flaw dimensions were estimated assuming a fatigue crack at the tube bundle and an erosion or wear hole in the cone and using the Bernoulli equation with friction head loss. An example of a similar leak rate analysis is in [4].

Three of the failed evaporators were forensically investigated, which was done as part of the effort to reuse them. Two of these evaporators had tube pitting at locations where the tubes join the tube-sheet. Halides concentrate in pits under the scale that accumulates on tubes. To prevent this, since about 1990, the site has required tube bundles be submerged in inhibited water within 30 days during outages.

The tubes are also periodically descaled by cycling steam flow and thermally flexing the tubes. However, descaling is only partially effective where tube flexing is constrained by the tube-sheets. The disadvantage of descaling is thermal cycling causes high stresses and fatigue. One earlier evaporator failed due to fatigue, attributed in that case to incorrectly installed tubes at the tube-sheet.

In summary, tube-related failures historically have limited evaporator service life. This stands to reason since the tubes are an evaporator's hottest components and are most susceptible to corrosion, cyclic thermal stresses, and fatigue. The 25H Evaporator design emphasized avoiding these tube and tube-bundle failure modes, but there may have been less emphasis on evaluating the possibility of shell failure modes, including fatigue.

Operationally-Induced Failure Modes

The 25H Evaporator was designed for caustic chemistry and moderate pressures and temperatures. The tube bundle design steam conditions were 2.3 MPa (340 psia) and 230^{o}C, which would be peak conditions during descaling. The tube bundle design fatigue life was 6,000 descaling operations, assumed to occur over 30 years.

The vessel shell was designed for 200^{o}C and absolute pressures of 0.2 MPa (15 psig) and full vacuum. Assumed specific gravity was 1.7.

Actual operating conditions have been less severe than assumed in the design. For example, normal shell operating pressure is near-atmospheric (0.1 MPa). Normal liquid temperatures are about 150^{o}C, which is 50^{o}C cooler than the design value. Operating parameters are continuously monitored such that an upset leading to an abnormal condition would cause an alarm and be addressed. Operationally-induced failure modes seem unlikely.

Material and Corrosion Related Failure Modes

During operation, the 25H vessel is exposed to highly caustic conditions, equivalent to boiling concentrated sodium hydroxide solution at 150^{o}C. Sodium, free hydroxide, nitrates, and nitrites are the dominant chemical species. Chlorine (~200 ppm), fluorine (~80 ppm), and mercury are also present. HLW evaporators may also need to be chemically descaled or decontaminated during their service life. Although the 25H Evaporator has not needed this, its design included considering decontamination agents, such as nitric acid, oxalic acid, and potassium permanganate.

After a mid-1980s evaporator failure with just two years of operation, SRS developed improved corrosion control practices, such as minimizing halides and using inhibited water (pH > 13) for evaporator lay-ups longer than 30 days. The three evaporators started up since then have achieved service lives of one to two decades, which may be due in part to an improved corrosion control program.

The earlier evaporators were fabricated from stainless steel 304L, which is more susceptible to general and pitting corrosion than nickel-based alloys. To increase service life, the eighth evaporator (242-16H) has a stainless steel shell and a nickel-based alloy tube bundle (Alloy G-30, UNS N06030); it is still operating. The larger 25H evaporator uses a similar nickel-based alloy (Alloy G-3, UNS N06985) for all components exposed to liquid waste, including the tube bundle and the shell.

Alloy G-3 was commercially developed for acidic applications in the chemical processing industry, primarily for phosphoric acid, but it has good general corrosion and pitting resistance under caustic conditions [5, 6].

In the mid-1990s, SRS tested Alloy G-3 and stainless steel 304L under conditions simulating tube heat transfer and evaporator solutions, including minor constituents. Alloy G-3 general corrosion rates were an order of magnitude lower than for stainless steel 304L. U-bend tests of Alloy G-3 showed evidence of surface micro-cracking but no evidence of significant crack extension in caustic solutions. Stainless steel 304L did not exhibit such cracking, but any cracking could possibly have been masked by stainless steel's higher general corrosion rate [7].

Pitting is possible but unlikely in the 25H Evaporator given Alloy G-3 has nominally 20% chromium and 7% molybdenum. All other factors being equal, pitting failure would have occurred on the hotter evaporator tubes before the cooler shell.

External corrosion of the G-3 shell was considered; however, external corrosion would have first been apparent on the external stainless steel insulation sheathing, which has not been seen.

Galvanic corrosion was considered. The G-3 shell is in contact with external stainless steel 316L components, such as the support ring and legs. While these are dissimilar metals, they have low galvanic coupling potential.

Mercury enhanced corrosion or fatigue is a possibility. Slow strain-rate tensile testing and fatigue testing indicate mercury and, similarly, hydrogen can promote surface cracking and reduce fatigue life [8]. The mercury concentration in the 25H Evaporator is lower than seen in other site evaporators (e.g., 242-16H). This seems unlikely, but material testing may be needed to completely eliminate this as a cause.

Overall, corrosion-related failure modes seem unlikely, primarily because of the use of nickel-based Alloy G-3, which is compatible with this application. Mercury could have had a role in the failure, since there is an absence of data to assert otherwise.

Fatigue Failure Modes

The 25H Evaporator pressure design was based on the American Society of Mechanical Engineers (ASME) boiler and pressure vessel code, ASME Section VIII, Division 1 (1989 version with 1991 addenda). Because of the site's history of tube failures, the 25H design was supplemented with fatigue analyses using methodology from ASME VIII, Division 2 (1992 version with addenda) – focused on the tubes and the tube bundle. The design objective was to achieve a 6,000 cycle service-life over 30 years for the tube bundle.

The geometry is complex where the shell meets the tube-sheet and the interconnecting sleeve (an obround nozzle). Therefore, as part of the 25H failure investigation, a finite element model was prepared with sufficient fidelity to inform engineering judgment on fatigue [3]. The model was based on nominal rather than design conditions. The model also only included features judged relevant to the failure. For example, it included full gravity loads but excluded external piping and nozzle loads. Some conclusions from this scoping analysis are:

- Calculated stresses in most locations are low for both normal and descaling operations. This is expected since the vessel is essentially at atmospheric pressure and at temperatures well below design.

- The highest calculated stresses are at the interfaces of the shell, the tube-sheets, and the sleeves for both the steam and the condensate chests (Figures 4 and 5). In these locations, calculated stresses during descaling operations exceeded yield, driven by a 135^{o}C temperature gradient between the steam and the shell over a short distance. The temperature gradient is lower (40^{o}C) during normal operations, leading to calculated stresses of about half of yield.

- For these stresses, calculated fatigue life ranged from about 300 to 4,000 cycles for welds and 900 to 14,000 cycles for base metal. For comparison, the 25H Evaporator has experienced about 500 to 700 thermal cycles, assuming about 20 descaling operations and 10 to 20 normal thermal transients per year.

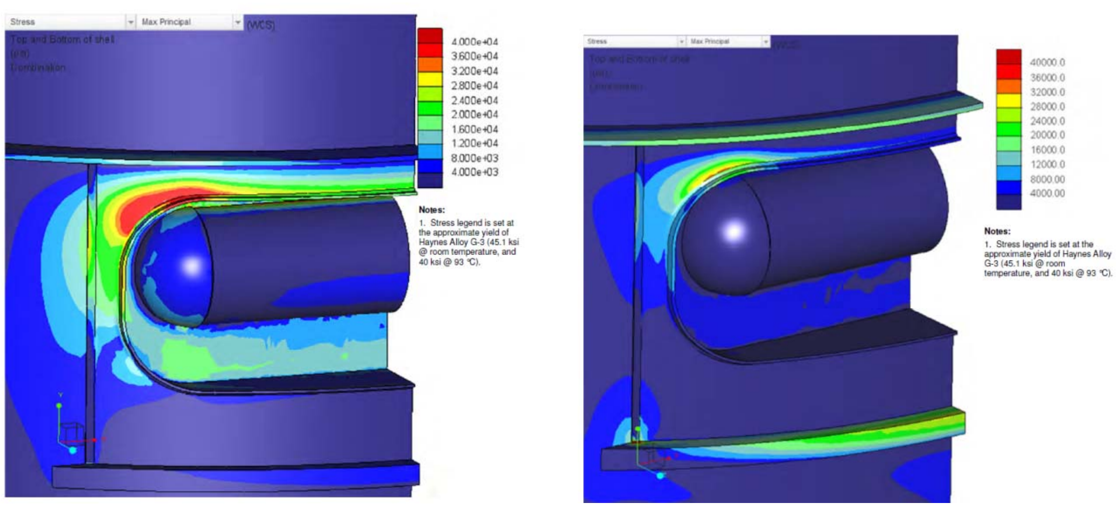

Fig 4. Maximum principal stresses for descaling and normal operations [3].

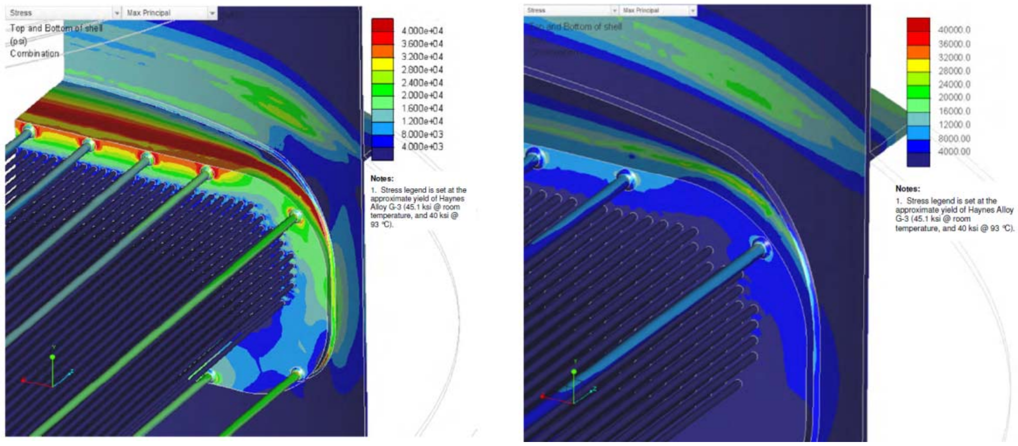

Fig 5. Maximum principal stresses for descaling and normal operations [3].

Given these results, thermally induced fatigue of the shell where it joins the tube-sheets is possibly but not conclusively the cause for the leak. Fatigue could be enhanced by environmental factors (e.g., mercury), an initial defect, or both. However, a fatigue failure at this location is contradicted by the lack of visible waste externally above the cone.

Erosion Failure Modes

To keep the waste mobilized, the steam lance in the cone operates continuously during evaporator operation and intermittently when operations are secured, using saturated steam at 0.27 MPa (40 psia), 131^{o}C. Once steam exits the lance, within centimeters, it mixes with the liquid and solids in the bottom of the evaporator, resulting in a steam-liquid-solid mixture impinging on the vessel. Given these conditions, the failure evaluation considered cavitation, liquid impingement, and solid particle erosion induced by lance steam flow as failure modes.

The lance mass flow and exit velocity are about 570 kg/hr and 80 m/sec, respectively. These values are about three times higher than for earlier SRS evaporators, creating the possibility that higher lance steam flow could cause a failure not seen in earlier site evaporators.

Cavitation was qualitatively evaluated by considering nuclear power industry guidance [9]. Cavitation occurs when locally varying pressures drop to vapor pressure, and it depends upon fluid momentum and vortex formation. While the evaporator bottom is operating close to vapor pressure, the steam in the mixture suppresses the creation of vapor bubbles and cushions their collapse. Injecting gases into a liquid is actually a technique used to suppress cavitation. Nickel-based alloys are also highly resistant to cavitation, making this an unlikely cause.

Steam-liquid impingement, without solids, was evaluated using an empirical approach recommended by the American Petroleum Institute (API) [10]. Particularly, API-14E has a recommended velocity limit for two-phase mixtures, which is a function of the mixture bulk density. The evaluation found the velocity of the mixture impacting the vessel is about two-thirds of this limit over the full range of possible mixture bulk densities, making steam-liquid impingement an unlikely cause.

Solid particle erosion involves harder particles being projected by a fluid and abrading a softer material. It depends on the hardness of the particles and target material, velocity, abrasive mass flow rate, particle size distribution, impact angle, and other factors [11, 12].

The technical literature considers two velocity regimes, depending on whether particle velocity is above or below 200 m/sec. In the lower velocity regime, wear rate is roughly proportional to velocity cubed (i.e., to fluid power). The 25H Evaporator's higher lance steam velocity indicates about an order of magnitude faster erosion rate than for previous SRS evaporators.

However, the small HLW particle sizes in the waste could mitigate this. While the particles tend to be hard, they also tend to be on the order of 3 μm. At least in the high velocity regime, erosion rate seems to be insensitive to particles with sizes of 100 μm or above and to fall off rapidly for smaller particles; some experimental data indicates wear rates for 5 μm particles at about 3% of those for 100 μm particles [13].

The effects of impact angle and particle size are interrelated. While the 25H configuration has a low impact angle that would promote erosion, the small particle size may strongly compensate for this.

Given all this, solid particle erosion was evaluated parametrically using the approach recommended in [11]. The analysis assumed failure required a steam-liquid-solid mixture abrading away a spherical depression in the vessel cone. Depending on the assumptions made, a fraction of a weight percent of entrained particles could conceivably erode through the vessel thickness in a few years. However, the effect of particle size was extrapolated, and small particle size would mitigate this effect. Solid particle erosion is a plausible but not conclusive cause of the leak.

Wear Failure Modes

Wear requires contact and motion and can occur with even minute motion. For example, the American Society of Materials (ASM) Handbook defines fretting wear as: "A special wear process that occurs at the contact area between two materials under load and subject to minute relative motion by vibration or some other force."

The 25H Evaporator steam warming coil, shown in Figure 1, developed a leak in 2004. This was attributed to the coil piping rubbing on the coil frame and wearing about a 2 mm diameter hole in the piping. While this did not impact evaporator operation, it does indicate the possibility of relative motion occurring among the components in the cone that could lead to rubbing and wear between the components and the shell.

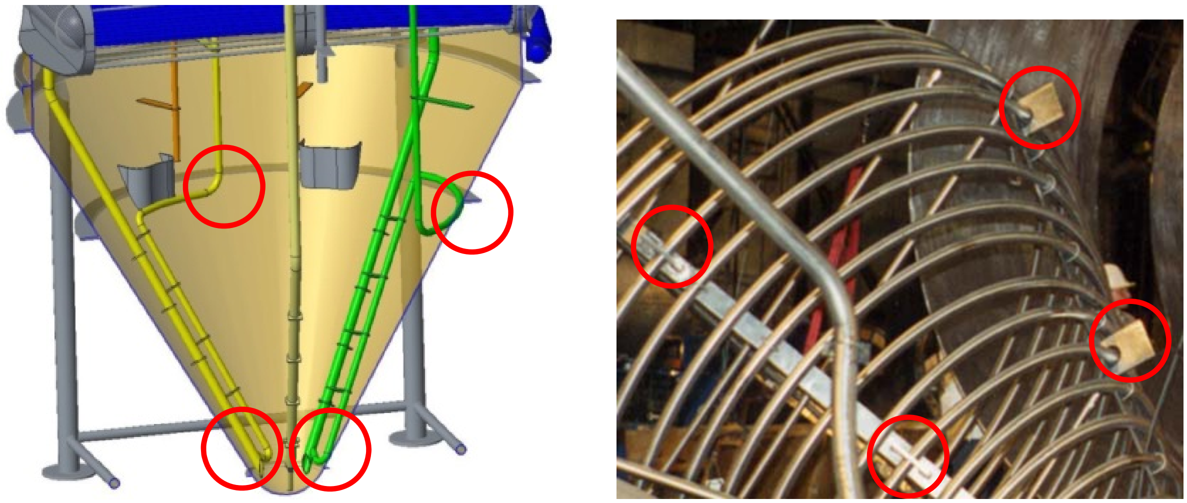

Fig. 6. Potential rubbing locations in the vessel cone: (1) possible steam line interferences; (2) warming coil support plates.

For the 25H Evaporator, two possible sources of metal-to-metal contact and relative motion in the cone are shown in Figure 6:

- There are two steam lines that run to the bottom of the vessel. These create a vacuum in the lift lines, causing the motive force to remove concentrated waste from the vessel. Drawing dimensions indicate the potential for these steam lines to interfere with the vessel at four locations. The steam lines would fit in the vessel, provided there is a small twist of the steam lines by a fraction of a degree. The resulting torsion could cause a high contact force between the steam lines and the vessel. Daily repetitive motions, perhaps caused by daily temperature swings or random building vibrations could cause relative motion.

- The warming coil frame has eight guide plates that may touch the vessel with a low contact force. The guides prevent excessive lateral motion in the event of an earthquake. The guide plates were not needed in earlier SRS evaporators because they used smaller warming coils. The warming coil has low natural frequencies and is susceptible to amplified motion, possibly caused by random vibrations or cross flows.

This evaluation parametrically considered adhesive wear, with both good and poor lubrication, and abrasive wear. Adhesive wear occurs when one surface slides over or is pressed against another and particles detach from one surface and pass to another. Abrasion involves a hard rough surface sliding against a softer surface and plowing grooves in the surface (two-body abrasion) or small hard particles being trapped between two softer moving surfaces and abrading both (i.e., three-body abrasion).

The methodology used and the wear parameters assumed are from [11] (i.e., the Archard equation). Since the wearing components are all from the same material (Alloy G-3), the evaluation assumed failure required wearing through twice the vessel thickness. Depending on assumptions made, the wear rate varies two orders of magnitude with the highest being for abrasion and the lowest being for adhesive wear with good lubrication.

The parametric study found, for the warming coil guides, the required contact force to fail the vessel would be low, ranging from about 1 N at 10 Hz under abrasion to 4 N at 200 Hz under adhesion with good lubrication. It is possible that cross flow or other disturbances could cause the warming coil to vibrate in this frequency range. For the steam lines, assuming a high contact force and low contact area indicated that a repetitive motion every twenty minutes to thirty hours would be sufficient to wear through the vessel.

Overall, a wear failure in the cone seems possible and intuitively more likely than erosion; however, the sources of motion are speculative, making wear failure not conclusively the cause.

CONCLUSIONS

Possible causes of the 242-25H Evaporator's recently developed shell leak are evaluated. An evaporator shell leak is unique in the site's operating history; previous on-site evaporator failures have predominantly involved the hotter steam tubes and tube bundle. Finding and characterizing the leak has been challenging because of conflicting information from leak rate data and the locations of externally visible waste. This led to considering failure modes both in the cone and on the cylindrical section at the tube bundle elevation.

An operationally-induced failure seems unlikely since the evaporator shell is kept at near-atmospheric pressure and at temperatures about 50^{o}C cooler than assumed in the design. A corrosion-related failure seems unlikely because wetted components are made from Alloy G-3, a nickel-based alloy with nominal 20% chromium and 7% molybdenum that has been tested for this high caustic service. The possible exception is the effect of mercury in enhancing corrosion because there is an absence of data to assert otherwise; however, the mercury concentration seen by the 25H Evaporator is lower than seen by other site evaporators.

Solid particle erosion is possibly but not conclusively the cause. A parametric study indicated that a small weight fraction of solid particles entrained by the steam lance at the bottom of the vessel might abrade through the shell in a few years. However, the particle size effect was extrapolated from data for larger particles, and the small particle size (3 μm) would tend to mitigate this effect.

Thermally induced fatigue where the shell joins the tube-sheets is also a possible but not conclusive cause. High transient stresses are calculated at these locations during descaling operations. The leak rate data is also consistent with the leak-site being at this location. However, the externally visible salt deposits are on the cone and the drawings indicate no means for a leak to originate at the tube bundle elevation and not be visible above the cone.

Wear between components in the cone could be a cause for the leak in the cone. The 2004 failure of the steam warming coil in the cone was attributed to the coil piping rubbing against its frame, indicating components may be moving in the cone. The drawings indicate interferences and points of metal-to-metal contact in the cone. An order-of-magnitude parametric study indicates that flow-induced vibrations or random building vibrations could cause the necessary rubbing motions; however, the specific sources of motion are speculative. At this time (October 2016), investigations continue to characterize the leak.

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