

Continuous digester rapid thinning and general corrosion

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ABSTRACT: Carbon steel continuous digesters built after the early 1980s are fully stress relieved, so stress corrosion cracking has been less of a concern. However, these newer digesters were designed to run modified cooking processes that have turned out to be much more corrosive than those running with conventional cooking. This corrosion is mainly associated with softwood digesters and appears to be flow related. Average corrosion rates of 40 mil/year are possible on the exposed shell between the wash and extraction screens. The corrosion patterns are visually distinct from surfaces in the upper digester and below the wash screens.

This paper goes into practical detail on where it occurs, the causes, visual identification, inspection planning and results evaluation, and finally, how to mitigate this damage, which consists of applying a corrosion resistant barrier. Some discussion on dealing with general corrosion throughout the digester is included.

Application: This will help those who are involved with continuous digester mechanical integrity to plan, conduct, and evaluate inspections.

The industry became aware of rapid continuous digester corrosion in the late 1990s. It occurred mainly in modified cooking digesters that had been built after the mid-1980s. Because these vessels had been fully stress relieved, the risk of stress corrosion cracking was low [1]. Rather, widespread uniform corrosion became a threat to digester pressure vessel integrity. The damage mechanism came to be known as “wash zone” corrosion, with TAPPI defining rapid thinning as greater than 20 mils/year (0.5 mm/year) [1]. The maximum average corrosion rate is about 40 mils/year (1 mm/year). The rates are high enough to consume a 0.25 in. (6 mm) corrosion allowance in less than 10 years. Today, a new digester would be built out of materials such as 304L clad carbon steel or duplex stainless steel because of their resistance to both stress corrosion cracking and general corrosion in alkaline liquor environments.

WHERE DOES RAPID THINNING OCCUR

Rapid thinning occurs on the exposed steel shell in the midsection of the digester between the top and bottom screens below the cooking zone. The bottom screens are called the wash screens. There is an intermediate set of screens and for the purpose of this paper, the top screens will be referred to as the extraction screens. Carbon steel blank and header plates between the wash and extraction screens can also corrode at high rates.

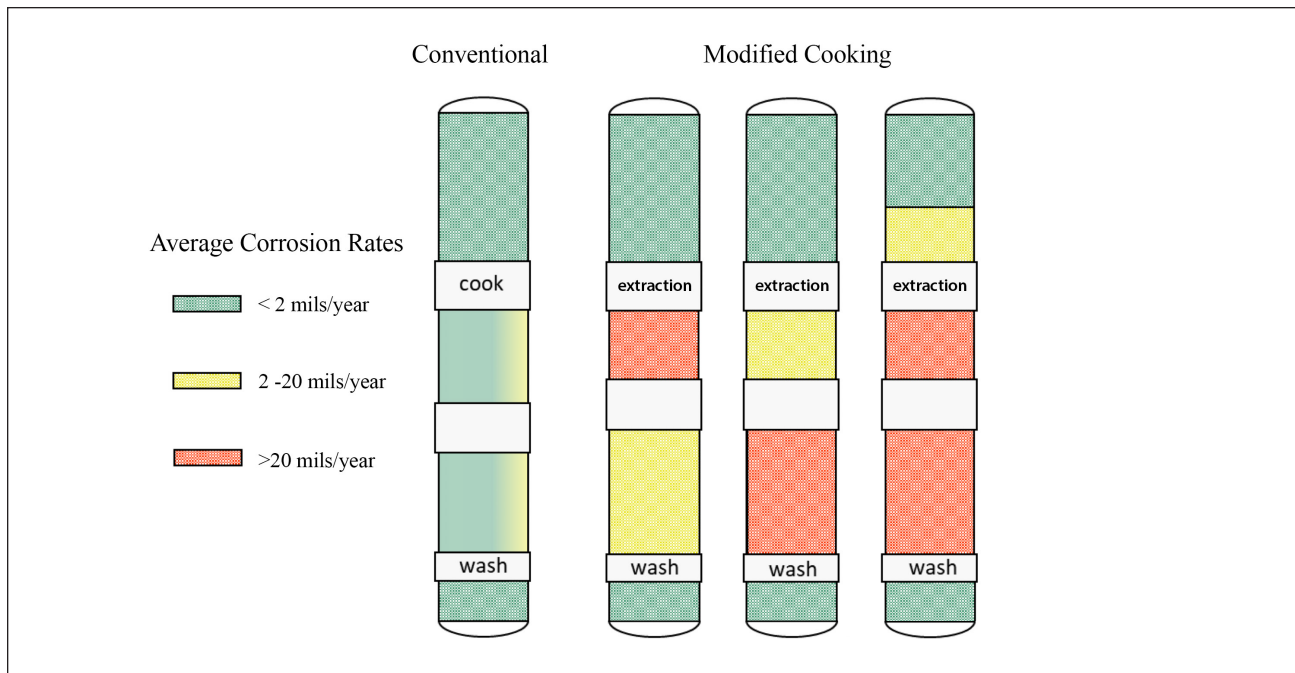
Figure 1 compares corrosion patterns of conventional cooking vs. modified cooking digesters. The sketches are simplified maps based on analyzing thickness data for 20 digesters over 30 years. Regardless of the process, carbon steel in the upper digester and impregnation vessel (in two vessel systems) remain passive with respect to corrosion,

i.e., the corrosion rates are well under 2 mils/year (0.05 mm/year). Below the wash screens, corrosion rates are usually 1 to 2 mils/year (0.02 to 0.05 mm/year) and often slightly higher than those in the top zone of the digester. Corrosion rates in conventional cooking digesters are low throughout the vessel. The midsection of the vessel may have a rate 1 or 2 mils/year (0.02 or 0.05 mm/year) higher than the those at the top and bottom.

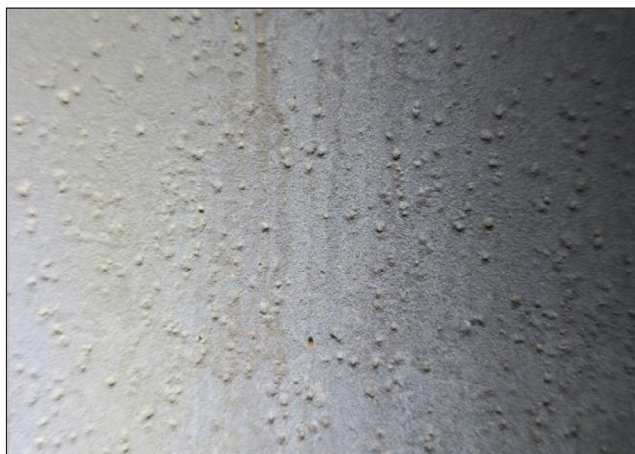
For modified cooking, the sketch on the far right of Fig. 1 shows an unusual corrosion pattern in that the area between the wash and extraction screens experiences high corrosion rates and moderate corrosion extends into the cook zone, reaching as high as the round trim (nozzle) screens. The two middle examples are more typical, with neither pattern more prevalent than the other. Usually, one area between the wash and intermediate screens or intermediate and extraction screens corrodes at a high rate while the other lags at moderate rates. Though corrosion protection may be needed throughout, it dictates the order of repair. Not shown in the diagram is a shadow effect in which the shell just below the intermediate or extraction screens corrodes at lower rates than the sections below. For the purpose of visualization, 3 ft (0.9 m) is a good estimation.

CAUSE OF RAPID THINNING

The cause of this corrosion has been attributed to low residual alkali in the extraction liquors [2]. Though the sodium hydroxide concentration in the wash zone may be lower than what is thought necessary to minimize carbon steel corrosion, later research and field experience does not bear this out. In situ monitoring concluded that rapid thinning can only be correlated with softwood pulping [3]. Softwood extraction liquors are known to be more corro-



1. Continuous digester thinning patterns. Corrosion rates are low at the top and bottom, regardless of the process. Rates are low for conventional cooking, shown on the left. Rates are moderate to high in the midsection for modified cooking (1 mil = 0.02 mm).



2. Upper digester pits are shallow, round, less than 0.25 in. (6 mm) in diameter, and dispersed. The surface is rough.



3. Preferential corrosion of a weld and heat affected zone. Rapid thinning can display a variety of colors.

sive than hardwood extraction liquors [4], and softwood digesters experience more corrosion than hardwood digesters. More recent research [5] found that the correlation with residual alkali was inconclusive. Temperature is probably a factor in that corrosion rates increase with increasing temperature.

Visually, the cause is erosion-corrosion, as described in WRC Bulletin 488 [6]. There are more aggressive situations as found in internal headers, the digester penthouse, and flash tanks. Nevertheless, as described in the next section, rapid thinning is accelerated by flow, which keeps the steel from maintaining its protective passive surface layer in alkaline solutions.

VISUAL IDENTIFICATION

Corrosion in the upper digester and below the wash screens can be described as spreading pit liquor corrosion [6], which is indicative of static conditions. The pits are uniformly distributed, round, shallow, and have the same depth. As noted, these areas have very low general corrosion rates. The color is typically rust red or grey if covered with a light scale, as shown in **Fig. 2**.

Rapid thinning manifests itself in several different ways that distinguish it completely from corrosion seen in passive locations. Preferential corrosion is common, as shown in **Fig. 3**. Weld caps corrode away, leaving them ditched out below the plate surface. Heat affected zones, grind

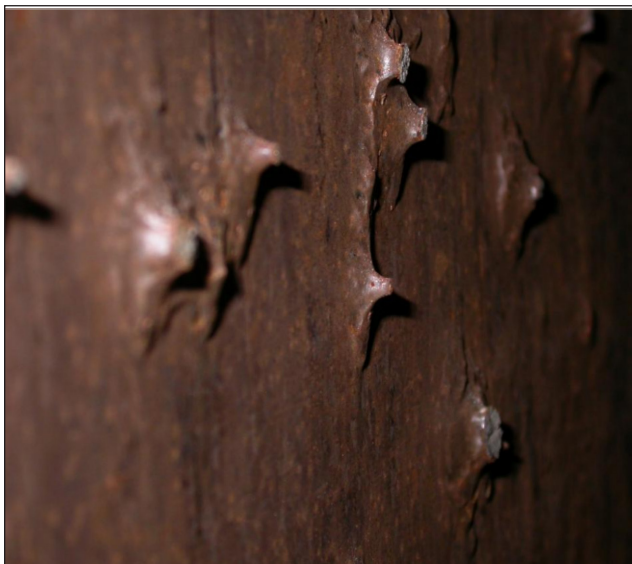


4. "Ocean-island" corrosion. Low areas drop off steeply from the high areas.

marks, scratches, and anywhere the original steel mill scale is disrupted are more susceptible to corrosion.

As to widespread corrosion, there are two main features. The first may be called "ocean-island" corrosion where small islands of metal protrude sharply, almost at right angles, above the lower ocean floor, as **Fig. 4** and **Fig. 5** display. The islands possibly consist of microchemistries that may be more resistant than the widespread ocean areas. The floor is smooth, a sign that flow is a factor. Colors may vary and for the most part, the corroded surfaces are not rust red.

The second way the corrosion is displayed is as complete polishing or flattening of the surface. Grooving may be



5. Sharp spikes of resistant metal protrude from the corroded surface.

present but any round liquor pitting is washed out. These surfaces appear to be shiny and can be light grey in color, as seen in **Fig. 6**.

INSPECTING RAPID THINNING

The fixed equipment inspection cycle [7] applies to continuous digesters. This means that recognized industry practices such as the following should be used to guide the development of the inspection program.

- NBIC "National board inspection code" from the National Board of Boiler and Pressure Vessel Inspectors.
- API 510 "Pressure vessel inspection code: In-service



6. Grooving on the corroded surface suggests a form of erosion-corrosion. Preferential corrosion of the weld is also occurring.

- inspection, rating, repair, and alteration” from the American Petroleum Institute.
- TAPPI TIP 0402-27 “Guidelines for inspection of continuous digesters and impregnation vessels” from the Technical Association of the Pulp and Paper Industry.

In its simplest form, there are three major steps in an inspection program:

1. Plan the inspection based on all known damage mechanisms.
2. Conduct the inspection as planned.
3. Evaluate the inspection results in a timely manner in order to schedule the next inspection and/or repairs.

Corresponding documentation includes the written scope, non-destructive testing (NDT) results, and inspection report — all of which need to be reviewed in preparation for the next outage.

The inspection program should include shell thickness testing. If rapid thinning is occurring, ultrasonic thickness testing (UT) of affected areas will have a high priority, and because outage maintenance time is limited, may be the damage mechanism that dominates the overall scope of and intervals between vessel inspections.

Internal UT is the primary method for monitoring corrosion. External UT, even on the run, is an option, but scaffolding is usually needed for access, and the insulation must be removed. It is better suited for specific areas of interest and must be matched up with the internal grids to be useful.

Thickness grids

A common practice is to measure thickness along four equally spaced vertical lines that are oriented so that a line intersecting the middle of the bottom manway is 0°. For a full shell course, which is approximately 10 ft (3 m) in height, a 4 x 3 grid can be used with a reading taken above the bottom weld, below the top weld, and in the middle of the plate. This grid is fine for areas that are not corroding. A 4 x 5 grid, with additional readings centered between the middle and welds, will produce an average course thickness that does not change much with additional readings. Partially exposed shells will have fewer readings relative to a full plate. Once a grid is established, repeat thickness readings should be taken at the same locations.

The grid should be adjusted to match the corrosion rate and can change from inspection to inspection. If rapid thinning is detected, a finer grid will map out the corrosion in more precise detail. As an example, **Fig. 7** shows such a grid that has been color coded to show the extent of thinning. These readings were obtained prior to the section being overlaid with stainless steel. Thicknesses were recorded on a 2 ft x 2 ft (0.6 m x 0.6 m) grid; however, for the purpose of display, widthwise only thickness every 4 ft (1.2 m) is included in Fig. 7. This example shows only the bottom 6 ft (1.8 m) of a 10 ft (3 m) shell course, because the top 4 ft (1.2 m) had already been overlaid with stainless steel. Thickness had been converted to remaining corrosion allowance (RCA), with red indicating an RCA less than 50 mils (1.2 mm) above the code minimum thickness, *Tmin*. The RCA increases successively through orange, yellow, and green. White areas have an RCA over 200 mils (5 mm). This chart shows that the corrosion is not uniform around the circumference and explains why thickness reading locations should initially be evenly distributed.

Analyzing the inspection data

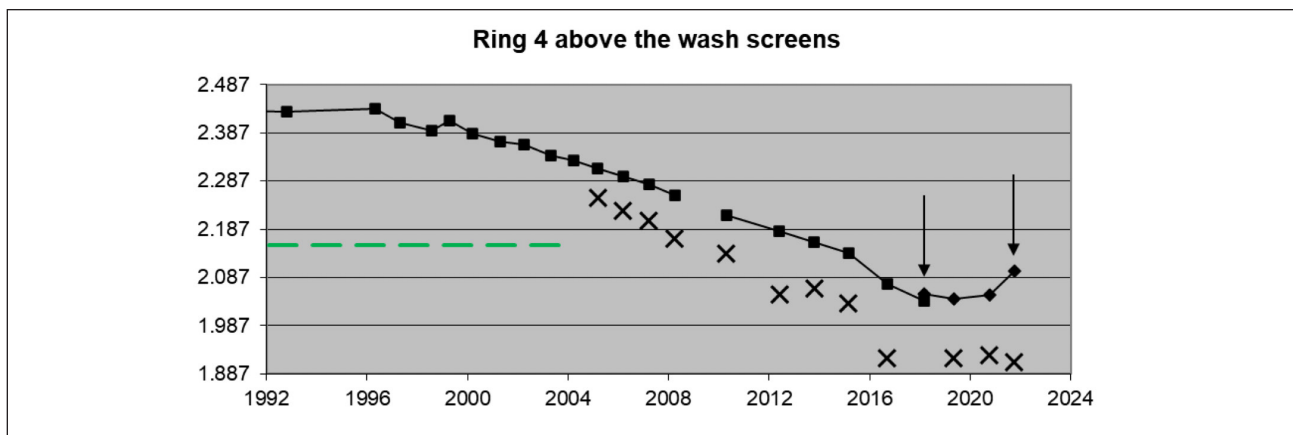
Thickness readings need to be analyzed as soon as the data is collected. There are three reasons for this: 1) to ensure that thickness has been accurately recorded; 2) with respect to rapid thinning, there are no areas below *Tmin*; and 3) to determine when the next inspection or repairs should be scheduled.

Based on the variability of measurements and corresponding corrosion rates for a single location from inspection to inspection, it is likely the accuracy of continuous digester UT is not as precise as assumed. A contributor to this may be that the digester shell surface is rough and uneven. This can be seen in areas where there is no corrosion. Rather than forming a flat, horizontal trend line, thickness over time can bounce above and below the average, which does not change, giving the impression of extreme corrosion in one inspection and wall thickening (which is not happening in reality) the next.

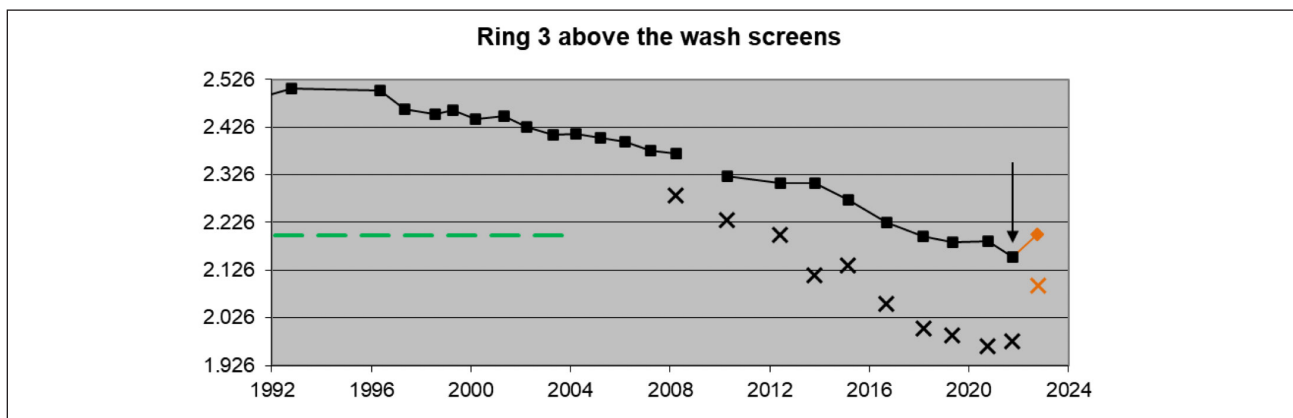
This situation could possibly be improved by defining a protocol for digester surface preparation. However, by using average thickness for a shell course or at specific elevations, when more precision is needed, the condition of the digester can still be assessed. The average RCA, average

109	123	218	123	130	186	168	154	200	134	185	101	120	36	43	1	42	28	58	130	137	113
146	132	188	141	192	214	228	199	174	168	171	123	90	81	59	31	97	95	97	127	145	152
167	145	199	153	192	238	246	189	196	130	162	165	133	72	48	49	85	92	123	156	162	145

7. Sample thickness grid displayed as remaining corrosion allowance. Red is within 50 mils (1.2 mm) of code minimum thickness, *Tmin*. Thickness increases through orange, yellow, and green. White represents over 200 mils (5 mm) above *Tmin*. Corrosion is not uniform around the circumference; one strip is thinning more than the rest of the shell.



8. A sample chart displaying average shell course thickness (in.) vs. time (year). The x-axis crosses thickness at T_{min} . The green dashed line represents the original T_{min} . It was recalculated in 2004, almost doubling the remaining corrosion allowance. "X" represents the lowest measured thickness, the location of which changes every inspection. Arrows point to the years the shell was overlaid with stainless steel. It is now 100% covered.



9. A shell course below that seen in Fig. 7. The corrosion pattern is similar, though the rates are lower. Over the years, the corrosion rate went from 0 to a moderate rate around 1996, to a high rate around 2014, and then to 0 again in 2019. The shell was partially overlaid in 2021 to cover areas with low minimum thicknesses. The remaining lower section now has a higher average thickness and remaining corrosion allowance.

thickness minus T_{min} , is useful for visualization. For a shell course, T_{min} at the bottom of the plate is used. For specific elevations, T_{min} at the bottom of the plate is acceptable or can be calculated at that elevation.

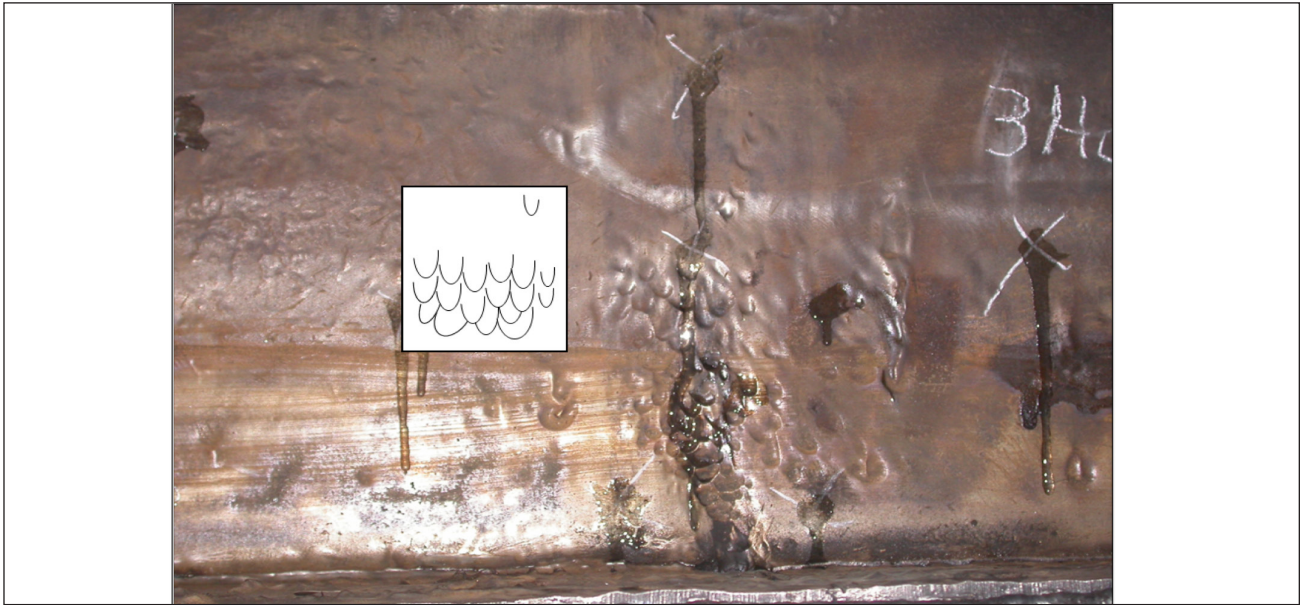
To trend the corrosion, plot average thickness vs. time by shell course or elevation. The corrosion rate produced by this graph provides a good planning tool for future repairs. The corrosion rate can change, often unpredictably, and it is not necessarily distinctly tied to a process change. On occasion, the corrosion will stop, and this may go on for a number of years. Because the rate can increase without warning, it is still important to make sure the data is analyzed during every outage.

Keep track of the lowest thickness reading to identify where the thinnest areas are. Given the testing accuracy, as already discussed, it cannot be used to calculate the corrosion rate, because it tends to "move" from inspection to inspection. It will locate areas that may need further investigation. If thicknesses below T_{min} are detected, they

should first be evaluated for pitting and local thinning by a post-construction code, such as NBIC. This may or may not lead to carbon steel weld buildup.

The digester can be further evaluated for pitting and localized and general metal loss [8] by using API 579-1/ASME-FFS-1 "Fitness-For-Service." This method is accepted by common industry standards and practices such as NBIC, API 510, and TAPPI TIP 0402-27. The outcome of a fitness-for-service study is the decision to return to service, to repair, or to replace. It does not prevent repairs but is useful for planning and can reduce the downtime required to complete them. With sufficient data, the calculations do not take long when done by an experienced evaluator and have even been turned around during an outage, providing useful results that can be immediately utilized.

Examples of trend charts that plot average shell thickness (in.) vs. time (year) for two shell courses in the same digester are shown in **Fig. 8** and **Fig. 9**. The x-axis crosses the minimum code thickness. This makes it visually



10. Horseshoe pitting indicating erosion-corrosion in an internal header.

easier to see the remaining corrosion allowance. The dashed green line represents the original minimum code thickness. In 2004, T_{min} was recalculated according to NBIC. This effectively doubled the corrosion allowance that, when built, was 0.25 in. (6 mm). The minimum thickness recorded for each outage is plotted as a single “X.” Though it is always in the same area, the exact location of the minimum thickness changes each time the digester is inspected.

Early on, there was no corrosion, and the trend remained flat. Starting around 1996, the corrosion rate increased and even further around 2014. These increases cannot be tied to a specific process change. After 2018, corrosion stopped and the trend flattened out again. In this case, the mill reported that the temperature had been decreased in the wash zone. Lower corrosion rates would be consistent with lower temperatures. The corrosion pattern around the circumference was non-uniform, with a similar pattern as that seen in Fig. 7. There was more thinning at the top of each course than at the bottom.

Figure 8 displays the trend chart for shell course 4, which is the second full ring above the wash screens. It had a corrosion rate of 20 mils/year (0.5 mm/year), which increased to 33 mils/year (0.8 mm/year) before it flattened out. Because the minimum thickness was approaching T_{min} , the upper half of the shell was overlaid with stainless steel in 2018. A fitness-for-service evaluation was done at the same time, because the average thickness of the remaining shell section was not much higher than the overlaid section. The result for the given corrosion rate indicated that the bottom half would need to be overlaid by 2021. Surprisingly, when the thickness was measured the next year, the corrosion appeared to have stopped. This continued through 2019 and 2020.

The decision was made to go ahead with the overlay in 2021, because if the corrosion started up again, the minimum thickness was low enough that carbon steel build-up would likely be required. Thickness was measured for the last time in 2021, and when plotted, the average thickness had increased, suggesting the shell had grown, which of course is not possible. It is more of a sign that the corrosion had not started up again. This shell course is now 100% covered with overlay.

Figure 9 displays the trend chart for shell course 3, which is between the wash screens and shell course 4. It did not corrode at the same rate as shell course 4. The initial corrosion rate was 10 mils/year (0.2 mm/year), which increased to 25 mils/year (0.6 mm/year) before the corrosion stopped after 2018. The top 4 ft (1.2 m) were again overlaid in 2021, because the minimum thickness was low. The average thickness did drop, suggesting that the corrosion on this course had started back up again. When the lower portion was measured in 2022, the average and minimum thicknesses were much higher, because there was less corrosion towards the bottom. The corrosion rate of this section needs to be re-established to determine when or if more overlay is required. All this work was done without carbon steel buildup and no extension to routine outages.

Inspection interval

According to TAPPI TIP 0402-27, carbon steel digesters are typically inspected annually until the corrosion patterns are established. The interval can be expanded based on sound evaluation of the inspection data. Even 18- and 24-month intervals can be managed with rapid thinning. The key is to assess the current data as soon as it is collected, so that the condition of the vessel is known before the out-

age ends. This provides more flexibility in setting the date of the next inspection and any repairs, which are usually unavoidable with rapid thinning.

The interval for thickness testing does not have to match other NDT going on in the digester. For non-corroding sections in the upper digester that still have plenty of corrosion allowance, thickness can be measured on a 4-to-6-year cycle. Industry codes may accept substantially longer intervals; however, a shorter interval will help with planning and record keeping, as it is not unusual to have a high turnover of the mill digester inspection coordinator.

MITIGATION

A physical corrosion resistant barrier is the best method for protecting the carbon steel shell experiencing rapid thinning. Stainless steel weld overlay, Alloy 625 thermal spray, and duplex stainless steel sheet lining are three suitable methods. Additional information and visuals are available [9].

Weld overlay

TAPPI TIP 0402-03 “Guidelines for corrosion resistant weld metal overlay of digester vessels in alkaline pulping service” provides guidance for applying corrosion resistant overlay to batch and continuous digesters. It advises to plan for overlay by the time the average remaining corrosion allowance is around 100 mils (2.5 mm). Below this, there is a higher risk of having to first build up the shell with carbon steel, because some areas have fallen below the minimum code thickness.

Though nickel alloys were used in the past, stainless steel now is the preferred material. An austenitic stainless steel with 18% chromium, 309L has sufficient resistance for continuous digesters. A 312 duplex stainless steel with 25% chromium is needed for batch digesters and can also be used in continuous digesters. One of the advantages of 312 is that its strength may be used if the shell is below the code minimum thickness. This eliminates the need for carbon steel weld build up. For it to apply, there are additional administrative steps required by the code, and the welds must be qualified as butt welds rather than as corrosion resistant overlay.

Quality requirements need to be established to prevent hot cracking in the overlay. That means the ferrite content in the stainless steel needs to be controlled. A 309L requires some ferrite and 312 not too much. The overlay can be applied horizontally or vertically down. The latter produces a thinner weld, but both equally protect the digester. Weld overlay may require an extended shutdown; however, with careful planning, the work can be completed in smaller segments or be scheduled against longer outages required by other mill areas. Once complete, it is long lasting and requires little maintenance.

Thermal spray

TAPPI TIP 0402-32 “Guidelines for thermal spray coatings installed to prevent corrosion in pulp mill process equip-

ment” provides guidance for applying thermal spray to pulp mill equipment. The advantage of thermal spray is that there is no heat-affected zone that may increase the risk of stress corrosion cracking of the carbon steel adjacent to the edge of the coating.

Twin wire arc spray was one of the early processes used in continuous digesters. It is less dense, contains more oxides, and is more porous than some of the new processes used; however, it is a rugged coating that has performed well. The newer, denser coatings, which are thinner, are more prone to blistering and spalling.

Similar to other corrosion resistant protection methods, thermal spray may require an extended shutdown. Again, the work can be completed over several years if it is well planned. For safety reasons, no one else other than the thermal spray contractor can be in the vessel while the coating is being applied. For large areas, thermal spray requires more maintenance than weld overlay.

Sheet lining

NACE SP0292-2024 “Standard recommended practice: Installation of thin metallic wallpaper lining in air pollution control and other process equipment,” from the Association of Materials Protection and Performance, provides guidance for applying sheet linings. There is limited experience with digesters; however, it has been successfully used in the bleach plant [10]. Even though less welding is required than overlay, seam and plug weld cracking is a concern. The risk of this, along with proper welding procedures, can be reduced by using duplex stainless steel, which compared to 304L austenitic stainless steel, is stronger and has a better thermal match with carbon steel.

OTHER CONSIDERATIONS FOR DIGESTER THINNING

Blank plates and screens

Blank plates contained within the area where rapid thinning is occurring may also corrode at high rates. It is usually visible by eye; for example, the cut edges are thin or no longer square. The corrosion can go as far as creating holes in the plate. For this reason, extensive UT is not required.

The shell behind screens and plates corrodes at much lower rates than the exposed surfaces. If corrosion rates are low, it is not necessary to check thickness behind every screen or plate that is open. Some mills will open entire rows of screens for hydroblasting. If the shell behind the screen is not corroding, only one or two can be checked. Of course, if severe corrosion is found more, shell sections behind screens will have to be examined. A 5-point grid, four corners and center, is commonly used as the thickness location grid for each screen or blank plate section.

For those mills that do not open all the screens, one or two can be opened for inspection. Blank plates should also be included, but again, it is not typically a location where

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high corrosion is detected and more effort is required to remove and reinstall them, so it is done as more of a spot check.

Screen and blank plate inspection is often opportunistic. If a row of screens is being changed as part of a capital project, a priority task for the total inspection scope is to inspect behind all of them before the new screens are installed. Since this may be part of a process change, it allows for gathering baseline data. Note that any weld seams behind open screens or plates should be checked for cracking with appropriate NDT.

Other locations that experience thinning

There are other areas that need to be included in the scope for thickness testing. Internal header erosion-corrosion, as shown in **Fig. 10**, is probably more common than rapid shell thinning and has been known to occur in conventional cooking digesters. Metal loss rates are as high as 200 mils/year (5 mm/year) [11], and there are incidences of near through wall thinning. Visually, it is more likely to display horseshoe-shaped pits, which are typical of erosion-corrosion. Erosion-corrosion can also occur in the doghouse/penthouse area where liquor splashes against the shell or false dome and with carbon steel outlet device rake arms. Mitigation methods include those already noted. For carbon

steel flash tanks that experience severe erosion-corrosion, replacement with duplex stainless steel is another option.

The 304L outlet device cones can experience erosion and thin to the point that they crack. Weld repairs to cracks and attaching 304L stainless steel liners over the thinned areas is not as permanent as replacing the cone with duplex stainless steel. Erosion is also common with impregnation vessel stainless clad bottom heads. Both 304L roll bonded cladding and 309L weld overlay are affected. Duplex stainless steel sheet lining or 312 weld overlay lasts longer because of a higher strength and hardness.

KEY LEARNINGS

There is no or unknown correlation of corrosion with residual alkali. This means that corrosion cannot be controlled according to the sodium hydroxide concentration in the extraction liquors. Since it is not known what concentration is necessary to reduce corrosion, arbitrarily raising it is not expected to have an impact on corrosion and may produce unintended consequences down the line in brown-stock washing and black liquor evaporation. As a general guideline, alkaline liquor corrosion cannot be controlled by process chemistry; corrosion resistant materials must be used for protection.

Corrosion protection for rapid thinning cannot be de-

ABOUT THE AUTHOR

Continuous digester inspection has mainly focused on stress corrosion cracking, which occurs towards the top of the vessel. There has been much less discussion on rapid thinning, which affects the section between the wash and extraction screens. This is an opportunity to provide practical information on dealing with rapid thinning in particular and digester corrosion in general.

My experience with mill liquor testing supports the finding that digester rapid thinning is not a result of low residual alkali concentrations. My recommendation for controlling liquor corrosion has always been to use a resistant alloy, usually stainless steel, whether as protection or material of construction, instead of chemistry changes to make the liquor less corrosive to carbon steel.

Getting the thickness data early enough so that it can be analyzed before the end of an outage is a challenge. Even if rapid thinning is occurring, ultrasonic thickness testing is often scheduled late in the inspection. Because the final report is usually not issued until after the outage is over, I make sure the raw ultrasonic thickness testing data is sent to me as soon as it comes out of the digester.

Through this work, I have discovered that rapid thinning corrosion rates are not runaway high compared to internal header erosion-corrosion. Even

though rapid thinning is unpredictable, it can be managed without causing unplanned downtime or having to extend outages. One interesting finding is that wash zone corrosion can change and even stop. Over time, the wall thickness trends downward, but the rates do change. Even though ultrasonic thickness testing is the only way to validate thinning, I was surprised how often I could visually detect the change in corrosion patterns.

The information in this paper offers mills a practical guide for conducting thickness inspections. It also helps to make overall digester inspection programs more efficient. The next step is to incorporate these findings into the next revision of TIP 0402-27 "Guidelines for inspection of continuous digesters and impregnation vessels."



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layed indefinitely. With the use of recognized industry post construction codes, it is critical to evaluate thickness results as they are received during an outage, so that by startup, it is known when the next inspection and/or repairs are required. With average thickness trending and the use of fitness for service techniques, repairs can be scheduled so they are much less disruptive to the mill. Other areas that corrode at very low rates do not have to be inspected to the same extent or frequency. **TJ**

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