Digester thinning: Erosion-corrosion of internal flow channel headers

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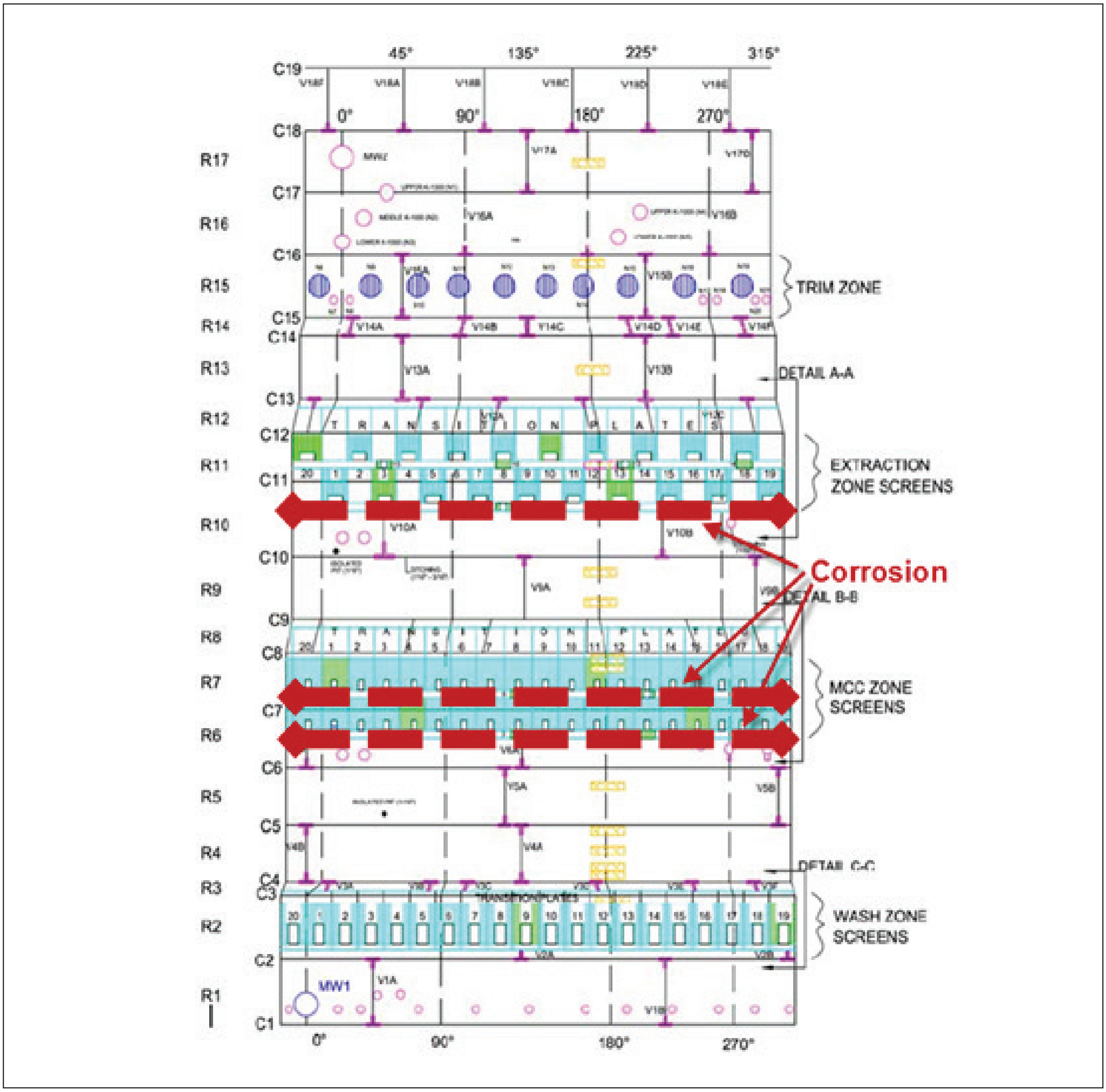
ABSTRACT: A softwood continuous digester has experienced severe erosion-corrosion of the shell wall inside the internal flow channel headers of the extraction and modified continuous cooking (MCC) zones. Although erosion-corrosion is a common form, it is not typically looked for inside digester flow channels. The worst damage was located where high velocity liquor exits the screen orifices and enters the collection headers. With erosion-corrosion rates as high as 200 m/year, the damage has effectively reduced the wall thickness almost by half in the worst areas. Also affected were the horizontal backing rings that form the bottom of the flow channels. An API-579/ASME FFS-1 Part 5, Level 2 analysis was performed to allow the mill to continue operating the digester until the next scheduled outage. Owner-users are encouraged to inspect these locations in their digesters to ensure that erosion-corrosion has not caused accelerated and/or unexpected shell thinning. The internal flow channels represent locations that are not readily accessible for internal visual inspection without removal of the flow channel header cover plates and removal of the residual black liquor typically retained in these flow channels. External, on-stream ultrasonic thickness testing (UT) at the proper collection header elevations has been determined to be an effective way to detect the presence of this erosion-corrosion phenomena. Also discussed are considerations to make on-stream UT as accurate as possible. Corrosion rates determined via electrochemical corrosion probe monitoring have correlated very well with the corrosion rates determined by on-stream UT data.

Application: The detailed results from this study should enable the users of continuous digesters with internal flow channels to improve their internal inspection techniques. Improved inspections will allow for safer operation of these type digesters.

As part of fitness for service and general safety guidelines, digesters are required to undergo routine shell thickness inspections. The digester involved in this study was originally designed in 1993 as a 1250 a.d. tons/day, 2-vessel hydraulic continuous digester. Operation began in March, 1995. The design consists of upper and lower internal flow channels for the extraction and modified continuous cooking (MCC) zones vs. external headers. The single-level of wash screens is equipped with an external ring header. The design is a Kamyr "wet feed system" consisting of a chip bin, chip meter, low-pressure feeder, steaming vessel, chip chute with a circulation pump, in-line drainers, and a sand separator in the circulation loop feeding the high pressure feeder. The digester has been routinely monitored and well maintained since it was first commissioned. Annual internal visual and ultrasonic thickness (UT) inspections through the years have always indicated that the general corrosion rates were low. Thickness readings were typically taken at three locations on each shell course at eight sectors around the circumference. The typical UT survey during the outages also included taking several thickness readings of the shell that is directly accessible by removing one of the flow channel clean-out windows. Usually, only one or two screens at each zone were opened for visual and UT of the shell, as well as wet fluorescent magnetic particle testing (WFMT) of shell welds or penetrant testing (PT) of stainless nozzle welds. Since the internal collection headers were not equipped with drains that would remove the residual heel of colored extraction liquor below the outlet nozzles, there was no visual inspection of the lower portion of the flow channels as viewed through the small clean-out windows.

In 2012, the mill asked for a six-month extension to the annual inspection frequency. This necessitated a critical review of the available thickness data. During this review, it was noted that the UT data that had been taken inside the flow channels through the clean-out windows varied by as much as 0.300 inch around the circumference at the same digester elevation. Even if the data were located on separate shell plates, all shell plates at any given elevation should have the same nominal thickness. This variation in thickness was the first indication that the shell behind the flow channels had experienced in-service thinning.

Based upon review of the literature, rapid thinning can be a common problem in softwood continuous digesters running modern cooking processes. Wensley reported in 1998 that continuous digester extraction liquors may produce corrosion rates up to nearly 0.25 in. per year [1]. Wensley's paper also showed that corrosion rates increase rapidly with increasing temperature. A corrosion rate of 0.079 in. per year in a softwood continuous digester extraction liquor at 327°F increased



1. Roll-out reference sketch of digester.

more than 3.5 fold to 0.290 in. per year when the temperature increased to 350°F.

Although equations are available to predict corrosion rates in white liquor from the liquor composition, no predictive equations have been developed to predict corrosion rates in extraction liquors. Predictive equations have not been correlated with the inorganic and organic constituents of extraction liquor. The available equations do not account for the extraction liquor temperature, or the liquor flow velocity. What is known is that extraction zone liquors are particularly corrosive because of their high temperature, low caustic concentration, and high flow rate.

PROBLEM IDENTIFICATION

The current work describes a softwood digester that has recently experienced severe erosion-corrosion of the carbon steel shell behind the internal flow channel headers. For the softwood continuous digester in this case study, the combination of liquor heaters operating wide open, a faulty alkali sensor that resulted in caustic concentrations below intended values, and a high flow velocity inside the flow channels resulted in serious wall thinning damage to the shell. The damage was greatest in the vicinity of the screen orifice holes, as well as the bottom 4 or 5 in. of the flow channels. Based upon observations such as the erosion patterns and location of damage, it was concluded the local flow velocity was a key parameter affecting the rate of thinning damage. Descriptions of how the damage was initially found and how it was monitored with on-stream ultrasonic thickness and electrochemical corrosion probe testing are reviewed. Also discussed are details specifically related to external on-stream thickness testing, which ensure that the corrosion rate data are accurate. A roll-out reference sketch of the digester in question, along with the areas of high corrosion, is shown in **Fig. 1**.

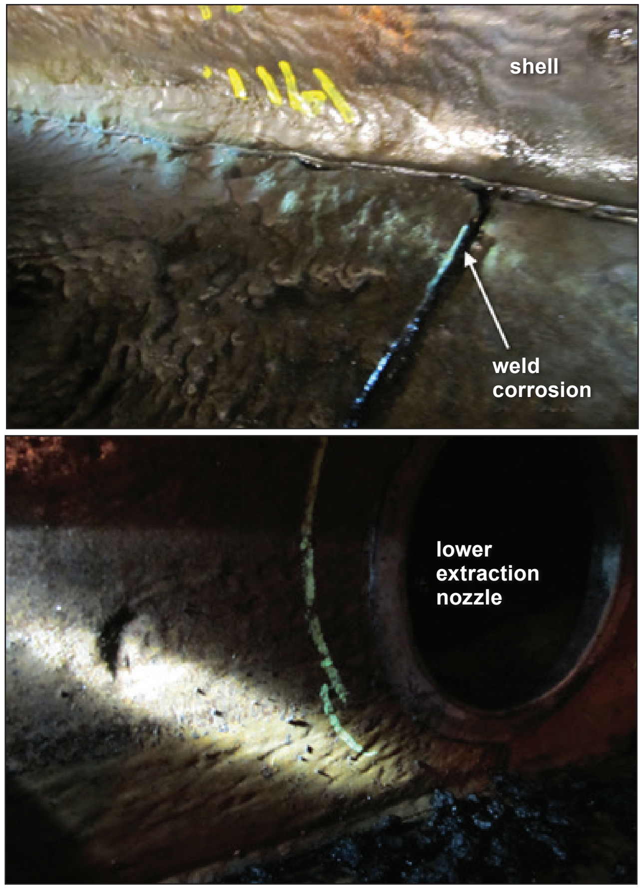
ONSET OF DIGESTER THINNING

The morphology of the damage inside the digester flow channels clearly indicates the thinning is the result of erosion-corrosion. Erosion-corrosion is an acceleration of corrosive damage caused by the relative motion of a corrosive fluid against a metal surface. When a certain velocity threshold is exceeded for a given alloy, the relative motion is capable of removing an otherwise protective (passive) film that forms on the metal surface [2]. The thinning damage found in this digester exhibited the classic erosion-corrosion features such as grooves, waves, comet-tails, teardrop-shaped pits, and horseshoe-shaped undercutting of the metal surface. **Figure 2** shows some of the classic erosion-corrosion pictures obtained from the digester flow channels. Erosion-corrosion can produce dramatic rates of damage, which were also experienced in this digester. Based on the locations and patterns of thinning, the flow velocity appears to be the primary component of the damage that occurred inside the digester's flow channel headers. Static corrosion rates have always remained relatively normal for this digester.

RESPONSE TO DIGESTER THINNING

On-stream thickness testing (pre-outage)

Once it was apparent that a hidden corrosion problem may have developed inside the internal flow channels, it was necessary to do external on-stream UT testing at the flow channel elevations in order to verify the scope and magnitude of damage. Originally, small 4 in. x 4 in. windows were cut in the insulation for thickness monitoring locations (TMLs). These TMLs were oriented 45° apart at the elevations that corresponded to the mid-height of the flow channel areas. The flow channels are actually 16 in. in vertical height, and the true placement of the TMLs within the flow channel zone was about midway. As the TML areas were scanned, the spot-to-spot thickness data varied considerably. The first impression was that the UT readings were widely inaccurate; however, it was determined that the true wall thickness actually did vary considerably from spot to spot in the TML. It was also clear that the thickness decreased near the bottom of each TML window. It was decided to remove the majority of the insulation corresponding to the flow channel zones. The new data collected indicated the true severity of thinning. Extreme substrate loss was found near the bottom 5 or 6 in. of the flow channels and also in separate vertical bands around the circumference corresponding to the location of



2. "Wavy" pattern of erosion-corrosion damage to the extraction header plate directly beneath the screen orifice. In the lower picture, notice the erosion-corrosion damage inside the flow channel in the vicinity of the extraction nozzle.

the screen orifice holes. When plotted, the thinning had an almost sinusoidal pattern around the circumference of the digester.

With the shell thickness as much as 0.300 in. below the calculated ASME t-min [3] in the worst areas, the mill contracted with an engineering consultant to perform an API-579/ASME FFS-1 fitness for service evaluation [4-5]. Using Part 5, a level 2 analysis was performed. Through the rigors of finite element analysis (FEA), it was possible to demonstrate that the digester was indeed safe to operate for a few more months until the scheduled outage, which was months away.

On-stream ultrasonic thickness data and accuracy

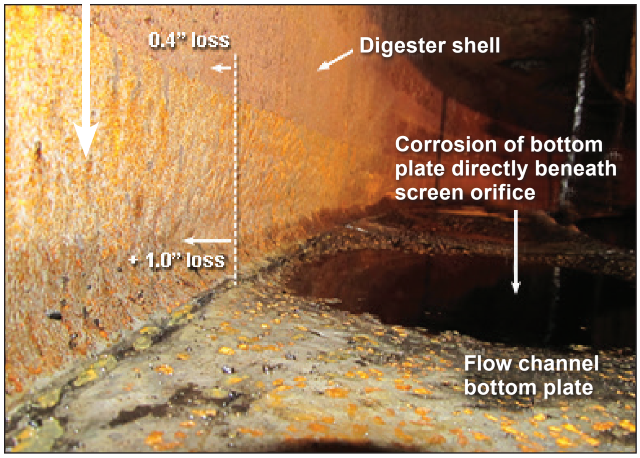
When trending UT data collected on a frequent basis, the data needs to be as precise and accurate as possible so that the indicated corrosion rates are not exaggerated. When ultrasonic thickness testing on operating digesters (on-stream inspection), three considerations are necessary for accurate and precise thickness data: 1) clearly identified and physically marked TML locations directly on the digester surface; 2) temperature-velocity compensation of the UT calibration; and 3) elimination of temperature drift effects of the transducer as it heats up.

As the temperature of a metal increases, the velocity of sound through the material slows down; thus, it takes longer to go the same distance (thickness). This change in sound velocity with temperature is an important variable for accurate readings. If the high temperature velocity effect is not accounted for when testing a hot component, a UT technician will erroneously get a reading that indicates the component is thicker than it actually is. For example, in the wash zone of a typical continuous digester with a thickness of 2 in. and an operating temperature of 320°F, the thickness error from operating temperature to ambient temperature (85°F) calibration will be about 0.050 in. [6]. ASME Section V indicates a temperature correction factor of 1% per 100°F difference between the calibration and testing temperature. The alternate way for high temperature calibration is to heat a thickness step block to the operating temperature and then store the calibration for this temperature corrected sound velocity. Done with care, there should be excellent correlation between these two high temperature ultrasonic thickness calibration methods for the normalized SA 516-70 plate [7].

Another temperature induced error that can easily be eliminated is one related to high temperature transducer drift. As the plastic potting material surrounding the transducer heats up, the sound velocity passing through this material decreases even more than it would when passing through a metal. Since the measured sound must travel through this part of the probe, as well through the digester shell, the timing and gated thickness will be altered by this effect, referred to as "transducer drift." An easy correction for transducer drift is to set the thickness gage in the "echo-to-echo" mode. In this test mode, the machine is set to gate the thickness between multiple echoes of the distance from the metal surface to the back wall. In this way, thickness readings in the echo-echo mode only represent the metal path distance and are not affected by the thickness of couplant, paint, or temperature drift. At typical digester operating temperatures and testing techniques, transducer drift can create another 0.020 to 0.030 in. of error in the thickness reading.

Internal inspection of digester flow channels — The moment of truth

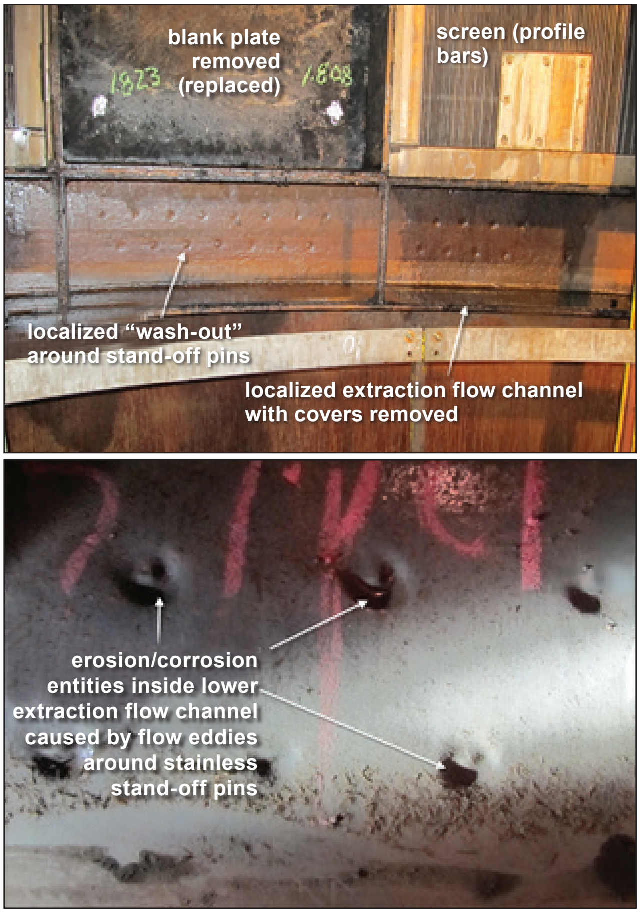
Consistent with TAPPI Technical Information Paper TIP 0402-27 "Guidelines for inspection of continuous digesters and impregnation vessels," the internal inspection consisted of direct visual inspection, ultrasonic thickness testing, and dye penetrant and wet fluorescent inspection of critical welds. Additionally, the flow channel cover plates were removed for the first time in the operating history of the digester. Once the flow channel cover plates were removed, it was obvious that significant and very real damage had occurring within the flow channels. The damage was found to be as bad as the on-stream UT data had indicated. **Figures 3-5** are photos of the extraction flow channels showing the extent of corrosion that was present within the digester at the time of the inspection.



3. Inside the lower extraction flow channel with cover removed for access. Note the severe erosion-corrosion of the shell near the bottom plate, as well as wash-out of the bottom plate (holding liquor) that is directly beneath the screen orifice.

4. Inside the lower extraction flow channel with cover removed for access.

5. Erosion-corrosion damage to the digester shell and bottom of the flow channel.



6. Note the localized damage around standoff pins that are attached to the flow channel covers that were removed. The lower photo is a close up detailing the localized corrosion caused by flow eddies around the standoff pins.

7. Upper MCC flow channel. (Nozzle height leaves 2.5 in. "heel" of liquor in the bottom).

Extraction zone

The upper and lower extraction zone consisted of a checkerboard pattern of ten alternating carbon steel blank plates with ten vertical stainless steel profile bar screens. The liquor collects through the screens and feeds through two flow orifices into the flow channel header. The flow channel headers have two outlet nozzles oriented 180° apart. The erosion-corrosion damage was concentrated near the flow orifice locations and affected the lower portion of the shell inside the flow channel. There was significant localized thinning of the bottom plate (backing bar) of the collection header where liquor flows through the screen orifices and impinges directly upon the bottom plate (Fig. 5). At the lower extraction zone, severe damage extended 5 or 6 in. up from the bottom of the collection header. Localized areas of shell thinning associated with the "stand-off pins" were observed behind the screen plates as well as inside the flow channel. Galvanic corrosion effects were not seen in these areas as the standoff pins do not actually touch the impacted area of the digester shell. Rather, these pins tend to collect pulp fibers and increase the flow rate of liquor around these pins. **Figure 6** shows the localized corrosion around the stand-off pins. Flow eddies appear to form around these pins, which causes accelerated erosion-corrosion with the classic "comet tail" and "horse-shoe track" patterns. The corrosion penetration into the shell at these stand-off pins located inside the flow channel were much deeper than that around the pins behind the screens. Even though the process chemistry in these two areas is nearly identical, higher velocities are present inside the flow channel than behind the screens, thus enhancing the erosion-corrosion rate.

MCC zone

The MCC zone consists of two levels of diagonal, mill-slotted screens with no blank plates. There are 20 screens in the upper zone and 20 screens in lower zone. At each screen, there is only one open flow orifice, as one of the two orifice holes was blanked in years past.

There was erosion-corrosion damage to the shell inside both MCC flow channels, similar to that found at the extraction zone. Although this damage required weld buildup repair to restore to ASME t-min thickness, the damage was much less severe than the damage at the extraction level. The bottom plates of the flow channel headers showed minor to moderate damage underneath the open flow orifice. In general, the damage to the shell in the MCC flow channels did not extend more than 2 or 3 in. above the bottom plate of the collection header. **Figure 7** shows the MCC channel along with the "heel" of liquor retained in the bottom of the flow channel that impedes visual inspection of the internal flow channels.

WELD REPAIRS

All areas of the shell below the corresponding ASME t-min value were repaired by weld overlay. Prior to welding, the area was preheated to 300°F using a rose-bud technique [8]. The welding was performed by shielded metal arc welding (SMAW) using 5/32 dia., E7018 electrodes in consecutive, horizontal weld beads. The weld overlay areas were built-up to the corresponding t-min value plus an additional 0.050 in. of corrosion allowance. In a few of the worst areas of the lower extraction zone, ER 309L SS electrodes were applied on top of the carbon steel weld build-up.

POST OUTAGE ON-STREAM CORROSION MONITORING

Because of the wide variance in local shell wall thicknesses caused by corrosion, TMLs used for UT comparison were marked directly on the digester shell. Thickness readings were taken at these precise locations for optimum corrosion rate monitoring accuracy. Due to the expected high erosion-corrosion rates inside the flow channels, the majority of TMLs were concentrated at the flow channel elevations. Areas below the flow channels were included to establish "static" corrosion rates outside of flow areas.

Baseline thickness readings were taken prior to the digester's return to service. On-stream thickness readings were taken approximately every 30 days for the next six months. Annualized corrosion rates were calculated for each TML to determine a short-term corrosion rate (between the last two readings) and a longer-term corrosion rate (between the baseline and the last reading). These data showed extremely high corrosion rates (100 to 200 m/year) in the majority of TMLs located in the flow channels and low corrosion rates (0-5 m/year) in static areas outside of the flow channels. Also, during the six months of on-stream thickness monitoring, the mill experimented with various cooking schemes that showed a wide variance in corrosion rates.

In addition to the on-stream UT thickness monitoring, six electrochemical corrosion monitoring probes installed by an anodic protection contractor during the recent outage were also used to trend the corrosion rates during the six month post outage period. In general, there was very good correlation between the UT thickness data and the electrochemical corrosion rate data.

CONCLUSIONS

Outside of the high velocity flow channel areas, the general corrosion rates on the digester shell range between 5 and 10 mils/year. Inside the flow channels, directly below the screen orifice holes and along the bottom of the flow channels, the localized erosion-corrosion rate appears to be as high as 200 mils/year. No thinning was noted behind the wash zone screens, as there is an external ring header instead of an internal flow header. Velocity appears to be the critical parameter affecting the erosion-corrosion damage found inside the flow channels. Throughout the vessel, there has never been any indication of stress corrosion cracking (SCC), and no indications of SCC were found during this outage. Because portions of the digester were well below the ASME t-min thickness, there was discussion about immediately shutting the digester down for overlay weld repair. Instead, API 579/ASME FFS-1 Fitness for Service Part 5 Level 2 analysis was performed to verify that the localized corrosion did not require an immediate shutdown of the digester. Rather, the digester was allowed to run until the next scheduled outage. Weld repairs were made to restore damaged areas to ASME t-min plus a small corrosion allowance.

Based upon on-stream ultrasonic thickness data collected since the outage, high erosion-corrosion rates still exist. However, after experimenting with various cooking changes, the

ABOUT THE AUTHORS

We chose to study this aspect of digester thinning because exploration of variations in routine thickness inspections led to the surprising discovery of extreme rates of erosion-corrosion occurring within the digester flow channels. The need to understand the cause, mitigation, and prevention of the rapid thinning led to the preparation of this work.

This work supports earlier efforts at identifying various forms of rapid digester thinning experienced in other continuous digesters. The current work compliments efforts in defining specific locations of erosion-corrosion.

Determining the root cause of the digester thinning and understanding the UT thickness testing data were the main difficulties in this work. The most interesting thing we encountered was discovering the extent of digester thinning in areas that were deemed to be relatively safe and rarely inspected.

We have identified specific causes and locations of potential rapid digester thinning. Mills may use this work to enhance their own digester inspection programs to ensure safe operation of the continuous digester. The next step includes rebuilding the lost base metal and overlaying the digester flow channels. Once this is done, routine monitoring of the flow channel thickness will be performed.

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mill determined the corrosion rate can be significantly varied. For instance, comparing UT survey data collected at the beginning of down-flow cooking (where no extraction flow exists inside the extraction headers) with data 30 days after the cooking change showed the corrosion loss went from an annualized 0.190 in. per year to essentially zero. These changes in cooking conditions show that the liquor velocity is a major component in the damage that has occurred within the flow channels. Being able to trial and error various cooking schemes and correlate these cooking schemes with corrosion rates only underscores the critical need for precise and accurate on-stream ultrasonic thickness testing techniques.

For digesters with internal flow channels, if no current or reliable wall thickness data from the shell near the bottom of the flow channel is available, owner/users are encouraged to schedule on-stream UT thickness measurements at the flow channel elevations or plan to remove flow channel covers directly below screens at an upcoming outage for inspection. **TJ**

LITERATURE CITED

1. Wensley, A., "Corrosion of batch and continuous digesters," *Proc. - Int. Symp. Corros. Pulp Pap. Ind., 9th*, CPPA, Montreal, 1998, p. 27.
2. Corrosion Technology Laboratory, "Erosion Corrosion, Corrosion Fundamentals," NASA. Available [Online] http://corrosion.ksc.nasa.gov/eroscor.htm >[31July2014].
3. ASME, "ASME Boiler and Pressure Vessel Code: An International Code, 2013." Available [Online] https://www.asme.org/getmedia/1adfc3df-7dab-44bf-a078-8b1c7d60bf0d/ASME_BPVC_2013-Brochure.aspx >[31July2014].
4. Antaki, G., *Fitness-for-Service Evaluations for Piping and Pressure Vessels: ASME Code Simplified*, McGraw-Hill, New York, 2005.
5. Bennett, D.C. and Mixon, N., "API 579-1/ASME FFS-1, Fitness for service post-construction code for pressure equipment with flaws and corrosion damage," *TAPPI PEERS Conf.*, TAPPI PRESS, Atlanta, GA, USA, 2011, p. 997.
6. Pezant, J.C., "High temperature thickness monitoring using ultrasonic waves," M.S. thesis, Georgia Institute of Technology, Atlanta, 2008.
7. ASME Boiler and Pressure Vessel Committee on Nondestructive Examination, "ASME Boiler and Pressure Vessel Code, Section V: Nondestructive Examination," American Society of Mechanical Engineers, New York, 1 July 2011. Available [Online] https://law.resource.org/pub/us/code/ibr/asme.bpvc.v.2010.pdf >[31July2014].
8. U.S. Department of Transportation Federal Highway Administration, "Guide for Heat-Straightening of Damaged Steel Bridge Members," Chap. 2, Section 2.7. Available [Online] http://www.fhwa.dot.gov/BRIDGE/steel/02.cfm >[31July2014].