INSPECTION OF RECOVERY BOILERS

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ABSTRACT

Equipment and procedures that ensure the safe and reliable operation of kraft recovery boilers should be inspected regularly to ensure both that equipment is in good working order and that personnel are trained to properly handle routine and non-routine situations. During scheduled outages, the integrity of the boiler's pressure parts should be systematically reviewed to monitor the extent of thinning and cracking. In addition, the operation of critical equipment like safety valves and systems that trip during unsafe conditions should be checked and critical instruments checked and recalibrated.

The most important element in a recovery boiler corrosion inspection is a careful and thoughtful visual inspection by an experienced boiler inspector. Additional non-destructive test methods are available to locate and size each type of defect produced by the various damage mechanisms that operate in recovery boilers before they can grow to cause leaks in pressure parts. Unfortunately, many mills focus almost exclusively on tube thickness measurements, often making far more measurements than are needed to calculate the remaining life of tubes in particular parts of the boiler. To determine what maintenance is required in a recovery boiler, an experienced corrosion inspector should tailor a non-destructive test program to monitor corrosion problems found during previous inspections, make a thorough visual inspection and review the test data before the shutdown ends.

INTRODUCTION

Within a kraft recovery boiler, at least seven distinctly different corrosion environments produce distinctly different types of corrosion, erosion or cracking (1). Corrosion control methods have been developed to minimize the thinning or cracking of pressure parts produced by each of these environments (1-5). However, even where the corrosion mechanisms are well established, it is not possible to predict tube thinning rates or crack progression rates from tube environment parameters, even if all the environmental parameters were measured continuously, which is generally not the case. Because recovery boiler corrosion cannot be predicted in advance, regular shutdowns must be scheduled to measure the extent and progress of thinning and cracking so that damaged parts may be repaired before they leak or rupture.

After noting the importance of routinely checking the control systems, standard operating practices and operator training that are critical to safe and reliable recovery boiler operation, this paper will focus on the types of measurements that can be made to establish the integrity of recovery boiler pressure parts. Later, best practices for choosing the scope, frequency and test methods to be used in routine corrosion inspections will be discussed.

NEED FOR INSPECTIONS

The integrity of its pressure parts is a necessary condition but not a sufficient condition for the safe and reliable operation of a recovery boiler. The organization and training of recovery department personnel, their standard and emergency operating procedures as well as preventative maintenance and repair strategies, are equally important in ensuring that a boiler operates efficiently, safely and reliably.

The integrity of each boiler's pressure parts and the adequacy of its operating systems must be evaluated at regular intervals. In addition to inspections during outages, routine walkdown inspections should seek unusual sights and sounds, including sootblower leaks, chemical leaks, areas of bulged casing, visible structural corrosion, missing insulation, evidence of air in-leakage and missing or damaged signage. Standard reporting and response systems must be in place, because the findings of walkdown inspections may require immediate attention.

BOILER SYSTEM INSPECTIONS

The evaluation of recovery boilers during shutdowns should include checks of the operation of critical control systems and safety systems in addition to corrosion inspections. If, for some reason, a particular shutdown had to be made as brief as possible, the minimum scope of these boiler system checks should include the following:

- ESP test, drum level trip test, low solids trip test and lift tests of safety valves using manual lift handles
- Calibration of boiler safety system instruments and switches

Detailed recommendations for routine boiler system checks have been developed by the Black Liquor Recovery Boiler Advisory Committee (6) and by insurance companies. These are beyond the scope of this paper, but a convenient summary can be found in the AF&PA Recovery Boiler Reference Manual (7).

AUDIT PROGRAMS

Prudent recovery boiler owners carry out regular audits that make a detailed evaluation of compliance to corporate and national standards, as well as to broader regulatory and insurance standards. Such audits help to eliminate situations that could cause explosions, interrupt operations, hazard personnel or cause environmental problems. Audits typically bring in a team to evaluate each boiler and its operation at least every second year. They also address the mill's progress on addressing previously non-compliant items. To be effective, audit programs must have energetic support from senior corporate managers. The scope of the audit program should be reviewed each year so that new areas of emphasis can be added and non-critical issues that are rarely out of compliance can be de-emphasized.

On-site audits usually involve the completion of checklists for personnel organizations, training programs, operator checklists for standard and emergency operating procedures, periodic testing of boiler systems and their auxiliary equipment, inspection and maintenance procedures for routine and emergency shutdowns. Actions required to achieve compliance are described in detail and initiate regular reporting to describe the mill's progress towards rectifying the non-compliant items.

METHODS FOR DETECTING POTENTIALLY HAZARDOUS DEFECTS

Causes of critical leaks

Our previous study of the recovery boiler explosions and critical exposures reported to the Black Liquor Recovery Boiler Advisory Committee from 1948 through 1990 (8) classified the primary causes of the critical leaks[1] that caused these incidents. More than half the critical leaks were associated with welds. Four times as many of the weld-related leaks occurred at external attachment welds than occurred at tube-to-tube butt welds. Tubes thinned by corrosion caused less than one-quarter of the critical leaks. Operational errors accounted for about one eighth of all the critical leaks, and the remaining one eighth of the leaks could not have been anticipated with existing inspection technology. It is important to remember that the major sources of critical leaks in pressure parts cannot be detected by the thickness measurements which continue to be the main focus of many recovery boiler inspections.

The emphasis on tube thickness surveys has substantially reduced the proportion of critical leaks attributed to corrosion thinning. In contrast, the attachment welds responsible for 40% of critical leaks are rarely inspected, even when a boiler is built. Thus, from the perspective of preventing critical leaks alone, traditional recovery boiler corrosion inspections have the wrong priorities. However, a thorough boiler inspection program requires a broader perspective, recognizing the

1 In this context, critical leaks are defined as pressure-part leaks that release water into the furnace cavity and therefore have the potential to cause smelt-water explosions.

damage mechanisms that operate in each part of the unit (9) and setting up inspections that will detect each type of damage before it progresses to the point of threatening the integrity of the boiler. Before discussing how to establish the scope and frequency of recovery boiler inspection programs, we will review the test methods available to detect potentially hazardous defects.

TEST METHODS AVAILABLE TO DETECT POTENTIALLY HAZARDOUS DEFECTS

Tube thickness measurement using ultrasonic testing

The non-destructive test methods used to evaluate the integrity of recovery boilers fall into three categories - those that indicate the thickness of the pressure part, those that detect the presence of surface cracks, and those that detect internal defects. Ultrasonic testing (UT) is the method used to determine tube wall thickness (10). A transducer, pressed onto a smear of sound couplant on the tube wall, sends a beep of very high frequency sound energy into the tube wall, and measures the time for this sound pulse to travel to the inner surface of the tube and reflect back to the outer surface. The UT instrument uses the velocity of sound in the tube material to compute the wall thickness from the travel time of the pulse. Some instruments average a number of measurements and display the thickness in digital form. Others use an oscilloscope screen to display the intensity of all the reflected sound pulses as they return to the transducer. These oscilloscope instruments provide more information than digital instruments. They also detect lamination defects within the tube wall. More training is required to set them up and to interpret their output than is required for digital instruments. Moskal (11) has concluded that oscilloscope-type instruments are preferable both because they are typically operated by more skilled technicians and because they can also be used to locate thin spots by scanning where locally varying thicknesses or internal defects are suspected.

Thickness measurements from the inside of generating bank tubes

Because generating bank tubes are packed together very closely, there is generally insufficient access to measure their thickness from the outside. However, access from inside the mud drum or steam drum enables their thickness to be measured using new ultrasonic testing systems mounted inside the tubes.

Measuring the thickness of generating bank tubes is important because they are typically installed with a particularly small corrosion allowance (zero to 0.050"). In order to detect external localized thinning of generating bank tubes where they exit the mud drum surface (12), a number of instruments have been developed to inspect 100% of the 1”-2" length of each tube that may be subject to near-drum thinning (13-15). These instruments are inserted into each tube in turn from the mud drum and use UT, sometimes with the tube flooded with water as a couplant, or eddy current methods, to determine the extent of thinning.

Thickness measurement using eddy current testing

In some cases, eddy current testing has been used to determine tube wall thickness. In this method, an alternating current passed through an exciting coil inside or near the tube creates eddy currents in the tube. The condition of the tube is deduced from the effect of the applied field on the electrical impedance, induced voltages or induced currents in the exciting coils, or by the induced voltage in a receiving coil. Eddy current instruments can measure tube thicknesses along the full length of generating bank tubes, although their readings are not accurate at bends and swages. Although these instruments can survey tube thicknesses more rapidly than ultrasonic instruments, they are less sensitive and less accurate.

Surface crack detection using liquid penetrant testing

There are two predominant methods for detecting surface cracks: liquid penetrant testing (PT) and magnetic particle testing (MT). In liquid penetrant testing, the surface is cleaned and degreased before light penetrating oil, usually bright red in color, is applied. The penetrant is left on the surface for a prescribed period, typically a minute or two, and is then cleaned off the surface with paper towels or rags. This surface cleaning does not remove penetrant that has seeped into cracks open to the surface. In the third step an oil-absorbing white powder (the developer) is sprayed onto the surface.

If a crack is present, the penetrant soaks back up into the developer and indicates the mouth of the crack like a narrow bleeding cut. Detecting cracks with these methods can demand particular skills, e.g. when examining composite floor and wall tubes for (typically very tight) fireside cracks (16).

Shear wave ultrasonic testing

A variant of ultrasonic testing known as "shear wave ultrasonic testing" launches an ultrasonic pulse into the tube surface at an angle. Because this pulse will be reflected by cracks in its path, the time it takes to return to the transducer can be taken to indicate the position of a crack at various depths. This enables the depth of surface-breaking cracks to be measured without grinding them out. It has also been used for estimating the depth of stress-assisted corrosion fissures. Shear wave ultrasonic testing requires technicians with much greater skills than conventional (straight beam) ultrasonic testing.

Surface crack detection using magnetic particle testing

In magnetic particle testing (MT), the metal surface is magnetized by an electromagnet yoke, while either a dry magnetic powder or a wet slurry of fluorescent magnetic particles is sprayed onto the surface. The magnetic particles are drawn to cracks because cracks produce a non-uniform magnetic field. MT will detect finer cracks than can be found by PT – including some cracks that are not open to the surface. Because of the great sensitivity of this test method, MT results can raise unnecessary concern about defects that are either too small to affect integrity or have not grown since the tube was fabricated. Prod-type equipment should not be used for the magnetization step, because the arcs it can produce can themselves initiate cracks.

Internal crack detection using radiographic testing

Radiographic testing (RT) is used to detect cracks on the waterside surface of boiler tubes or within their wall thickness. In this method, X-rays or gamma rays emitted by a radioactive source placed close to the metal surface pass through the tube material and produce an image on film placed on the far side of the metal. The intensity of the film image at any particular point depends on how much energy the beam has lost in traveling to that point. If the path of the beam includes a crack or void, less energy will be absorbed, so the crack or void will appear as a dark area on the film. Calibration standards called penetrameters allow semi-quantitative estimation of the depth/length of defects in the direction of the beam. Note that crack-like defects are not detectable by radiography unless they are aligned with the beam direction. Radiographic testing is routinely used to evaluate the integrity of welds in pressurized equipment and TAPPI has published guidelines for using it to evaluate the quality of butt welds in recovery boiler tubes (16).

Special radiographic procedures have been developed to detect stress-assisted corrosion (17). Recently developed digital radiographic imaging techniques (analogous to the image capture in a digital camera) allow the contrast and density of digital radiographs to be manipulated with a computer. This enables areas hidden in the "shadow" of an intervening structure (like a buckstay) to be evaluated by subtracting out the "shadow". As a result, the radiography can be completed without having to cut away windboxes, smelt boxes and buckstays to place the film against the tube.

This review of inspection methods is necessarily brief. Additional information is available in other publications (11, 16-24), or in encyclopedic form in Volume 17 of the ASM Metals Handbook (25).

The importance of visual inspection

Each recovery boiler inspection should be directed and coordinated by an inspector who is familiar with the condition of the unit in previous inspections and who has years of experience gathering and interpreting inspection data from similar units. The inspector's visual inspection skills are very important in finding critical defects and in directing non-destructive testing into areas that appear suspicious. Relying on a fixed protocol of measurement and testing without regard to the condition of the boiler increases the possibility of overlooking important defects and of overspending on inspection costs. An excellent set of visual inspection checklists can be found in Volume 1 of the AFPA Recovery Boiler Reference Manual (7). In addition to the inspector directing the inspection, everyone else working in the boiler during the shutdown should be encouraged to look for and report conditions that seem unusual.

Fitness-for-service - cracks

Every indication of a crack-like flaw should be taken seriously and evaluated carefully. Both the ASME pressure vessel code that governs the design and original construction quality of most pressure parts in recovery boilers, and the National Board Inspection Code that governs the inspection and repair of operating boilers in most jurisdictions, state that linear indications cannot be tolerated in pressurized equipment. (Linear indications are defects that are at least three times as deep/long as they are wide). For this reason, linear indications should not be left in a boiler unless there is compelling evidence that they have not grown in size since the boiler was manufactured, and are not of a size or shape that could propagate to cause a tube leak or rupture. Evaluating whether crack indications are "fit-for-service" requires unusual skill and experience as well as knowledge of the precision of the test methods. This should never be left to non-destructive testing technicians, because their training is to detect the location, shape and size of flaws, rather than to determine their impact on the integrity of the boiler. The recently-published API/ASME FFS-1 Fitness-for-Service code (26) describes methods for quantitatively evaluating the impact of cracks and other defects on the integrity of a boiler. These methods are particularly valuable because their results and the results of destructive examination of flawed components can be counter-intuitive. For example, a recent study (19) found that stress-assisted waterside corrosion (SAC) fissures that penetrated up to 32% of the tube wall did not decrease the burst strength of 46 tubes recovered from two recovery boilers. All these tubes failed away from the SAC fissures at pressures more than 7.6 times the operating pressure of the boiler. Evidently, the attachment welds that had initiated these fissures were able to provide external strengthening to the fissured area unless the fissures were extremely deep.

Because of the complexity of making fitness-for-service calculations, it is wise to have a specialist on-site or on-call during boiler inspections to evaluate the impact on the integrity of the boiler of crack-like flaws that may be detected. Not all "significant indications" may require removal.

Fitness-for-service - thinning

Like flaw data, tube thickness data need to be carefully studied and carefully interpreted. To interpret tube thickness data we need to understand the accuracy and precision of UT measurements. The precision of measurements made at any given inspection can be estimated from the standard deviation within data sets where thickness variations arise primarily from reading errors rather than from real thickness differences. Our statistical analysis of many thousands of tube thickness measurements obtained by several non-destructive testing contractors indicates that the standard error in UT wall thickness readings recorded during a boiler inspection is typically between 0.005" and 0.007". Some part of this standard error may be attributable to the UT transducer not being placed on exactly the same spot as in previous tests, i.e., to spatial variations in tube thickness. In addition, the accuracy of the measurements (i.e. the standard error in the calibration of the UT instrument), is typically between 0.004" and 0.006". The accuracy of the measurements is indicated by the distribution of the mean thicknesses in each part of the boiler at each inspection about the best fit line through all the thickness data points obtained at a number of successive inspections.

The square root of the sum of the variances of the reading errors (precision) and the calibration errors (accuracy) indicates that the combined standard error is about 0.007". If we assume that the tube thickness data belong to a normal distribution[2] this predicts that one in 20 tube thickness readings (95% confidence) will contain errors greater than 0.014", and one in 100 (99% confidence) will contain errors greater than 0.021". In a parallel study of actual measurements, Moskal (11) analyzed test data from 62 contractor UT technicians using ultrasonic instruments with oscilloscope displays and calculated the combined standard error in their measurements as 0.017" on normal tubes and 0.023" on tubes with hidden defects. The nominal thickness of the tubes was about 0.200". If we recalculate Moskal's statistics, omitting the largest

2 This is not exactly true, but a reasonable estimate.

errors (e.g., those greater than 0.030"), we obtain standard errors of about 0.007" and 0.010" on normal tubes and tubes with hidden defects.

Because the standard error in tube thickness measurements is greater than the annual corrosion rate in most parts of most recovery boilers, small errors in thickness measurement can produce large errors in calculated corrosion rates. This is particularly true when the measurements span only a short period of time. For example, consider a tube that is thinning at 0.003" per year. If the measured thickness is 0.007" (one standard deviation) high one year and 0.007" (one standard deviation) low the next year, a calculation based on only these two measurements would give a thinning rate of 0.017" per year. If the measured thickness were 0.007" low the first year and 0.007" high the second year, the calculation would show an apparent thickness increase of 0.011" per year. As a result, corrosion rates calculated from two thickness measurements made at the "same" location one year apart are almost always imprecise.

Fitness-for-service – near drum thinning

Ultrasonic testing systems that scan the area of generating bank tubes subject to near-drum corrosion require particular care in interpretation. These systems scan 100% of the surface of generating bank tubes, but technicians typically record only the thickness of the thinnest reading, regardless of the size of the thinned area. Although the diameter of a single spot measurement made by one of these instruments is typically 0.030", so many overlapping readings are taken that the data display may show a data point (pixel) size as small as 0.001" x 0.002". Since the impact of a small thin area on the integrity of a tube depends critically on its size and shape, inspectors should always record the size and shape of the thinnest area. If a significant area is thinned below the code minimum, the tube must be repaired or replaced. However, if the thinned area is very small, like a pit, it is prudent to examine its effect on the integrity of the tube by fitness-for-service methods (26) rather than condemn the defect without further analysis.

Minimizing errors in tube thickness measurements

Three approaches may be used to minimize errors in corrosion rate calculations. The first (11, 20) is to verify the ability of testing personnel to obtain accurate UT measurements on blind samples, and to only allow those personnel who show a minimum competence to make measurements inside the boiler. The second is to require that UT technicians recalibrate their instruments after a certain number of readings (perhaps 100) or a certain length of time (perhaps 15 minutes) and repeat the last group of readings if the calibration is off by more than a certain amount (perhaps 0.003"). The third method is to recheck every thickness reading that is unusually low or high compared to neighboring tubes or to thickness predictions calculated from previous data (e.g. more than two standard deviations from the predicted value). Rechecking should be done by a different technician using a different instrument. In this author's experience almost all outlying thickness measurements made during recovery boiler shutdowns are found to be erroneous when re-checked. Experience shows that, when tubes are cut out after minimum thickness measurements were carefully rechecked, the UT measurements are almost always within 0.005" of the minimum thickness that can be found with a needle point micrometer.

SCOPE AND FREQUENCY OF RECOVERY BOILER INSPECTIONS

Inspection planning

The previous discussion has shown that established test methods are available to detect dangerous thinning in recovery boiler tubes, and to detect cracks that could propagate and fracture pressure parts. However it is important to remember that test methods cannot find potentially hazardous defects unless an appropriate test method is applied at the location of the critical defect before it has time to grow and cause a leak.

There are no North American standards for the scope, method, or frequency of recovery boiler inspections. In fact, industry standards would not be appropriate, because each boiler behaves uniquely and should be inspected uniquely. Several useful publications are available to those who plan inspections (7, 9, 21-27). In particular, the first volume of the American Forest and Paper Association's Recovery Boiler Manual gives practical guidelines to inspectors (7), and TAPPI has published a Technical Information Sheet about how to survey the thickness of recovery boiler tubes (10).

As a minimum, a recovery boiler owner must perform sufficient inspections and maintenance to satisfy state and federal laws and the requirements of his insurance carrier. However, many companies do much more to try to increase the safety and reliability of their recovery boilers. Their additional activities can include establishing extensive programs to assure design and workmanship quality in new construction and maintenance and auditing operation, inspection and maintenance programs to check that they meet company standards. Boiler owners also need to maintain awareness of new inspection and maintenance technology through their corporate specialists or through contractors. Useful sources of new technology include industry groups such as BLRBAC, NACE International’s TEG 198X (Technical Exchange Group on Recovery Boiler Fireside Corrosion), the Research and Development Subcommittee of AFPA's Recovery Boiler Committee, as well as direct or indirect sponsorship of recovery boiler research.

Three approaches to inspection planning

Since the cost of recovery boiler inspections depends on the scope of the non-destructive testing that is undertaken, we will now evaluate the three approaches that have been used to plan the scope and frequency of recovery boiler inspections. These are: thickness testing in predetermined grid locations, inspection in proportion to the historical risk of critical leaks in particular parts of a boiler and thickness measurements based on previous corrosion rates plus additional testing in areas of concern. We will discuss each approach in turn.

1. Inspection based on thickness measurements at predetermined grid locations

Most recovery boilers are inspected at frequencies between 12 and 24 months. There is no standard scope for tube thickness inspections and inspection practices vary widely. For example, the AFPA Recovery Boiler Reference Manual (7) does not suggest any routine measurement of floor tube thickness, while some companies inspect every second tube along lines one foot from the front and rear walls and at four-foot intervals between these lines. With regard to water wall tubes, the AFPA Manual suggests measuring every tube at four elevations, while some mills measure the thickness at the crown of the tube and each shoulder at each measurement location at elevations ranging from 2 to 3 feet apart in the lower furnace to 10 feet apart in the upper furnace.

Many surveys that measure tube thickness at large numbers of elevations only measure the thickness of every other tube or every fifth or tenth tube at any given inspection. Tubes surrounding ports and openings in the lower furnace typically have their thickness measured or scanned only at the top, center and bottom of the port. Roof tube thickness surveys range from a single line of measurements halfway between the furnace screen tubes and the front wall of the boiler to lines at 4-foot intervals from the front wall. Roof tubes are generally inspected less frequently than water wall tubes, although severe thinning has been reported (24) on roof tubes surrounding superheater tube penetrations. Some companies inspect screen tubes at a single point halfway up their vertical section as per the AFPA manual, while others scan the thickness of the outermost screen tube in each platen in the outermost part of the bend and at locations one and two feet each side of that location. Similar disparities exist in the extent of inspection of nose arch tubes, superheater, generating bank and economizer tubes.

Because of the wide disparity in the extent of recovery boiler tube thickness measurement in North America, a recovery boiler owner can find little assurance that he has ensured the safe and reliable operation of the unit by basing the scope and frequency of his tube thickness survey on those used elsewhere. More tube thickness measurements will not necessarily detect critical flaws with more certainty, because thin spots are typically much smaller than grid sizes. The value of thickness surveys is that they can highlight suspicious areas where evidence of local thinning requires further investigation and that they can provide data to calculate average rates of tube thinning in particular regions of a boiler.

It is very important to remember that most types of potentially hazardous service-related corrosion and cracking cannot be detected by tube thickness surveys. These include waterside pitting , waterside scaling (that produces insulating deposits which increase the tube surface temperature and hence the corrosion rate), waterside stress-assisted corrosion (29) - corrosion-fatigue-like fissures in the waterside of tubes where heavy attachment welds are present on the outside of the tubes – and fireside cracking of composite tubes (30, 31). Waterside corrosion and deposition cannot usually be assessed without removing sections of tubes. Waterside stress-assisted corrosion fissures are most likely to be found at highly restrained attachment welds in the lower furnace, e.g., welds at floor-to-wall joints, air port scallop bars seals, and buckstay welds.

Thinning of the outer stainless steel layer of composite tubes often occurs at small areas in the crotch of port openings in the lower furnace (32). Although this thinning is unlikely to be detected by thickness measurements at predetermined grid locations, it can be measured with magnetic lift-off gauges that measure the distance between the gauge head and the underlying carbon steel tube. These gauges are also useful for to measure the thickness of non-magnetic thermally sprayed coatings on carbon steel tubes. Eddy current gauges are available that can estimate the thickness of non-magnetic layers in less accessible areas. Thin areas in the outer stainless steel layer of composite tubes can be identified by visual inspection or by feel and thickness measurements in these areas can be used to locate the thinnest spot.

Carbon steel water wall tubes can suffer fireside thinning alongside the welds that attach them to the (vertical) membrane bars that separate them. These thinned areas cannot be detected by ultrasonic thickness measurements, because they are too close to the membrane to be reached by conventional transducers. They can instead be detected using either templates or light shadowing.

Water wall tubes in older, non-membrane boilers, i.e., those with non-welded tangent tubes or with flat stud construction, are vulnerable to casing-side corrosion on the external surfaces that face away from the furnace, especially when the tubes remain moist for extended periods following water washing. This type of corrosion cannot be detected without removing sections of the insulation and casing on the outside of the boiler. Casing-side corrosion is usually most severe between the levels of the secondary air ports and the nose arch. It is best evaluated visually, using ultrasonic thickness testing for measurements in the areas that look thinnest.

Because UT thickness surveys will not detect cracking, areas to be inspected for fatigue cracks or thermal fatigue cracks should be designated by a knowledgeable inspector for inspection by other methods. Liquid penetrant (PT) or magnetic particle (MT) testing methods can detect these cracks. Locations vulnerable to fatigue cracking include areas beside strong restraints like fixed supports, headers or vibration restraints. Areas subject to thermal fatigue include attachment welds to composite tubes, pin stud and flat stud attachments, tubes surrounding smelt spouts and air ports and areas where smelt washes up and down against the surface of lower furnace tubes.

Because so many types of potentially harmful defects cannot be detected by thickness measurements on predetermined grids, it is essential that other types of non-destructive tests and expert visual inspection be added to tube thickness surveys to complete an inspection.

<u>2. Inspection based on risk of critical leaks</u>

A second approach to determining the scope and frequency of recovery boiler inspections is to inspect different parts of the boiler according to the historical risk of failures in that part of the boiler. Our previous study of explosions and critical exposures reported to BLRBAC (7) shows that 32% of critical leaks occurred in lower water wall tubes, 15% in upper water wall tubes and 3% at unspecified wall tubes. 12% occurred in furnace screen tubes, 12% in boiler bank tubes (with an additional 3% reported to have been at the mud drum ends of these tubes and 3% at the steam drum ends of these tubes), 8% in floor tubes, 6% at the spouts and 5% in other parts of the boiler. If the grid size for ultrasonic thickness measurements were made inversely proportional to the historical likelihood of critical leaks in particular areas, the grid size should be smallest on the lower water walls, about twice as large on the upper water walls, furnace screen and generating bank tubes, about twice as large again in the floor, in the superheater and economizer, and so on. Because of the unusually high risk of failure in the small areas of tubes exposed at spout openings and at the top and bottom ends of generating bank tubes, a “leak-risk” based inspection would probably scan tube thicknesses in 100% of these critical areas.

Although the concept of inspecting according to the risk of failure has great merit, we have pointed out (8) that, because the BLRBAC data do not record explosions that were avoided by the discovery of incipient problems that were repaired before they propagated to cause leaks, they do not indicate the overall effectiveness of particular types of inspection in detecting critical leaks. The BLRBAC data should be regarded more as an indication of what careless inspectors have missed than of what careful inspectors have found. As a result, historical information about critical leaks has more value for planning quality assurance programs to verify critical aspects of the design and construction of new recovery boilers than for planning the scope and frequency of boiler inspections.

<u>3. Inspection based on calculated corrosion rates, visual inspection and other non-destructive tests</u>

The AFPA Recovery Boiler Handbook affirms that ultrasonic tube thickness surveys should be conducted to survey tube thicknesses and to calculate rates of tube metal wastage in different parts of the boiler. To improve the accuracy of metal wastage calculations, thickness measurements should be made at exactly the same locations during successive inspections. The AFPA Handbook recommends installing benchmarks for this purpose, preferably on the tube-to-tube membrane, so that chalk lines can be applied to mark the exact height of the thickness measurement locations.

To make precise calculations of thinning rates, it is necessary to compare measurements taken at 100 or more points on at least four separate occasions. The development in recent years of computer-based data management programs for tube thickness measurements has greatly facilitated this type of calculation. Commercial programs are available that indicate tube thicknesses on computer-generated maps of the boiler surfaces. These maps indicate patterns of tube thinning much more clearly than the tables of thousands of data points they replace. Unfortunately most of these programs calculate corrosion rates by comparing thicknesses at particular locations at successive shutdowns. Such calculations are neither accurate nor precise, as was shown above, because of inherent limitations of the ultrasonic data.

Careful analysis of thickness data is required to determine the regions in a boiler within which the tube thicknesses belong to the same statistical population. This might be done, for example, by dividing a large wall area into 9 separate sectors (high, middle, low and left, center and right) to determine whether the tube thickness distributions in the sub-areas differ significantly.

Analysis of thinning rates in about 30 statistically distinct areas of several recovery boilers has shown that calculated thinning rates averaged over the life of a boiler range from about zero to about 0.006" per year. The highest rates of metal wastage typically appear on wall tubes at port and sootblower openings. As has been discussed above, the standard error of about 0.007" in tube thickness measurements precludes attempts to calculate corrosion rates at individual locations from repeated thickness measurements at single locations. However, realistic corrosion rates within particular areas of a boiler can be calculated by comparing the sums of thickness measurements taken at the same locations at successive shutdowns. Some data management programs, such as the UTmost program developed by MeadWestvaco, regress these sums of thickness data to calculate corrosion rates. This type of program can also combine the corrosion rate data with current tube thickness data and allowable minimum thickness data to estimate the remaining service life of particular sections of a boiler. Such estimates are extremely valuable. They allow thinned portions of a boiler to be replaced on a scheduled basis, coordinated with other major work anticipated in the mill, which always costs much less than unscheduled replacement.

Inspection strategies to equalize the risks from thinning and cracking

Despite the fact that more than half the critical exposures reported to BLRBAC occurred because of cracks at welds, most recovery boiler inspections continue to devote far more effort to evaluating corrosion thinning than to locating and evaluating fireside and waterside cracks. This emphasis on thinning rather than cracking arises because most inspections are managed by testing companies rather than by inspectors. It is easier for testing companies to sell their ability to measure tube thickness, than to take responsibility for finding all significant crack-like defects in a boiler and evaluating their effect on the integrity of the unit. Most testing companies do not have staff skilled in making fitness-for-service determinations and do not wish to be held responsible for such determinations.

To reduce the hazards associated with cracking to the same level of risk as the hazards associated with thinning, inspection programs must emphasize visual inspections, including crack detection inspections, by experts familiar with recent findings in similar recovery boilers around the world. Based on findings elsewhere, such experts inspect areas susceptible to external cracking by liquid penetrant testing or magnetic particle testing, and inspect areas subject to waterside cracking by radiography or perhaps shear wave ultrasonic testing. If cracks are detected, the inspector establishes their size and shape, either by additional non-destructive testing or by grinding. The impact of remaining cracks on the integrity of the tubes should be quantitatively evaluated by an fitness-for service expert.

Role of original weld quality in cracking at attachment welds

Both fireside cracking of composite tubes (30, 31) and waterside stress-assisted corrosion of carbon steel tubes (29) are influenced by the design and quality of the original attachment welds. Many types of weld defects that can develop to threaten the integrity of a tube are relatively easy to detect during fabrication and erection, but very difficult to detect after the boiler is built, when access and inspection time are restricted. Because more than half the critical leaks reported during recent years were associated with welds, it is critically important when purchasing a new recovery boiler or rebuilding an existing unit to thoroughly review the vendor's proposals for the design, fabrication and erection to insure that appropriate quality requirements have been incorporated in the purchase specifications. The design and quality of attachment welds should be reviewed with particular care.

Quality assurance specifications should always be established before bids are sought for new or replacement boiler parts, because additional requirements introduced later are likely to produce significant cost escalations. The owner should clearly establish his/her own accept/reject standards for quality based on expert advice and industry experience, e.g. to require radiography of butt welds in places where this may not be required by the (generic) ASME code, and to require careful inspection of attachment welds to water-filled tubes. Quality assurance requirements established for new construction should also be applied to repair and replacement work once the boiler is in service. Inspections by owner personnel, or by contractors reporting directly to the owner, should be scheduled to verify that the quality control programs established by boiler fabricators, erectors, and their sub-contractors have ensured that critical quality specifications have been met.

Recommended strategy for corrosion inspections

We have shown that it is not necessary to take many thousands of tube thickness readings each year in order to establish rates of corrosion thinning. In addition we have shown that increasing the number of routine tube thickness measurements has little effect on the likelihood of finding the thinnest areas of the thinnest tube, because the inspection grid is so much larger than most of the thinnest areas Therefore, rather than decrease inspection grid sizes in the (unrealistic) hope that increased numbers of measurements will discover local thin spots, it is wiser to measure tube thicknesses carefully in repeated inspections at selected and identifiable representative grid sites and look to human inspectors to find thinned areas and suspicious indications. Corrosion rates should then be calculated for each distinct area of the boiler. Additional inspection should be made in areas found to be thin in previous inspections and to examine suspicious features found during the current inspection.

Regardless of the size of the pre-determined inspection grid, criteria should be established in advance of the inspection so that if unusually thin tube measurements are obtained and verified, the thickness of surrounding tubes will be investigated using a much smaller inspection grid or by scanning the thickness of the surrounding tubes. The most cost-effective inspection strategy involves the repetition of thickness measurements at selected points to determine corrosion rates plus additional inspector-directed measurements to seek the thinnest tubes and critical defects. Visual inspection and other types of testing are essential to detect cracking and thinning in areas not normally measured or inaccessible to ultrasonic transducers (e.g. between non-welded tangent tubes, and on wall tubes adjacent to membrane bars).

OPPORTUNISTIC INSPECTIONS

If a recovery boiler becomes unexpectedly available for inspection, e.g. because of an emergency shutdown, opportunities should be sought to inspect as follows:

- Visual inspection of all tubes surrounding smelt pouts, primary and secondary air ports
- Visual check for out-of-plane wall tubes and visual check for out-of-plane pendant tubes from scaffold boards in sootblower lanes
- Visual inspection from access doors in sootblower lanes
- Waterside inspections from inside the mud drum and steam drum
- Tube thickness measurements more than 12 months overdue
- Replacement of tubes projected to thin below code within 24 months
- Visual inspection of smelt spouts
- Hydrostatic test at 90% of normal steam outlet pressure to detect leaks

CONCLUSIONS

- Volume 1 of the AFPA Recovery Boiler Reference Manual provides very useful guidelines for the planning of recovery boiler inspections.
- Non-destructive testing techniques are available that can indicate excessive thinning or incipient cracking if they are applied to the area where the damage is occurring.
- To increase the probability of detecting the thinnest tubes, and to detect incipient cracking, additional testing should be performed at the direction of an inspector who has years of experience inspecting similar boilers, and is aware of recent industry findings and state-of-the-art inspection methods.
- Typical UT thickness data obtained by contractor personnel have a standard error of 0.005 to 0.007" in their precision and 0.004 to 0.006" in their accuracy. As a result, corrosion rate calculations based on the difference between two thickness measurements made at successive shutdowns at the same location are almost always imprecise.
- Rates of tube wastage in different parts of a boiler, calculated from tube thickness data, can be used to schedule the replacement of different sections of the boiler as the average tube thickness approaches the code minimum thickness.

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