Interpreting recovery boiler tube thickness data*

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ABSTRACT

Recovery boiler tube thickness surveys typically generate several thousand measurements each year. It is a challenge to understand tabular lists of tube thickness data because of the large number of measurements and their inherent errors. Carefully designed graphs are useful tools to show trends in the tube thicknesses, variability in individual tube corrosion rates, and approximate distributions of remaining tube lifetimes.

In this paper, we describe common errors involved in tube thickness measurements, along with some strategies for reducing these errors. We discuss the reliability of corrosion rates and remaining lifetime estimates derived from tube thickness measurements. A method is explained for condensing large amounts of thickness data on a single graph so that the condition of boiler tubes can better be understood.

Application:

Application of the methods described in this paper can help boiler owners to interpret tube thickness data and to plan future tube thickness surveys more effectively.

TUBE THICKNESS MEASUREMENT IS one of several inspection methods used to assess the condition of a recovery boiler. However, analysis of thickness measurements is not simple because of the large numbers of measurements and their uncertainty. In years past, thickness data were presented mainly in voluminous tables of numbers. Personal computers are now available to condense the data into maps of graphs *(1)* that can be comprehended visually with far more clarity and speed. Maps and graphs are complementary; maps are best for showing spatial relationships, and graphs show temporal relationships. With a better grasp of the meaning of tube thickness data, the boiler owner can focus his energy on planning for the boiler's future inspections, maintenance, and, if necessary, eventual replacement.

How reliable are tube thickness measurements, and how can the reliability be improved? How can we derive the most essential information from the measurements? This paper discusses measurement errors and describes actions that can reduce such errors. A graphical method, which captures key features of the data, is suggested. Examples from actual boilers are shown that illustrate important information contained in the tube thickness data.

*Disclaimer: This paper was prepared for TAPPI as a collection of the opinions of the authors at the time of writing. Following their opinions and recommendations does not guarantee that recovery boiler inspections will be successful.

BASIC CONCEPTS

Tube thickness surveys. Recovery boiler tube thicknesses are usually measured by one of two methods. Ultrasonic testing (UT) instruments are commonly used for measuring total tube wall thickness (2), and magnetic lift-off gauges are used to measure the stainless layer on composite tubes (3). Although the ideas discussed in this paper apply to both types of measurements, the examples here are for UT measurements.

UT measurements in a recovery boiler are often made at a pattern or grid of locations, for example, every 2 m (6 ft) on every fifth tube. The grid spacing depends on the part of the boiler being inspected. Several thousand measurements may be taken in a single boiler inspection. Measurements are typically repeated every 1–2 years *(4)*.

We begin by considering measurements at a single location. Assume that, for several years, we have used UT to measure the thickness of a single location on a single tube. In Fig. 1, these measurements are plotted vs. time. Tube thickness is usually initially slightly above the nominal wall thickness specified for the tube [e.g., 0.5 mm (0.020 in.)].

Ideally, the thickness at each location would show a steady, slow decrease over time and therefore would fall on a straight line (points "a" on Fig. 1). Any two points would be sufficient to determine the thinning rate with 100% confidence, and the remaining life could be calculated by dividing the difference between the current and minimum thicknesses by the annual corrosion rate.

Unfortunately, actual measurements, as shown by points "b" in Fig. 1, do not typically fall exactly on a straight line. The measured loss from year to year is usually not constant, and the thickness may even appear to increase. We cannot reliably calculate the corrosion rate from just two points but instead must estimate it by a statistical analysis of several measurements taken over time.

The calculated rate and projected remaining life have some uncertainty, depending on the number of measurements and the magnitude of the measurement errors. Taking measurements more often usually increases confidence in the

data but may not be practical. Taking measurements over a longer time span also increases the confidence.

For safe operation, all tube locations should have a thickness greater than the minimum allowed by the boiler owner; when this minimum thickness no longer exists, the tube is replaced. Minimum allowable thickness depends on the boiler operating pressure. The difference between the current thickness and the minimum allowable thickness is the remaining corrosion allowance.

VARIABILITY IN TUBE THICKNESS MEASUREMENTS

We now consider the analysis of groups of measurements.

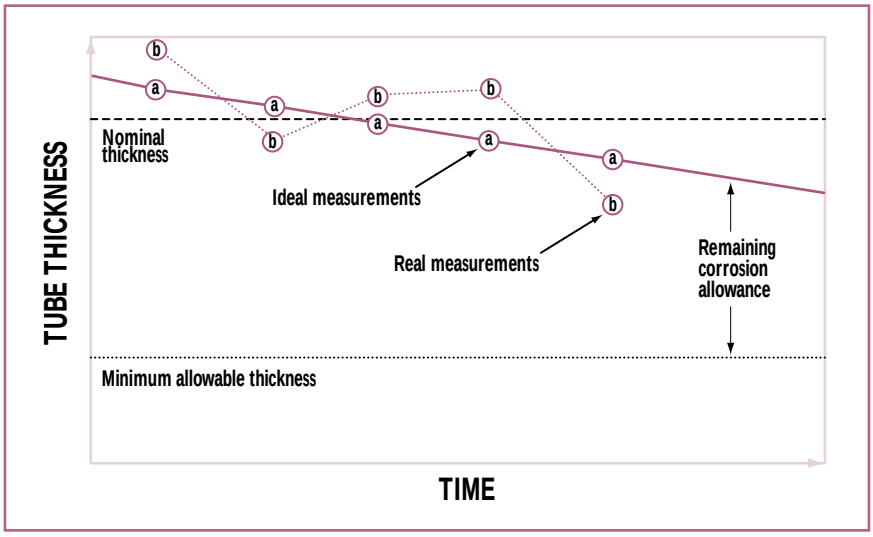
Precision and accuracy

Assuming that errors in the UT readings follow a normal distribution, the measurements can be characterized by two statistics: the standard deviation and the average or mean value. In practice, one measurement is made in each inspection at each location. If the standard deviation of the measurement for a given location is small [e.g., 0.1 mm (0.004 in.)], the measurement is repeatable, or *precise*. Generally, small year-to-year variations in measured thickness at individual locations suggest good precision.

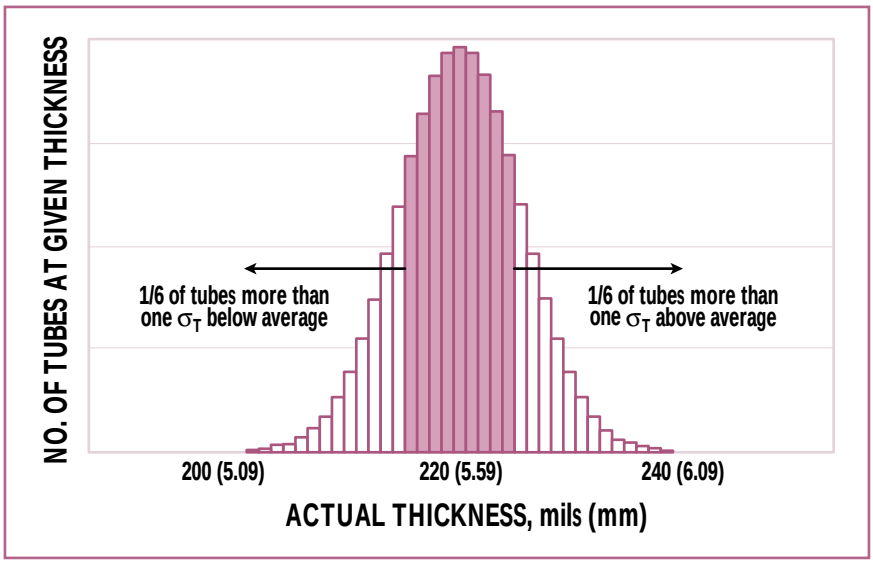
If the average measurement is equal to the true thickness, the measurement is *accurate*. Generally, small year-to-year variations in average measured thickness for many locations in one region of the boiler suggest good accuracy. The UT measurement accuracy is primarily related to instrument calibration. It should be possible to achieve an accuracy of ±0.08 mm (0.003 in.) or less *(2)*.

Actual variability in tube thickness

Boiler tubes manufactured to the same specifications show some initial variability *(5)*. Figure 2 is a hypothetical thickness distribution



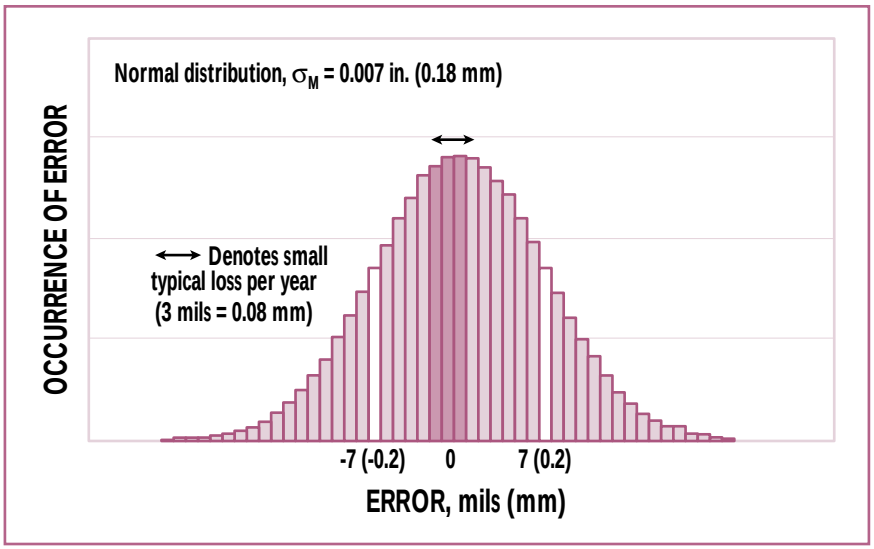
1. UT thickness measurements at a single point



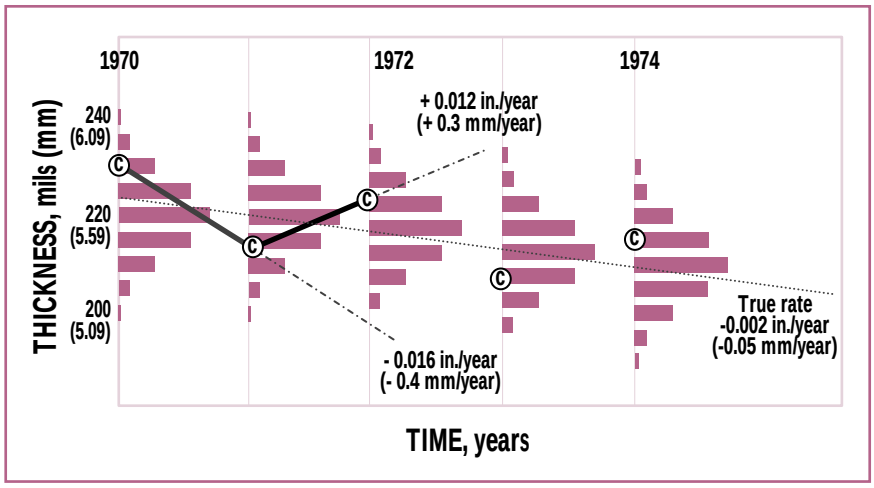
2. True thickness variations

representing new tubes with a nominal wall thickness of 5.08 mm (0.200 in.). This normal distribution has a mean of 5.59 mm (0.220 in.) and a standard deviation (S_T) of 0.13 mm (0.005 in.). For carbon steel tubes with nominal thickness of 5.08 mm (0.200 in.), the standard deviation could be as large as 0.15–0.22 mm (0.006–0.009 in.), depending on how the tubes were manufactured *(6)*.

If the actual tube thicknesses lie in a normal distribution, about one-sixth of the distribution will be thinner by more than one standard deviation from the mean, and one-sixth will be thicker by the same amount. As time passes and corrosion thins some locations more than others, the true variability in the thicknesses in each part of the boiler is likely to gradually increase.



3. Measurement error at a single point



Errors in measurement of tube thickness

A second source of variability in tube thickness data is measurement error. Figure 3 shows the error distribution (measured thickness minus true thickness) that could arise if a large number of UT measurements were made repeatedly at the same location on a typical boiler tube. The measurement error standard deviation, S_M, of the distribution in Fig. 3 is 0.18 mm (0.007 in.).

Moskal *(1)* has studied the precision of UT tube thickness measurements by examining test results from 62 technicians. For tubes without hidden defects, he reported a standard deviation of 0.44 mm (0.017 in.) in single-point measurements. This included some errors larger than 0.75 mm (0.030 in.), which are not typical of skilled UT technicians. If these large errors are excluded, the standard deviation would be about 0.18 mm (0.007 in.).

Studies by the authors have shown that, in controlled tests, the best UT technicians can achieve standard deviations as low as 0.1 mm (0.004 in.), but slightly higher values are typical. Data from actual boiler tube thickness surveys suggest, for some parts of the boiler with little corrosion, that s_M approaches 0.1 mm (0.004 in.). However, a more typical value is 0.18 mm (0.007 in.), provided occasional large errors are excluded.

With a normal distribution, one measurement in three has an error of more than one standard deviation [0.18 mm (0.007 in.)] from the mean. Five percent of the errors exceeds two standard deviations, or 0.36 mm (0.014 in.). These 5% are said to exceed the two-sigma limits.

One percent of the errors exceeds three standard deviations [0.54 mm (0.021 in.)]. A small fraction of 1% exceeds 0.72 mm (0.028 in.), but errors this large are generally recognized as outliers, and the measurements are discarded.

The error distribution in Fig. 3 arises even if the thickness of the measured tube does not change. It represents only the measurement error. A typical corrosion rate is 0.08 mm (0.003 in.) per year, which is small enough to be hidden by the measurement error characterized by S_M = 0.18 mm (0.007 in.).

Measured thickness for a tube

Variations in measured thickness at a given point in time reflect both the effect of true thickness variations and the effect of measurement errors. The range of measured thicknesses is larger than the range of true thicknesses because of the measurement error. The standard deviation of the measured thickness, S_{T+M}, is calculated by the following equation:

$$S_{T+M} = \sqrt{S_T^2 + S_M^2} \qquad (1)$$

For our new tubes in this example, the measured thickness standard deviation is 0.22 mm (0.009 in.). We later show that S_{T+M} at a given

inspection can be calculated from actual data. Note that corrosion causes S_T and S_{T+M} to increase with time.

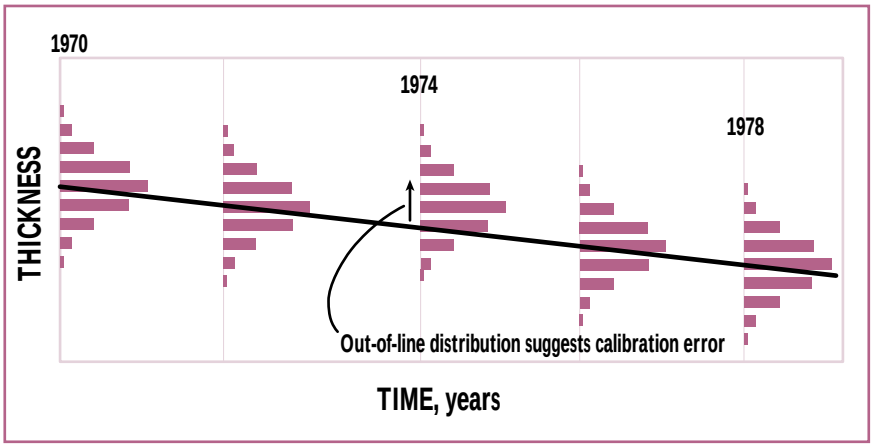
Calculated corrosion rates

Assume that a boiler has operated for several years with a uniform, constant corrosion rate of 0.05 mm/year (0.002 in./year). Tube thickness measurements have been repeated at several inspections and presented in histograms, as shown in Fig. 4. Note that, although the mean of possible values drops at successive inspections, measurements at a given location (the "c" points) may show erratic trends.

When we consider individual locations, there is a *random* chance (1 in 6) that any single measurement is erroneously high or low by 0.18 mm (0.007 in.), which is the standard deviation of the measurement. At 3% of the locations (1/6 x 1/6), the combination of high/low or low/high measurement errors in consecutive years would show either an erroneous decrease of 0.41 mm (0.016 in.) or an erroneous increase of 0.30 mm (0.012 in.), where the real corrosion rate is only 0.05 mm/year (0.002 in./year). This exercise emphasizes that it is impossible to reliably determine corrosion rates for individual locations with just two measurements taken within a short time span.

The effect of random measurement errors on average corrosion rate should be zero. Averaging the measurements cancels the random error, so that for the example shown in Fig. 4, the average rate can be reliably calculated to be about –0.05 mm/year (–0.002 in. per year).

Table I gives examples of some errors that can occur in calculating individual tube corrosion rates from only two points. The corrosion rates calculated for individual locations become more reliable when measurements are made over a longer time span. However, even after 10 or more years, the calculated rate for an individual location based on just two measurements may be in error by 0.03 mm/year (0.001 in./year).



5. Calibration error

The examples in Table I each represent only about 3% of all individual locations, and such errors are less likely when an analysis of data from more than two inspections is used to determine the corrosion rates. Ultimately the following factors have an effect on the calculated corrosion rate at an individual location:

- True corrosion rate
- Measurement standard deviation (S_M)
- Number of inspections used to determine rate
- Time span between measurements.

Reducing the effect of measurement error

In a given time interval for which corrosion rates are being calculated, it helps to have several measurements (e.g., four or more inspections instead of the minimum two). When data from more than two inspections are available, the corrosion rate can be calculated by least-squares analysis, and the chances of getting extreme results, like those described in Table I, become less likely.

The effect of measurement error can be minimized by taking measurements over a longer time span and by averaging thickness data from all the locations in a similar corrosion environment (e.g., within a section of the boiler). From now on, we focus not on data from individual locations but rather on groups of data from particular sections of the boiler.

Systematic error

Another type of error is not random but is *systematic*. Such an error is not canceled by taking more data. Figure 5 shows hypothetical data from five inspections. Note that the middle inspection (1974) is out of line compared with the others. The entire distribution of measurements for the inspection is shifted upward. This represents a systematic error, most likely arising from an inaccurate calibration of the UT instrument. This type of error is called *calibration error*.

Consequences of calibration error. If large calibration errors occur frequently, analysis of historical data will be misleading or meaningless. A calibration error in the most recent inspection is particularly troubling, because if the boiler is restarted before the measurements are rechecked, there is no way to determine what has happened until the next inspection. Calibration

Inspection interval, years	Pessimistic loss per year, mm (in.)	Optimistic loss or [gain] per year, mm (in.)
1	0.41 (0.016)	[0.31] ([0.012])
4	0.14 (0.0055)	[0.04] ([0.0015])
10	0.09 (0.0034)	0.015 (0.0006)
True rate	0.05 (0.002)	0.05 (0.002)

I. Measured corrosion rate at individual locations for extreme cases of measurement error

THICKNESS LIMITS

Section name	Projected average thickness, mm (in.)	s_{T+M}	−2s low	+2s high
Lower wall	4.93 (0.194)	0.28 (0.011)	4.37 (0.172)	5.49 (0.216)
Nose arch	5.11 (0.201)	0.15 (0.006)	4.80 (0.189)	5.41 (0.213)
Screen bends	4.75 (0.187)	0.20 (0.008)	4.34 (0.171)	5.16 (0.203)

II. Checklist for UT data quality. (Updated before each inspection, based on previous data. Values shown are hypothetical.)

errors toward lower measurements may cause alarm, and errors toward higher measurements may result in skepticism about inspection quality.

Calibration errors should be minimized by proactive efforts, e.g., by using prequalified technicians and having them recalibrate their UT instruments every 15 min. Diligent calibration procedures *(2)* should hold calibration errors below 0.08 mm (0.003 in.), a level at which they may not be apparent in a graph such as Fig. 5. In addition, the occurrence of calibration errors can be minimized by screening incoming data to detect measurements consistently out of line compared to data from the same locations at previous inspections.

Quality checks on incoming UT data

A list, such as that shown in Table II, can be generated by analysis of the thickness data from prior surveys. For each section of the boiler that is to be inspected, the list shows the expected average thickness, extrapolated from the least-squares fit through previous inspection averages. With less than two prior inspections, there are insufficient data to determine corrosion rates. For the initial inspection, which is often more extensive than most subsequent inspections, the expected average thickness, somewhat above nominal, could be used. If only one previous inspection is available, as in the case of a new boiler, average thickness can be used as a basis for comparison.

Table II lists the standard deviation of the thickness distribution s_{T+M}, calculated at the last inspection, which reflects both real variation and measurement errors. Based on the expected average and the standard deviation s_{T+M}, the two-sigma low- and high-thickness limits are also shown.

Using the checklist. For each section of the boiler, the average thickness measured during an inspection is expected to be within about 0.1 mm (0.005 in.) of the projected value unless a calibration error or a change in the corrosion rate has occurred. The agreement between the projected and actual average can easily be checked if the UT measurements are run through a computer data-logging system as they are acquired. The standard deviation s_{T+M} could also be checked.

If measurements are printed on-site in color-coded printouts or maps, the color ranges can be set to highlight values outside the two-sigma limits. Approximately 3% of the new measurements can be expected to fall above the two-sigma high limit and 3% below the two-sigma low limit. If on-site computer logging is not available, data sheets can be reviewed to highlight measurements exceeding the limits.

Rechecking doubtful thickness measurements. If the observed average thickness deviates substantially from the projected value, or if more than a few percent of the measurements exceed the high or low limits, enough thicknesses should be remeasured to determine if they are correct. The rechecked measurements should be done by a different technician, using another UT instrument, to prevent a recurrence of either operator or instrument error. If a recheck fails to verify the measurements, the suspect readings should be repeated. To avoid bias, technicians making original or repeat measurements should not have access to any earlier data. To use thickness data projections effectively, any questionable measurements must be identified and rechecked while the boiler is still open.

Some "calibration" errors are not really errors

An unexpected, usually slight drop in thicknesses compared with the least-squares line could mean that the corrosion rate has accelerated.

On the other hand, large drops, or any increases in thickness, should be treated as suspect. However, some discrepancies that appear to be calibration errors may arise, but they really are not, as discussed below.

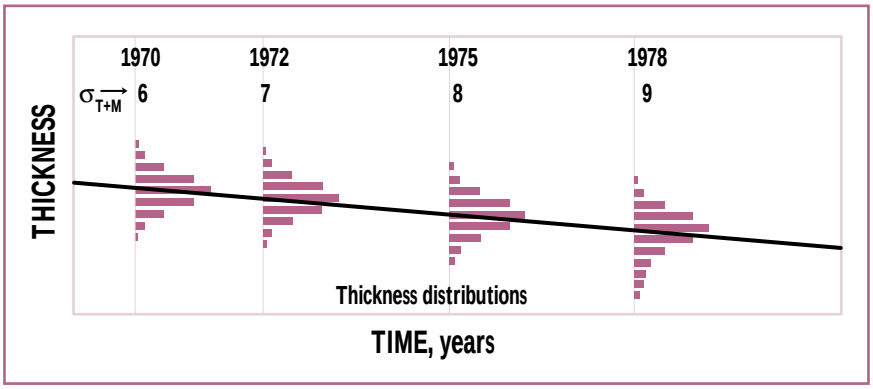
Use of a different transducer size. On boiler tubes with nonuniform localized corrosion, changing to a slightly smaller diameter transducer may cause a decrease in measured thicknesses. The use of small transducers is valuable to provide access to previously inaccessible areas, but their measurements may not compare directly to measurements made with larger transducers.

A focus on thinned areas. Inspection of older boilers may focus on problem areas by taking more measurements, e.g., tightening the inspection grid in known thinned areas. For example, after several years, part of the measurement grid for one section may be tightened to take more readings in a locally thinned area. This causes the average measured thickness of the section to suddenly drop, not because the measurements are incorrect or because corrosion has suddenly accelerated, but simply because data points in unusually thinned areas have been added. When analyzing boiler sections with localized corrosion, statistics for the problem areas therefore should be calculated separately to understand what is really happening.

Assumption of constant corrosion rate

Corrosion rates in a recovery boiler may change because of operating practice. However, for this analysis, the corrosion rate for an individual tube at a particular location is assumed to be constant. Rates may vary from location to location, but the rate at any particular location is assumed not to change. This assumption allows us to calculate the corrosion rate by least-squares analyses using all measurements taken at the location. For these calculations to be reliable, data from at least four inspections over five years are usually required.

Although locations in a similar corrosion environment usually corrode at similar rates, adjacent tubes can corrode at different rates. If significant corrosion occurs, variability in tube thicknesses will increase with time. The average thickness always decreases, while the standard deviation S_T (and therefore S_{T+M}) increases. The thickness of tubes manufactured to a wall specification of 5.59±0.13 mm (0.220±0.005 in.) after many years might be 4.83±0.20 mm (0.190±0.008 in.).



6. Tube thickness data

DATA FROM ACTUAL BOILERS

Tube thickness data from actual boilers are now presented. The format shown simplified in Figs. 6–8 has been developed by Westvaco *(7)* for interpreting thickness data for tubes in similar corrosion environments within a given boiler. Figure 6 shows measurements presented as thickness distributions vs. time, with standard deviations S_{T+M} listed above each distribution for ready reference. Despite the limited reliability of calculated corrosion rates and remaining lifetimes at individual tube locations, it is helpful to see the distributions of these individual rates and lifetimes, which are provided in Figs. 7 and 8.

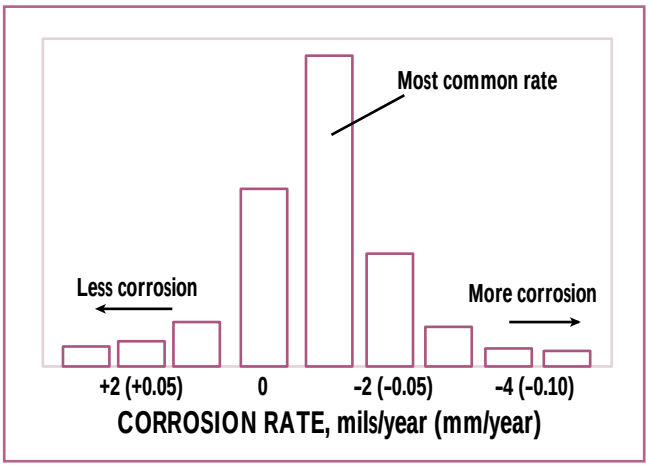
Figure 7 shows an example distribution of corrosion rates at individual locations. It is not unusual for the distribution to represent some locations shown toward the left as apparently getting thicker rather than thinner. This is because of measurement errors discussed earlier. Figure 8 shows an example distribution of remaining life at individual locations. The shortest projections may be erroneous, again because of measurement errors.

Mild corrosion in the upper furnace

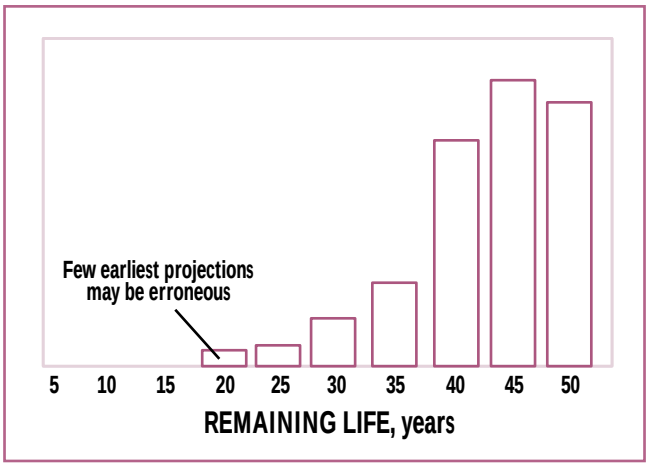
Figure 9 is a simplification of a computer screen display showing data from an upper furnace region, where corrosion is usually mild. The horizontal axis is years, and the vertical axis is in thousandths of an inch (mils). Small histograms show the UT data from several inspections.

Average corrosion rate. The average corrosion rate calculated by a least-squares fit through the average thickness of the measurements in this section at each inspection is shown by the heavy broken line. This rate, 0.04 mm/year (0.0017 in./year), is called the *section average rate.* Note that there are no obvious large calibration errors.

Individual corrosion rates. Corrosion rates at individual locations are calculated from measurements repeated at the same location. A histogram of rates at individual loca-



7. Corrosion rates at individual locations



8. Remaining life at individual locations

tions is shown in the lower left corner of Fig. 9. Variability in the calculated individual corrosion rates reflects erroneous variations arising from measurement errors as well as variations in the rates at individual locations. Most of the individual corrosion rates are 0.02–0.05 mm/year (0.001–0.002 in./year), which is within 0.02 mm/year (0.001 in./year) of the section average rate. This suggests that the section average rate of 0.04 mm/year (0.0017 in./year) represents this section fairly well.

How should remaining section life be estimated? For the conditions shown in Fig. 9, the average thickness is calculated to reach the minimum allowable thickness around the year 2050. However, it would be inappropriate to expect all the tubes to serve this long, since by the year 2050, half the locations would be below the minimum allowable thickness. A better estimate of remaining life therefore is needed.

Remaining life of individual tubes. A histogram of projected tube lives at all locations with lifetimes less than 50 years is shown in the lower right corner of Fig. 9. The distribution of remaining lifetimes suggests a probable remaining life of at least 20 years for most locations. Only about one-third of the locations are projected to reach the minimum allowable thickness within 50 years.

Service life remaining before section replacement. The average remaining tube life overestimates the remaining section life. However, the shortest projected individual life is unrealistic and too conservative. A practical compromise is to adopt, as the section's remaining life, the number of years until 15% of the measured locations are projected to reach the minimum allowable thickness. (The arbitrary value of 15% would include those projections more than one standard deviation below the mean.)

In the example of Fig. 9, this suggests that the section must be replaced in about 40 years. Most of the estimates of life less than 40 years (15% of the individual locations) are probably due to measurement errors. Of course, the owner may choose to replace part or all of the tubes well before they approach the minimum allowable thickness. As time passes and before the 40 years have passed, spot replacements of some tubes will probably be necessary. However, no such replacements appear necessary in the near future.

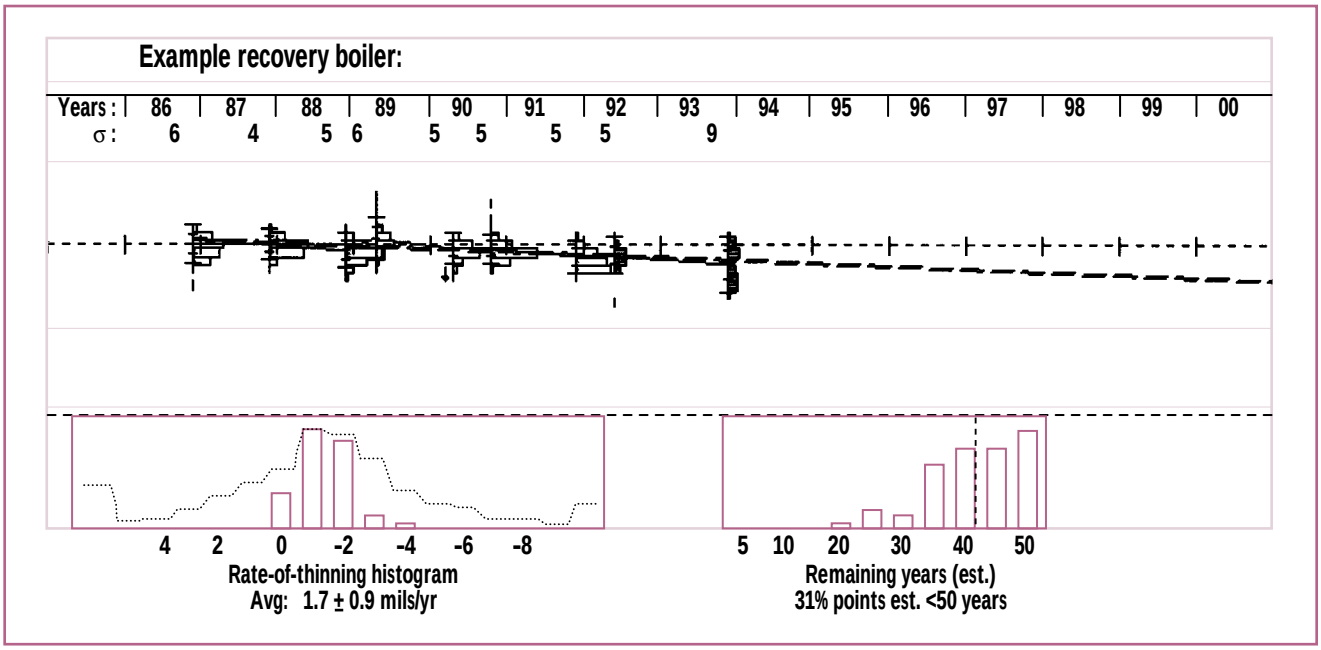
Localized corrosion

Figure 10 shows data for tubes around the primary air ports of a 20-year-old boiler. The tubes were originally above their nominal wall thickness of 5.08 mm (0.200 in.). The tubes now average near nominal thickness, with some tubes at about 4.3 mm (0.170 in.) thick. Localized corrosion is more likely at the air ports than in most upper wall areas, and individual rates therefore are more variable. The standard deviations S_{T+M} of the thickness distributions, listed near the top of the graph, gradually increase from about 0.15 mm (0.006 in.) to about 0.30 mm (0.012 in.). This gradual increase in S_{T+M} is attributed to a real increase in tube thickness variations caused by variations in corrosion thinning rates between locations.

Figure 10 contains apparent calibration errors in the fifth and eighth inspections, where measurements should have been verified at the time of the inspection using a checklist such as the one shown previously in Table II.

SUMMARY

Two types of potential errors affect tube thickness measurements: measurement error and calibration error. It is important to understand how these errors can affect the calculations of corrosion rates and remaining lifetimes. Boiler owners should be aware of these errors and implement procedures to control them.



9. Data for tubes in an upper furnace region

KEYWORDS
Computation, corrosion, data processing, dimensions, errors, furnaces, measurement, recovery furnaces, surveys, thickness, tubes.

Rapid analysis of tube thickness data at the time of inspection can indicate questionable data that should be rechecked. Analysis of tube thickness data, presented in a condensed format that can be easily assimilated, can also be valuable for planning future inspections and maintenance, particularly when estimates of corrosion rates and tube lifetimes are included with the thickness distributions.

CONCLUSIONS

The following conclusions were drawn from this work:

- Graphs of measured thickness distributions vs. time provide an effective means to interpret a boiler's corrosion history.
- A least-squares line fit through the average thicknesses at prior inspections provides an estimate of the average corrosion rate for each section of the boiler. The projected average at the next inspection and the standard deviation S_{T+M} can be used as part of a program to ensure quality of tube thickness measurements.
- A typical standard deviation S_M due to measurement error in UT tube thickness data is 0.18 mm (0.007 in.).
- The standard deviation S_{T+M} of the measured thickness distribution in any section of the boiler is expected to increase slowly with time because of corrosion. The most recent value of S_{T+M} can be used to set the expected range for thickness measurements at the next inspection.
- The calibration error for UT measurements should be no more than 0.08 mm (0.003 in.). It can be minimized by technician testing, by careful calibration procedures, and by comparison checks against projections from prior inspections.
- A histogram of the remaining life at individual locations is useful in estimating the remaining life of the section.
- A histogram of individual point corrosion rates is useful in identifying sections that have localized corrosion. For these areas, maps showing spatial distribution of tube thicknesses can be valuable to help visualize corrosion patterns. TJ

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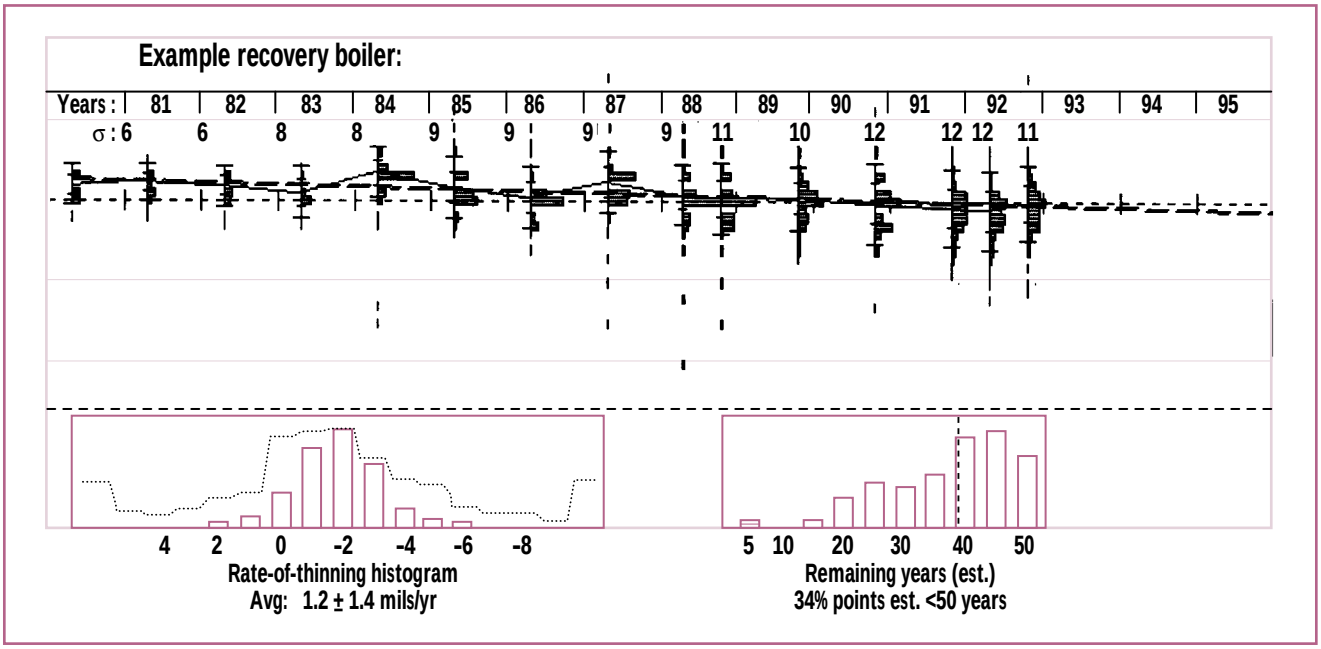

10. Data for tubes around the primary air ports of a 20-year-old boiler

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