Best practice guidelines for detecting and mitigating waterside cracking (stress-assisted corrosion) in power and recovery boilers

Summary

This Technical Information Paper (TIP) provides guidelines for detecting and mitigating stress-assisted corrosion (SAC) in boiler components. SAC, also called corrosion fatigue or waterside cracking (WSC), is a corrosion mechanism that produces crack-like damage, often in a multi-crack network, on water-contacted surfaces in tubes, headers and piping in all types of boilers. SAC usually occurs adjacent to the footprint of an external attachment, near a weld and wherever the internal surface of a carbon steel tube or pipe experiences cyclic stress high enough to cyclically rupture the magnetite scale. A potential consequence of this corrosion damage mechanism is a leak, which may cause jet-eroding consequential damage on adjacent components. In some instances the cracking damage weakens the tube or pipe so it splits open or produces a “window” leak/hole.

Scope

This TIP describes the SAC damage mechanism and its controlling parameters, based on comprehensive research studies by the power utility industry in Europe and N. America; boiler components likely to experience SAC; inspection and testing methods; fitness-for-service assessment, and general guidelines for mitigating SAC.

SAC is most effectively found and managed with an owner-accountable testing and inspection program with formal analytical and testing practices and procedures, done by mill personnel and non-destructive testing technicians qualified to find SAC and monitor its progress over time.

Safety precautions

Non-destructive testing methods and other tasks and procedures described in this TIP have safety risks associated with entering boilers and pressurized equipment for inspection and repair. All jurisdictional and mill safety requirements for these activities apply.

Background

Carbon steel in contact with deaerated boiler feedwater relies on a protective, iron oxide (magnetite) scale to control corrosion. SAC, a corrosion fatigue mechanism, cyclically fractures magnetite scale in boiler tubes and pipes in a network pattern related to stress acting on the internal surface. Steel exposed at the fractured scale corrodes a bit to reestablish the protective scale layer, producing a surface locally more susceptible to continual fracture of the scale layer in the established pattern. The resulting damage typically is a cluster of parallel, elongated pits, grooves and fissures. Since SAC depends on the local stress, more than one affected place can occur in one tube header or pipe. In cross-section the damage is characterized by blunt-tipped, trans-granular cracks. From the multiple cracks one or two cracks ultimately predominate and penetrate far into and ultimately through the component wall.
SAC can affect all types of pressurized carbon steel boiler components – tubes, pipes, headers and drums. Because corrosion rates are slow, SAC rarely affects boilers <10 years old, but affects about 50% of boilers >20 years old. SAC growth rates are accelerated by higher levels of dissolved oxygen in the feedwater and more frequent scale-fracturing stress cycles. Boilers that see more trips and service cycles are more likely to have SAC.

SAC has been comprehensively studied by organizations in the power utility industry, including the Electric Power Research Institute (EPRI), whose published research and service findings include:

1. SAC occurs where the local strain exceeds 0.2%, i.e., exceeds the steel yield strength.
2. Components operating at higher temperature (pressure) are more susceptible to SAC because magnetite scales fracture more easily and reform more slowly in higher feedwater temperature.
3. SAC is more likely and grows more rapidly in boiler feedwater with higher dissolved oxygen content, typically resulting from inadequate feedwater deaeration or periodic emptying of the waterside. Boilers restarted with nondeaerated water are more susceptible to SAC damage.
4. Acid cleaning to remove scale inside boiler tubes and headers does not, per se, exacerbate SAC but often is followed by leaks because chemical cleaning unblocks scale-filled fissures and grooves.
5. SAC damage associated with external attachments on tube and pipe does not automatically reduce the component’s pressure rating because of the attachment’s reinforcing effect. [This also is discussed in detail in Sharp’s paper in Reference Articles below.]

Practical guidelines issued by EPRI relating to corrosion fatigue are paraphrased as follows:

- Corrosion fatigue failures occur near support attachments, usually in water-wall tubing but also in economizer tubing, particularly where there is high heat flux and where stress from high restraint can develop. Typical locations include attachments for wind-box casings, buckstays and scallop-bars; also where tubes connect to headers and to other tubes.
- Corrosion fatigue is discontinuous. It is characterized by multiple, trans-granular cracks, with small cracks adjacent to at least one main crack, initiating on the inside of the tube in-line to the highest applied stresses and propagating during transient periods. Tube sampling and metallurgical analysis is the most reliable way to validate corrosion fatigue.
- Eddy current testing (ferritic materials only), digital radiography, magnetic particle testing and/or phased array ultrasonic shear-wave testing may be used to detect and quantify damage. Determining the extent of damage is difficult due to access limitations, but vulnerable locations should be determined. Enlist qualified professional support when resolving the problem for the long-term as it may require redesigning and/or modifying existing attachments.

Severe SAC damage is visible inside a tube or pipe, especially after acid-cleaning removes magnetite scale. Indeed, as discussed later, methodically examining the ID tube samples removed for other purposes is a recommended practice for determining if a boiler has SAC. However, remote or video visual inspection in tubes in place is not a reliable method for detecting SAC. Figure 1 shows the cleaned internal surface of a boiler tube with typical SAC caused by local strain from an external attachment.

Figure 2 shows a cross-section through and the waterside surface a boiler tube with SAC almost halfway through a 6.4 mm (0.26 in.) tube wall. The SAC damage has typical wide, oxide-filled, trans-granular fissures with rounded shapes and narrow parts along the crack believed to be where the crack grows faster, probably because greater crack depth increases the pressure-induced stress at the crack tip.
3 / Best practice guidelines for detecting and mitigating waterside cracking (stress-assisted corrosion) in power and recovery boilers

Fig. 1. Stress-assisted corrosion (SAC) damage in the internal surface of a 75 mm (3-in.) OD steel boiler tube with the scale removed to expose the crack-like damage.

Fig. 2. Internal surface (left) and cross-section (right) of hot wall from 65 mm (2.60 in.) tube in a power boiler (1).

Figure 3 shows SAC in the blast-cleaned internal surface of superheater tube bend with no attachment. Internal pitting initially detected by ultrasonic thickness testing was not severe enough to matter and the SAC damage was detected by random “shadow” RT of the superheater loops for internal pits. [Bennett and Meiley provide a similar case history (2).]
Fig. 3 Axial waterside cracks (SAC) at "equator line" inside surface of 50 mm (2 in.) superheater tube bend after bead blasting to enhance cracks, which were found with RT (3).

Finding SAC in the boiler

What boilers to investigate

Every power, recovery and biomass boiler > 20 years old could have some degree of SAC, even if specific mitigating measures were incorporated in the boiler design. Mitigation measures basically involve deliberately reducing the presence of local, tensile, bending stress conditions ("hinges") in water-contacted surface of tubes, headers and pipes by designing attachments and other stiffness transitions to minimize macro-stress concentration in the component.

Where SAC is more likely

SAC-susceptible locations are methodically identified by systematically reviewing the construction details and by reviewing leak records for each boiler. Not finding SAC at predicted locations or configurations does not mean the boiler is free of SAC because the mechanism can affect only a few of many places with similar geometry and nominal stress conditions.

SAC is far more likely at attachments and sharp shape transitions, but has been reported in tube locations away from attachments, e.g., along membrane welds in sealed boiler tube wall panels, especially at corners of the boiler, in screen-tubes at bends and tube connectors, and in superheater tube bends, where ovaling from severe bending produces a hinge effect at the longer axis of the oval – see Figure 3. (The list of references at the end of this TIP provide more information on these and other industry experiences.)

In a particular boiler SAC statistically is more likely in thinner tubes than thicker tubes because the latter have lower tensile stress at the internal surface at attachments. SAC also affects headers, a classic case being bottle headers in economizer modules, and external steam and water piping.

Recovery boiler considerations

In a recovery boiler more stiffness contributed by the composite tube layer – 1.5 mm thick sleeve around the steel core – decreases the tube’s susceptibility to SAC precisely because the internal surface sees lower tensile stress under all service conditions. Conversely, SAC always is more likely at locations in tubes, headers, etc., with sharp or narrow stiffness transitions or other "hinge-type" stress concentrating features.
SAC susceptible locations in the lower furnace of a recovery boiler include, but are not limited to, connections and locally strained places at corners of wind boxes, smelt-spool hood attachments and floor seal welds. As stated above, SAC has been reported at bends in screen and wall tubes; axially in superheater tube bends at the smallest radius of the oval from bending (equator); at bends in circulation piping; at bifurcated tube connections; at swaged tube diameter changes, especially at economizer headers, and at buckstay welds.

Nondestructive testing

All NDT techniques have specific requirements and/or limitations for SAC. Radiographic testing (RT) and ultrasonic testing (UT) are used to find and trend SAC. Eddy current testing (ECT), remote visual inspection (RVI) and magnetic particle testing (MT) with DC are used within their limitations.

Radiographic testing (RT) was the first non-destructive method used in the paper industry to test for SAC, with mixed results. Main challenges in developing a reliable RT procedure include:

1. Aligning the severest crack-like damage with the direction of radiation to obtain images that allow the damage severity to be reliably ranked or assessed.
2. Sizing SAC damage in a way that correlates with the header or tube’s remaining pressure-containing properties. (Ref. Sharp 2004)
3. Radiation safety requires evacuating all personnel the required distance from the RT source for the duration of the RT test. Contact RT and computed/digital radiography (DT) are techniques with short radiation safety distances.

Ultrasonic shearwave (flaw detection) methods were initially used to detect SAC in other industries. Modern ultrasonic testing (UT) flaw detection methods, especially with phased-array technology, reliably detect and size SAC damage when the technique and technician are qualified on tubes or headers with real or synthetic flaws. SAC is not always limited to axial or circumferential direction in a tube or header. Although they typically present in parallel lines, the cracks can also radially disperse in concentric parallel lines to follow an external attachment or strained area. Manual manipulation of a UT shearwave probe increases the probability of finding SAC damage in tubes, headers and pipes. Phased array UT provides digital imaging options to trend the crack-like damage over time. Encoded UT scans permit damage symptoms to be reliably examined at the same encoded coordinates.

Considerations for developing an ultrasonic technique include:

1. The surface must be smoothly dressed to allow an acceptable sound transfer, especially if there is external pitting or corrosion.
2. Probe frequency should be selected to ensure the ultrasonic wavelength detects SAC cracks of a specified minimum size.
3. Rotation of an ultrasonic or phased array wedge to follow the indication shape and to scan at appropriate angles around attachments is difficult on curved surfaces and may inhibit acceptable mapping of detected indications. Modeling is often required to ensure that a return signal is obtained by the probe.

Magnetic particle testing (MT), especially using DC technique, can reveal the presence of internal cracks that are within 3 mm (0.12 in) of the external surface of a steel tube or header (see Notes 1 and 2).

Visual inspection (borescopic) or laser-optical (LOTIS) scanning the internal surface of a tube or header often finds SAC evidence, especially in acid cleaned surfaces, and permits ranking of the damage severity for further investigation by other NDT methods, or by destructive testing methods discussed below.

NOTE 1: For every type of NDT a written test procedure should be developed and qualified by a Level 3 technician in the appropriate method. Appendix A has requirements for qualifying NDT technicians.

NOTE 2: Regardless of which written, qualified NDT procedure is used, it is essential to pre-qualify the technicians who will use it to find and size SAC damage in representative damaged specimens.
Because SAC is a slow damage mechanism, especially when the quality of the boiler water is acceptable, trending crack growth rates is a challenge, even with careful use of a carefully qualified NDT procedure at a particular SAC location. (Written procedures improve test accuracy.) Periodic retesting of a known condition at a particular SAC location/configuration, preferably with a qualified UT flaw sizing procedure or phased array UT is an acceptable way to monitor the effectiveness of SAC mitigating measures.

**Destructive testing**

It is good practice to confirm NDT indications of SAC either by removing the affected part or, less expensively, by using a “window removal” procedure common in the power industry. This cuts out a window sample that could contain the indications and allows the internal surface to be directly examined.

As mentioned above, a successful SAC detection program for each boiler carefully investigates every crack-like leak in a tube or header with no external evidence of an external corrosion or cracking damage mechanism to determine if the leak is due to SAC. This requires avoiding the typical practice of immediately grinding out the leak location and welding to repair the cavity, which obliterates evidence of SAC. Leaks resulting from SAC damage, when simply weld repaired, usually leak again because the ID crack condition may be more widespread than appears from the outside, and because welding exacerbates residual stresses.

**Fitness for service analysis**

Correlating the NDT severity of SAC damage with the degree of tube weakening is not reliable, even with the best NDT methods like phased array UT flaw detection. The most probable consequence of SAC is a leak before the tube or header ruptures. However substantial leaks occur when extensive SAC causes a part of the tube to break away - a ‘window leak’.

Analysis per Part 9 of the API 579-1/ASME FFS-1, Fitness for service, post construction code can define SAC “crack depth criteria” at each level of analysis in the code. This analysis and long-standing practical experience show that SAC damage typically becomes a real concern when the corrosion is more than 50% through the wall.

**Inspection frequency**

In general non-destructive testing for SAC at high-susceptibility locations - identified by systematic risk analysis recommended elsewhere in this TIP - should commence before 15 years of boiler service. Because SAC is a slow damage mechanism that typically causes affected components to leak before they burst except in rare instances, inspection intervals can be three or four years without incurring excessive risk.

It never is too soon to start non-destructively testing high risk locations for SAC damage and to destructively inspect the inside surface of tube samples removed from the boiler for other purposes. It is generally acceptable to retest some of the test locations every three or four years until the first leaks occur if no mitigation is done.

**Testing scope**

The scope of testing each time, i.e., precise locations tested for SAC damage, should include up to 5% of the same type of recognized highest susceptibility locations, and investigate random types of less susceptible locations. UT shear-wave flaw detection testing procedures permit many locations to be tested in one or two shifts and also permit testing around other maintenance work in the boiler.

**Mitigating SAC**

Because waterside cracking is inevitable, mitigation should begin immediately. Accepted methods of mitigating SAC in boiler tubes include:
Best practice guidelines for detecting and mitigating waterside cracking (stress-assisted corrosion) in power and recovery boilers

- Optimize boiler feedwater deaeration to limit the dissolved oxygen content below 10 ppb in boilers operating at pressure >70 bar (1,000 psi); below 15 ppb for boilers >40 bar, and <20 ppb for boilers < 40 bar. Consistent boiler feedwater quality and deaeration reduce the likelihood and severity of SAC.
- Decrease the number of boiler service interruptions and of shutdowns by extending the time between planned outages. Another way to decrease boiler cycles is to improve operation of the boiler to avoid trips, and improve fuel, water and steam control sensors and control schemes.
- Reduce the cyclic tensile stress magnitude in the internal surface of the tube, pipe or header by altering the attachment design or by modifying the stress-concentrating geometry to mitigate flexing/bending at the internal surface. (External pad welding to increase wall thickness adds more material for cracking, decreases hoop tensile stress and modifies the through-wall stress pattern to mitigate crack grown can be done with computer modeled welding procedures that are validated with test specimens to confirm their beneficial effect.)

Literature cited


References


Keywords

Stress, Corrosion, Cracks, Boilers, Tubes, Feedwater, Nondestructive tests, Waterside cracking, Stress assisted corrosion

Additional information

Effective date of issue: January 13, 2015

Working Group:
- David C. Bennett, Chair, Corrosion Probe Inc.
- Mark Gilkey, FM-Global
- Margaret Gorog, Weyerhaeuser Company
- Ronald Lansing, M&M Engineering Assoc., Inc.
- Michael Lykins, Packaging Corp. of America
- Max D. Moskal, M&M Engineering Assoc., Inc.
- Douglas Sherman, Corrosion Probe, Inc.
- Adam Stasuk, Stasuk Testing & Inspection, Ltd.
Appendix A. Qualifications of nondestructive testing (NDT) personnel

1. Every NDT technician should be trained and certified in each NDT inspection method they use. The NDT Contractor’s practices and procedures for certifying their technicians should be reviewed by a knowledgeable mill representative (KMR) for compliance with regulations relevant to the job.

2. In the United States and Canada, respectively, NDT technicians should be certified in accordance with:
   - SNT-TC-1A - American Society for Nondestructive Testing. (ASNT, P.O. Box 28518, Columbus, OH 43228, Ph: 614-274-6003), or
   - Canadian General Standards Board. (CGSB, Ottawa, ON, K1A 1G6, Ph: 819-994-5373).

3. Technician certification records should be reviewed by the KMR before testing is done.

4. The mill may require additional documentation to confirm a technician has the skill and recent experience or training for the specified testing, or to interpret results produced by qualified technicians. It always is good practice to require NDT technicians to directly show their competence in using a specific NDT method to detect and accurately size the particular type of defect or damage symptom of interest, using test specimens with real or synthetic defects, before the technician is allowed to do the NDT.

5. Written NDT procedures are essential and should be reviewed by the KMR before the agreed testing commences.