Two boilers involved in tube failures are traditional water-cooled boilers and were placed in service in 1974. They are natural circulation boilers with steam and mud drums and include an economizer and superheater section. They are rated for 400,000#/hr (50 Kg/s), with design pressures of 1,800 psig (12 MPa). The boilers operate at approximately 1,500 psig (10 MPa). The furnace walls are constructed of 3-in. (76-mm) OD by 0.200-in. (5-mm) minimum wall, type A-210 carbon steel tubes on 4-in. (100-mm) centers. Fuel can be either fuel oil or distillate oil blended with fuel gas.

Feedwater treatment for the two boilers is identical and is fairly typical for a high-pressure boiler. Historically, the boilers' internal treatment consisted of a standard coordinated phosphate program, with the chemicals added to the mud drum. Dispersants for scale control were not used. Makeup water was deoxygenated in a standard deaerator with hydrazine added to facilitate oxygen removal. Cyclohexylamine was added for condensate system corrosion control. Strong base/acid demineralization units were used for dissolved solids removal. Detailed records of treatment control were not available; however, oxygen breakthrough and copper contamination were known to have occurred.

Case History 1

Rupture at a Repair Window

After 19 years of operation, a tube ruptured in one of the two high-pressure boilers, resulting in a shutdown of the boiler. A north wall tube near the northwest-conner burner had ruptured at a circular "window" repair where a coupon had been cut from the tube four years before to permit observation and inspection of the ID. Repairs had been made by welding a patch over the hole. No other damage to the waterwall tubes was obvious, nor was evidence of overheating.

Laboratory Analysis

A section of the failed tube with the rupture was analyzed (Figure 1). Window repair coupons which had been cut from three unfailed tubes, two from east wall tubes and one from a west wall tube, also were analyzed.

The failed tube sample ID had experienced severe gouging-type corrosion at the rupture (Figure 2). The fracture was thick-lipped and did not exhibit significant ductility. The internal surface was covered with a relatively thick red scale which had spalled at the rupture. A black scale was underneath the reddish scale.

The sample ID was severely corroded and contained numerous circular cracks. The fracture followed the contour of a repair weld around half the sample; the remaining section was base metal torn from the tube during the rupture. The sample OD contained appreciable weld reinforcement which appeared to have been made by shielded metal arc welding (SMAW). Figure 3 shows the sample ID after chemically removing the scale deposits. The unfailed portion of the tube sample was not cor-
roded. The window samples removed from the unfailed tubes were corroded with deposit buildup, although not as much as the failed window coupon. The window samples had appreciable amounts of elemental copper in the deposits. In all three samples the ID corrosion was confined to the circular coupons.

Metallographic analysis of the failed window coupon revealed that the corroded areas were completely decarburized and fissured (Figure 4).

The extent of decarburization experienced by one of the window coupons is shown in Figure 5. The cross section of the corroded sample was rough-polished and immersed in boiling 15% hydrochloric acid for several minutes. The dark area at the ID, containing the cracks, represents the decarburized area.

EDS analysis was conducted on the scale deposits from several of the window samples. The outside deposit layer contained appreciable quantities of copper, zinc, phosphorus, calcium, sulfur, and iron. Analysis of the internal surface deposit showed that in addition to the elements detected in the outside layer of the deposit, significant quantities of sodium and silicon were also detected.

**Conclusion**

The tube sample failed from accelerated corrosion and hydrogen attack on the internal surface of a window repair coupon. Disruption of the water flow at the coupon caused water solids to precipitate, promoting corrosion. The tube sample failed when the remaining wall thickness in the corroded area was not able to withstand internal boiler water pressures. Based on observation of oxides in the cracks and fissures, the initial corrosion may have occurred some time before the failure. It was not determined with certainty whether the corrosion was caused by high or low pH conditions.

**Laboratory Analysis**

The tube and window coupons removed from the boiler are shown in Figure 6.

The appearance of the ruptured tube sample (Figure 7) suggested that it had failed in a manner similar to that previously described: from accelerated corrosion and hydrogen attack at a circular window coupon. Visual examination of the circular window coupons from unfailed tubes indicated that some window coupons had experienced severe corrosion, and some showed no corrosion. Of the five smaller coupons, three of the five had corroded. Those coupons that had been installed recessed with respect to the tube ID typically were severely corroded. Those that had been installed either flush with the ID or with the ID weld reinforcement had not corroded.

Other significant observations included: A sample with a butt weld that had been removed based on ultrasonic detection of ID indications contained gross burn through but had not corroded; the tube sample downstream of the OD blister had experienced severe corrosion of the base metal. The tubes containing recessed window coupons also had experienced fatigue cracking at the
FIGURE 1
As-received failed waterwall tube, case history 1.

FIGURE 2
ID of tube sample shown in Figure 1 at rupture.

FIGURE 3
ID of window coupon from failed tube after deposit removal.

FIGURE 4
Microstructure of failed tube sample at corroded ID showing decarburization and fissuring.

FIGURE 5
Cross section of one of the window coupons from an unfinished tube after immersion in boiling 15% hydrochloric acid. The dark stained areas with the cracking define the extent of hydrogen attack.
water solids with reverse-solubility characteristics. Unfortunately, since the greatest interest in observing for ID scale is at locations of high heat flux, cutting window coupons at these locations greatly increases the possibility of failure of those tubes.

Examining corroded window coupons vs uncorroded ones and tubes containing severe ID weld penetration was useful in drawing some correlations between ID geometries that are conducive for initiating corrosion and those that appear to be more tolerant. Most of the corroded coupons were recessed with respect to the tube ID. The coupons installed flush or protruded into the ID typically did not corrode. This observation is also true for the butt weld with ID burn-through, in that the protrusion did not create corrosive conditions. Also, the larger-diameter coupons seemed less likely to corrode than did the smaller-diameter coupons.

The procedure developed for repairing the failed tubes and for replacing the window coupons included using entire tube sections and minimizing the practice of welding the cold side of the tube joint from the hot side of the tube, a practice sometimes referred to as “window welding.” This practice was performed only when access to the tube OD from the cold side was not practical. Particular attention was paid to joint fit; 100% radiography was performed, where possible. The procedure included specifying tungsten inert gas (TIG) for welding the root pass. The tube removal section of the procedure specified cutting the bottom portion of the tube sample first and installing a barrier to prevent weld spatter, etc., from falling down the tube ID while cutting the top half of the sample.

**Water-Cycle Chemistry Influence in Hydrogen Attack**

Regardless of the presence of window coupons and other flow disrupters in the boiler water circuit, accelerated corrosion and tube failures are ultimately initiated by out-of-specification water chemistries, whether from incorrect treatment chemicals, incorrect dosages, or contamination.

Treatment control and boiler maintenance play significant roles in boiler tube failures. A 1990 survey of five utilities that were experiencing
Environmental Effects

A notch created by the ID geometry (Figure 8), which also would have eventually caused the tubes to fail. These observations tend to indicate a correlation between increased susceptibility to corrosion of tubes containing recessed flow disrupters vs those containing protruding flow disrupters.

Metallographic examination of the failed tube sample, the tube with the OD blister, and several of the corroded window coupons confirmed that hydrogen attack accompanied the ID corrosion.

EDS analysis was conducted on deposits at the base metal ID deposit interface, at the scale mid-thickness, and at the outside layer. The results indicate that adjacent to the base metal the scale is primarily composed of iron (presumably iron oxide), and in the outer layers, the scale deposits contain significant quantities of precipitated water chemicals. All three analyses detected quantities of chlorine.

**Conclusion**

Analysis indicated that the root cause for failure of the ruptured tube was accelerated corrosion and hydrogen attack at a window coupon similar to case history 1. The fish-mouth rupture downstream of the failed window coupon occurred due to overheating, thought to be caused by loss of water through the failed upstream window coupon. The corrosion may have been caused by localized low pH conditions, based on the significant amount of chlorides detected in the ID scale deposits and the morphology of the deposits. The geometry of the window coupons probably influenced the failures.

**Case History 3**

**Second Failure in Boiler Tube**

One year from the time of the tube failures reported in case history 1, another waterwall tube from the same boiler failed. This was considered unusual because the primary culprit in the previous failures, the circular window coupons, had been removed or replaced using more stringent repair procedures. Dispersants also had been added to the chemical treatment to control solids deposition in high heat flux areas, and in general, treatment control had been given a higher priority.

Inspection of the boiler following shutdown revealed that a tube on the north wall had failed (the same wall as the previous failed tube). It appeared to have failed in a manner identical to that previously discussed: accelerated localized corrosion and hydrogen attack. However, this tube had not failed at a circular window coupon but at a circumferential butt weld with no obvious defects or ID flow disrupters. The failed weld was approximately 6 ft (2 m) from the long radius where the tube curved upward from the floor to the wall. The tube section was replaced and the boiler was hydrotreated. Upon reaching test pressures of 1,800 psig (boiler design conditions), a second tube from the north wall failed at approximately the same elevation. Initial observation indicated that it also had failed at an original circumferential butt weld.

**Laboratory Analysis**

The tube sample that caused the initial boiler shutdown is shown in Figure 9. An irregularly shaped window had partially ruptured just downstream of a butt weld. The tube sample ID in the corroded area is shown in Figure 10. The corroded ID appearance is similar to that previously discussed.

The ID of the tube sample that failed during the hydrotest is shown in Figure 11. The corroded area is on the downstream side of the weld and appears to have initiated at the weld. The corroded butt weld ID was covered with what looked like weld flux (Figure 12); EDS analysis indicated that it contained an appreciable amount of titanium. Based on the appearance of the material and the detection of titanium, it was thought that the material was welding flux from an SMAW-type electrode.

Metallographic examination of the failed samples confirmed hydrogen attack. It is interesting to note that the large transverse cracks occurred at breaks in the ID scale deposit.

**Window Coupons and Tube Failure**

The rationale for prohibiting the use of window coupons is based on the well-established propensity for boiler water solids to precipitate at areas of high heat flux. Disruptions to the boiler water flow contribute to increased tube metal temperatures, which promote precipitation of
hydrogen damage and were operating in the 1,800 psig range on phosphate revealed several common features:
- Hydrogen damage had been present for five to seven years.
- Hydrogen damage had been initiated by a water treatment breakdown resulting in acidic boiler water.
- Frequent condenser leaks had resulted in chloride contamination of the boiler water.
- None of the units had been chemically cleaned following the upsets.
- None of the units had cleanup systems (condensate polishers, etc.).
- All of the boilers were very dirty, with substantial internal deposits.
- None of the plants had a qualified chemist.
- None of the plants had sufficient instrumentation for tracking water chemistry.

**Conclusions**
The following major conclusions can be drawn from this article:

- Diligence in operating and maintaining high-pressure boilers should be a priority.
- Target chemistries should be established, and the system and instrumentation must be installed to ensure meeting those targets.
- Upsets in the boiler system should be documented and investigated to determine their potential effects on the boiler.
- Tube internal surfaces should be monitored and maintained free of harmful buildups of scale and corrosion products.
- Using window coupons for monitoring tube ID surfaces in high-pressure boilers is not recommended.

Reference

More information is available in paper no. 613, presented at CORROSION/95 in Orlando, Florida.

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