1. SCOPE

This Note provides information on cracking in welded fire-tube boilers, including location of cracks, failure modes, causes, detection, repair and prevention. The necessary actions to be undertaken when cracking is suspected or confirmed are provided. The information provided is based on global experience.

2. BACKGROUND

Cracking in fire-tube boilers at welded joints is a frequent, costly and potentially dangerous occurrence. The shortest recorded time for serious cracking to leak is 3 years, representing less than 20,000 cycles, and occurred on a laundry boiler subjected to frequent and rapid firing.

A number of cracked boilers have exploded resulting in major damage and fatalities. Fortunately, recent improvements in materials, welding and non-destructive testing (NDT) together with a greater awareness of the potential for cracking have greatly reduced the incidence of failures. As current boilers age, more cracking is likely to occur.

3. FIRE-TUBE BOILERS

This Note covers cracking in “economic” type fire-tube boilers, where the “dry back” or “water back” boilers represent the largest use in Australia. The information presented is applicable to virtually all fire-tube boilers made of carbon-manganese steels with diameters up to 3 metres, operating pressures generally up to 1 MPa and operating temperature up to 180°C. AS 1228 provides further details on these boilers. Fig. 1 shows typical details.

4. FIRE-TUBE BOILER CRACKING

4.1 Cracking Occurrence

Virtually all cracks occur at welded joints or at openings. The root cause is corrosion fatigue with the fatigue cycling being thermally driven. Over 100 boilers in Australia suffered this type of cracking in the 1950 – 1975 period. The change to natural gas firing initially accelerated the rate, but it has since fallen. UK inspection data from 2001 showed that 2% of fire-tube boilers inspected had service defects – mainly cracks.

Figure 1 shows a schematic representation of the side and end elevation of a fire-tube boiler. The front and rear closure plates and reversal chambers have been omitted for clarity.

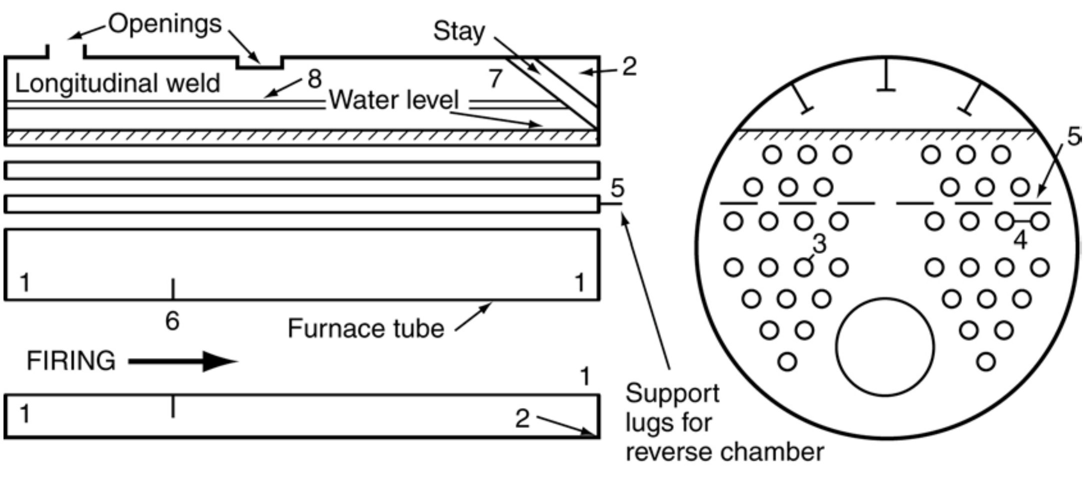
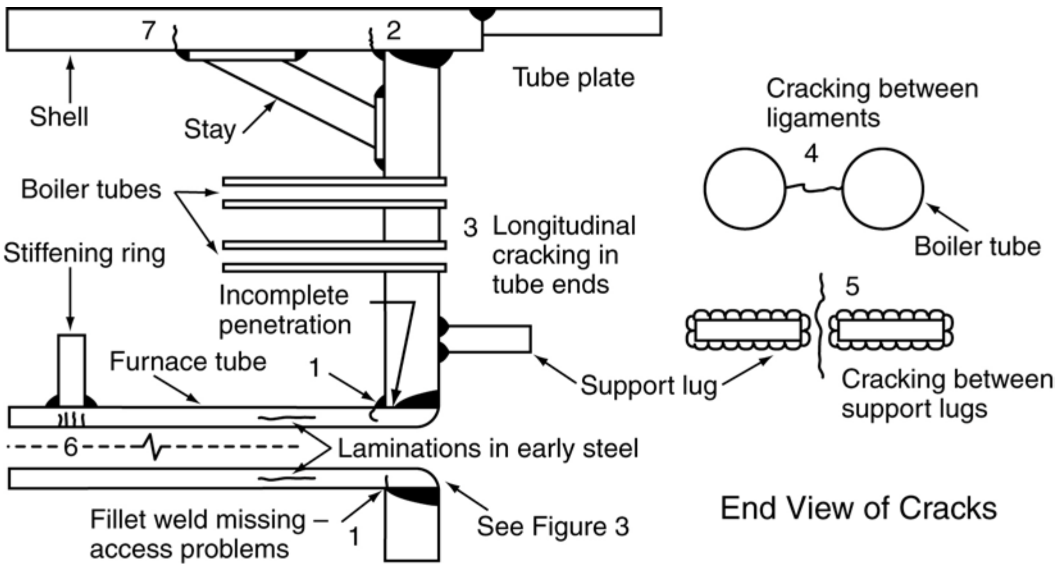


Figure 1. Fire-tube boiler showing eight potential cracking locations



Crack Location	Crack Description
1	Furnace tube circumferential cracking at tube plate weld
2	Shell circumferential cracking at tube plate and shell weld
3	Tube end cracking
4	Tube plate ligament cracking between boiler tubes
5	Tube plate cracking at or between reversal chamber support lugs
6	Furnace tube cracking at stiffening ring
7	Shell cracking at gusset stay welds
8	Shell cracking in longitudinal seam weld

Figure 2. Details of crack sites

Of the eight potential crack locations shown, the major occurrence is furnace tube cracking adjacent to the tube plate weld identified as number 1 in Figures 1 and 2. Other locations of the boiler also exhibit cracking particularly cracking associated with fire-tubes identified as numbers 3 and 4 in Figures 1 and 2.

4.2 Furnace Tube Cracking (location 1)

Cracking occurs in a highly localised area in the furnace tube on the water-side of the boiler. The cracks originate at the root of the furnace tube to tube-plate weld. Cracking can occur at both front and rear ends at any position around the furnace tube plate but cracking is most common at the bottom of the tube plates. Cracking generally occurs in the furnace tubes as they are thinner, and hence more highly stressed than the tube plate (see Figure 3).

Figure 3. Typical furnace tube cracking

The failure mode is corrosion fatigue. Slight corrosion occurs as a result of contact with the water. Fatigue arises from thermal cycling and pressure cycling. The primary causes of furnace tube cracking are a combination of:

- High thermal stress generated by large temperature or material thickness differences;
- Bending stresses due to pressure;
- Poor weld shape, particularly at the weld root in the lower part of the furnace;
- High number (over 10,000) of pressure and temperature cycles;
- Fracture of the protective magnetite layer due to cyclic stresses. Magnetite forms on the furnace tubes and acts as a protective layer but it is brittle and subject to spalling under cyclic stresses. Its fracture exposes unprotected surfaces to further corrosion;
- Un-removed slag from furnace tube to tube plate welds providing corrosion initiation sites.

The secondary (or service) causes of cracking include:

- Rapid firing from cold resulting in high thermal stresses;
- Over firing, typically when changing to gas firing, resulting in severe cracking at the rear tube plate due to higher temperature differentials;
- Insulation effect of scale deposits on both surfaces giving increased temperature gradients;
- Increased boiler pressure and decreased water return temperatures;
- Untreated feed water leaving deposits that accelerate local corrosion;
- Incorrect pH of feed water or excessive O_2 levels;
- Reduced circulation and increased temperature differentials due to poor feed water entry;
- Boilers with low slung furnaces or made from higher strength steels operating at higher stress.

For short cracks, the most common type, the resulting failure has generally been leakage. For longer cracks, the result can be large scale fracture with a dangerous explosion.

4.3 Shell Cracking (location 2)

A rare but dangerous occurrence is circumferential shell cracking at the tube plate weld shown at location 2. Extensive cracking at this location can cause the tube plate to tear away from the shell in a catastrophic manner. This type of cracking is generally limited to highly stressed shell boilers constructed of high strength materials and consequently operating at higher relative stress range.

4.4 Tube End Cracking (location 3)

This longitudinal cracking of tube ends is sometimes encountered in ERW tubes or tubes with poor ends.

4.5 Tube Plate Ligament Cracking (location 4)

Ligament cracking has been reported in boilers with high operating temperature differentials up to 400°C. Tube plate cracking typically starts at toes of boiler tube fillet welds and grows across the tube plate ligament from one boiler tube to another. Cracking has also occurred from centre-pop marks forming a small notch in the edge of the tube hole with expanded tubes. Ligament cracking is serious.

Depending on the age and fracture toughness of the tube plate, material crack extension can occur suddenly by brittle fracture when the boiler cools down to ambient temperature. High local residual stresses can trigger brittle fracture in heavily cold worked and aged steel. This occurred with a unique case at location 5 from a 6 mm deep fatigue crack.

4.6 Other cracking locations (locations 5 to 8)

Cracking has been reported at all locations depicted in locations 5 through 8 in Figures 1 and 2- mainly at attachments. Although cracking in these locations is relatively rare they also should be subject to examination by the boiler inspector.

5. CRACK DETECTION

Good access is required to visually detect cracks and surfaces should be clean for 50 mm each side of the weld where cracking initiates.

Visual examination with the aid of lights can detect cracks over 5 mm in length and over 1 mm deep depending on adequate surface cleanliness. Endoscopes and digital cameras can be used to aid detection (particularly with low slung boilers), with computers to record information.

Magnetic particle testing (MT) and penetrant testing (PT) are more sensitive than visual inspection if the suspected crack area is accessible for examination. Ultrasonic testing (UT) is probably the best method to detect serious cracking.

6. INSPECTION INTERVAL AND MONITORING.

The annual intervals specified in AS/NZS 3788 should be applied in normal circumstances for visual inspection. If the operational circumstances are such that none of the primary and secondary causes mentioned above are applicable the inspection limits can be extended. Conversely frequent rapid firing under harsh conditions requires more frequent NDT especially as boilers age.

Ultrasonic testing should be carried out within 10 years from the construction date in normal circumstances or more frequently under harsh conditions. Similarly if there are significant changes in operating temperature or pressure, ultrasonic testing should be carried out more frequently e.g. after initial 10,000 cycles. The ultrasonic testing program should include a reasonable length of weld at both ends of the furnace and at the top, bottom and sides of the weld circumference at locations 1 and 2. Extra care should be taken with tubes near to stay tubes or near the shell.

Increased inspection frequency should also be implemented if the furnace was manufactured from steel with R_m>460 MPa, or if the design strength value used is above 110 MPa.

7. OPERATING OPTIONS FOLLOWING CRACK DETECTION

7.1 General

Once cracking has been detected, confirmed and sized, an informed decision is needed on whether to continue operation, repair or scrap. This decision depends on the estimated remaining SAFE life of the cracked part and the desired remaining life of the boiler.

7.2 Fracture Mechanics Analysis

In order to determine the estimated cycles to failure and the nature of the failure (leak or break) a fracture mechanics assessment may be used. A number of options are available, but the methods described in AS/NZS 3788 provide instruction on how to carry out the analysis. The accuracy of the following data is critical:

- Crack position, depth, and length around the weld circumference;
- Physical properties of parent plate – fracture toughness, yield and tensile strength;
- Parent plate inclusions, laminations and any banding and direction of rolling;
- Number of anticipated cycles.
- Developed stress range which is often very difficult to quantify particularly at location 1;

Only personnel with proven expertise and experience should undertake a fracture mechanics assessment.

7.3 Remaining life assessment

Practically, a better method of assessment is to use world experience, coupled with the basis of fracture mechanics.

Experience with early ductile, low strength steels indicates that furnace tube cracking can be tolerated up to the lower of 2 mm and 30% of the furnace tube wall thickness. Operation changes should be implemented to eliminate some of the primary or secondary causes of cracking and de-rating the boiler output may be required. If crack depths are 50% or more through the furnace wall, the boiler should be isolated for repair or replacement.

Determination of remaining safe life should take into account:

- Quality and properties of the steel, direction of rolling, presence of inclusions and age. (Prior to about 1985, most steel in Australia was ingot-poured, with the associated risk of occasional centre-line inclusions and laminations);
- Severity of future cycling;
- Worst crack length and depth;
- Ratio of furnace tube to tube plate thickness;
- Age of the boiler (gives an indication of the probable origin and properties of the materials used and the number of cycles experienced);
- Measures to be taken to reduce further corrosion and thermal cycling;
- Preparedness, time and available resources to carry out the repair;
- Feasibility of crack repair;
- Results of any fracture mechanics analysis;
- Residual stress and risk of brittle fracture;
- The measures taken to avoid gas explosions and low water failures. Both can result in severe plastic straining across the crack leading to furnace tube rupture. These measures are essential where cracks over 2 mm deep have been detected.
- Outcomes of a risk assessment
- Management responsibility in the event of a failure leading to an explosion.

Given that the crack growth mechanism is corrosion fatigue, the number and extent of thermal cycles to which the boiler will experience is the primary issue in determining the length of time the boiler can be operated. In assessing the consequences of failure, it must be determined if the failure mechanism is likely to be a through wall leak of a boiler tube or a catastrophic rupture of the furnace or tube plate, potentially leading to an explosion.

8. REPAIR OPTIONS FOR FURNACE TUBE CRACKS

8.1 Local Weld Repair of Furnace Tube

Local weld repairs have been widely used for the repair of cracks with limited length. Low hydrogen welding processes such as GTAW, MMAW (with EXX16/EXX18 electrodes designed for single sided complete penetration V butt welding) or GMAW. A relatively high preheat should be used, and then no postweld heat treatment is required. The method involves:

- Removal of crack and associated damaged material from the inside of the furnace tube;
- Weld with a AS 3992 qualified welding procedure using low yield strength weld metal;
- Ultrasonic testing using angle probes to establish quality of repair weld;
- Dressing the bore of the furnace tube flush by grinding;
- Hydrostatic pressure testing using warm water (at least 20°C) to full the test pressure, ie. 1.5 times the design pressure.

Successful repairs rely on competent welders, good weld shape, low hardness, negligible defects and competent NDT technicians and importantly, proof by tests or previous work that the inside root profile is as shown in Figure 4.

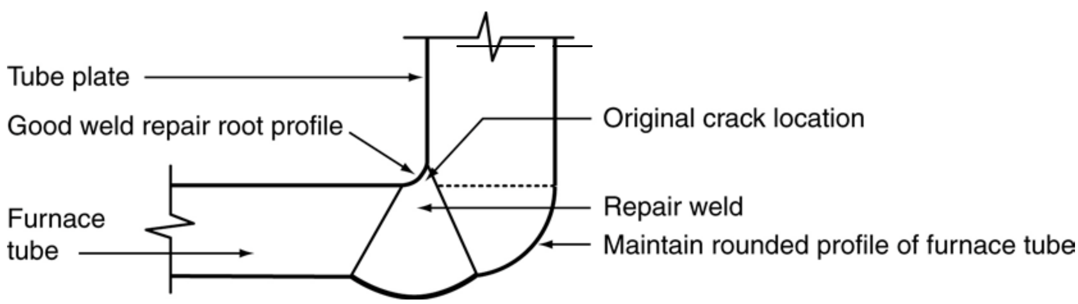


Figure 4. Local repair technique for furnace tube cracks located at toe of original installation weld

8.2 Replacement of One End of Furnace Tube

This option should be considered where there is extensive cracking at one end and there is good access from inside the furnace. The repair will involve using procedures, inspection and testing practices similar to the original construction.

8.3 Removal and Replacement the Complete Furnace Tube

This option is only practical when both ends have extensive cracking and there are no stiffening rings to impede removal of the tube.

8.4 Repair of Other Cracks

Such repairs should be made using the principles in 8.1.

9. MEASURES TO PREVENT OR CONTROL CRACKING

9.1 Prevention Measures

Boiler life is proportional to the number of thermal cycles experienced during operation. With continuous uniform firing and negligible cycling boiler lives 50 or more years are achievable. Thus to prevent cracking it is necessary to establish operating conditions that reduce the severity of cycling as far as possible. The following recommendations apply to all modes of cracking depicted in Figure 1. However the emphasis is on furnace tube cracking.

9.2 Control Measures

Whilst it may not be feasible to run a boiler continuously to avoid thermal cycling the following control measures will maximise boiler life for the applied operating conditions:

- Reduce the risk of low water conditions with reliable low water controls;
- Do not exceed manufacturer's recommended firing rates and metal temperatures;
- Reduce risk of excess pressure by checking and correctly maintaining safety valves;
- Minimise cycling of pressure and temperature;
- Minimise shock loading - avoid rapid heating and cooling particularly below 80^{0}C - preferably use modulated burners and mixing of feed water;
- Review water treatment to ensure appropriate de-aeration and pH control;
- Review blow-down procedures and ensure water sediments are flushed out regularly.

10. REPORTING AND DOCUMENTATION

It is necessary to maintain appropriate operating, inspection and maintenance records for boilers so they can be operated, inspected and maintained in a pro-active manner.

Documenting the number of operating cycles the boiler undergoes together with the severity of those cycles provides the baseline that will ultimately dictate the frequency of inspection and remaining life of the boiler.

The service records should include:

- Inspection history listing the dates and type of inspections undertaken and results received;
- All repairs including observations, actions taken and the basis for those actions;
- Correspondence with Regulatory Authorities (where required);
- An inspection and NDT plan based on operating history and inspection results;

NDNP TECHNOLOGY DIFFUSION ACTIVITY # 27	WTIA Welding Technology Institute of Australia ABN 69 003 696 526 **NATIONAL DIFFUSION NETWORKS PROJECT TECHNOLOGY QUESTIONNAIRE** **Pressure Equipment Industry Group** **"Cracking in Fire-tube Boilers"**	**Document No:** 9.4.4 – QR - 002 **Revision No:** Rev 0 **Page 1 of 2** **Date:** 18 Nov 2005

As part of the WTIA National Diffusion Networks Project the Pressure Equipment Industry Sector has identified the need to provide guidance, identify and remedy cracking in fire-tube boilers. The WTIA has prepared a Technical Guidance Note "Cracking in Shell Boilers" to explain the features, control and repair of such cracking. As a valued technology expert in this area we would like you to be part of the Technology Expert Group to review this note. Please complete this questionnaire so that we can gauge the success of meeting this need.

Objective 1: Identify the need to understand, control and remedy shell cracking

As the Australian fire-tube boilers become increasingly older, there is an increasing need to understand and control the degradation mechanisms that can lead to failures of such equipment. This guidance note is intended to provide the Pressure Equipment Industry understanding of fire-tube boiler cracking so an informed decision can be made on inspection frequencies and repair strategies. How well does the document explain inspection and repair of shell cracking?

poor ☐ average ☐ good ☐ very good ☐

Comments: ______________________________

____

Objective 2: Identify appropriate technology receptors in the Pressure Equipment Industry

This document was written for fire-tube boiler owners, operators, Inspectors and Maintenance personnel in the Pressure Equipment Industry. Are these people the appropriate individuals we should be targeting?

yes ☐ no ☐

What other types of companies and/or personnel do you suggest we target? ______________________________

____

Objective 3: Identify current best practice for inspection and repair of shell boilers

The document was written to reflect current best for service practice for inspection, operation and repair of fire-tube boilers. Do you envisage opportunities for the use of this practice in the industry?

yes ☐ no ☐

If yes, what and where, if no why not? ______________________________

____

Objective 4: Is the information provided clear, concise and accurate?

yes ☐ no ☐

If not, why? ______________________________

Objective 5: Broad dissemination of technology to the Pressure Equipment Industry

Please indicate how best to disseminate this Technical Guidance Note to the appropriate Pressure Industry Recipients

Free Website Download ☐ Poster☐ Pocket Guide ☐ Pamphlet ☐

If poster, what size? A1 ☐ A2 ☐ A3 ☐ Laminated ☐ What selling price? $

If a pocket guide, what selling price? $

Other format? ______________________________

Objective 6: Continuous Improvement

Please Identify areas where the document can be improved or return the document with your recommended additions/amendments. Alternatively, please use the area below to provide any additional comments.

____

____

____

____

____

____

____

*Respondents Name:*________________*Company:* _________________*Phone:* ____________________

Fax: ____________________________*Email:* ___________________________*Date:* _______________

Please Fax (02 9748 2858) or E-mail (j.baker@wtia.com.au) your response.

Your prompt response is appreciated.