Environmentally Induced Transgranular Stress-Corrosion Cracking in 304L stainless steel piping and components at Koeberg

J.P. Basson **ESKOM, Koeberg Nuclear Power Station**
Melkbosstrand, Cape Town, South Africa

C. Wicker **TSI, Koeberg Nuclear Power Station**
Melkbosstrand, Cape Town, South Africa

Koeberg is a seawater-cooled, 2x920 MW Pressurised Water Reactor plant, with a three-loop Framatome nuclear steam supply system. Koeberg is situated 30 km North of Cape Town, South Africa, on the Atlantic coast.

In February 2001 a leak associated with a through-wall crack was discovered on a 304L stainless steel seamed elbow on one of the piping systems. Investigation revealed the leak to be associated with a transgranular stress-corrosion crack which emanated from a pit on the external pipe surface. Previous Dye Penetrant Inspection of the area showed only pitting. It was concluded that the crack was caused by a corrosion pit on the pipe surface growing to a depth where high residual stresses due to the component fabrication process (bending without solution treatment followed by welding) initiated the stress-corrosion cracking. Pitting was initially caused by breakdown of the passive surface layer of the component by chloride contamination due to the marine environment.

It was postulated that all 304L stainless steel components with potentially high residual stresses and which were exposed to the marine environment were at risk of being affected by the phenomenon. This caused concern over the integrity of other piping and components of which a large percentage was affected by surface pitting. The subsurface nature of the cracking implied that Dye Penetrant testing would only be effective in revealing cracks after removal of the piping surface layer. Koeberg subsequently embarked on an extensive inspection programme of nuclear safety related piping and components. The process involved removal of approximately 250 μm of the component surface layer by grinding followed by Dye Penetrant testing. The depth of surface removal was selected based on the expectation that cracks would initiate at an approximate depth of 100 μm. The inspection results showed that the problem was generic and that a large percentage of pits were associated with subsurface stress-corrosion cracking. At one stage 148 out of 344 inspected components were found to be cracked. Cracks found were between 2 and 20 mm in length.

The cracked components are seam-welded pipes and elbows manufactured in 304L stainless steel. The systems affected are low pressure, low-temperature systems. Cracks found are of a transgranular nature and were found to be initiated by pitting in most cases. Chemical analysis of swipes taken on pipes revealed high chloride levels.

Later Inspection of the refuelling storage water tanks revealed a similar generic problem of transgranular stress-corrosion cracking associated with residual stresses at attachment welds to the tanks.

Corrective action included integrity analyses, replacement of worst affected components, preventive measures, an ongoing monitoring programme and development of a longer term refurbishment plan.
The paper discusses the background to the problem, the morphology of the cracking, the impact on plant nuclear safety and operation and the preventive and mitigative measures put in place to manage the problem until its final resolution.

ENVIRONMENTALLY INDUCED TRANSGRANULAR STRESS-CORROSION CRACKING OF 304L STAINLESS STEEL COMPONENTS AT KOEBERG

J.P. BASSON – SENIOR ENGINEER, KOEBERG
C. WICKER – MATERIALS CONSULTANT, KOEBERG

ABSTRACT

Koeberg is a seawater-cooled, 2x920 MW Pressurised Water Reactor plant, with a three-loop Framatome nuclear steam supply system. Koeberg is situated 30 km North of Cape Town, South Africa, on the Atlantic coast. Koeberg have detected numerous externally initiated cracks, some through-wall, on seamed piping of safety related systems, the refuelling storage water tanks and cast valves of both units. The tanks, piping and valves are manufactured out of austenitic stainless steel grade 304L and the systems typically operate at temperatures below 50°C. Metallurgical assessment of the cracks concluded it to be transgranular Stress-Corrosion cracking (SCC) associated with the marine environment (chlorides), susceptible material (304L) and stresses associated with cold forming, welding and casting shrinkage. The cracking was almost exclusively initiated through surface pitting of the components. The problem presented a challenge in that a vast number of components were affected by SCC and due to the largely subsurface nature of the cracking the inspection method had to include grinding of all the pipe surfaces to allow use of dye penetrant testing (PT) to reveal cracks. This paper describes the background to the problem, the inspection method, the morphology and the recovery strategy.

INTRODUCTION

In 1989 and 1990, 2 pinhole leaks were found on the Refuelling Storage Water Systems of Koeberg unit 1 and 2 respectively. These defects at that time were assumed to be associated with construction weld anomalies. Between 1995 and February 2001 eight leaks on thin walled stainless steel piping operating at below 50 °C were recorded on the 2 units at Koeberg. The leaks were all associated with pits or small cracks. Following each detected leak piping in the general area was subjected to additional visual and dye penetrant testing with no significant degradation being detected. Up until February 2001 Koeberg did not treat the cracking as a generic concern but did implement an augmented (to the In-Service Inspection Requirements) visual examination that required piping in the fuel building and Refuelling Storage Water tank rooms to be examined on a 3 monthly basis from February 2001. During such a visual inspection another leak was noted. Metallurgical evaluation showed the leak to be associated with a crack which developed below the metal surface and which was only revealed after removal of approximately 250µm of the pipe surface. Prior to surface removal only pitting was visible on the pipe surface. This led to the postulation that pitted areas could be hiding subsurface cracks. As large areas were affected by pitting Koeberg embarked on an extensive inspection programme of surface removal by polishing/grinding and dye penetrant testing. Following detection of a large C-shaped crack Koeberg unit 2 was shut down for limited piping replacements while inspections continued. Due to the large number of cracks found (not exceeding acceptance criteria developed for short term integrity) it was decided to replace only the most affected sections and plan the replacement or repair of the rest of the piping for future refuelling outages. A fracture mechanics analysis was done to justify operation with cracks below a conservatively determined allowable length and with an extensive monitoring programme in place to verify the absence of crack growth in operation. On-line inspections are ongoing with repair/replacement actvities being planned in refuelling outages to limit the impact on production.

PREVALENCE OF CONDITIONS AVAILABLE TO INDUCE SCC AT KOEBERG.

Three fundamental conditions must co-exist before SCC can occur in a material. These are that

- The material must be susceptible to SCC
- The material must be under stress.
- The material must be exposed to an environment that can promote SCC.

The larger proportion of pressure retaining components forming part of the nuclear island is manufactured out of stainless steel grade 304L. This material is accepted as being susceptible to SCC if under stress and in an adverse environment.

The Koeberg piping was procured under specifications that included a final cold work forming of the plate material into pipe shapes. The specifications require that the mechanical properties of the final product be confirmed to be acceptable to the requirements of the specification. Should the mechanical properties of the final product not meet the requirements the material is to be heat-treated (solution annealed). Review of the manufacturer's Quality Assurance Data Package could not confirm that the required appropriate tests had been performed to confirm that the mechanical properties had not changed through the cold forming.

Metallurgical evaluation of the piping cut out of Koeberg indicates that the material had not been solution annealed and that the material contained tensile residual stresses of more than 50% of the yield strength. Hardness tests of a sample from an elbow using a Vickers hardness tester measured values of the order of 210 VHN whereas the final mechanical properties of the rolled and annealed sheet prior to forming (according to manufacturer's data sheet) showed the hardness to be 155VHN. The increase in hardness and thus tensile strength can be attributed to cold working during forming.

Environmental conditions necessary to promote SCC are prevalent at Koeberg. The geographical location of Koeberg on the Atlantic coast results in chloride contamination on the outside surfaces of components. The Refuelling Water Storage tank room can be considered to be open to the outside environment, whilst the Fuel Building, Nuclear Auxiliary Building and Reactor Building are exposed to the marine environment to lesser degrees in the order of their listing. Although the general chloride levels in these buildings are up to a level of 200 ppm, concentrating mechanisms could allow localised levels of 100000 ppm. The storage tank areas were previously open to atmosphere, but were enclosed in 1990. The discovery of the SCC problem has led to speculation that the enclosures contributed to the concentration of chlorides on the pipe and tank surfaces in these areas as they prevent the regular washing down of the equipment during rainfall periods.

SYSTEMS/COMPONENTS AFFECTED BY SCC.

Considering the content of the above all systems/components manufactured out of stainless steel grade 304L, that are excessively stressed, inherently or in operation and are exposed to an appropriate environment are susceptible to SCC. Cracking has been detected on the piping of portions of the Containment spray, Safety Injection and Refuelling Water Storage systems (including cast valves) and on the Refuelling Water Storage tanks of both units. These are the only parts of systems/components which to date have been adequately inspected. The inspection scope prioritisation is based on the failure risk ranking of the systems/components when assessed to nuclear safety criteria (accident initiation and/or mitigation). The systems/components inspected so far are those responsible for ensuring design basis accident mitigation functions as defined in the Safety Analysis Report. The initial scope was performed to ensure that design basis coolant mass was available to the core and the containment. All systems/components considered susceptible to SCC will be inspected in the next 5 years.

CRACK MORPHOLOGY

Cracks were detected on three pipe elbows during a refuelling outage in February 2001. These cracks were detected by leakage and characterised using conventional liquid penetrant testing. The cracks were mostly linear defects up to 25mm long and perpendicular to the longitudinal seam welds, but a bi-axial crack was found as well. There were no other defects detected on any other elbows during this inspection or the extended scope of inspection. The cracks were all dispositioned metallurgically by replication and confirmed to be stress corrosion cracking (SCC). During a required three monthly visual inspection subsequent to the detection of these cracks, leaks were detected on other pipes that had been 100% inspected with dye penetrant testing in February 2001. The cause of the leaks was confirmed to be SCC. The reason for the previous non-detection of these defects was the following: the cracks were through-wall at the time, internal fluid pressure in the crack had prevented dye from entering the crack and had diluted it on the surface with the effect that there was light water staining on the developer and not pink penetrant as expected.

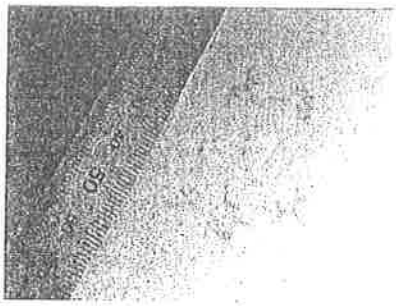

Fig.1: Example of PT test of elbow

Since the water staining was light, the inspection personnel could not distinguish it as abnormal and did not record a defect. This event resulted in requalification of the Penetrant Testing technique for detection of defects specific to this pipe in these conditions. Penetrant dwell times were extended from the originally specified and proceduralised 30 minutes to 24 hours. Four more cases of SCC were found on all the pipes that were inspected (100% inspection). It was concluded that all defects had been found and dispositioned.

Further metallurgical investigation incorporating light surface abrasion (depth of approximately 50µm) revealed another defect that had not been detected with 24 hour Penetrant Testing. The appearance of this defect indicated that the 24 hour Penetrant Testing had no relevance for this specific defect. Metallurgical dispositioning of this specific indication revealed that there was a corrosion pit approximately at its centre.

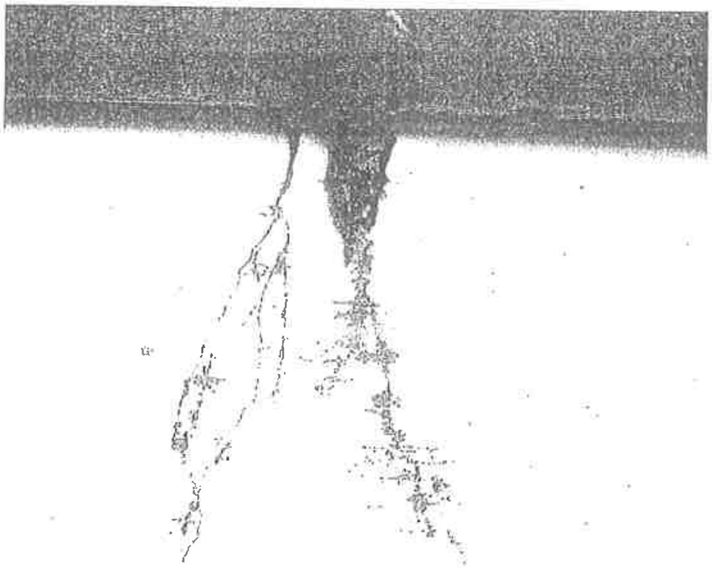

Fig. 2: Cross-section of corrosion pit

The primary initiator of the pits is chloride deposition. Chlorides are especially harmful to the passive layer on the 300 series of austenitic stainless steels. Considering the layout of the plant, operating history, shipping, handling, construction and maintenance it is likely that during all stages, the pipe was exposed to varying levels of chloride deposition/contamination. Swipes that have been taken on top and bottom surfaces of 31 pipe sections have returned preliminary values that are exceptionally high in chlorides. Hence, regardless of initial delivery/construction conditions there are sufficient chlorides throughout the affected areas for pit formation.

Since the piping was substantially pitted, it was possible that based upon the above defect, there would be more cracks associated with pitting. Ultrasonic testing (UT) was performed and where signals were generated, surface removal was performed (150 grit to a depth of 50 – 100µm) to confirm the presence of a defect. In many cases where there was a UT signal and material was removed by sanding, a crack became evident. It was then concluded that the sections of the pipes under question would require surface preparation (removal of 100 – 250µm) for PT confirmation of the condition of the piping. The PT revealed multiple SCC (linear and networks) on 10% of all the piping tested.

The morphology of the SCC was concluded to be as follows: the formation of a corrosion pit with subsequent subsurface SCC initiation and growth. Pits initiate on the surface and break down the passive oxide layer. The formation of a pit leads to concentration of chlorides at the bottom of the pit. Where the conditions are suitable (high residual stress), SCC can initiate and propagate from this point. The pit does not need to be very deep before SCC can develop. In this case, it was assumed that the residual stresses below the surface of the pipe were sufficiently high to initiate SCC (QADPs did not confirm solution treatment of the pipe after forming). Subsequent in-situ residual stress measurement revealed values in excess of 280 MPa. Residual stresses as low as 135 MPa have been shown to be sufficient to initiate SCC. Yield stresses were measured on previously removed pipe and found to be as high as 388MPa. This further supported the postulation that the pipe had not been solution treated after forming (high cold working and residual stresses). Optical microscopy of cracks showed it to be transgranular.

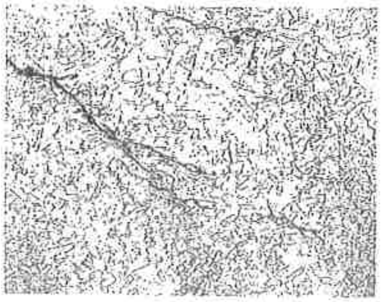

Fig.3: 100X magnification of crack

Measurement of the concentration of chemical species using Energy Dispersive X-Ray Spectroscopy (EDX).clearly shows that there is a very high concentration of chlorides in the cracks (Figure 4). The format of presentation giving the spectrum plot instead of numerical values was chosen to avoid confusion.

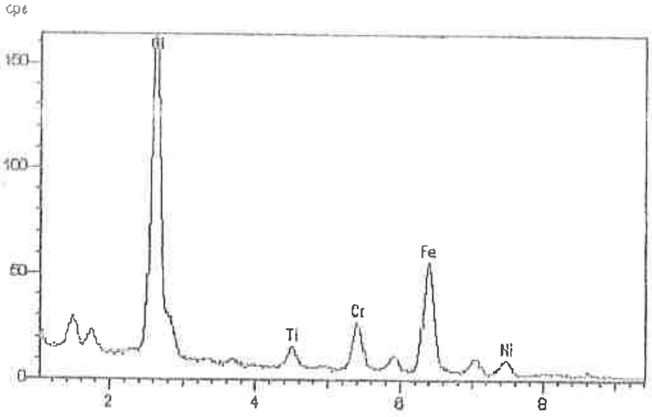

Figure 4. EDX of cross section of crack

The environment is clearly localised and may vary along the length and width of the crack. The necessary electrolyte to cause pitting will have been present when the tank rooms were open to the environment (and collected within the insulation) and may become available if there is condensation on the piping (as a result of the temperature dropping below dew point).

The external surface of a crack was also analysed to measure the concentration of chemical species and possible contaminants. EDX of the external surface of the crack shows the presence of chlorine (chlorides), silicon (silicates) and magnesium (magnesium compounds) (Figure 5). There was however, no evidence of

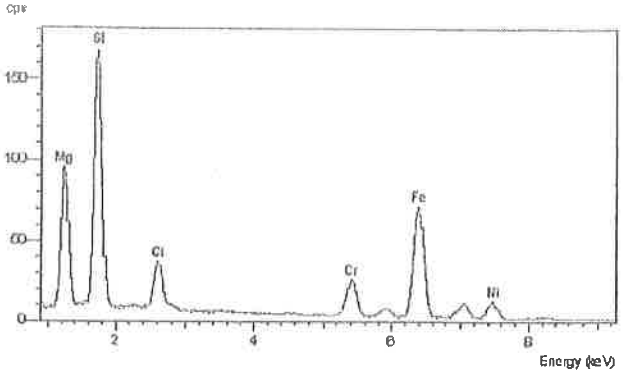

Figure 5. EDX of external surface of pipe and crack.

boron in any of the EDXs, which would be indicative of through-wall defects where process fluid was leaking out. The presence of the high concentrations of chlorides and absence of any other contaminants that can initiate and propagate SCC implies that it is chloride contamination that is exclusively responsible for the chemical contamination element of the stress corrosion cracking.

METHODS EMPLOYED FOR THE DETECTION OF SCC AT KOEBERG.

Initially, detection of the problem was through pressure boundary leakage, augmented by dye penetrant examinations of components in the area of the leak. This philosophy was applied while the generic nature of the phenomenon was not recognised. Subsequent to the understanding that the concern was generic as well as that the cracks predominantly initiate subsurface, a new detection strategy was applied.

The present applied strategy includes removal of approximately 250 microns of the material thickness from the outer surface with 60-150 grit sanding disk. The surface is then subjected to a dye penetrant (solvent removable) examination. The test technique has been qualified and concluded that, as a result of the penetrant viscosity and volume required to stain the developer:

- Pits smaller than 0.8mm diameter x 0.6mm deep (volume rather than length or depth being the important factor) may escape detection and
- Linear flaws smaller than 6.0mm long x 0.1mm wide x 0.2mm deep may escape detection (depth criteria being the major determinant).

Once cracks are detected depth determination with eddy current to a maximum depth of 3.9mm (± 0.9mm) can be performed.

Routine visual inspections are performed to detect leakage on a monthly basis.

CRACKS DETECTED.

Approximately 10% of the pipe spool pieces examined on unit 2 are cracked. Unit 1 is cracked to a lesser degree. The cracks vary in length between 1mm (detection capability differentiation between cracks and pits) and approximately 35mm for any individual crack. Only one crack network was found that was conservatively considered as a potential window failure site. Many (more than 80%) of the spool pieces contain indications resulting from pits. The unit 2 Refuelling Water Storage tank has cracks associated with nearly all of its integral welds. All of the cracks fall within the short-term acceptance criteria. The unit 1 tank is cracked to a lesser degree. The cracks found on the 4 valve bodies in the Refuelling Water Storage tank room vary between 1mm and 13mm.

ACCEPTANCE CRITERIA.

The piping that is in the examination scope is all classed as low energy (less than 19 bar and 93°c). The Safety Analysis Report considers low energy piping to satisfy leak before break criteria. A generic first level acceptance criterion was developed for all linear defects. If a larger crack was detected defect specific analysis was performed. For all cracks specific consideration is given to defects with orientations that could result in "window failure" i.e. failure by ejecting of a piece of metal opening up a "window" in the component wall. All such defects that exceed 30mm receive specific evaluation. This is based on evaluation of make-up capability of the systems involved and consequences to nuclear safety. Further specific interacting (proximity) rules are applied to multiple defects to ensure that the criteria are not violated.

Note. A large percentage of the cracks detected on the components examined do not meet the initial acceptance criteria of ASME section XI (Rules for In-service Inspection of Nuclear Power Plants) which is the licensed In-Service Inspection code for Koeberg.

RECOVERY STRATEGY

Due to the large number of components affected a phased strategy was adopted for repair/replacement of these components. Where possible defects are removed by local grinding and/or weld build-up. Components that cannot be repaired are replaced systematically.

PREVENTATIVE MEASURES

Several solutions were evaluated to prevent recurrence of the cracking problem. After careful consideration it was concluded that the most desirable solution would be to improve the environmental conditions in the areas of the plant where the susceptible components are situated. Measures to be implemented include sealing of rooms and areas to prevent ingress of chlorides and modifications to ventilation systems to promote dry and clean atmospheric conditions in these areas.

CONCLUSION

Koeberg has a generic SCC problem on components that are manufactured out of stainless steel grade 304l, that have an inherent or high operational stress and that are exposed to an environment conducive to SCC. The integrity statement for the piping, tank and valves in the degraded condition is supported by fracture mechanics studies that demonstrate that while defects are below a specific size ductile tearing is improbable. The modification to core damage frequency with the plant in its current state is acceptable when reviewed against the nuclear license. The total recovery of the plant to meet longer term operational integrity requirements is being progressed over a period of approximately 5 years.

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