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# Study of Scratch-Induced Stress Corrosion Cracking for Steam Generator Tubes and Scratch Control

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## Abstract

This paper introduces field cases for scratch-induced stress corrosion cracking (SISCC) of steam generator tubes in PWR and current studies in laboratories. According to analysis result of broke tubes, scratches caused intergranular stress corrosion cracking (IGSCC) with outburst. The effect of microstructure for nickel-base alloys, residual stresses caused by scratching process and water chemistry on SISCC and possible mechanism of SISCC are discussed. The result shows that scratch-induced microstructure evolution contributes to SISCC significantly. The causes of scratches during steam generator tubing manufacturing and installation process are stated and improved reliability with scratch control is highlighted for steam generator tubes in newly built nuclear power plants.

## 1. Introduction

Steam generator (SG), as the key component, connects primary and secondary side in PWR. The reliability of SG and safety operation of nuclear power plant is assured by very high quality of SG, especially the SG tubes. Failures of SG tubes could be caused by stress corrosion cracking (SCC), fatigue, wall-thinning, erosion, pitting or intergranular attack (IGA) and many other mechanisms historically. It has been reported by EPRI that the main failure mechanism of SG tubes is SCC in recent years [1]. SCC of steam generator tubes is often associated with abnormal surface conditions such as surface dents or scratches, which are produced during manufacturing, transportation or assembly process. Until now, numbers of SCC cases which are related to scratch on outer diameter of SG tubes occurred in field [2–6].

In 1989, a leak was detected on McGuire Unit 1 and the main cause was rupture of SG tubes which was Alloy 600 [5]. The ruptured tube was removed from McGuire Unit-1 SG and examined metallurgically. Intergranular stress corrosion cracking (IGSCC) along a shallow scratch on outer diameter of SG at cold leg was found. The maximum depth of these cracks was about 30% of the original wall thickness. Only about three years later, SG tubes in McGuire Unit 1 leaked again and the IGSCC cracks initiated at surface scratches [6], which was the same as before. Some cracks even reached up to 60% of wall thickness of tubes. In McGuire Unit 2, IGSCC was also found that cracks initiated along scratches in outer diameter of SG tubes as shown in Figure 1 [2, 3].

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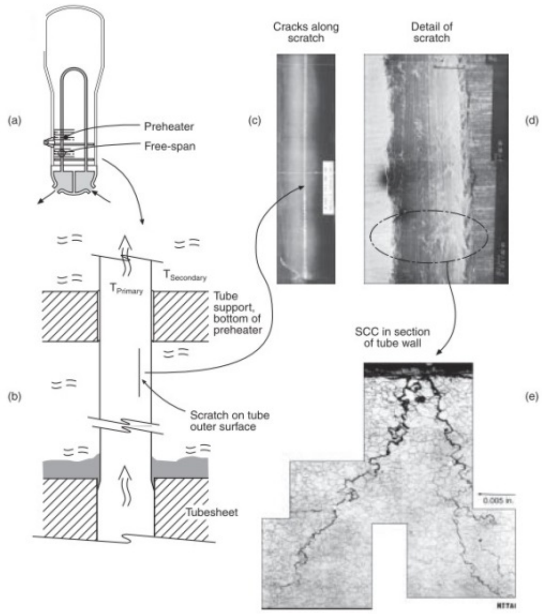


Figure 1 Scratch-induced SCC of steam generator tubing on secondary side in McGuire 2 [6]

During the 1994 refueling outage, the eddy-current results indicated that some SG tubes degraded [2]. Defects responsible for the indications consisted of shallow cracks in the free span regions and axially aligned IGA of up to 47% through-wall. After bursting test and extensive microstructure investigation, it was confirmed that those axial cracks initiated and propagated along surface scratch. The burst result is shown in Figure 2.

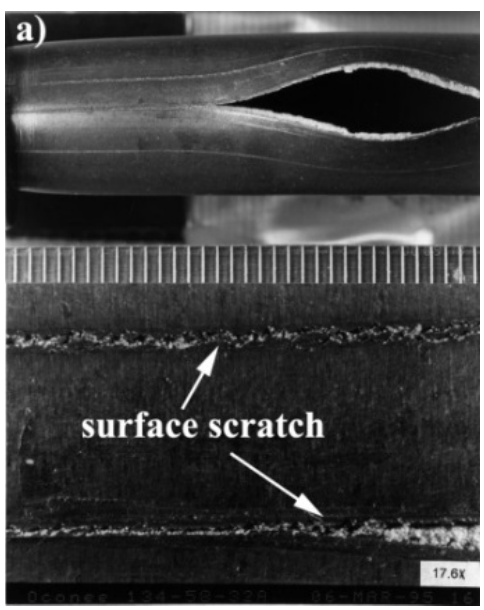


Figure 2 Scratch-induced SCC of steam generator tubing on secondary side in Oconee Unit 1 [2]

Besides McGuire Unit 1, McGuire Unit 2 and Oconee Unit 1, scratch related IGSCC was found on tubes used in Palo Verde Unit 2 [2, 3], Oconee Unit 2 [3] and Oconee Unit 3 [4] SGs. The statistics of these cracking cases was listed in Table 1. It is not a coincidence that scratch induced SCC of SG tubes occurred in these nuclear power stations. According SG tube leak time in Table 1, the lifespan of tube with scratches was far below its design life. SISCC of SG tube can always cause an outburst of case.

Table 1 Statistics of scratch-induced SCC cases on steam generator secondary side

| NPP | Start operation | Time to failure | Material | Causes |
|---|---|---|---|---|
| McGuire-1 [6] | 1984 | 1989 | Alloy 600 | Axial scratch |
| Oconee-1 [2] | 1973 | 1994 | Alloy 600 | Axial scratch |
| Palo Verde-2 [2, 3] | 1986 | 1993 | Alloy 600 | Axial scratch |

Considering different leak accidents of SG tubes in different nuclear power plants as described above, several features in common can be concluded: (a) All of the SCC was related to scratch; (b) Most of SCC occurs at cold leg and free span that concentration of deleterious ion was not rigorous; (c) Leak appeared during early stage of plant operation and crack initiation cycle was very short.

These typical features for SCC of SG tubes indicate that environment condition, such as temperature and water chemistry, is not the leading role that produces SCC. The introduction of scratch is a key element that accelerates initiation and propagation of SCC. To ensure the high reliability of SG tubes during plant operation, the causes of scratches should be well controlled and tubes should be monitored and inspected periodically.

Alloy 690 is more resistant to SCC in pure water and in acidified solutions and has largely replaced Alloy 600 usually in the thermally treated form. Alloy 690TT is also chosen as SG tubes for the third generation nuclear power station in China. Since scratches of tubing may hardly be avoided during the assembling of steam generator tubes and the consequence caused by small size scratch is always significant. Detailed studies of the deformation caused by scratching and the significance of scratching for SCC were done on Alloy 690TT [7-9]. Three factors that affect SCC and the possible mechanism are analysed in the following chapters according to laboratory studies.

## 2. Factors and mechanism analysis of SISCC

It is well known that SCC refers to the environmental degradation of structural materials as a response to aggressive combinations of stress, environment and low material resistance to the corrosion process of interest. For a scratched SG tube, the material-mechanical-chemical interaction, which indicates SISCC, is shown in Figure 3.

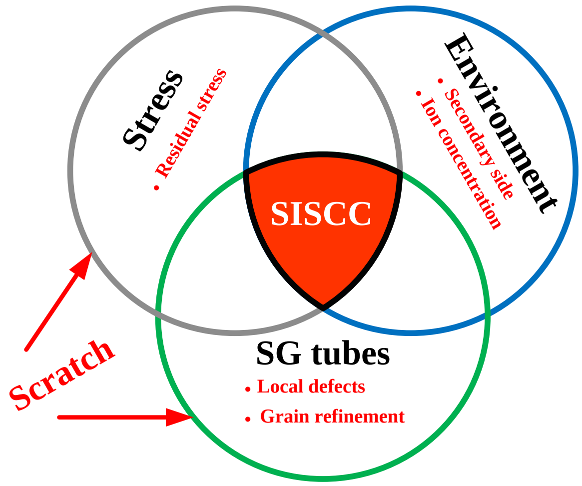


Figure 3 Schematic of SISCC

## 2.1 Microstructure evolution after scratching

Fuller et.al [10] studied the plastic zone around a scratch on Alloy 600 by using synchrotron X-ray radiation. The results show that different grains had different strain state and dislocation structure in the scratch-affected zone.

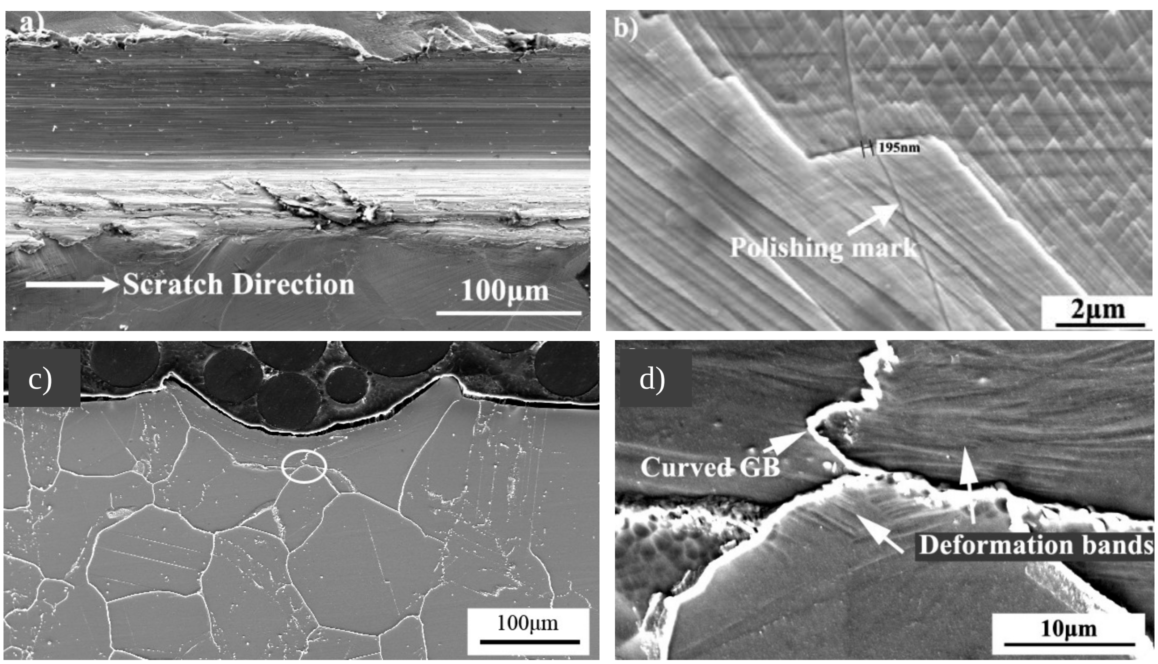


Figure 4 Microstructure of Alloy 690 after scratching process [7]

A type of scratch (300μm in width and 50μm in depth) which has similar variables with scratches found in fields was simulated and studied in laboratory [7]. The microstructure in the surrounding scratch is shown in Figure 4. Grains were highly deformed and exhibited slip bands as shown in Figure 4a and grain boundaries and twin boundaries were curved and visible as shown in Figure 4b. The deformed area was approximately 50-100μm from the scratch to non-deformed surface. The triggered slip systems were different in grains with different orientations. Some grains sustained more than one slip system. Cross-section of a scratch in Figure 4c shows that there were accumulations at the edge of the scratch-bank and a deformation layer, about 30μm deep, beneath the scratch-bed. The grain boundary underneath the scratch-bed was curved and the deformation bands were visible as shown in Figure 4d. According to result of microhardness measured along scratch surface and cross-section, strain hardening was found at scratch bed and two banks of scratch [9]. The ratio of strain hardening zone to scratch width was about 1, which is consistent with others work [8, 9]. The ration of depth of strain hardening at scratch bottom to scratch width was close to 0.5.

The immersion tests in caustic lead-containing solution were performed and SISCC was found on Alloy 690TT. The results also shows (Figure 5) that SCC cracks preferentially initiated along slip steps, microcracks and deformed grain boundaries produced during scratching process [7, 9].

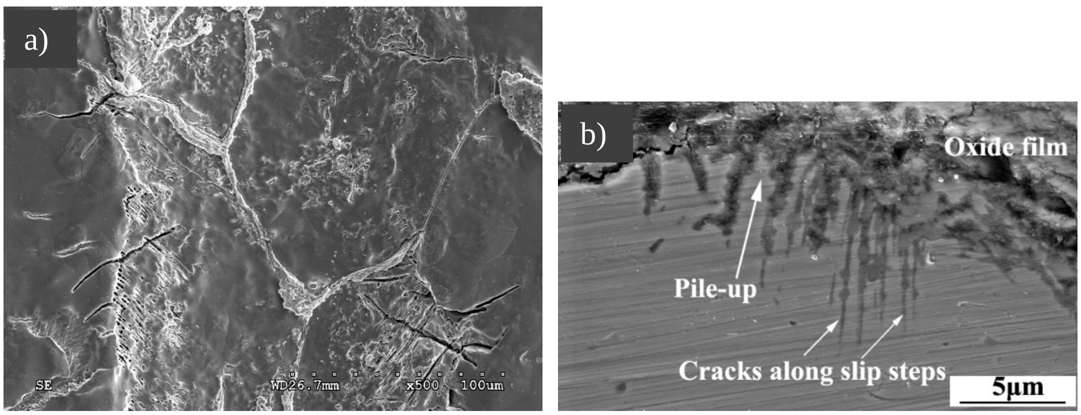


Figure 5 Growth of SCC cracks along (a) grain boundaries and (b) slip steps around scratch groove [7, 9]

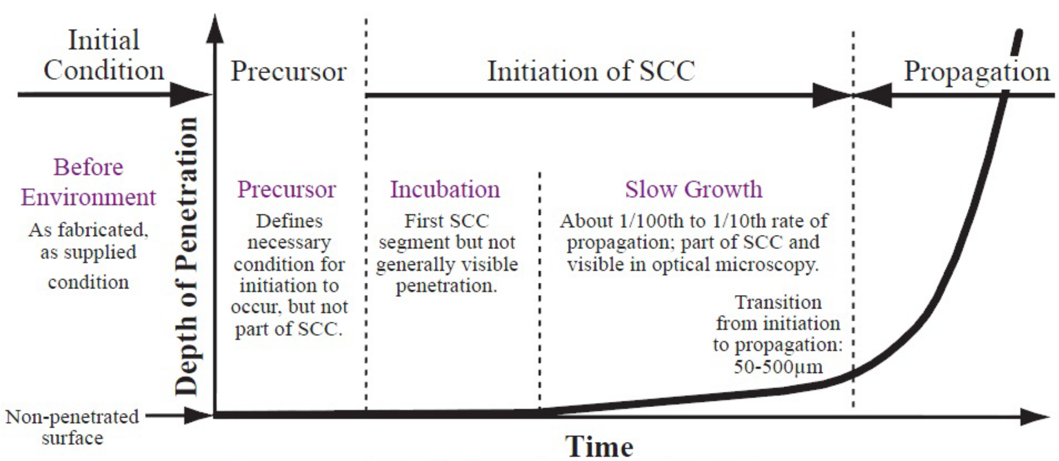


Figure 6 Five segments of SCC [6]

The five segments of SCC put forward by Staehle [6] were displayed in Figure 6. Even not in service environment, scratched tubes as supplied condition could already be the initial step for crack initiation. If initiation time is not taken account of, SISCC crack growth rate for Alloy 600 tube used in Oconee Unit 1 was about 23.8μm/y and in McGuire Unit 1 the growth rate was higher, which was as high as 130μm/y. The SISCC crack grew rapidly. It evidenced that the accelerated effect of scratch to SCC for SG tubes.

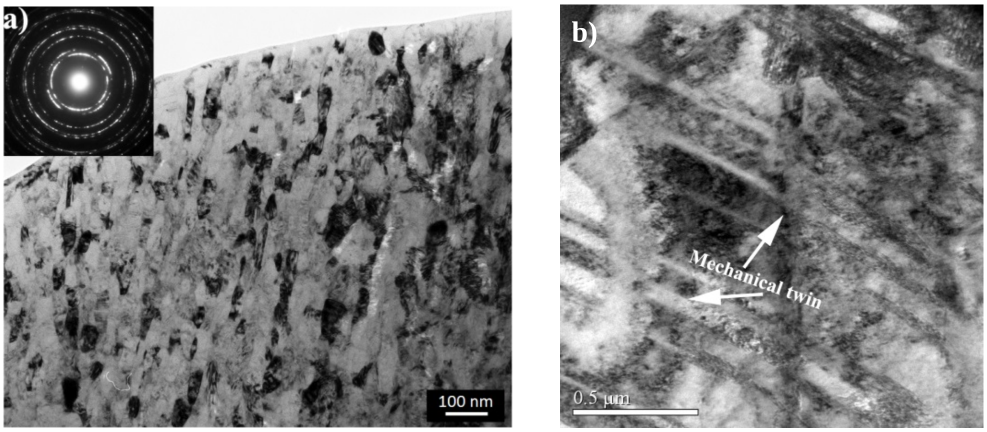


Figure 7 TEM observation of scratches for Alloy 690TT [8, 9]: (a) bottom of scratch groove, (b) scratch banks

The microstructure of scratch groove and scratch banks on Alloy 690TT observed in TEM is given in Figure 7. As shown in Figure 7a, grains in the shallow layer around the scratch groove was nano-structured, which is consistent with fine grain produced during mechanical attrition of Alloy 690 [11]. Because of high strain and high strain rate, numbers of mechanical twins formed after scratching process at scratch bank (Figure 7b). Since Alloy 690TT possesses low stacking fault energy, mechanical twins are easier to form. Sub-grain layer was also found on scratches of SG tubes in Oconee Unit 3 which was the same results with laboratory study [4].

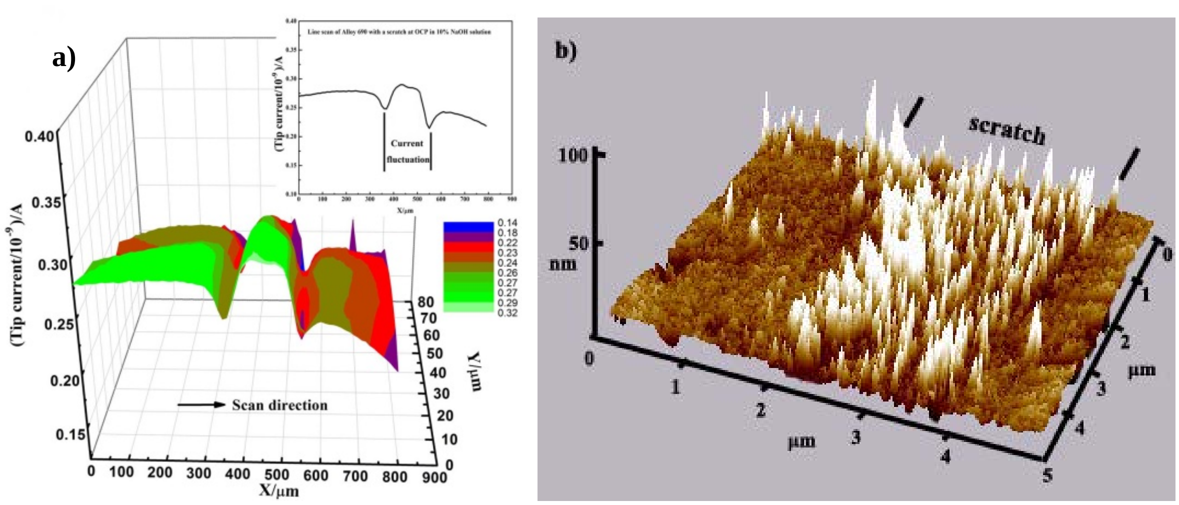


Figure 8 Localized dissolution (a) and oxidation (b) along scratch groove for Alloy 690TT [8]

As shown in Figure 8a, the scratch affected zone turned into a local anode and dissolved rapidly. According to Gutman[12], plastic deformation makes a heterogeneous micro-electrochemistry on material surface, and increases standard potential localized. The electrochemical activity of slip steps is much higher than surface without slip steps. Since existence of nanostructure at the scratch groove, oxides nucleated preferentially and grew rapidly (Figure 8b). This result demonstrates that scratching process created different energy distribution around the groove, especially nano-grains on the scratch groove stored higher energy which dissolved and oxidized preferentially [8].

It is a common sense that corrosion behaviour of structural materials is not only related to inert properties of materials, e.g. chemical composition, microstructure and mechanical property, but also related to manufacture, heat treatment and the existence of scratches. However, surface condition plays a significant role during corrosion process when surface of structural materials exposes in corrosive medium and interacts with it. Scratching process introduced localized deformation and caused cold working on the basis of laboratory results as described above. While chemical composition, microstructure, mechanical property, manufacture process and heat treatment are solidified for Alloy 690TT, microstructure evolution and plastic deformation caused by scratching affect SCC behaviour for sure.

## 2.2 Effects of residual stress on SISCC

The cracked tube in McGuire Unit 1 was examined by X-ray and tensile residual stress which was lower than yield strength was found on the scratch [5]. However, compressive residual stress along circumference was measured on scratched tube in Oconee Unit 1 and the residual stress could not be counteracted by stress produced by pressure difference between primary side and secondary side [2], which implies that IGSCC cracks may initiate in a compressive region.

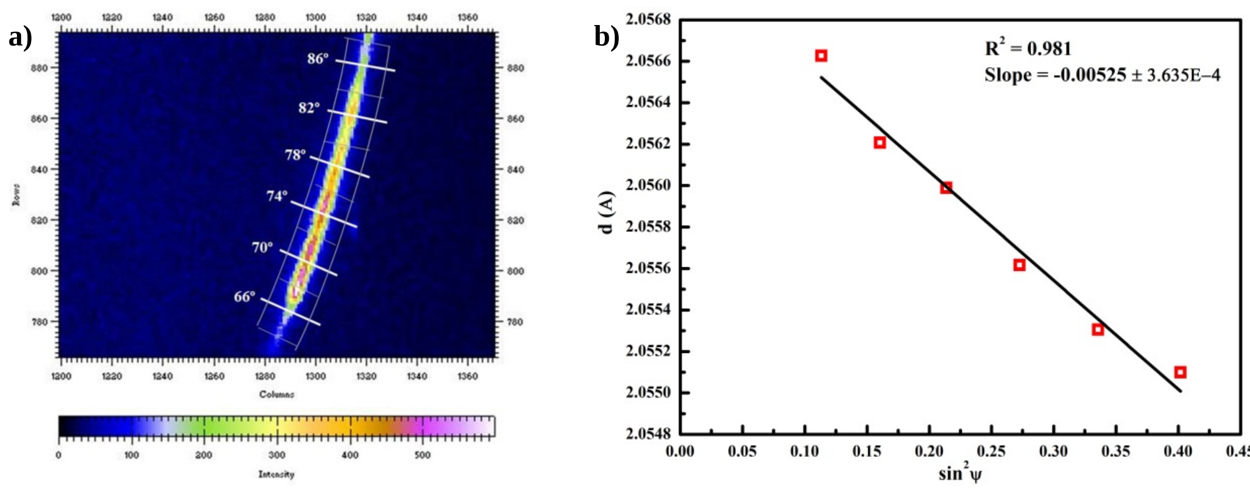


Figure 9 Calculation of residual stress at bottom of the scratch for Alloy 690 [13] (a). Integration of the Debye Ring; (b). d-$\sin^2\Psi$ fitting

Compressive residual stress, which was the same with Oconee Unit 1, was measured on shallow surface of a typical artificial scratch by synchrotron radiation as shown in Figure 9. The result shows grains that 20μm below the scratch bed was compressive and the residual stress was about 414±29MPa [13]. However, high tensile residual stress of 467±15MPa along scratching direction was measured [13]. High residual stress indicated that scratching process introduced very high cold working in local surface around the scratch.

In general, SCC crack propagate vertical to tensile stress. According to the immersion test result of Alloy 690TT in caustic lead containing solution at elevated temperature [7, 9], SISCC crack path was identical with scratching direction, which implies that tensile residual stress produced by scratching is not the main cause of SCC. SISCC initiated and propagated in a macro-compressive region, and its driving force was jacking force produced during oxide growth along defects produced by scratching [7, 13].

## 2.3 Effect of water chemistry on SISCC

Further analysis by TEM for the SCC crack on tubes of Oconee Unit 1 was conducted and lead was examined on the crack path [2]. It has been reported that lead can undermine the stability of oxide film, make it become loose and advance crack initiation and propagation around scratch which is evidenced in lab study. As shown in Figure 10, a mount of lead was enriched in crack path and chromium oxide nearly disappeared.

However, SISCC in McGuire Unit 1 occurred in free span and ion concentration in this region was not rigorous. No corrosion product was found on the fracture surface after EDS analysis. Before leaking, no apparent corrosion problem appeared in steam generator of McGuire Unit 1 and chemical that could initiate SCC was absent on the secondary side. This kind of condition indicates that SCC of SG tubes is not highly depended on water chemistry once a scratch is present.

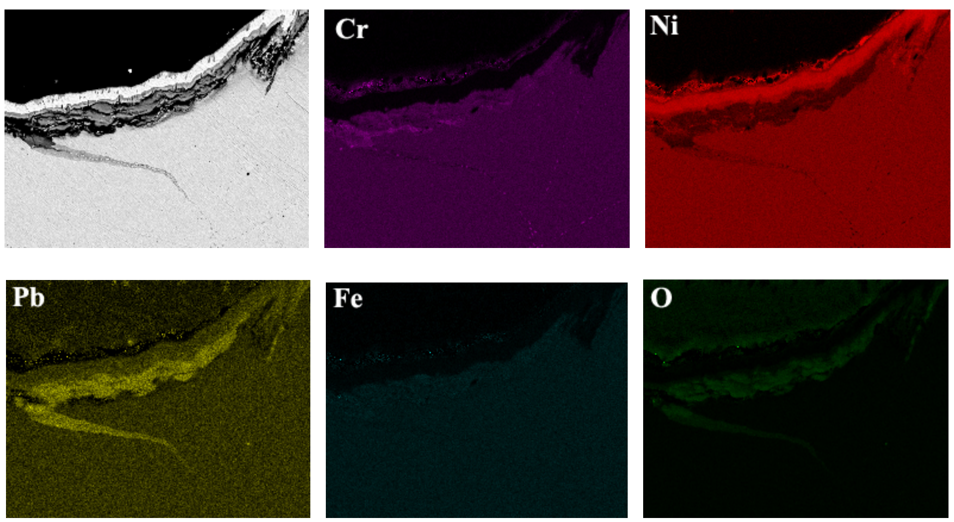


Figure 10 Elemental area scan of Alloy 690TT SISCC path (Test condition: 330℃, lead containing caustic solution)

## 3. Scratch control

There are two possible causes for scratches. The first cause that may produce surface scratches is manufacturing process, especially TT process. Since thermal-expansion coefficients between SG tubes and plates for supporting SG tubes are different, scratch may be produced at the contact region during TT. This kind of scratches could be found by visual inspection. According to the character of scratch and requirement of specification, the tube could be treated locally to remove the scratch or eliminate it.

The second possible cause that can produce a scratch is installation process of SG tubes. The geometry of tube supports are broached trefoil for AP1000 & CAP1400. The trefoil design could decrease local concentration of ion and the possibility of crevice corrosion. SG tubes are installed over several tube supports in parallel after U bent and the outer diameter is linearly contacted with tube supports. Because of line contact, production of scratches is easy and almost inevitable during installation. For scratches introduced during TT, residual stresses will relief after heat treatment. However, scratches introduced during installation may bring to more negative effect to tubes in service. For instance of SCC occurred in McGuire Unit 1 SG tube, the residual stress was very high and crack propagated much fast [2], which means this kind of scratch was more detrimental. The installation related scratch must be avoided or minimized. For that in-service tube with scratches, enhanced monitoring via online NDE [14] and continuous tracing must perform.

## 4. Conclusion

Alloy 690 is chosen as SG tubing of the third generation nuclear power station. The newly designed Alloy 690 tubes possess smaller diameter, lower thickness and increased numbers used in one SG and the design life is 60 years, which has higher requirement in SCC resistance of Alloy 690TT. For fulfilling this requirement and having safety operation, scratches on OD surface must be avoided during manufacturing and installation of SG tubes. For those tubes with scratches, enhanced inspection and monitoring must be performed during operation.

## 5. References

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