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# DETECTION OF ODSCC IN SG TUBES DEPENDING ON THE SIZE OF THE CRACK AND ON THE PRESENCE OF SLUDGE DEPOSITS

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It was discovered in a Korean PWR that an extensive number of very short and shallow cracks in the SG tubes were undetectable by eddy current in-service-inspection because of the masking effect of sludge deposits. Axial stress corrosion cracks at the outside diameter of the steam generator tubes near the line contacts with the tube support plates are the major concern among the six identical Korean nuclear power plants having CE-type steam generators with Alloy 600 high temperature mill annealed tubes, HU3&4 and HB3~6. The tubes in HB3&4 have a less susceptible microstructure so that the onset of ODSCC was substantially delayed compared to HU3&4 whose tubes are most susceptible to ODSCC among the six units. The numbers of cracks detected by the eddy current inspection jumped drastically after the steam generators of HB4 were chemically cleaned. The purpose of the chemical cleaning was to mitigate stress corrosion cracking by removing the heavy sludge deposit, since a corrosive environment is formed in the occluded region under the sludge deposit. SGCC also enhances the detection capability of the eddy current inspection at the same time. Measurement of the size of each crack using the motorized rotating pancake coil probe indicated that the cracks in HB4 were shorter and substantially shallower than the cracks in HU3&4. It is believed that the cracks were shorter and shallower because the microstructure of the tubes in HB4 is less susceptible to ODSCC. It was readily understood from the size distribution of the cracks and the quantitative information available on the probability of detection that most cracks in HB4 had been undetected until the steam generators were chemically cleaned.

KEYWORDS : Steam Generator, Alloy 600 Mill Annealed Tube, Outside Diameter Stress Corrosion Cracking, Eddy Current Inspection, Probability of Detection, Steam Generator Chemical Cleaning, Sludge Deposit

## 1. INTRODUCTION

HU3&4 and HB3~6 are six identical Korean nuclear power plants, CE-type 1,000MWe PWRs having Alloy 600HTMA SG tubes. The SG tubes were mill annealed at temperatures higher than 1040ºC per the CE purchase specification. The high temperature mill anneal is believed to reduce susceptibility of the tubes to SCC by developing networks of grain boundary carbides. The 3/4” diameter tubes are supported by egg-crate TSPs. Structures of the SG and the TSP are shown in Figure 1. CE steam generators are susceptible to ODSCC. The Alloy 600HTMA tubes are more susceptible to ODSCC than Alloy 600TT tubes, since the high manufacturing tensile residual stress of the mill annealed tube is relieved to a low level by the TT heat treatment at around 700ºC. A few design features of the CE steam generator are also responsible for their susceptibility to ODSCC. More sludge is deposited in the upper region than in other types of steam generators. The egg crate TSP does not provide rigid support against possible tube rupture from the cracks contacting the TSP. For this reason, the current regulatory requirement is that all cracks detected by the eddy current inspection need to be repaired, however small the size is. The design hot leg temperature of those six reactors was 327ºC, the highest among CE-type reactors, but the real operating hot leg temperature has been maintained near 323ºC. The high operating temperature is also responsible for the high susceptibility to ODSCC.

Since an extensive number of the SG tubes had been affected by ODSCC in HU3&4, their SGs were replaced during the 12th and 10th refueling outages respectively. Details of the ODSCC were reviewed and discussed in the previous paper [1]. Axial cracks had developed near the line contacts between the tubes and the strips of the TSPs, where an occluded region formed preferentially by sludge deposition. It is understood that the corrosive en-

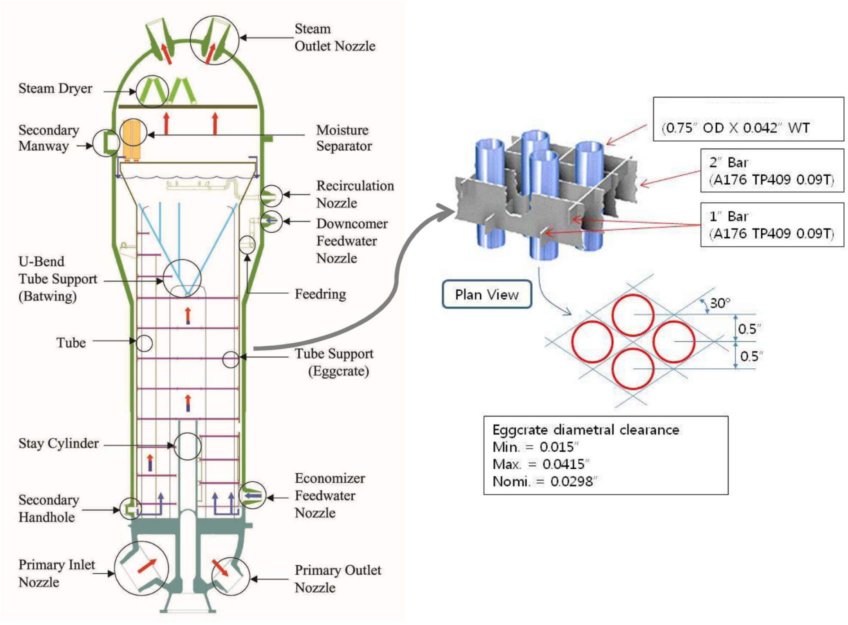


Fig. 1. Steam Generator and Egg Crate Tube Support Plate

vironment formed by concentration of impurities inside the occluded region causes ODSCC. It is a hideout mechanism that impurities are concentrated inside the occluded region by localized boiling under heat flux from the inside to the outside of SG tubes [2, 3]. The ODSCC was found to occur mostly in the heavy sludge deposit zone of the SG. The heavy sludge deposit zone was near the center of the hot leg half circle in the elevations between the 5~9th TSPs, as defined by a thermal-hydraulic analysis using the ATHOS code [4]. The Thermal Hydraulic Aided Colloidal Concentration deposit parameter is defined as ρv/(1−x), where ρ is the two phase fluid density, v is the fluid velocity, and x is the steam quality. The higher the THACC deposit parameter, the heavier the sludge deposit. Figure 2 shows the distribution of the THACC deposit parameter as analyzed by the thermal hydraulic calculation. The thickness of the sludge deposit can be estimated by analyzing the bobbin coil probe eddy current inspection signal, since the magnetic permeability is increased by the sludge deposit [5]. Careful analysis of the plant bobbin coil inspection signals indicated that the trend in Figure 2 was valid.

The investigation for the root cause of the ODSCC in HU3&4 suggested that the cracks developed under a mildly alkaline environment formed inside the occluded region, and that the specific microstructures and manufacturing residual stress are the key elements controlling the susceptibility of the Alloy 600HTMA tubes to ODSCC [1, 6]. The microstructures of CE type Alloy 600HTMA tubes depend on the cooling rate from the final mill anneal temperature of 1040ºC. The slower the cooling rate the coarser the grain boundary carbides. The microstructures of the tubes in the six Korean units are shown in Figure 3. The tubes of HU4 were the most susceptible, and those of HB3&4 were the least susceptible. The manufacturing residual stresses of the tubes in the six units are shown in Table 1. The residual stress was measured by the split tube method [7] and X-ray diffraction [8]. It is noted that the manufacturing residual stress played a critical role in the development of ODSCC, since the residual stress was higher than the operational stress caused by the pressure and temperature differential, as the operational stress is estimated below 100MPa. It is understood that the manufacturing residual stress is generated during the straightening rolling and

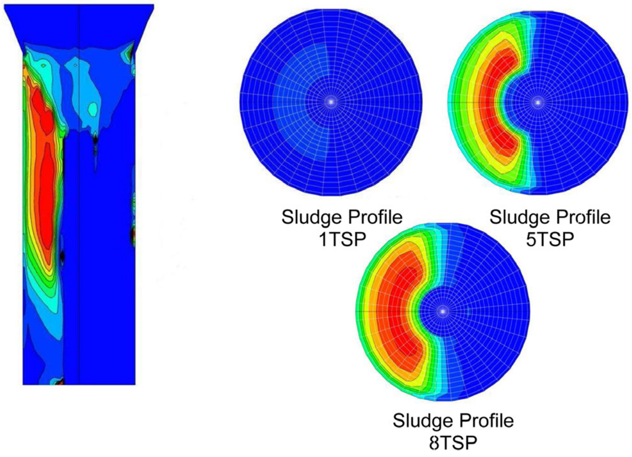
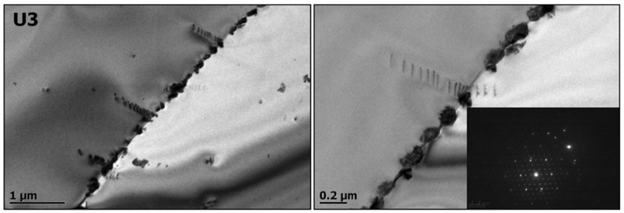
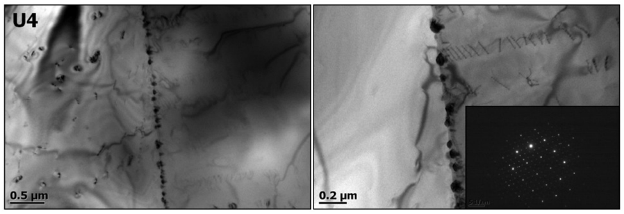


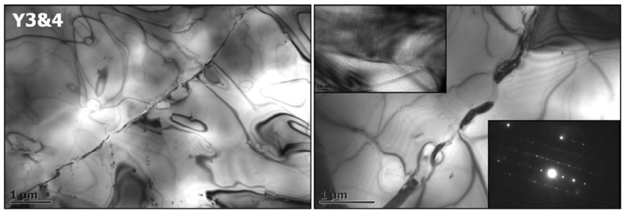
Fig. 2. Distribution of THACC Deposit Parameter Inside the SG as Calculated using the ATHOS Code



(a) HU3, identical with HB5&6



(b) HU4



(c) HB3&4

Fig. 3. TEM Images in the Grain Boundary and Diffraction Patterns of Carbides; (a) HU3, (b) HU4, (c) HB3&4 [1]

**Table 1.** Manufacturing Residual Stresses of SG Tubes in Six Units [1]

| Name of units | Residual stress (MPa) | |
|---|---|---|
| | XRD | split ring |
| HU4 | - | 147* |
| HU3 | 100 ~ 220 | 208 |
| HB3&4 | 200 ~ 370 | 250 |
| HB5&6 | -100 ~ 50 | 112 |

* U4 specimen is the tube pulled out during the 10th refueling outage. All the other specimens are archive tubes.

then belt polishing after the final mill anneal. The microstructures of tubes of HB5&6 were identical with those of HU3, but the manufacturing residual tensile stress was lower.

This paper describes findings based on evaluation of the development of ODSCC in HB3~6 where the tubes are less susceptible.

## 2. DEVELOPMENT OF ODSCC IN HB3~6

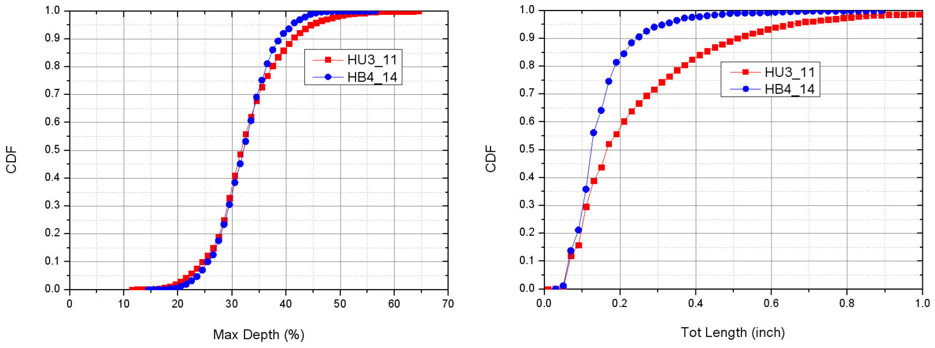
ODSCC had been substantially delayed in HB3&4 compared to HU3&4, as expected from the microstructures. SGs of HB3&4 were chemically cleaned in the 14th refueling outage, while those of HU3&4 were cleaned in the 10th outage. The in-service inspections were performed after SGCC. It is well known that SGCC mitigates ODSCC, and enhances the crack detection capability of eddy current inspection at the same time. The amounts of sludge deposit removed by each SGCC are shown in Table 2. Nearly half of the total of 8,214×2 tubes were affected by ODSCC by the inspection in the 10th RFO in HU4. Eight tubes were affected by ODSCC in the 14th RFO in HB3. 67 tubes were affected by ODSCC in the 13th RFO, and 1,063 tubes in the 14th RFO in HB4. SGs of HB6 were chemically cleaned in the 9th RFO, and HB5 is yet to be cleaned in the upcoming 10th RFO. ODSCC has not been detected in HB5&6. It is believed that ODSCC is delayed in HB5&6 since the residual tensile stress in the tubes is lower while the microstructure is identical with HU3.

The development of ODSCC was faster in HB4 than in HB3. The design and the tubing material are identical between the two units. Investigation of the details of the plant water chemistry databases did not reveal any meaningful difference between the two units, except that there was more iron ingress through the feed water into the steam generators in HB4. It is noted in Table 2 that more sludge was removed by SGCC from HB4 than HB3. Measurement of iron ingress through the feed water and the thickness of sludge profile as measured by analyzing the bobbin coil eddy current inspection signal also con-

**Table 2.** Amount of Sludge Deposit Removed by the SGCC

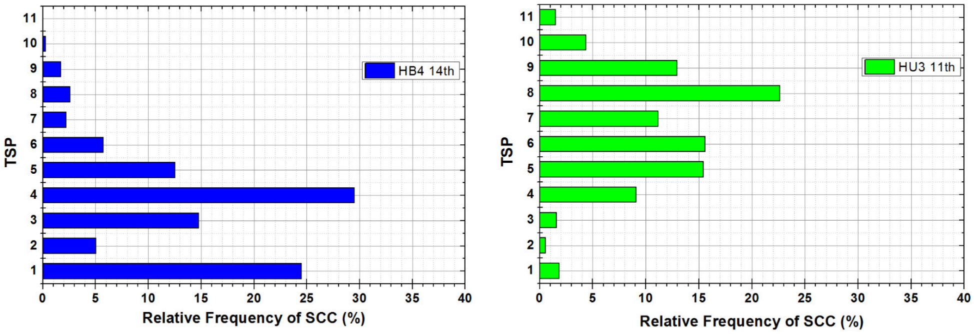
| Name of units | Refueling outage | EFPY | total removal (kg as $Fe_3O_4$) | |
|---|---|---|---|---|
| | | | SG #1 | SG #2 |
| HU3 | 10th | 11.7 | 1,693.7 | 1,938.7 |
| HU4 | 10th | 11.5 | 1,895.0 | 1,891.0 |
| HB3 | 14th | 16 | 2,408.4 | 2,360.2 |
| HB4 | 14th | 16.4 | 2,715.0 | 2,747.0 |
| HB6 | 9th | 10.4 | 1,577.9 | 1,623.2 |

HB5 will be chemically cleaned in the upcoming 10th refueling outage



(a) (b)

Fig. 4. Cumulative Distribution Fraction of Maximum Depth and Total Length of Cracks for EOC 14 in HB4 and EOC 11 in HU3; (a) Maximum (peak) Depth (b) Total Length



(a) (b)

Fig. 5. Distribution of ODSCC Depending on Vertical Locations of TSPs: (a) 14th EOC in HB4, (b) 11th EOC in HU3

sistently indicated that there is approximately 20% more sludge deposit in the SGs of HB4 than HB3. It is readily understood that the heavier sludge deposit is responsible, at least partially, for the faster development of ODSCC in HB4. This argument is supported strongly since sludge deposit is a key factor causing development of ODSCC and no difference was identified other than the amount of sludge deposition.

It is noted that the number of tubes with ODSCC indications increased drastically in the post chemical cleaning inspection in the 14th RFO of HB4. During the plant inspection, 4,813 tubes were sampled for pre-SGCC inspection in order to compare the POD performances between the pre- and the post-SGCC inspections. ODSCC was detected in only 20 tubes by the pre-SGCC inspection, while 552 tubes were detected in the sample by the post-SGCC inspection. It has been known that the number of tubes detected with ODSCC jumps substantially by post-SGCC inspection. Industry experiences of a few similar cases have indicated a 2.5~8 times increase by post-SGCC inspection compared to pre-SGCC inspection [9]. The big jump in HB4 is unprecedented. It is apparent that most cracks were not detected by the pre-SGCC inspection.

Figure 4 shows the cumulative distribution fraction of the peak depth and length of cracks detected at the 14th EOC inspection of HB4 and at the 11th EOC inspection of HU3. It is noted that the cracks are substantially smaller in HB4. 93% of the total cracks are shallower than 40% peak depth, and 83% of the total cracks are shorter than 5mm.

It was found that most ODSCC indications were detected in the elevations below the 5th TSP in HB4, as shown in Figure 5. This trend is clearly different from HU3&4, where most cracks were detected in the elevations between the 5th and 9th TSPs, where the sludge deposited most heavily.

## 3. DISCUSSION

### 3.1 SGCC and POD

SGCC is a process to chemically dissolve and then remove the consolidated sludge deposit, which is hardly removable otherwise [10, 11]. The purpose of SGCC is to mitigate ODSCC by removing the sludge deposit which forms the occluded region. A strong mitigation effect is expected if consolidated sludge forming the occluded

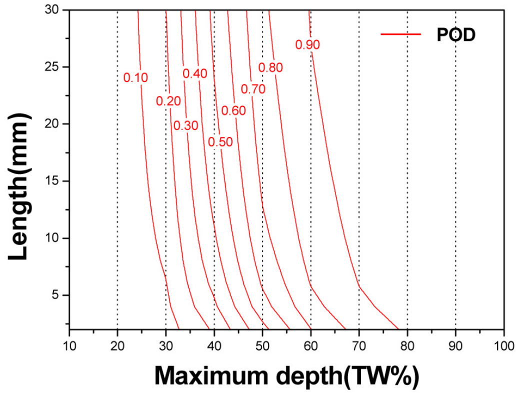


Fig. 6. POD Curves Depending on Peak Depth and Length of Axial ODSCC, MRPC Inspection [13]

zone is removed effectively. SGCC enhances the crack detection capability of the eddy current inspection at the same time.

Careful examination and comparison of the pre and post-SGCC eddy current inspection signals of ODSCC indicated that the voltage amplitude is increased and the phase angle is decreased (moving toward the vertical direction) by SGCC. Both changes enhance the detection capability. It is readily understood that the opening of a crack is cleaner after SGCC so that the impedance of the eddy current through the crack is higher, giving increased amplitude. It is understood that the electromagnetic signal from the sludge deposit distorts the signal from a crack into a more horizontal direction.

POD is an element of practical importance for the engineering assessment of structural and leakage integrity of SG tubes, since undetected cracks may grow to a size which threatens the structural and leakage integrity. There have been engineering estimations of pre and post-SGCC POD of bobbin coil eddy current inspection for detecting ODSCC of CE steam generators [12]. POD is often expressed as a function depending on the peak depth of the crack. The heavy dependence of the POD on the sludge deposit and other factors affecting the quality of the inspection signal renders POD highly plant specific. Review of a few pre and post-SGCC PODs indicates that SGCC enhances POD substantially, and that the extent of the enhancement is marked mostly in the range of peak depth between 20~50% through-wall [10]. Most cracks shallower than 20% tube wall are not detected irrespective of SGCC. Figure 6 shows POD curves of MRPC eddy current inspection for axial ODSCC [13, 14]. Information on the dependence of POD on the length of the crack is limited. Figure 6 was constructed based on databases developed by a Korean round robin inspection program using tubes from a retired steam generator [14]. Most cracks used for figure 6 were on the free span of the tubes covered with sludge deposit. It is seen from figure 6 that POD depends not only on the peak depth but also substantially on the length of the cracks, when, in particular, cracks are very short. It is readily understood that most of the short and shallow cracks in HB4 were not detected by the pre-SGCC inspection. The shallowness of the cracks may be explained by the slower crack growth rate of the less susceptible microstructure. The shortness of the cracks may be explained by the lower density of crack initiation so that there was less coalescence of short cracks into longer cracks.

### 3.2 Different Aspects of ODSCC

It was already described that most cracks were detected below the 5th TSP in HB4, while most cracks in HU3&4were detected in the heavy sludge deposit region, near the center of the hot leg semicircle in the elevation between the 5th and 9th TSPs. HU3&4 and HB3~6 are of identical design and the analyses of the bobbin coil eddy current inspection signals confirmed that all the units have an identical distribution profile of sludge deposition.

It is believed that an identical environment was formed in the heavy sludge deposit zone of HB3&4 as HU3&4, but that ODSCC did not develop there since HB4 tubes are less susceptible to ODSCC. The hot leg and cold leg temperatures are 323ºC and 293ºC, respectively. The temperature of the reactor coolant inside the tube decreases from the hot leg to cold leg temperature almost proportionally along the length of the tube. The hot leg temperature below the 5th TSP is lower than between the 5th ~ 9th TSPs, by up to approximately 10ºC. It is understood that the sludge deposit occluded zone is formed earlier in the heavy sludge deposition region where the temperature is lower than the regions below the 5th TSPs where the temperature is higher. Once an occluded zone forms below the 5th level TSPs, at a time later than in the heavy sludge deposition zone, it may provide a stronger corrosive environment than the upper region because the temperature is higher. The higher temperature not only accelerates the kinetics of the corrosion reaction, but also leads to a higher hideout concentration factor of impurities inside the occluded zone [2, 3].

## 4. CONCLUSION

The less susceptible microstructure of the HB3&4 SG tubes substantially delayed the onset of ODSCC compared to other similar units with more susceptible microstructures. The cracks in HB4 were found to be substantially shorter and shallower than in other units. This is attributed to a slower crack growth rate and to a less dense population of crack initiation of the less susceptible tubes in HB4. It is understood that most of the short and shallow cracks in HB4 had remained undetected by the pre-SGCC eddy current in-service inspection until a very big jump in the number of tubes having ODSCC was detected by the post -SGCC inspection.

## ACRONYMS

| | |
|---|---|
| ATHOS | Analysis of the Thermal Hydraulics of a Steam Generator |
| CE | Combustion Engineering |
| EFPY | Effective Full Power Years |
| EOC | End Of Cycle |
| EPRI | Electric Power Research Institute |
| HB | Han-Bit (new name of the Young-Gwang nuclear generation station) |
| HTMA | High Temperature Mill Annealed |
| HU | Han-Ul (new name of the Ulchin nuclear generation station) |
| ISI | In-Service Inspection |
| MA | Mill Annealed |
| MRPC | Motorized Rotating Pancake Coil |
| ODSCC | Outside Diameter Stress Corrosion Cracking |
| POD | Probability Of Detection |
| PWR | Pressurized Water Reactor |
| RFO | Re-Fueling Outage |
| SCC | Stress Corrosion Cracking |
| SG | Steam Generator |
| SGCC | Steam Generator Chemical Cleaning |
| THACC | Thermal Hydraulic Aided Colloidal Concentration |
| TSP | Tube Support Plate |
| TT | Thermally Treated |

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