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터보발전기에서 수랭식 고정자의 부식으로 인한 유량 감소 기구

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A Mechanism of Corrosion-induced Flow Degradation in Water-cooled Stator of Turbogenerators

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Water-cooled stator windings of large turbogenerators experience flow blockages due to the localized accumulation of corrosion products in their hollows copper strands. Stator flow degradation phenomenon at a nuclear power plant has been studied to develop a mechanistic understanding. A physico-chemically scaled corrosion loop test showed that arrays of flower-shaped Cu_2O flakes developed on copper surface in water flow direction with about 200 ppb of dissolved oxygen at 60℃. Simulations of air in-leakage triggered massive release of the oxide flakes followed by a gradual increase in the strand hydraulic resistance. Examination of the inner surface of strands revealed the evolution of blocky CuO layer underneath the released oxide flakes. Although a severe corrosion of copper occurred in 200 ppb water, the flow degradation was not developed in the loop, in contradiction to the earlier belief. Therefore, it is the large increase in redox potential due to air leakage that is identified as the primary cause for producing the waterborne oxide flakes and flow degradation. A tightened oxygen control procedure developed from the mechanistic understanding has stopped the flow degradation phenomenon in the nuclear power plant from recurring.

1. Introduction

1.1 Background

Large scale turbogenerators at nuclear power plants and contemporary fossil power plants have employed water-cooled stator windings. The turbogenerator of a nuclear power plant has experienced stator cooling water flow reductions to a severity that threatened power operation schedule and required chemical cleanings during the last several years, as described in Fig. 1. The stator water cooling system of the unit is described in Fig. 2. The cooling system design requires a nominal flow rate of high purity water at 45.5 l/sec with typical inlet and outlet temperatures of 40℃ and 60℃, respectively.

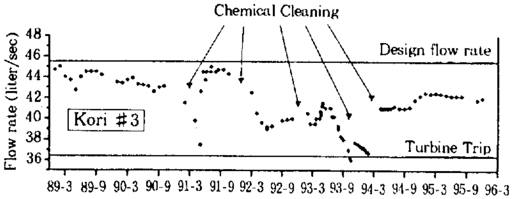

Fig. 1. Stator Flow Rate History at a Nuclear Power Plant during 1989~1996.

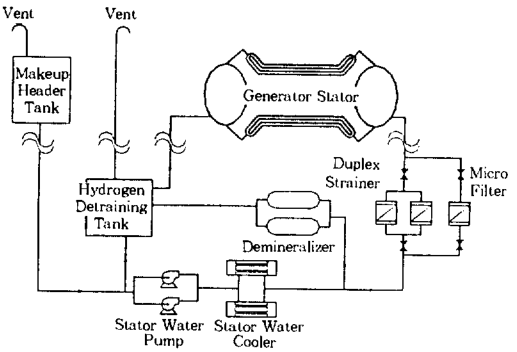

Fig. 2. Generator Stator Water System Schematic for the Nuclear Power Plant.

A typical water-cooled stator is consisted of several thousands of strands; each with about a 10m length and its hollow flow area of about 1.5mm by 3mm. A low-flow alarm is activated at 36.4 l/sec, or 80% of the nominal, with an automatic start of a standby water pump. When the alarm condition persists for more than a minute the generator power is reduced to cause a plant shutdown. The procedure is intended to avoid a localized overheating and failure of stator insulation materials which is expected to occur at about 130℃.

Since the introduction of water-cooling technique for large capacity stator windings in 1960's, there has been a number of reports on cooling flow degradation that is associated with the localized accumulation of copper corrosion product in the hollow strand. In order to minimize the corrosion, two types of water chemistry

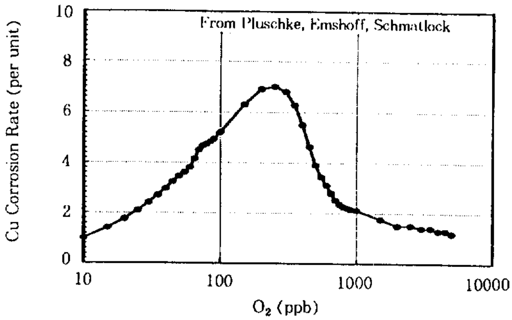

Fig. 3. Corrosion Rate of Copper Determined by 10,000 Hour Test in Neutral Stator Water Environment(reproduced from Ref. 2).

have been employed in the industry; namely, the low oxygen and the high oxygen water chemistry.[1] Intermediate oxygen concentration is believed to be undesirable since earlier study results have shown that copper corrosion rate reaches a maximum rate at about 200 ppb by weight in water, as shown in Fig. 3.[2] The low oxygen water chemistry is established by air-tight sealing of the water system assisted with hydrogen gas permeated from the rotor side through PTFE(polytetrafluoroethylene) hoses that provide electrical insulation between the stator and outside water supply system. The low oxygen system can lower the rate of copper corrosion without resorting to passivation. High oxygen water chemistry is established by exposing the water storage tank to air such that oxygen concentration in water can be raised close to its solubility at the temperature. At the high oxygen concentration copper surface is known to be passivated with black adherent oxide layer lowering further corrosion rate.[1] However the corrosion-induced problems have occurred in both type of water chemistry in the past. The flow degradation in particular is observed more often in the low oxygen system.

1.2 Problem Statements

A state-of-the-art review of open literature has been made by the present authors and published elsewhere.[1] Unpublished experience with the water-cooled stator operation has been surveyed via communications with major vendors and utilities. We can summarize the findings, as follows;

1) Stator water cooling flow blockage problem has been experienced by utilities all around the world. France, Germany, Ireland, Italy, Norway, South Africa, Spain, Switzerland, U.K., U.S.A. and Korea, at least, are identified as countries that have experienced the problem. Several generators had overheating incidents due to strand blockage. An European utility is still experiencing the problem to a severity that requires repeated chemical cleanings.

2) The problem occurred in both nuclear and fossil power plants where the dissolved oxygen concentration in stator cooling water is specified to be low. Although an agreement exists in that the problem is caused by high oxygen concentration, the allowable oxygen concentration has been debated. As high as 200 ppb was allowed by the manufacturer at the nuclear power plant during the period of flow degradation.

Although severe corrosion product transport and local accumulation are suggested as the results of high corrosion rate, a mechanistic understanding on detailed process inside the strand is still lacking. Partly for this reason, the principal remedial measure to the stator flow degradation has been the chemical cleaning and prolonged water flushing. This approach is often met with the problem repetition and even worsening which lead to premature replacements of stator windings at a significant economic penalty.

A mechanistic understanding based on electrochemical and hydrodynamic characterization is necessary to formulate more fundamental remedies. For this purpose a stator simulation loop has been developed with which the evolution of copper surface condition, coolant particle population and flow resistance can be measured online under the controlled water chemistry environments. In this paper the result of the simulation loop experiments are reported with the mechanistic understanding on the flow degradation phenomenon developed from the experiments.

2. Stator Corrosion Simulation Experiments

Fundamental understanding of the copper corrosion behavior is essential to the development of preventive diagnostics and corrective measures. For this purpose a scaled model loop has been developed for the simulation of stator water system. Fig. 4 describes the test loop flow diagram. Hollowed copper strands with a cross section of 1.5×3.0mm were obtained from Korea Heavy Industries and Construction Company(KHIC). The material represents a typical commercial strand used in the generator manufacturing made of oxygen-free high conductivity (OFHC) copper. Optical metallography of the strand inner surface showed a partially-recrystallized microstructure with no second phase particles.

Unique features of the developed simulation loop compared with those developed by earlier investigators[2-4] include a) physico-chemical

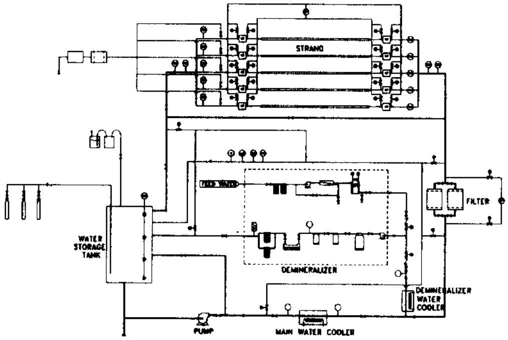

Fig. 4. Schematic of Stator Simulation Loop System.

scaling using the same copper surface area to water volume ratio and Reynolds number, b) A. C. resistive heating of five 10m long strands using the current density that is comparable to that in actual stator windings, c) viewports at Roebel transposition[2)] allowing for microscopic observation of oxide evolution during operation, and d) a fully computerized data acquisition and control allowing for unattended long-term loop operations. Resistive heating power for the strand was maintained constant throughout experiments. The secondary cooling water flow rate was regulated such that the strand water inlet temperature was maintained at a constant desired value within 2℃.

Important measurement parameters include dissolved oxygen concentration, conductivity, particle size distribution of flowing water, differential pressure over the stator flow path length, and strand flow rates. An Orbisphere model oxygen analyzer, a Signet model conductivity meter, a Hyac model particle counter were employed for on-line monitoring and recording. Dissolved oxygen concentration, one of the most important parameters, was controlled with accuracy and stability by bubbling the storage tank with a specific mixture of nitrogen and oxygen gas. An oxygen level below 1 ppb could be obtained by maintaining a hydrogen pressure of about 1.3 atm. in the free gas space in a storage water tank of Fig. 4. The flow rate of each strand was measured using a turbine-type flow meter. It was necessary to install an inlet water filter with a nominal size of 45μm in order to avoid malfunction of the flow meters due to interaction with coarse particles. All the measurement sensors and indicators were calibrated to available standards prior to the loop operation.

Out of total five strands, one has been autoclaved in flowing steam at 150℃ for an hour prior to the loop experiment in order to reproduce a passivation layer on inner surface which represents an initial surface condition of new stator windings from the manufacturer. During the first 350 hours, the simulation loop was run with deionized water at 200 ppb by weight of dissolved oxygen and a conductivity of 0.5 Siemens/cm or less at an inlet and outlet temperatures of 40℃ and 60℃, respectively. The flow rate of each strand was about 0.45 l/min. that approximates the actual hydraulic condition in the nuclear power plant. Strand inlet and outlet pressure at the condition was 6 atm. and 2.7 atm., respectively. A small fraction of total flow at the level of 0.1 l/min. was bypassed to a water deionizer and the returned to the storage tank in order to maintain stator water purity following the scheme used in the actual plants. The initial oxygen concentration of 200 ppb was chosen because the value represents the upper limit of allowed oxygen concentration at the time flow degradation. Subsequently, the inlet and outlet temperature was increase to 50℃ and 70℃, respectively, in order to accelerate the corrosion process for a period of 735 hours. Later dissolved oxygen concentration was varied step-wise in order to examine the effect on corrosion and hydraulic characteristics.

3. Results and Discussion

3.1 200 ppb Oxygen Water

A total of 1,085 hours of loop experiments was conducted at 200 ppb oxygen concentration, initially at 40/60℃ and later at 50/70℃ for inlet/outlet temperature, respectively. During the initial 650 hour period, there were major flow rate changes caused by factors other than strand effect such as filter clogging or drifts in the deionization bypass flow rate. In order to eliminate these factor in the analysis, the net change in the hydraulic condition of stator strand during the experiment was determined in terms of the strand hydraulic resistance, defined as follows;

$$f = P/Q^2$$

where f is the strand hydraulic resistance, ΔP the pressure drop between the inlet and outlet of the strand in psi, and Q the strand flow rate in l /min. The strand hydraulic resistance is equivalent to the flow friction factor for a given flow length.[5] Hence its increase can be used as a quantitative measure of friction development inside the hollow strand associated with surface roughening or a local constriction.

The result of loop experiment at 200 ppb oxygen during the next 425 hour period is presented in terms of the hydraulic resistance, as shown in Fig. 5. The hydraulic resistance of all five strands remained fairly constant during the entire period. A strand specimen was taken from a viewport at the end of the 1,085 hour experiment in 200 ppb oxygen. Inner surface was examined under a JOEL model 6400 scanning electron microscope(SEM). The result is shown in Fig. 6. The copper surface was covered with arrays of flower-shaped oxide flakes that are aligned in the water flow direction. A detailed examination showed needles of copper oxide with about 1m length and 0.2μm diameter. Wavelength dispersed x-ray(WDX) analysis on the oxide needle surface revealed a well-defined composition ratio between Cu and O that indicates the oxide as Cu_2O. The flower-shaped oxide morphology is consistent with those observed from strand inner surfaces of a failed generator.[4] Although the flower-shaped oxide was extensively produced on the surface there was no detectable increase in the strand hydraulic resistance. The particle number density remained low near 100#/ml indicating that the extensive oxide flake formation on the copper surface does not result in a massive particle release in the stable 200 ppb oxygen water.

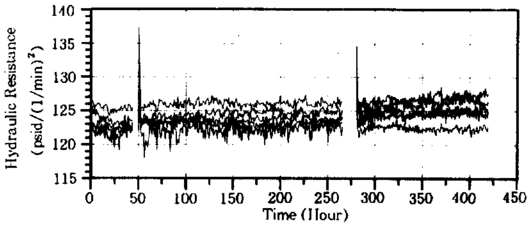

Fig. 5. Strand Hydraulic Resistance during the Final 420 Hour Period of 200 ppb Oxygen Water Experiment.

3.2 Hydrogenated Water

In an attempt to identify the condition where flow degradation develops readily, the subsequent loop experiment was made using

Fig. 6. SEM Photograph of Flower-shaped Copper Oxide Structure Observed from Strand Inner Surface after 200 ppb Oxygen Water Experiment.

hydrogenated water using 1.3 atm. of hydrogen cover gas in the storage water tank. Dissolved oxygen concentration quickly dropped to below 1 ppb in a few hours of operation in the hydrogenated water. The transition from 200 ppb oxygen water to the reducing environment simulates that of a plant start-up period when the initially high oxygen concentration(near 1 ppm) in make-up water is reduced by hydrogen gas permeated from the rotor side through the PTFE hoses. Continued loop operation for about 200 hours, however, did not produce any significant change in the hydraulic resistance of all five strands, as shown in Fig. 7. Particle number density measurement during this period failed due to inadvertent particle contamination in the beginning. Since the observation of strand surface through the viewport revealed no changes, the test in hydrogenated water was concluded.

3.3 Aerated Water

Since water leakage was often reported for the stator cooling water system at actual plants, it is likely that air gets into the system through the leaks and the oxygen concentration can in-

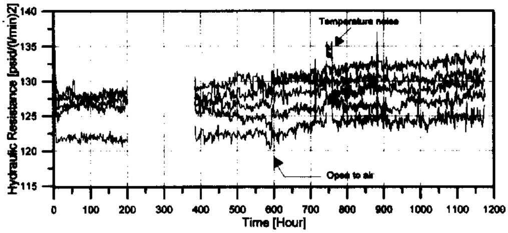

Fig. 7. Strand Hydraulic Resistance with Time during Hydrogenated Water Experiment (from 0 to 200 hr) and Aerated Water Experiment (from 450 to 1,150 hr).

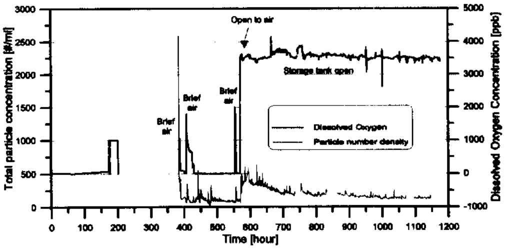

Fig. 8. Water-borne Particle Number Density and Dissolved Oxygen Concentration with Time during Hydrogenated Water Experiment(from 0 to 200 hr) and Aerated Water Experiment(from 450 to 1, 150 hr).

crease step-wise in the low oxygen stator water chemistry.[1)] The situation has been simulated with the loop by a) brief air intrusions and b) a sustained aeration by allowing air contact the initially hydrogenated water in the storage water tank. Response to the step increase in oxygen concentration was conspicuous in very short time, as shown in Fig. 7 and 8. The brief air intrusion increased oxygen concentration immediately up to 1～2 ppm from nearly zero ppb range. Each of three brief air intrusions triggered a sharp increase in the particle number density by a factor of about ten followed by a stabilization to the original level of about 100 # /ml, as shown in Fig. 8. Hydraulic resistance did not change significantly during the initial 200

Fig. 9. SEM Photograph of Blocky Copper Oxide Structure Observed from Strand Inner Surface after Aerated Water Experiment.

hour period following any of the brief air intrusions.

Finally the storage tank was left open and the hydrogen gas supply was discontinued which raised oxygen concentration up to the solubility limit that is about 3.5 ppm at the temperature, as shown in Fig. 8. The particle number density increased by several times initially and then exhibited a slow decrease. Almost immediately, the hydraulic resistance began to increase with time at all five strands, as shown in Fig. 7. At the end of the 600 hour operation in aerated water, the increase in hydraulic resistance leveled off and so did the particle number density. A strand specimen was removed again from a viewport and examined under the SEM. The results shown in Fig. 9 have clear contrast with those obtained from 200 ppb oxygen water test of Fig. 5. Most of flower-shaped oxide layer was removed and a new blocky crystalline oxide layer was developed underneath the remaining Cu_2O flakes. Both WDX analysis of the surface showed that the new oxide structure has a composition ratio that corresponds to CuO.

3.4 Discussions

The result of stator simulation loop experiments indicates that the flower-shaped coppe oxide flakes were formed extensively on the copper surface in 200 ppb oxygen water. But the particle number density remained low and the flow degradation phenomenon was not observed during over 40 days of loop operation. Therefore the flower-shaped Cu_2O layer is believed to be a stable form of oxide at the intermediate oxygen concentration of 200 ppb. In contrast the blocky CuO has been found in aerated water. The observation is consistent with Pourbaix diagram for $Cu\text{-}H_2O$ system.[6] A strand that was passivated in oxygen containing aerated steam at 150℃ also revealed the blocky CuO layer, as shown in Fig. 10. The blocky oxide is known to be more adherent and passive in the flowing water by earlier corrosion studies.[2-4]

Fig. 10. SEM Photograph of Blocky Copper Oxide Structure Observed after Passivation Experiment in Aerated Flowing Steam at 150℃.

Particles collected from water sample taken during 200 ppb oxygen experiment was examined under SEM to confirm that copper oxide particles in the environment has a broken-needle shape with about 1 m length which appear to match the remnants of released oxide flakes on CuO layer of Fig. 10. The sharp increase in the particle number density upon the aeration at 390 hours of Fig. 8 indicates that Cu_2O oxide flakes are destabilized due to a redox potential jump to the CuO stability regime. The continued aeration of the loop water showed fairly high particle number density over a long period, starting from about 570 hours of Fig. 8.

The flow degradation phenomenon was observed to be related with the sustained high particle density which can be produced in several hours from the aeration of loop. The fact that no flow degradation was observed in 200 ppb water for over 40 days suggests that the extensive oxide flake formation is not the direct cause. The importance of oxide release rate is highlighted by the fact that high particle density can lead to a localized accumulation and sedimentation at an eddy flow geometry.[7] Such an eddy flow geometry exists both in the stator and the simulation loop at such locations as curved windings and sudden bends called Roebel transposition that is employed in all stator designs to distribute current uniformly among strands. A non-destructive examination of a failed stator strand indeed revealed blockage of hollow strands by accumulation of copper oxide particles at the Roebel transposition.[4]

During the last quarter of 1993 when the flow degradation phenomenon was in progress actively, the particle number density of the nuclear power plant was measured for a range between 5μm and 100μm. The density was also measured at the loop experiment for a range between 1μm and 10μm. Fig. 11 compares the particle size distribution between those of the nuclear power plant stator and the loop experiment. Although the loop measurement and the plant data have different range of measurement due to the detector differences, the loop experiment with aeration, except the end of test, is shown to produce a particle size distribution and the number density that are consistent with those of the nuclear power plant. Therefore a large increase in water-borne particles is concluded to have a direct impact on the stator flow degradation phenomenon. The earlier belief that the stator flow problem is caused by high corrosion rate at oxygen concentration near 200 ppb[2-3] is contradicted by this study since both particle release and flow degradation did not occur in water with a steady 200 ppb oxygen. Although the particle density slowly decreased near the end of test, high particle density in flowing water can be sustained by alternating oxygen concentration between the aerated condition and that below 200 ppb. Such an alternation in oxygen concentration often occurs at the plants with

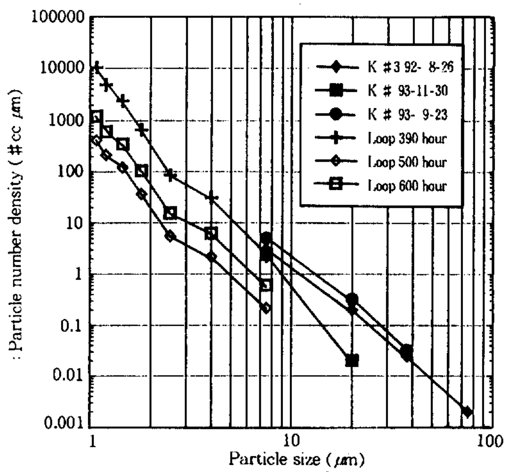

Fig. 11. Comparison of Water-borne Particle Number Density between Loop Experiment with Aerated Water and the Nuclear Power Plant during Flow Degradation Period.

low oxygen water chemistry by the random repetition of system water leakage and/or water make-up using high-oxygen water. A new procedure for tight control on the system leakage and oxygen removal from make-up water is applied to the system to avoid large redox potential changes. Since then the flow degradation phenomenon has not been recurred at the nuclear power plant.

4. Conclusion

A stator simulation loop experiment has been conducted for mechanistic understanding on cooling water flow degradation phenomenon occurred at a nuclear power plant. Arrays of the flower-shaped Cu_2O flakes are observed to form at the inner surface of hollow strands in 200 ppb oxygen water flowing at 60℃. The strand hydraulic resistance, equivalent to friction factor for a given flow length, did not change in 200 ppb water. Oxygen removal by hydrogen gas did not cause any significant increase in the strand hydraulic resistance. Aeration of water to simulate the stator water system leakage and high oxygen make-up occurring frequently at the plant is found to trigger massive release of the flower-shaped oxide which led to the increase in water-borne particle number density to comparable levels observed at the nuclear power plant during the flow degradation period. Final surface of strand in the aerated water was covered with a blocky CuO layer which is known to be more adherent and passive. The primary cause for the stator flow degradation is, therefore, the massive release of Cu_2O flakes which causes a local accumulation at eddy flow geometry in strand down stream. The earlier belief that the problem is caused by high corrosion rate at oxygen concentration near 200 ppb is contradicted by this study. A new procedure for tight control on the redox potential changes has stopped the recurrence of the flow degradation phenomenon at the nuclear power plant

5. Acknowledgment

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