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Safety Review on Recent Steam Generator Tube Failure in Korea and Lessons Learned

Youn Won Park and Jin Ho Lee
Korea Institute of Nuclear Safety, Taejon, Korea

ABSTRACT

Recently Korea experienced a steam generator tube failure. The failure occurred during the reactor shut down process, so its consequence was relatively less serious compared with those failures during the power operation [1]. Prompt investigation on the failure cause was taken. The failed tube was pulled out from the steam generator for metallurgical examination. The root cause is still under investigation but so far the major contributor is known to be the corrosion attack developed in the axial direction above the top of tube sheet. An extensive additional inspection was performed to confirm that the failure was a tube-specific problem and not a generic problem. The thermal hydraulic evaluation was also conducted to investigate the plant response and appropriateness of the operating procedures. This event provides valuable lessons learned to improve the steam generator tube integrity in Korea.

INTRODUCTION

There was a steam generator tube failure at Ulchin Unit 4 nuclear power plant (UCN4) in Korea on April 5, 2002 when the reactor was shutdown at 00:10 hours and was in the course of cooldown in the borated condition for refueling outage. The operator recognized that the pressurizer level began to decrease rapidly at 18:33 hours and subsequently the radiation monitor on the steam generator B blowdown line was on alarm at 18:46 hours. Recognizing the incident as a steam generator tube rupture, the operator immediately implemented a tube leakage procedure. The faulted steam generator was immediately isolated, and at 18:49 hours the operator started the safety injection manually since the pressurizer level continued to decrease. He kept on cooling down the reactor using the intact steam generator and reduced the primary pressure using auxiliary spray of pressurizer. The reactor coolant system pressure and the steam generator B secondary side were equalized at 19:59 hours and the break flow stopped. The reactor was connected to the shut down cooling system at 02:58 hours on April 6 and finally reached the cold shutdown condition at 13:35 hours.

After placing the plant in the cold shutdown condition, Korea Hydro and Nuclear Power Company (KHNP) examined the faulted steam generator with a boroscope and found that row 14, column 38 (R14C38) tube failed. Subsequently, a comprehensive inspection was conducted and the failed tube was pulled out for a root cause analysis.

KEYWORDS: safety knowledge, Steam generator tube, tube failure, corrosion, failure causes, generator tube leak

PLANT TRANSIENT

UCN 4, which started commercial operation in December 1999, was in the normal cooldown process when the steam generator failure occurred. The primary pressure was at 158kg/cm^2 and the RCS temperature at 290^{o}C.

At 18:33 hours on April 5, 2002 with the unit under a hot shutdown condition, the operators of the UCN4 received an indication of decrease in pressurizer level. The pressurizer level drop was interpreted as a transient due to over-cooling effect because the reactor was in the course of cooldown. When this indication was observed, the reactor had already been in shutdown condition from 01:20 hours of the same day and the reactor coolant system began to cool down just 40 minutes before. The cooling was being done by stem dump to condensers. After one minute (18:34), the operators closed steam bypass valves to reduce the cooling rate and one minute later, the third charging pump at standby started automatically due to the pressurizer low level signal. At 6 minutes (18:39), letdown line was closed to decrease the primary inventory loss but the pressurizer level decreased rapidly to zero level at 8 minutes (18:41). By this time, there was no indication of leak. The N-16 radiation monitor was out of service during reactor shutdown condition, and the condenser air ejector radiation monitor did not indicate any increase of radiation level.

At 13 minutes (18:46), the radiation monitor on the B steam generator blowdown line was the first indication of primary-to-secondary leak. The operators recognized the incident as a steam generator tube leak and implemented their tube leak procedures. At 16 minutes (18:49), the operators manually initiated the safety injection which was reset for plant cooldown. In addition, they began to isolate the B steam generator and reactor coolant system depressurization. The main steam bypass valves to condenser were opened for short periods of time at 21 minutes (18:54) to decrease pressure of the faulted steam generator. At 29 minutes (17:02), the reactor coolant pump 2B was stopped and at 32 minutes, pressurizer spray valves opened for a short period and again at 42 minutes (17:15). At 86 minutes (19:59), the reactor coolant system pressure and the B steam generator secondary side pressure were equalized and the break flow stopped.

The Fig. 1 shows trends of principal parameters of primary system, such as pressurizer level, primary pressure and temperature. At about 7 hours, the shut down cooling system (residual heat removal system) was in service and finally at 13:25 hours on April 6, the reactor arrived at cold shutdown condition of reactor coolant system temperature of 99°C and pressurizer pressure of 27kg/cm^2. As shown in Fig. 1 and 2, there was no significant excursion in primary to secondary pressure.

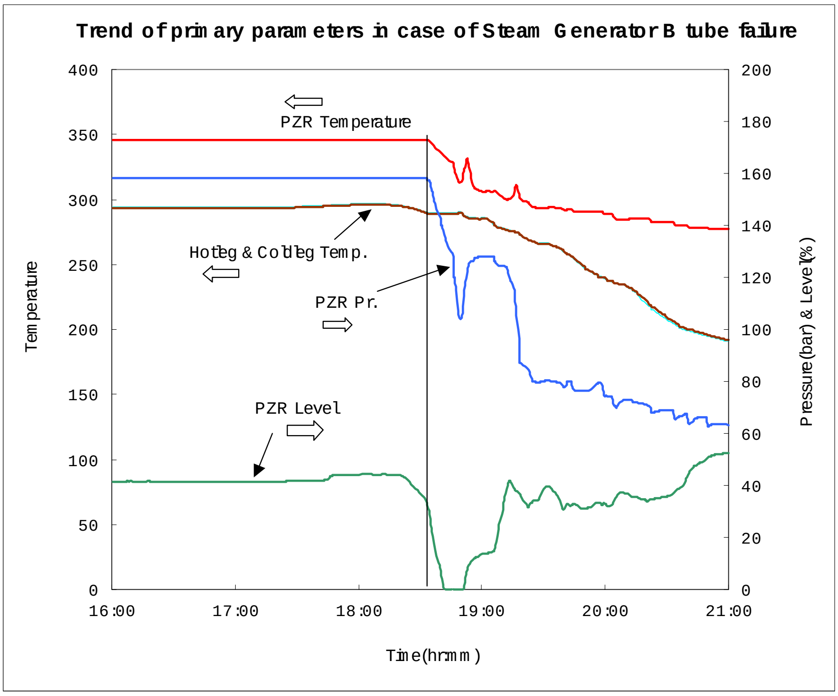


Fig. 1 Principal parameters of reactor coolant system of the Ulchin unit 4 during steam generator tube failure event of April 5, 2002.

CAUSE OF FAILURE

The UCN 4 tube failure was almost unique in the sense that it was not preceded by significant primary-secondary leakage which is normally expected for similar incidents. The investigation on the cause of failure was conducted in two approaches: the visual and metallurgical examination, and reevaluation of the eddy current records of the failed tube were performed.

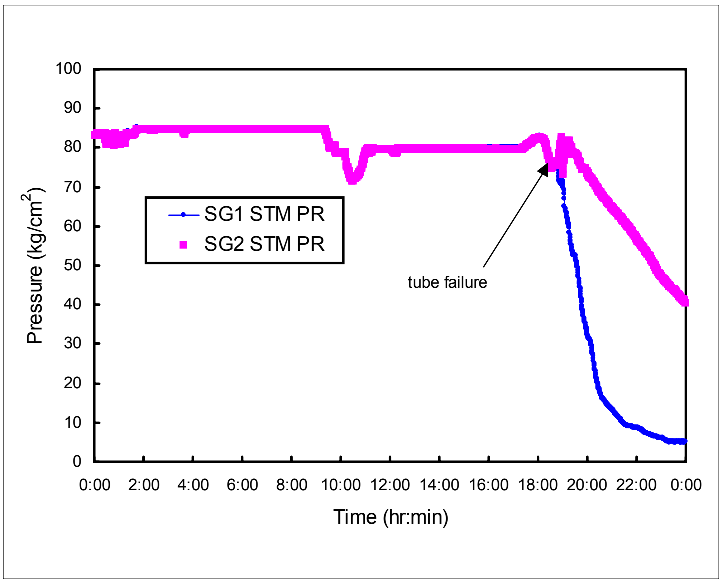


Fig. 2 Steam generator secondary side pressure during Ulchin Unit 4 steam generator tube failure event of April 5, 2002.

Visual and Metallurgical Examination

The failed tube was visually examined just after the event at UCN 4. The failure was located on the hot leg side of the tube in Row 14, Column 38 at the top of tube sheet. The R14-C38 is near the center of the tube bundle. The failure consisted of a longitudinal split about 80mm long in fish mouth opening shape and a circumferential rupture that completely severed the tube at the top of tube sheet about 80mm high.

The failed tube was removed from the B steam generator. The circumferentially severed section showed that there were two tearing areas. The one is located at the junction area with longitudinal split at the top of tube sheet and the other in the final ligament that seemed to rupture when the ligament could not sustain the transient loads. The severance propagated in helical way through the direction of 45 degree against the horizontal direction. This indicates that the circumferential severance developed after the longitudinal failure occurred as the secondary effect.

The failure in longitudinal direction was in a fish-mouth type opening and the maximum opening was located in the middle of the ruptured tube. The longitudinal failure is thought to propagate in both ways, up and down. The upper propagation went through the circumferential severance changing its orientation about 45^{o} to the circumference of the tube. The lower propagation arrived at the top of the tube sheet and continued in the circumferential direction to about 240^{o} of the tube circumference. The failure shape is a "T" type that is a combination of normal fish-mouth opening in axial direction and circumferential severance.

The rupture was caused mainly by SCC developed in the longitudinal direction from the top of tube sheet to the location of circumferential severance on the inside diameter of the tube. The cracks are shown to penetrate through wall of the tube in about all along the longitudinal failed section. Several secondary cracks branched from the main axial crack were also observed. At the near longitudinal crack, a deformed area in a banded shape were observed along the crack faces. So far, the root cause is not clear, but this banded area seems to provide some primary effect on developing stress corrosion cracks.

The metallography of the failed tube showed typically well structured grains of Inconel 600 HTMA. From this metallography, it was difficult to conclude that the material of failed tube is susceptible to stress corrosion cracking. In the past the SCC test of the same material showed that the material was resistant to SCC. The detailed investigation on the root cause is still underway.

Re-evaluation of eddy current examination records

The failed tube was subject to three previous eddy current examinations before the event. The first was the preservice inspection (PSI) using bobbin and motorized rotating pancake (MRPC) probes in 1998, the second was the first inservice inspection (ISI) using both probes in March 2000, and the third was the second inservice inspection in February 2001 using only bobbin probe.

The MRPC probe consists of three types of coils: two pancakes and a +point. The pancake coils consist of two different diameters: 2.0mm and 2.9mm. The larger diameter pancake coil is to improve penetration to the outside surface. Field experience shows that pancake coil has better sensitivity to volumetric defects whereas +point coil has better sensitivity to crack like defect[1]. Since complete coverage of the steam generator tube with MRPC can be a time consuming process, the MRPC is generally used to screen indication identified with a bobbin coil or to scan only critical regions of tube. The scan of MRPC at PSI was limited to the zone from –3 to +3 inch from top of tube sheet.

The PSI result of the failed tube was recorded as "no recordable indication" in bobbin as well as MRPC data. However, the reevaluation results conducted after the tube failure showed that the MRPC data had significant signals whereas the bobbin data had no meaningful signals. In particular, the C-scan of pancake data shows series of signals like ridge of mountains that could be interpreted as a bulge developed in longitudinal direction along the failed section. However, there was no significant indication in the +point data. It means that there is a bulge like deformation but no crack in the tube. The examination personnel of PSI said at the interview that he interpreted this type of signals not to be defective and judged it to be "no recordable".

Comparing with the PSI results, the revaluation of the first ISI data shows that the bobbin signals had no visible difference in differential mode but they show some noticeable changes in absolute mode. Especially, the profilometry read from the absolute mode of bobbin data provides a relatively good way for distinguishing their difference as shown in Fig. 3. There was some change in the amplitude of the pancake signal that was about 30 % higher than those of PSI. However, the +point signals had no noticeable change. It means that some defects begin to develop but are not enough to be identified as a defect. The ECT examiner of the first ISI identified such change and called it permeability variation cluster (PVC). The failed tube had no defective signals in the first ISI so that it was recorded as "acceptable as-is".

The second ISI on the failed tube was conducted only with a bobbin probe. The differential mode does not provide any meaningful change in comparison with the previous inspection but the profilometry shows small change in the profile as shown in Fig. 3.

From the reevaluation process, it was concluded that the difference in the signals obtained from the PSI, the first ISI, and the second ISI can be distinguished only if those signals were carefully examined. Unfortunately, the +point probe that is known to be sensitive to crack like defect was almost incapable of identifying the defect developed at the bulged section. The pancake probe was better in detecting the meaningful signals from the defect but most of them were masked by the relatively strong signals of the bulge. The profilometry is a powerful tool to detect not only the geometrical variation but also development of defect in the deformed section.

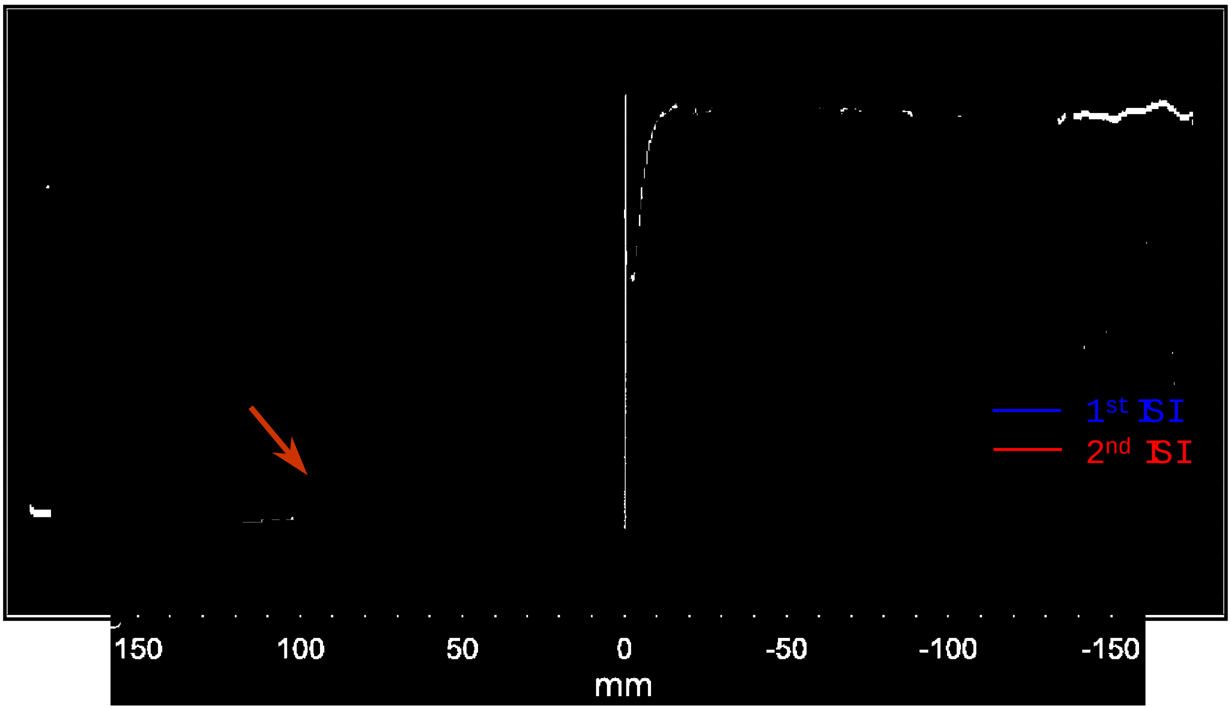


Fig. 3 Changes in profile between the PSI, the first ISI, and the second ISI.

LESSONS LEARNED AND REGULATORY ACTIONS

The regulatory body advised the overall improvements in the integrity of steam generator tube based on the defense-in-depth concept. The first concern was whether the failure mechanism is generic. Some of the characteristics of the steam generator tube failure at UCN 4 are as follows:

- complex failure mode: longitudinal and circumferential failure
- no leak-before-break (break before leak)
- tube failed during cooldown process under hot shutdown condition
- no noticeable indications in previous
- rapid progress of SCC through the tube wall

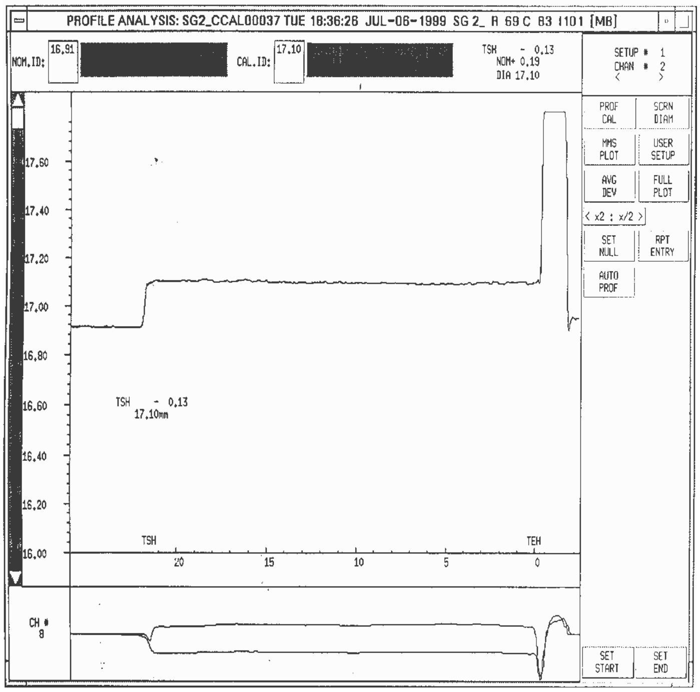
In order to investigate whether the failure is tube specific problem or generic one, the KHNP performed extensive inspections on all the tubes of UCN 4 steam generator and found that the characteristics of the failed tube were pertaining to the longitudinal SCC cracks initially developed in bulge section. The KHNP also found that such characteristics could be identified in the profile of failed tube which had an intermediate overexpansion as shown in Fig. 4 (b). The failed tube was removed from the B steam generator for detailed examination. The interim conclusion from examination on the removed tube is that the stress corrosion cracking begins to develop at the bulged section in the longitudinal direction and propagated at a growth rate high enough to penetrate the tube wall in three years of operation.

The second concern was whether all the other steam generators are exempted from the similar failure characteristics. The KHNP conducted eddy current examination over 100% of tubes with bobbin probe, and 100% of hot leg tubes and 20% of cold leg tubes with MRPC probe. The profilometry was also performed on all the inspected tubes. The KHNP concluded that no tube had the same characteristic as the failed tube at UCN 4 steam generators.

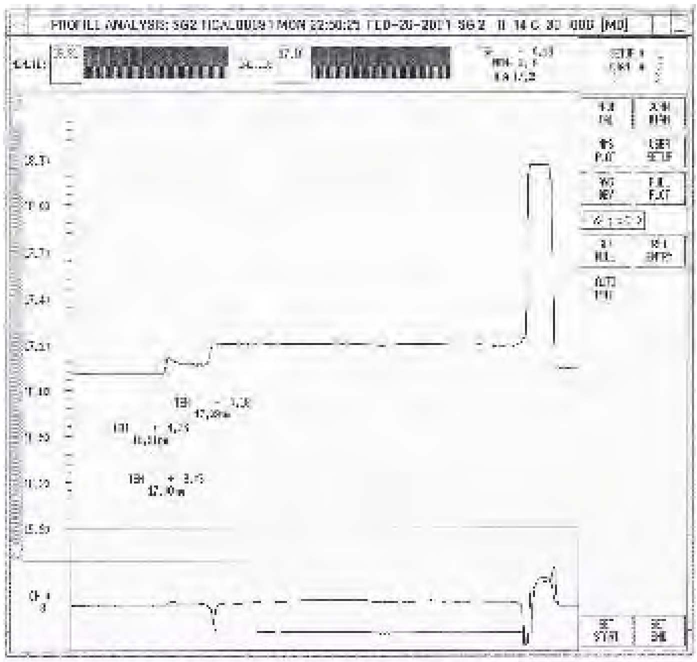
The third concern was whether, in case of tube leak, the monitoring systems were sensitive enough to provide alarms in advance before the leaking tube break. Unfortunately, the most sensitive radiation monitor, N-16, was out of service when the reactor was placed in the shutdown condition. To have a good sensitivity to tube leak during reactor shut down condition, the warning thresholds were lowered in radiation monitor of condenser vacuum system and steam generator blowdown system, and the frequency of chemical sampling was increased.

The fourth concern was whether the operator actions could be taken appropriately at the same incident in accordance with the emergency operating procedures. By the time the tube failure occurred at UCN 4, the emergency operating procedures were developed based on the idea that all the significant incidents could occur at normal power operation. However, the tube failure at UCN 4 took place unexpectedly at hot shutdown condition under reactor cooling process. Therefore, the emergency operating procedures were revised to incorporate the recent experience.

Just after this event, the regulatory body set up a task force team to prepare extensive measures to improve the integrity of steam generator tubes. Since the failure cause resulted from the bulge that was probably made during manufacturing process, the eddy current examination is to be introduced from the fabrication stage. Once a steam generator is put into service, the inservice inspection is the most effective way to prevent the steam generator tube failure so that the regulatory body requires the augmented inspection on all the steam generators tubes in service in Korea. For example, at the upcoming overhaul period, every steam generator will be subject to the inspections: ECT on 100% of tubes with bobbin probe, and 100% of hot leg tubes and 20% of cold leg tubes with MRPC probe, and on 100% of tubes with profilometry.



(a) Profilometry of sane tube



(b) Profilometry of failed tube

Fig. 4 Profilometry of sane tube and failed tube

CONCLUSIONS

The first steam generator tube failure in Korea occurred at UCN 4 on April 5, 2002 just before the fourth overhaul for refueling. This event has been managed in accordance with the operating procedures developed for a steam generator tube failure and no radioactive materials were released to the environment. However, this event left us many points to consider: upgrade in the inspection technology and the development of a more sensitive leak detection system capable of covering all the operating range, and the improvement of the operating procedures to be able to respond to similar incidents during the cooldown process.

The removed tube and all the previous eddy current examination records were investigated to define the cause of failure. The major cause of failure is pertaining to the longitudinal SCC cracks initially developed in bulge section.

After this event, in order to improve steam generator tube integrity the regulatory body prepared the 'Enhanced Steam Generator Tube Integrity Program' and many of the counter measures have been taken place in Korea.

However, to cope with the potential threat of the unexpected nuclear incidents like UCN 4 tube failure, international cooperation should be strengthened.

REFERENCES

1. "Steam Generator Tube Failures" NUREG/CR-6365, April 1996, USNRC