REGULATORY ACTIVITIES ON STEAM GENERATOR TUBES IN KOREAN NUCLEAR POWER PLANTS

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Abstract

To date 20 nuclear power plants are in operation and 6 plants are construction in Korea. Among these plants Kori unit 1 has been operating commercially for 28 years and replaced their steam generators, having 11.5% plugging rate per steam generator as an average value, to delta 60 ones in 1998. The causes of tube plugging were various: for example, pitting, primary and secondary stress corrosion cracking, sleeve bulging, preventive plugging, and so on. At present major concerns of domestic steam generators are ODSCC and PWSCC in roll transition region, fretting wear in upper support structures, and wear and deformation damage by foreign objects.

In this paper, an overview of operating experiences as well repair histories, integrity assessments, and leakage of steam generator tubes including a SGTR (steam generator tube rupture) accident in Korean nuclear power plants is introduced. Also regulatory activities and strategy on steam generator management are presented.

1. Introduction

20 nuclear power plants are in operation and 6 plants are construction in Korea as shown in table 1. The degradation type of operating steam generator tubes in Korea can be divided to two groups. One is corrosion and the other is wear. At first, corrosive degradations with various types of defects were occurred in Kori units 2 and 3, Yonggwang units 1, 2, 3, 4, and 5, and Ulchin units 1, 2, 3, and 4. Kori unit 2 has experienced denting, secondary side stress corrosion cracking at the top of tube-sheet, pitting, wear at anti-vibration bars, volumetric defects, and cracking at the U-bend area and Yonggwang units 1, 2 have experienced wear at anti-vibration bars and secondary side stress corrosion cracking at the top of tube-sheet (maybe not defects). Ulchin units 1 and 2 have suffered from primary water stress corrosion cracking at roll transitions. Secondly, the structural wear defects which occurred by the contact of between tube and upper support structures were detected Kori units 2, 3, and 4, Yonggwang units 1, 2, 3,

4, 5, and 6, and Ulchin units 3 and 4. Wear defects by foreign materials induced into steam generators were also detected in most domestic steam generators. In addition, locations of structural wear defects are as follows; tube/anti-vibration bar of Westinghouse F type steam generators and tube/vertical strip, tube/batwing, and tube/egg-crate of OPR(optimized power reactor)-1000 steam generators. The other hands, locations of wear defects by foreign materials are mainly on the tube-sheet and the flow distribution plate. Wear defects by foreign materials is a degradation mechanism that can result in tube leak accidents and unexpected defects in early operation and during normal operation. Table 2 and 3 shows the status of tube plugging and major causes of tube plugging and tube sleeving of steam generator in KNPPs (Korean nuclear power plants) up to April 2006 respectively.

Table 1 Status of nuclear power plants in Korea

Units		Reactor Type	Capacity (MW)	Project Management	NSSS Supplier	A/E	Commercial Operating Date
Kori Div.	#1	PWR	587	W/H	W/H	Gilbert	Apr. 1978
	#2		650	W/H		Gilbert	July 1983
	#3		950	KHNP		Bechtel/KOPEC	Sept. 1985
	#4		950	KHNP		Bechtel/KOPEC	Apr. 1986
Shin Kori Div. (under construction)	#1	PWR	1000	KHNP	DooSan	KOPEC	Dec. 2010
	#2		1000		DooSan	KOPEC	Dec. 2011
	#3		1400		DooSan	KOPEC	Sept. 2011
	#4		1400		DooSan	KOPEC	Sept. 2011
Wolsong Div.	#1	PHWR	679	AECL	AECL	AECL	Apr. 1983
	#2		700	KHNP	AECL/HanJung	AECL/KOPEC	June 1997
	#3		700	KHNP	AECL/HanJung	AECL/KOPEC	July 1998
	#4		700	KHNP	AECL/HanJung	AECL/KOPEC	Sept. 1999
Shin Wolsong Div. (under construction)	#1	PWR	1000	KHNP	DooSan	KOPEC	Mar. 2011
	#2		1000		DooSan	KOPEC	Mar. 2012
Yonggwang Div.	#1	PWR	950	KHNP	W/H	Bechtel/KOPEC	Aug. 1986
	#2		950		W/H	Bechtel/KOPEC	June 1987
	#3		1000		HanJung/CE	KOPEC/S & L	Mar. 1995
	#4		1000		HanJung/CE	KOPEC/S & L	Jan. 1996
	#5		1000		DooSan/WEC	KOPEC/S & L	May 2002
	#6		1000		DooSan/WEC	KOPEC/S & L	Dec. 2002
Ulchin Div.	#1	PWR	950	KHNP	Framatome	Framatome	Sept. 1988
	#2		950		Framatome	Framatome	Sept. 1989
	#3		1000		HanJung/CE	KOPEC/S & L	Aug. 1998
	#4		1000		HanJung/CE	KOPEC/S & L	Dec. 1999
	#5		1000		DooSan	KOPEC	July 2004
	#6		1000		DooSan	KOPEC	Apr. 2005

Table 2 Status of tube repair of steam generator in KNPPs

(As of April 2006)

Unit No.	Kori1 (PWR) new	Kori1 (PWR) old	Wol-song1 (PHWR)	Kori2 (PWR)	Kori3 (PWR)	Kori4 (PWR)	Young-gwang1 (PWR)	Young-gwang2 (PWR)	Ulchin1 (PWR)	Ulchin2 (PWR)	Young-gwang3 (PWR)	Young-gwang4 (PWR)	Wol-song2 (PHWR)	Wol-song3 (PHWR)	Ulchin3 (PWR)	Ulchin4 (PWR)*	Wol-song4 (PHWR)	Young-gwang5 (PWR)	Young-gwang6 (PWR)	Ulchin5 (PWR)	Ulchin6 (PWR)
Number of tubes per steam generator	4,934	3,388	3,558	5,626	5,626	5,626	5,626	5,626	3,330	3,330	8,214	8,214	3,530	3,530	8,214	8,214	3,530	8,214	8,214	8,340	8,340
Number of plugged tubes (S/G A/B/C)	4 /15*	346 /338	1 /1 /1 /6	215 /142	42 /35 /24	53 /27 /25	73 /24 /12	60 /38 /36	19 /12 /20**	57 /93 / 0	110 /153***	158 /142	-	0 /5 /2 /5	88 /90	109 /104	6 /8 /0 /1	10 /15	20 /13	4 /0	5 /0
Numbers of sleeved tubes (S/G A/B/C)	-	947 /1765	-	-	-	-	-	-	581**** /807 /1,065	943 /1,374 /8	301 /339	293 /219	-	-	-	-	-	-	-	-	-
Plugging rate, % (S/G A/B/C)	0.08 /0.30	11.1 /11.8	0.03 /0.03 /0.03 /0.17	3.82 /2.52	0.75 /0.62 /0.43	0.94 /0.48 /0.44	1.30 /0.43 /0.21	1.07 /0.68 /0.64	1.00 /0.95 /1.38	2.40 /3.80 / 0.01	1.45 /1.99	2.03 /1.81	-	0 /0.14 /0.06 /0.14	1.07 /1.10	1.33 /1.27	0.17 /0.23 /0 /0.03	0.12 /0.18	0.24 /0.16	0.05 /0	0.06 /0
Average plugging rate,%	0.19	11.5	0.06	3.17	0.60	0.62	0.65	0.79	1.11	2.07	1.72	1.92	-	0.08	1.08	1.30	0.11	0.15	0.20	0.02	0.03
Plugging limit, %	10	15	10	10	5	5	5	5	10	10	8	8	6.4	6.4	8	8	6.4	8	8	8	8

* : 15 tubes were plugged prior to operation.

** : Five tubes were pulled out in order to perform metallurgical examination.

*** : Two tubes were pulled out in order to perform metallurgical examination. 33 PLUSS sleeves are equivalent to 1 plug.

**** : 41 PLUSS sleeves are equivalent to 1 plug.

Table 3 Major causes of tube repair of steam generator in KNPPs

(As of April 2006)

Plants	S/G Manufacturer - Model	S/G Tube Materials	No. of Tubes per S/G (ea)	Degradation Type of S/G Tubes							No. of S/G Tubes plugged /sleeved (ea)	Average Plugging Rate of S/G Tubes (%)	Plugging Limit (%)
				CORROSION				WEAR		OTHERS			
				DENTING	PITTING	PWSCC	ODSCC	FRETT-ING	FOREIGN OBJECT				
Kori-1(Old)	WH-51	I-600MA	3,388	O	O	O	O	-	-	O	684/2712	11.5	15
Kori-1(RSG)	WH-Δ60	I-690 TT	4,934	-	-	-	-	O	-	O	19	0.19	10
Kori-2	WH-F	I-600 TT	5,626	O	O	O	O	O	O	O	357	3.17	10
Kori-3	WH-F	I-600 TT	5,626	-	-	O	O	O	O	O	101	0.60	5
Kori-4	WH-F	I-600 TT	5,626	-	-	-	-	O	O	O	105	0.62	5
Yonggwang-1	WH-F	I-600 TT	5,626	-	-	-	O	O	O	O	109	0.65	5
Yonggwang-2	WH-F	I-600 TT	5,626	-	-	-	O	O	O	O	134	0.79	5
Ulchin-1	Framatome-51B	I-600 TT	3,330	-	-	O	-	-	-	-	51/2453	1.11	10
Ulchin-2	Framatome-51B	I-600 TT	3,330	-	-	O	-	-	-	-	150/2325	2.07	10
Wolsong-1	Foster Wheeler	I-800M	3,558	-	-	-	-	-	O	O	9	0.06	10
Yonggwang-3	CE-Sys80	I-600 HTMA	8,214	-	-	O	O	O	-	-	263/640	1.72	8
Yonggwang-4	CE-Sys80	I-600 HTMA	8,214	-	-	O	O	O	-	O	300/512	1.92	8
Wolsong-2	B&W Int'l	I-800M	3,530	-	-	-	-	-	-	-	-	-	6.4
Wolsong-3	B&W Int'l	I-800M	3,530	-	-	-	-	-	-	O	12	0.08	6.4
Ulchin-3	CE-Sys80	I-600 HTMA	8,214	-	-	O	O	O	O	O	178	1.08	8
Wolsong-4	B&W Int'l	I-800M	3,530	-	-	-	-	-	-	O	15	0.11	6.4
Ulchin-4	CE-Sys80	I-600 HTMA	8,214	-	-	O	O	O	-	O	213	1.30	8
Yonggwang-5	CE-Sys80	I-600 HTMA	8,214	-	-	-	O	O	-	O	25	0.15	8
Yonggwang-6	CE-Sys80	I-600 HTMA	8,214	-	-	-	O	O	-	O	33	0.20	8
Ulchin-5	CE-Sys80	I-690 TT	8,340	-	-	-	-	-	-	O	4	0.02	8
Ulchin-6	CE-Sys80	I-690 TT	8,340	-	-	-	-	-	-	O	5	0.03	8

* : No. of Tubes plugged/No. of Tubes sleeved. In Ulchin 1, 41 PLUSS sleeves are equivalent to 1 plug.

** : In Kori 1, old steam generators(WH 51) were replaced with new steam generators(WH Δ60) during planned overhaul in 1998 and restarted September in same year.

2. Overview of Operating Experiences

The degradation status of steam generator tubes in KNPPs was reviewed as follows in detail. Kori unit 1 with WH Δ60 steam generators firstly selected Alloy 690TT materials as the materials of steam generator tube in Korea. After steam generator replacement on Sept. 1998, any corrosion degradation as well stress corrosion cracking have not been detected until now, otherwise in case of structural wear at anti-vibration bar which it has began to occur since 2000, total 66 tubes with wear defects (46 tubes of SG A and 20 tubes of SG B) was detected on March 2004. Of these tubes, 2 tubes with wear depth exceeding 40% of tube wall thickness were plugged.

Kori units 2, 3, and 4, and Yonggwang 1 and 2 with WH type F steam generators used Alloy 600TT as tube materials of steam generator. Kori unit 2 with first type F steam generators (not replacement steam generator) in the world had various corrosion defects such as denting, pitting, secondary side stress corrosion cracking, and so on at the sludge pile-up area on tube-sheet. Those defects mainly resulted from improper water chemistry control in early operating period. Wear degradation that is a typical degradation mechanism of type F steam generators was occurred and propagated gradually and tubes with wear depth exceeding plugging criteria were plugged continuously. In Kori unit 2, 2 tubes of U-bend area with crack like indication respectively were confirmed, but then no more detected. U-bend cracking of type F steam generator in US was reported from Callaway plant. Nevertheless this tube was plugged without the following inspection and pull out examination. In Yonggwang units 1 and 2 with type F steam generators, some secondary side stress corrosion cracks were detected beyond sludge pile-up zone and evaluated to be unique phenomena. The result of next periodic inspection after one cycle operating notes that there was no crack indication in adjacent area to tubes with crack indications. Otherwise axial stress corrosion cracks at tube support confirmed in Seabrook and Braidwood-2 plants recently is considered as a major aging phenomena of steam generator with Alloy 600TT materials. These defects could be detected by using bobbin coil probe basically. For Kori unit 3, UBIB (upper bundle in bundle) examination was performed to confirm the reliability of upper tube support plates. That result shows some blocking of quartre-foil flow holes. Therefore KINS recommended that the examination to detect secondary stress corrosion cracks at tube support plates have to be conducted carefully.

Steam generators of OPR-1000 plants were installed in Yonggwang units 3, 4, 5, and 6 and Ulchin units 3 and 4. These steam generators was scaled down for application of Korean electricity network and their tube materials is Alloy 600HTMA. According to experiences of these steam generators, stress corrosion cracks at the top of tube-sheet of hot-leg side in early operating stage. Tubes with these cracks were mostly located in sludge pile–up area. The number of axial cracks tends to be smaller than that of circumferential cracks and both primary water stress corrosion cracks and secondary side stress corrosion cracks were originated. In addition, wear degradation at batwings and vertical strips that act as anti-vibration bars was gradually propagated and defective tube with wear were largely located near the stay cylinder and tube with defect exceeding plugging criteria were plugged. Also the number of tubes plugged preventively tends to increase since Aug. 2002 due to the application of enhanced plugging criteria. The examination results of tube pull out noted that the cause of crack initiation was deeply related to shape of roll transition by explosive expansion and denting occurred at sludge regions produced during plant operating.

Ulchin units 1 and 2 had type 51B steam generators manufactured by Framatome co. in France. The materials of steam generate tube is Alloy 600TT fabricated by Vallourec co. which is a French tube manufacturing company. These steam generators were suffered from lots of axial primary stress corrosion cracks distributed on all areas of steam generator randomly. Recently minor cracks in cold-leg area began to initiate. So the extent of tube examination was enlarged. On the other hands, there are no wear defects at anti-vibration bar up to now and no other defects. Framatome type 51B steam generators have the unique tube expansion method, so called Kiss DAM roll expansion method. This method consists of two stage of tube expansion. Tube is expanded hydraulically and then secondly expanded by mechanical rolling. Therefore expanded tube has two transition areas. Based on operating experiences, all tubes with such expansion method had axial cracks. Tube pull-out examination of Ulchin units 1 and 2 was reported that carbon content was somewhat higher than that of other Alloy 600TT with nuclear grade and the precipitation shape of carbide particles was look like the streaks of slant rain in the grain. That such a microstructure has lower resistance than microstructure with semi-continuous carbide precipitates along to grain-boundary for primary water stress corrosion cracking is believed. Steam generator C of Ulchin unit 2 had no tube plugged due to cracks as of the present. That reason is that the design of all steam generators is same, but materials fabricated by Huntington co. of USA, that materials is believed having optimized microstructure for stress corrosion cracking, was used for steam generator C tube. The leakage of condenser tube at Ulchin unit 1 occurred twice since November 2003. So secondary side corrosion is possible to be initiated by ingress of seawater flowed into steam generators. Now temporary alternate repair criteria based on operating experiences is being applied and the limit of tube leak rate was reset to 5ℓ/hr for the prevention of large volume of leakage accident such as the leakage of multiple cracked tubes and steam generator tube rupture. Steam generator replacement of Ulchin units 1 and 2 was reviewed and will be planned in the near future. In case of steam generator B of Ulchin unit 2, the rate of defect initiation approaches about 50% of steam generator tubes.

Wolsong unit 1 which is PHWR plant had 4 CANDU-6 steam generators manufactured by Foster Wheeler co. and its tube material was Alloy 800M. Wolsong units 2, 3, and 4 had also steam generators with design same to CANDU-6 ones manufactured by B&W Canada co. and tube material was Alloy 800M. These steam generators had no cracks and wear defects up to now after commercial operation. All steam generators of Wolsong units was without hand-holes. So sludge lancing for these ones was not performed till 2002, but since then, according to KINS recommendation, hand-holes and inspection holes were installed in the rest of units as well Wolsong unit 1 and sludge lancing was conducted in Wolsong unit 1 at the same time.

3. Integrity Assessment of Steam Generator Tubes

As results of implementation of Korean steam generator management program as a topical report approved by KINS, DAs (degradation assessment) of 14 operating plants were conducted for the integrity evaluation of steam generator tubes as of July 2006. As results of DA, predictions on degradation initiation and propagation and recommendations of inspection planning were reasonable relatively. On the other hand, results of CM/OA (condition monitoring/operating assessment) met the performance-based integrity criteria for degradation, but more accurate assessment based on data of their own was required at the present. Above all evaluation procedures related to DA and CM/OA were based on Westinghouse procedures [1~3]. Table 4, 5, and 6 show the summary of degradation assessment for Westinghouse, OPR 1000, and Framatome steam generators respectively. As shown in these tables, main ADM (active degradation mechanism) of WH steam generators were fretting wear at anti-vibration bars as well as SCC (stress corrosion cracking) at the top of tube-sheet and U-bends. In OPR 1000 steam generators, main ADMs were SCC (stress corrosion cracking) at the top of tube-sheet and fretting wear at batwings and vertical strips, while that of Framatome steam generators was axial PWSCC of tube roll transition area. Predictions of defect initiation and propagation as results of DA were well consisted of practical examination results for all steam generators. Table 7 shows an example of CM/OA for KNPP steam generators. As we can see in this table, CM assessment results demonstrate that the structural integrity requirements are to have been met via analysis. Further the OA results demonstrate that the performance criteria will be maintained throughout the next operation.

Table 4 Summary of degradation assessment for WH steam generators

Units	S/G Overview	Operating History	Repair History		Main Issues	Degradation Assessment				Prediction of defect	Inspection Program
			Plugging	Sleeving		ADM	NADM	PDM	NRDM		
Kori-1	WH-△60, Alloy 690 TT	ETA Treatment ('98.10~), KALANS- I (19th O/H~)	15 (Shop) 4 (AVB wear)	-	- MN2004-13 - GL 2004-01 - DB of abnormal Indication - FAC Reduction	-	AVB Wear	TTS SCC U-bend SCC Dent/Ding SCC FM Wear	IGA TS SCC Wastage Fatigue Pitting Impingement	-AVB wear initiation: ↑ propagation:↓	MN2004-13 +SGMP
Kori-2	W-F, Alloy 600 TT	Chem. Clean ('93) ETA Treatment ('00.9~), KALANS- I (17th O/H~)	15 (Shop) 10 (PSI) 20 (leak) 132(AVB wear) 129(SCC) 12 (VOL) 37 (Others)	-	- TTS Dent/SCC - MN2004-13 - GL 2004-01 - Tube Crack(TSP) - DB of abnormal Indication - Sludge Reduction & Control	TTS Dent/SCC U-Bend SCC AVB Wear	Pitting	Axial ODSCC Dent/Ding SCC TTS RT SCC IGA FM Wear	Wastage Fatigue Impingement	-TTS Dent/SCC initiation: limit -U-Bend SCC initiation: very low -AVB Wear initiation: ↑ propagation:↓	MN2004-13 +SGMP
Kori-4	W-F, Alloy 600 TT	ETA Treatment ('01.9~), KALANS-III (14th O/H~)	6 (Shop) 16 (PSI) 55 (AVB wear) 19 (BLG) 7 (VOL)	-	- GL 2004-01 - Tube Crack(TSP) - MN2004-13 - DB of abnormal Indication - Sludge Reduction & Control	AVB Wear	-	TTS SCC U-bend SCC Axial ODSCC Dent/Ding SCC TTS RT SCC IGA FM Wear	Wastage Fatigue Pitting Impingement	-AVB wear initiation: ↑ propagation:↓	MN2004-13 +SGMP
Yong-gwang-1	W-F, Alloy 600 TT	ETA Treatment ('00.12~), KALANS-III (15th O/H~)	11 (Shop) 14 (PSI) 69 (AVB wear) 7 (FDB wear) 1 (SCC) 2 (BLG) 3 (Others)	-	- TTS SCC - Tube Crack(TSP) - MN2004-13 - GL 2004-01 - DB of abnormal Indication - Sludge Reduction & Control	TTS SCC	AVB Wear	U-bend SCC Axial ODSCC Dent/Ding SCC TTS RT SCC IGA FM Wear	Wastage Fatigue Pitting Impingement	-TTS SCC initiation: very low -AVB Wear initiation: ↑ propagation:↓	MN2004-13 +SGMP
Yong-gwang-2	W-F, Alloy 600 TT	ETA Treatment ('00.11~), KALANS-III (14th O/H~)	7 (Shop) 2 (PSI) 89 (AVB wear) 4 (TTS crack) 2 (FM wear) 24 (TE leak) 5 (Others)	-	- TTS ODSCC - Tube Crack(TSP) - MN2004-13 - GL 2004-01 - DB of abnormal Indication - FAC Reduction & Sludge Control	TTS Circ. SCC AVB Wear	FM Wear	TTS Axial ODSCC TTS Circ. ODSCC TTS Axial PWSCC U-Bend SCC Axial ODSCC Dent/Ding SCC TTS RT SCC IGA	Wastage Fatigue Pitting Impingement	-TTS SCC initiation: very low -AVB Wear initiation: ↑ propagation:↓	MN2004-13 +SGMP

Table 5 Summary of degradation assessment for OPR-1000 steam generators

Units	S/G Overview	Operating History	Repair History		Main Issues	Degradation Assessment				Prediction of defect	Inspection Program
			Plugging (*stabilizer)	Sleeving		ADM	NADM	PDM	NRDM		
Yong-gwang-3	CE-Sys80, Alloy 600 HTMA	ETA Treatment (8th Fuel Cycle) ORT (8th Fuel Cycle) 618.8°F→614°F	187(VS,BW wear) 2(Eggcracte wear) 1(U-Bend NQI) 5(TTS VOL) 8(Others) 46(TTS Crack)*	10(TTS ODSCC) 21(TTS IDSCC) 3(TTS OD+ID) 246(Preventive)	- TTS Circ. Crack -Degradation Trend - Water Chemistry Improvement - Lancing Effect - IGA - GL 2004-01 - MN 2004-13 - DB of abnormal Indication	TTS Circ. SCC (ID & OD) VS,BW Wear	FM Wear	TTS Axial ODSCC TTS Axial PWSCC UB Axial ODSCC U-bend SCC Dent/Ding SCC TS EZ SCC IGA	Pitting Wastage Impingement	-TTS ODSCC initiation: ↑ propagation: ? -VS,BW Wear initiation: ↑ propagation:↓	MN2004-13 +SGMP
Yong-gwang-4	CE-Sys80, Alloy 600 HTMA	ETA Treatment (7th Fuel Cycle) ORT (7th Fuel Cycle) 618.8°F→614°F	5(Shop) 250(VS,BW wear) 10(PLP&VOL) 3(Denting) 5(TTS VOL) 3(Others)	34(TTS Circ. IDSCC) 80(TTS Circ. ODSCC) 18(TTS S/N+ VOL) 1(TS Axial) 223(Preventive)	- TTS Circ. Crack -Degradation Trend - Water Chemistry Improvement - Lancing Effect - IGAI - GL 2004-01 - MN 2004-13 - DB of abnormal Indication	TTS Circ. SCC (ID & OD) TTS Axial OD TTS Axial ID VS,BW Wear	FM Wear	UB Axial ODSCC Axial ODSCC U-bend SCC Dent & SCC TS EZ SCC IGA	Pitting	-TTS ODSCC initiation: ↑ propagation: ? -VS,BW Wear initiation: ↑ propagation:↓	MN2004-13 +SGMP
Ulchin-3	CE-Sys80, Alloy 600 HTMA	ETA Treatment (4th Fuel Cycle) ETA effect is not good. (3,4,5,6 cycles →2.01,2.78,3.15, 3.26 ppb Fe)	5(PSI) 9(TTS Circ. ODSCC)* 96(VS,BW wear) 18(FM wear) 20(FM Prev.) 1(Dent) 1(Others) 4(S/N)	-	- TTS Circ. Crack -Degradation Trend - Water Chemistry Improvement - Lancing Effect - IGA - GL 2004-01 - MN 2004-13 - DB of abnormal Indication	TTS Circ. SCC (ID & OD) VS,BW Wear	FM Wear	TTS Axial ODSCC TTS Axial PWSCC UB Axial ODSCC FA Axial ODSCC U-bend SCC Dent & SCC TS EZ SCC IGA	Pitting	-TTS ODSCC initiation: ↑ propagation: ? -VS,BW Wear initiation: ↑ propagation:↓ (somewhat higher)	MN2004-13 +SGMP
Ulchin-4	CE-Sys80, Alloy 600 HTMA	SGTR (2002.4) ETA Treatment (4th Fuel Cycle)	2(PSI) 14(TTS Circ. IDSCC)* 1(TTS Axial ODSCC) 54(VS,BW wear) 123(Prev.) 21(Others)	-	- TTS Circ. Crack -Degradation Trend - Water Chemistry Improvement - Lancing Effect - IGAI - GL 2004-01 - MN 2004-13 - DB of abnormal Indication	TTS Circ. SCC (ID & OD) TTS Axial OD VS,BW Wear	FM Wear	TTS Axial PWSCC UB Axial ODSCC FS Axial ODSCC U-bend SCC Dent/Ding SCC TS EZ SCC IGA	Pitting Wastage Impingement	-TTS ODSCC initiation: limit propagation: ?	MN2004-13 +SGMP

Table 6 Summary of degradation assessment for Framatome steam generators

Units	S/G Overview	Operating History	Repair History		Main Issues	Degradation Assessment				Prediction of defect	Inspection Program
			Plugging (*stabilizer)	Sleeving		ADM	NADM	PDM	NRDM		
Ulchin -1	Framatome -51B, Alloy 600 TT	small tube leak ('96.9, 8th cycle) High pH Oper. (8.8~9.2→ 9.1~9.7, first half of 1993) CECIL (11th Fuel Cycle) Condenser Leak (13~14th Fuel Cycle)	51(TTS RT Axial PWSCC)	2453(TTS RT Axial PWSCC)	- SGMP Review for TTS Crack - Inspection Plan - ECT Reliability - Degradation Trend Improvement - GL 2004-01 - DB of abnormal Indication	TTS RT Axial-PWSCC	-	TTS Circ. PWSCC TTS Axial ODSCC TTS Circ. ODSCC UB Axial ODSCC U-bend SCC Dent/Ding SCC TS EZ SCC IGA AVB Wear FM Wear	Wastage Fatigue Pitting Impingement	-TTS PWSCC initiation: ↑ propagation: ↓	MN2004-13 +SGMP
Ulchin -2	Framatome -51B, Alloy 600 TT	small tube leak ('96.5, 7th cycle) High pH Oper. (8.8~9.2→ 9.0~9.7) CECIL (11th Fuel Cycle)	135(TTS RT Axial PWSCC) 1(Sleeve DTS) 1(PVN+DTS) 2(NQI)	1760(TTS RT Axial PWSCC)	- SGMP Review for TTS Crack - MN 2004-13 - ECT Reliability - SG Replacement - GL 2004-01 - DB of abnormal Indication	TTS RT Axial-PWSCC	-	TTS Circ. PWSCC TTS Axial ODSCC TTS Circ. ODSCC UB Axial ODSCC U-bend SCC Dent/Ding SCC TS EZ SCC IGA AVB Wear FM Wear	Wastage Fatigue Pitting Impingement	-TTS PWSCC initiation: ↑ propagation: ↓	MN2004-13 +SGMP

Table 7 Summary of condition monitoring and operating assessment for KNPP steam generators

Units	Inspection Scope	Repair Status	Bobbin Offset Voltage	CM & OA			Evaluation	Results
				Input Data	CM Criteria	OA Criteria		
Yong-gwang -2	Bobbin 100% MRPC(H) 100% MRPC(C) 20% U-bend R1,R2 TE(SG A,,B) 21% TSP 0.9% TS MRPC 3%	1 plugging (AVB Wear depth:40%TW) Max.wear depth of residual tubes: 39%TW	≤Row10: Normal ≥Row10:S/G A 204, S/G B 222 S/G C 140 ---------------- Total: 566 tubes	Temp: 650°F YS+UTS: 139.07ksi STD: 6.71 ΔP(Performance Criteria): 3813psi EFPD(15th cycle): 472	71.93% TW (for AVB Th:7.08mm, wear length: 0.5")	63.74% TW (for AVB Th:7.08mm, wear length: 0.5)"	40%TW < CM Criteria 39%TW < OA Criteria	Acceptable
Ulchin -2	Bobbin 100% MRPC(H) 100% MRPC(C) 20% U-bend R1,R2 Sleeve 33% Dent >5V 100% TS MRPC 3%	565 Sleeving 11 plugging Max crack length: 7.41mm Max. crack length of residual tubes: 4.62mm Max. crack growth rate during prior cycle: 1.98mm	N/A	Temp: 650°F YS+UTS: 138.81ksi STD: 3.74 ΔP(Performance Criteria): 4233psi EFPD(15th cycle): 488	Not necessary to assess (Max.crack length does not exceed the alternative repair criteria, 13mm)	Not necessary to assess (Max.crack length does not exceed the alternative repair criteria, 13mm)	7.41mm < ARC 6.6mm < ARC (by EOC)	Acceptable
Yong-gwang -3	Bobbin 100% MRPC(H) 100% MRPC(C) 20% U-bend R1,R2 Upper Bundle 1.2% Sleeve 79% TS MRPC 3%	1 sleeving (TTS Circ. PWSCC) 20 plugging (AVB Wear depth: 38%TW, Max. rate: 13%TW/ EFPY) 359(preventive plugging) PDA of TTS PWSCC: 3% Max. VM_L : 0.56Volt PDA of TTS PWSCC at BOC : 31% Max. wear depth of residual tubes: 29%TW	N/A	Temp: 621°F YS+UTS: 129.35ksi STD: 2.691 ΔP(Performance Criteria): 3792psi EFPD(9th cycle): 472	65% PDA (for tube with OD: 0.75",Th: 0.042") V_{THR-L}:1.25Volt V_{CRIT}:5.5Volt (for tube with OD: 0.75",Th: 0.042") 57.2% TW (for VS,BW Th:2", wear length: 2")	49% PDA (for tube with OD: 0.75",Th: 0.042") 56.9% TW (for VS,BW Th:2", wear length: 2")	3% PDA < CM Criteria 0.56Volt < V_{THR-L} Criteria 38% TW < CM Criteria 31% PDA < OA Criteria 29%TW < OA Criteria	Acceptable

4. Experience with leakage forced shutdown

There were 20 times of steam generator tube leakages in Korean nuclear power plants. Of these the number of forced shutdown due to steam generator tube leak was 8 times. Table 8 shows the related information of steam generator tube leakage. Old steam generators of Kori unit 1 with Alloy 600MA as tube materials experienced 6 times of forced shutdown resulted from tube leakages. Their main causes of leakages were pitting and other ones were wear, PWSCC, and ODSCC. Leak rates of Kori unit 1 were values calculated by means of radioactivity analysis for condenser off-gas before June 1993. In Kori unit 1, N-16 radiation monitors were installed and worked since June 1993. Causes of tube leakage of Yonggwang unit 2 and Ulchin unit 4 were the wear by a welding residue as foreign object and PWSCC respectively. Tube leakage of Ulchin unit 4 was the first and the only accident of steam generator tube rupture. Fortunately the accident was occurred not during normal operation but during hot standby for planned shutdown. That cause of tube leakage and actions for this accident were same as follows [4].

Table 8 Experiences of forced outages with steam generator tube leakage

No. of Leakage	Date	No. of leak tube & Leak rate	Cause	Action
Kori unit 1(Retired steam generators)				
1	13th Aug. 1985 (6th fuel cycle)	4 tubes of S/G A cold-leg side Leak rate : 9ℓ/hr	Pitting	Early overhaul (Planned O/H date : 14th Aug.)
2	18th Feb. 1986 (7th fuel cycle)	1 tube of S/G B cold-leg side Leak rate : ~ 21 ℓ/hr	Wear by loose part *Hand-hole structures	Intermediate maintenance (707 hours) (Plugging : 123 tubes)
3	9th Oct. 1986 (7th fuel cycle)	2 tubes of S/G B cold-leg side Leak rate : unidentified	Pitting	Early overhaul (Planned O/H date : 11th Oct.)
4	28th Mar. 1989 (9th fuel cycle)	4 tubes of S/G B cold-leg side *1 tube with sleeve 1 tube of hot-leg side Leak rate : ~ 25ℓ/hr	Pitting	Early overhaul (Planned O/H date : 28th Mar.)
5	16th Mar. 1990 (10th fuel cycle)	7 tubes of S/G B hot-leg side *1 tube with tube-sheet crack Leak rate : 30ℓ/hr	PWSCC(TS)	Intermediate maintenance (344 hours)
6	15th Oct. 1994 (14th fuel cycle)	S/G A&B hot-leg side (A: 4 tubes, B: 6 tubes) Leak rate : 6ℓ/hr	ODSCC	Intermediate maintenance (1321 hours) 01:20 8th Nov. repair started. 02:40 2nd Jan. 1995 operation restarted
Yonggwang unit 2				
1	20th July 1996 (9th fuel cycle)	I thbe of S/G A cold-leg side Leak rate : 9ℓ/hr	Wear by foreign object at the top of tube-sheet	Intermediate maintenance (Planned O/H date : 6th Aug.) Initial leak rate : 0.75ℓ/hr Occurred during 100% full power operation
Ulchin unit 4				
1	5th Apr. 2002 (the end of 3 fuel cycle)	1 tube rupture of S/G #2 hot-leg side Leak rate : 556.3 gpm	IGA/PWSCC	Occurred during hot standby for planned shutdown (10th Apr. Planned O/H started) 3 tubes pulled out for metallurgical exam.

On April 5, 2002, a single tube in one of two steam generators at Ulchin unit 4 (UCN 4) was failed during the shutdown. This failure is tube-specific and not generic [5]. The failed tube was identified as the row 14, column 38 tube of steam generator #2, in which no sludge had piled up. Observation of inside of the failed tube (R14C38) confirmed that the tube had been ruptured circumferentially at the location of about 75mm above the top of tube-sheet. The ruptured tube was broken off 10mm apart from the upper remaining tube after the rupture. Axial crack with fish mouth opening shape was also observed from about 3mm to 78mm above the top of tube-sheet, the upper end of which was connected to the upper circumferential crack (ruptured). In addition, another circumferential crack connected to the lower end of the axial crack was found between about 3mm to 10mm above the top of tube-sheet. Figure 1 shows the failed tube of UCN 4.

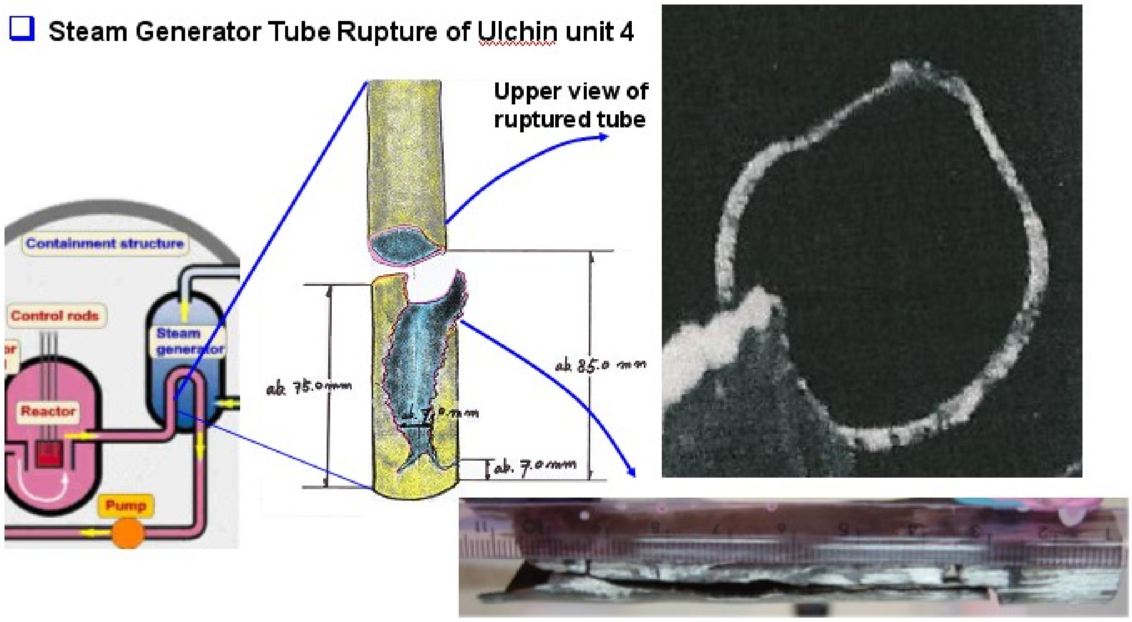

Figure 1 Failed tube of Ulchin unit 4

The investigation on the cause of failure was conducted in two approaches: the metallurgical examination and reevaluation of the eddy current records of the failed tube were performed. 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^{o} against the horizontal direction. This indicates that the circumferential severance developed after the longitudinal failure occurred as the secondary effect. 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 PWSCC with minor indications of IGA 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 the 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 was 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 Alloy 600 HTMA. From this metallography, it was difficult to conclude that the material of failed tube is susceptible to stress corrosion cracking. On the other hand, from the revaluation process, it was concluded that the difference in the signals obtained from the PSI, the first ISI, and the second ISI could be distinguished only if we scrutinize those signals. 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. 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 Figure 2.

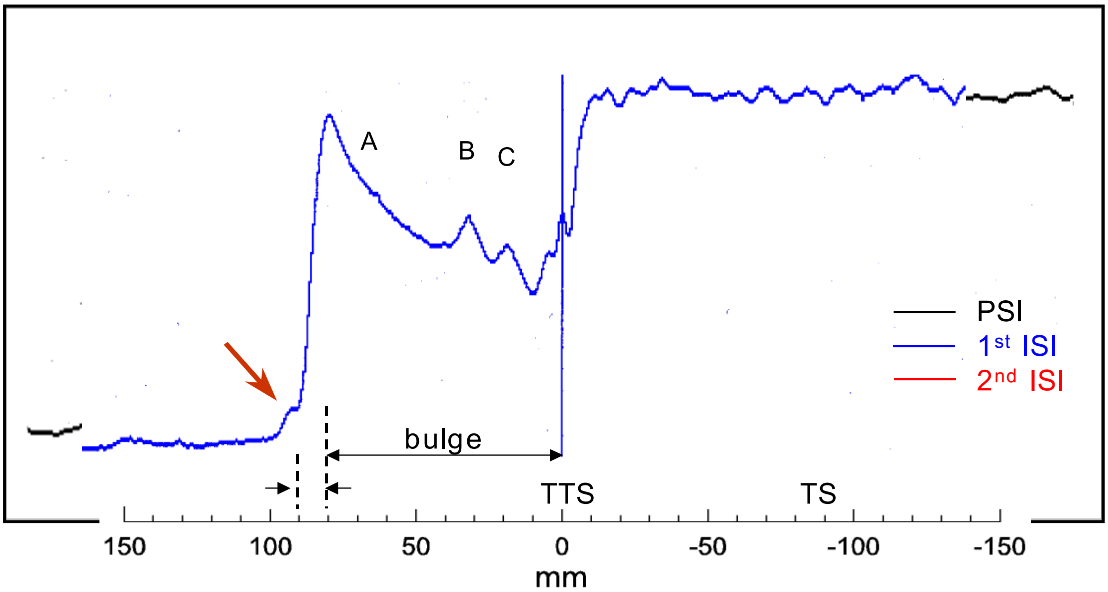

Figure 2 Changes in profile between the PSI, the first ISI, and the second ISI.

The KINS required the overall improvement in the integrity of steam generator tube based on the defense-in-depth concept. The first concern was whether the cause of failure is generic or not. 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 failure during cool-down process at the reactor hot shutdown condition
- No noticeable indication in previous inspections in bobbin nor in MRPC signals
- Rapid progress in SCC through the tube wall

In order to demonstrate that the failure is due to a specific problem and not a generic issue, the KHNP performed extensive inspections on the entire steam generator tubes of UCN 4 and found that the peculiarity of the failed tube was in the longitudinal SCC cracks developed in bulge section. The KHNP also found that such characteristic could be identified with a profilometry that shows the profile with intermediate over expansion as shown in Figure 3. The conclusion from the examination of pulled tube is that the crack began to develop at the bulged section in the longitudinal direction and propagated at high growth rate enough to penetrate the tube wall in three years of operation.

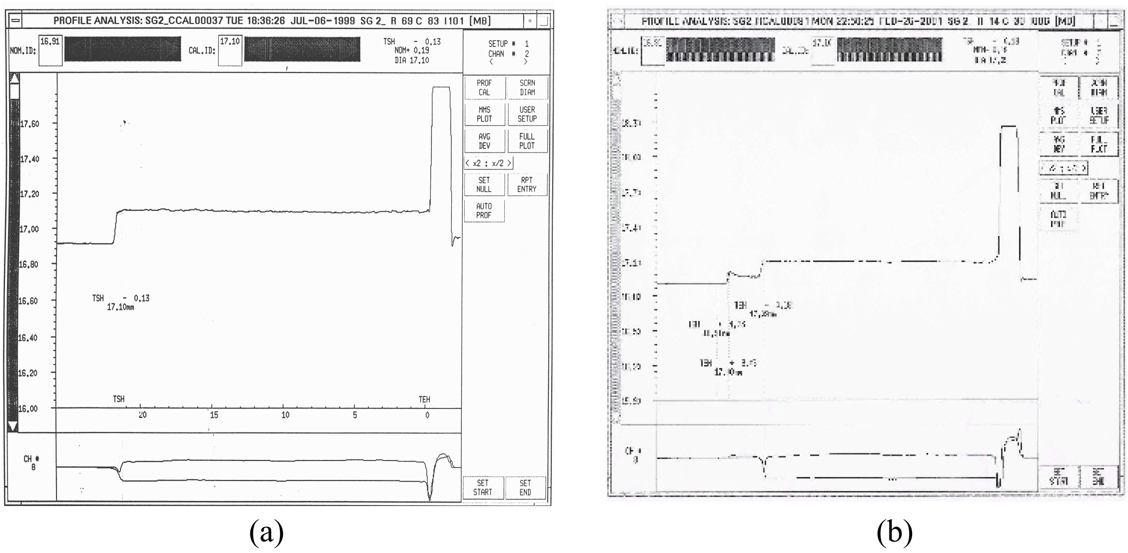

Figure 3 Profilometry of (a) sane tube and (b) profilometry of failed tube

The second concern was whether all the other tubes are exempted from the likelihood of similar failure. 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 KHNP performed also profilometry on the full coverage of the tubes and concluded that the tube having the same characteristic as the failed tube does not exist in UCN 4 steam generators.

The third concern was whether in case of tube leak the monitoring systems are 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 provide a good response to rapidly increasing leakage during reactor shut down, the warning thresholds were lowered in radiation monitor of condenser vacuum system and steam generator blow-down line and the frequency of chemical sampling increased.

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

In the past, the steam generator tubes had no weld points except the seal weld between the tube and bottom of tube sheet, the inspection was in place from the PSI. But since the original cause considered that bulge existed in the failed tube probably made during manufacturing process promoted the development of SCC, the nondestructive examination was enhanced from this point. Once a steam generator is in service, the in-service inspection is the most effective way to prevent the steam generator tube failure. So KINS requested the augmented inspection not only on the concerned steam generators but also on all the steam generators in service in Korea. According to enhanced inspection strategy, every steam generator has been subject to the augmented inspections up to date: ECT on 100% of tubes with bobbin probe, and 100% of hot leg tubes and 20% of cold leg tubes with MRPC probe and profile evaluation on 100% of tubes at a time.

5. References

[1] "Steam Generator Program Guidelines" NEI 97-06 Rev. 1, Nov. 1999, NEI

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[3] "Westinghouse Steam Generator Integrity Tool - Rev. 2" Dec. 2002, Westinghouse

[4] "Safety Review on Recent Steam Generator Tube Failure in Korea and Lessons Learned" Proc. of the TM on SG Problems, Repair and Replacement, Prague Czech, Feb. 2003, IAEA

[5] "Steam Generator Tube Failures" NUREG/CR-6365, April 1996, USNRC