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Root cause of thermal sleeve loosening in optimized power reactor 1000 unit 5 and 6 Part (I)
– A theoretical approach to the root cause and probabilistic revision of acceptance criterion at explosive expansion –

Sang-Gyu Lim, Sung-Yeop Jung and Sang-Nyung Kim*

Kyunghee University1 Seocheon-dong, Giheung-Gu, Youngin-si, Gyunggi-do, Korea

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Abstract

Four of safety injection (SI) nozzles in a 1000 MWe-class Optimized Power Reactor (OPR-1000) are fitted with thermal sleeves (T/S) to alleviate thermal fatigue. Thermal sleeves in #3 and #4 of Younggwang (YGN) & Ulchin (UCN) nuclear power plant are manufactured out of Inconel-600 and fitted solidly without any problem, whereas YGN and UCN in #5 and #6, also fitted with thermal sleeves made of Inconel-690 for increased corrosion resistance, experienced a loosening of thermal sleeves except T/S of YGN #5-1A.

To identify the root cause of T/S loosening, three suspected causes were analyzed: (1) the shear force of flow on the T/S when the safety SI nozzle was in operation, (2) the differences between Inconel-600 and Inconel-690 in terms of physical and chemical properties (notably the thermal expansion coefficient), and (3) the positioning error in explosive expansion of the T/S as well as the asymmetric expansion of T/S. It was confirmed that none of the three suspected causes could be considered as the root cause.

However, after reviewing the design change history from the Palo Verde nuclear power plant to YGN and UCN #3,4 and #5,6, it was realized that the two stage design modifications (in terms of groove depth & material) made an additional explosive energy required by 172% in aggregate, but the amount of gunpowder and the explosive expansion method were the same as before, resulting in insufficient explosive force that led to poor thermal sleeve expansion. T/S measurement data and rubbing copies also support this conclusion. And the T/S loosening was also attributable to lenient quality control before and after fitting the T/S that resulted in significant uncertainty. In addition, it is our judgment that the acceptance criterion applicable to T/S fitting was not strict enough, failing to single out thermal sleeves that were not expanded sufficiently. Lastly, the acceptance criterion was scientifically revised to incorporate the thinning effect and inherent uncertainties of measurements.

Keywords: Thermal sleeve; Explosive expansion; Required energy; Acceptance criteria; Quality control

1. Introduction

Yonggwang nuclear power plant (YGN) #5 & #6 fitted with four thermal sleeves (T/S) is a 1000MWe-class Optimized Power Reactor (OPR-1000) that went into commercial operation in 2002. During scheduled preventative maintenance on OPR YGN #5 in April, 2003, three of the four T/Ss installed on the SI nozzles were found to be loosened and separated. Then, during the scheduled preventative maintenance on OPR YGN #6 in November of the same year, all four T/Ss in the reactor were found to be loosened and removed. Furthermore, nearly all of the T/Ss in Ulchin (UCN) #5 were found to be loosened and those in UCN #6 were removed as they were suspected of being loosened during pilot operation.

T/Ss in OPR #5 & #6 in YGN and UCN (hereinafter referred to as 'OPR 5 & 6') were all loosened or separated, but OPR #3 & #4 in the same power plants

*Corresponding author. Tel.: +82 31 201 2564, Fax.: +82 31 204 2564
E-mail address: snkim@khu.ac.kr
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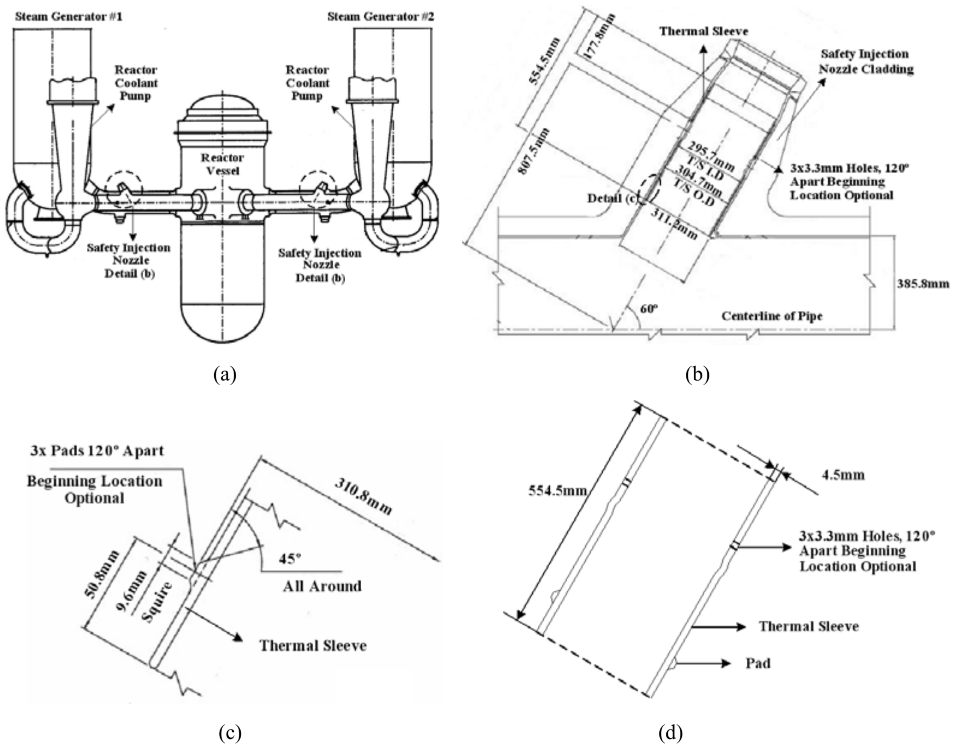

Fig. 1. Configuration of thermal sleeve and design specification: (a) General arrangement of OPR, (b) SI nozzle and thermal sleeve, (c) thermal sleeve pads, (d) Detailed drawing of thermal sleeve.

(hereinafter referred to as 'OPR 3 & 4') have been operating continuously without any failure to date. In addition, T/Ss in OPR 5 & 6 were all loosened or separated during pilot operation. However, the T/S in YGN #5-1A (each of T/Ss is given a number such as 1A, 1B, 2A, 2B) was removed despite not experiencing any trouble. Many experts have suggested a variety of probable causes for the T/S loosening, but they have failed as yet to provide any definitive answer to date.

Therefore, theoretical and experimental studies were performed to uncover the root cause of T/S loosening in OPR 5 & 6. This paper (PART I) focuses on the theoretical approach to the root cause and on the probabilistic revision of acceptance criterion at explosive expansion. An experimental study was performed by flow-induced vibration test and its results will be treated in the part II paper.

2. Thermal sleeve overview

2.1 Configuration and functions

Four T/Ss were installed with one T/S fitted in each inlet of a safety injection (SI) nozzle to alleviate thermal fatigue and stress from low-temperature SI water (minimum 4^{o}C). Each T/S was fitted from the inside of the SI nozzle by explosive expansion. The T/Ss fitted in OPR 3 & 4 are manufactured of Inconel-600 by Doosan Heavy Industries, while the material of T/S in OPR 5 & 6 was changed to Inconel-690 for enhanced corrosion resistance by the same company.

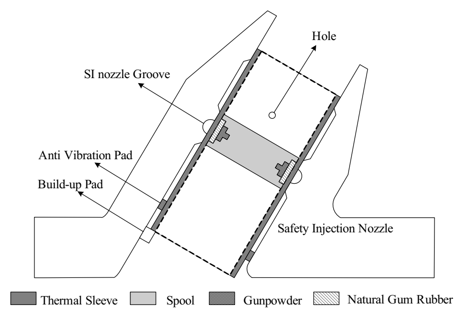

Fig. 2. Schematic drawing of explosion expansion.

After experiencing T/S loosening, T/S of UCN #5 at the bottom of SI nozzle inside three build-up pads was welded for each T/S to prevent from loosening.

2.2 Installation of T/S

T/Ss were installed by explosion expansion method that was used to manufacture T/S in the Bechtel-CE type of nuclear power plants. Before explosion, SI nozzle cladding and T/S are manufactured. Then, as shown in Fig. 2, gunpowder and natural gum rubber are filled in the spool. And then, T/S and spool are set in SI nozzle. When the preparation is finished, T/S is expanded by explosive energy of gunpowder.

Lastly, after the explosion, the inside diameter of the expanded area (Groove) is measured per each position. And T/S fitting is checked according to the acceptance criterion [1].

2.3 Inspection of loosened T/S

The T/Ss loosened out of place and the SI nozzles in YGN 5 & 6 and UCN 5 were inspected. The inspections were performed as follows.

First, the anti-vibration pad installed at the bottom of the T/S seemed noticeably worn away by the pipe lining. At the bottom of the SI nozzle inside there were three circumferential dimples which may have been formed by T/S vibration.

The depths of dimples were more than the clad thickness of SI nozzle lining.

Second, the upper part of the T/S revealed signs of wear over a significant length and its cylindrical portion that was also closed inward to a considerably equal degree, indicating that the surrounding pipe and the T/S were subject to fretting wear, and the T/S diameter crimped by vibration. In addition, a dent was formed in the upper part of the T/S as if it had been knocked against a round pole. The resistance temperature detector (RTD) tap in the cold leg of reactor coolant system (RCS) was bent at two locations, which is believed to have been caused when the T/S hit structural members after it had become loosened. Given the findings, it is believed that the edge of the T/S became worn and deformed as a result of vibration.

Third, T/Ss in UCN 5, restricted by build-up pad as an ad-hoc remedy, cut the build-up pad sharply and almost loosened. This meant that the T/S experienced severe vibration and rotation.

Table 1. Comparison of Inconel-690 & Inconel-600 in terms of thermal expansion coefficient [2].

Components	Materials	Temp (°C)	Instant of Thermal Expansion Coefficient $\alpha_I (1/°C\times 10^{-6})$
OPR 5 & 6	Inconel-690	21	13.92
		93	14.33
		149	14.66
		204	14.91
		260	15.11
		315	15.36
OPR 3 & 4	Inconel -600	21	12.17
		93	13.50
		149	14.22
		204	14.73
		260	15.12
		315	15.38

3. Analysis of the root cause of T/S loosening

3.1 T/S loosening by safety injection flow

The possibility that the T/S became loosened by leakage-flow-induced vibration (LFIV) during SI operation was analyzed. LFIV test was performed by a 1/5th scale prototype. As a result, the amplitude of vibration was not greater than the background vibration of the test loop induced by the pump. As a matter of fact, there was no noticeable vibration when the T/S vibration was observed visually, which indicates that the T/S did not vibrate to a detrimental extent. Hence, the pressure drop actually impacting the T/S was not strong enough to induced T/S vibration.

In addition, given that the T/Ss in OPR 5 & 6 all became loosened in the early operational stage, the SI nozzles were operated 2 to 3 times at best and the flow rate was just 5m/s. It is difficult to believe that the T/Ss became loosened due to excessive vibration induced by SI flow. Therefore, we concluded that LFIV did not cause the OPR T/S to become loosened. More detailed results of the test will be published in the part II paper.

3.2 Difference between inconel-600 and inconel-690 in terms of physical properties

As the loosening of the T/S occurred after the material was changed from Inconel-600 to Inconel-690, the physical differences between the two grades, especially the thermal expansion coefficient, were naturally highly suspect. We can calculate amount of thermal expansion in Inconel-690 and Inconel-600. The radial thermal expansion of T/S is,

$$\delta = \alpha \Delta T R_S \quad (1)$$

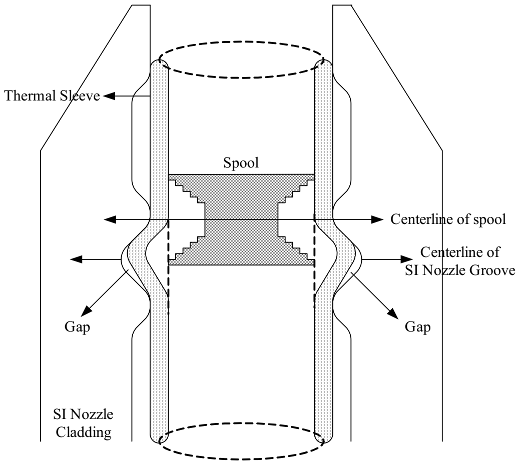

Fig. 3. Asymmetric expansion of T/S.

So, the amount of thermal expansion in Inconel-600 is,

$$15.25\times10^{-6}\frac{1}{°C}\times(296\text{-}4)°C\times152.4\text{mm}=0.6786\text{mm} \quad (2)$$

And the amount of thermal expansion in Inconel-600 is,

$$15.27\times10^{-6}\frac{1}{°C}\times(296\text{-}4)°C\times152.4\text{mm}=0.6795\text{mm} \quad (3)$$

As shown, the difference of thermal expansion between Inconel-690 and Inconel-600 is approximately 0.001mm.

Consequently, it was determined that the differences between the two grades were too minor (5~10%) to be of any probable cause.

3.3 T/S positioning error and asymmetric T/S expansion

The T/S is fitted either by welding or explosive expansion. The explosive expansion method has been used for all OPR. Therefore, it was confirmed whether there had been any error in the explosive expansion of the T/S. If the T/S is expanded by explosion while the center-lines of the SI nozzle and spool are not properly aligned with each other, the T/S expands asymmetrically and consequently does not fit completely. Additionally, if a T/S is exposed in the RCS direction excessively, as it is not properly positioned during explosive expansion, the T/S fits poorly and becomes highly vulnerable to flow-induced vibration (FIV) as well (Refer to Fig. 3).

Therefore, the distance between the edges of the T/S that was forcibly removed from UCN #6-2A and the groove center-line was measured and then compared with the design data to check if the T/S was expanded asymmetrically. The measurement confirmed that the T/S expanded properly. In addition, inspection of the rubbing copy of the T/S groove also revealed that expansion occurred completely symmetrically.

3.4 Analysis of design change history

Lastly, we reviewed the history of T/S loosening in the Palo Verde and San Onfre plants designed by CE and known to have experienced similar T/S loosening incidents and derived significant information. The two power plants where the T/S was fitted by the same explosive expansion method as the one used for OPR experienced similar incidents of T/S loosening. Therefore, CE recommended that the T/S groove depth be increased from 2.48 mm to 3.3 mm. In line with this recommendation, the T/S groove depth in OPR 3 & 4 was increased to 3.3 mm and the same amount of gunpowder and the same explosive expansion method as the one used in Palo Verde were used to fit the T/Ss. As a result, they have been in service to date without any trouble. After then, the material of T/S in OPR 5 & 6 was changed to Inconel-690 for increased corrosion resistance. As a result, all T/Ss therein (except for the one used for 1 A) were either loosened or removed as they were suspected of loosening.

Overall, the T/S design was modified two times, but the amount of gunpowder and the explosion method were all the same for both the Palo Verde power plant and OPR 3, 4, 5 and 6.

Therefore, the adequacy of explosion energy required for T/S expansion in the two design modifications was analyzed. Accordingly, the amount of additional energy required for deformation of the T/S was calculated.

In case of elastic deformation, the amounts of energy required are in proportion to ε^2. They are in proportion to ε as well in case of plastic deformation. Therefore, as the groove depth was increased from 2.48 mm to 3.3 mm, the explosion energy additionally required increased by elastic deformation,

$$\frac{[(3.3)^2\text{-}(2.48)^2]}{(2.48)^2}=0.77 \quad (4)$$

And by plastic deformation,

$$\frac{3.3\text{-}2.48}{2.48} = 0.33 \quad (5)$$

In other words, an additional explosion energy of anywhere from 33% to 77% was required.

In addition, more energy was required for the T/S in YGN and UCN 5 & 6 given the T/S material change. Four sample plates per two thicknesses each material (Inconel-600 and Inconel-690) were tested their bending strength. As shown in Table 2, the test revealed that additional explosion energy of up to 54% from stress strength was required.

$$\frac{72.50\text{-}47.08}{47.08} = 0.54 \quad (6)$$

$$\frac{66.09\text{-}53.23}{53.23} = 0.24 \quad (7)$$

To sum up, it is estimated that an additional energy of up to,

Table 2. Inonel-600 vs. Inconel-690 in terms of bending strength [4].

Classification			3mm-Bending Strength (ksi)
Inconel-600	12mm-Thickness Sample	1	56.10
		2	60.16
		3	60.57
		Avg.	58.94
	4.5mm-Thickness Sample	1	47.08
		2	53.23
		3	52.43
		Avg.	50.91
Inconel-690	12mm-Thickness Sample	1	90.55
		2	94.33
		3	94.72
		Avg.	93.20
	4.5mm-Thickness Sample	1	72.43
		2	72.50
		3	66.09
		Avg.	70.34

Table 3. Analysis of T/S elements in YGN #5-1A & UCN #6-2A [XRD INCA].

Classification	Ingredients		
	Fe	Ni	Cr
Inconel-600	6.68~9.21	74.9~75.9	15.0~16.3
Inconel-690	9.86~10.9	59.4~59.6	29.4~29.47
Sample of YGN #5-1A	10.40	59.00	30.60
Sample of UCN #6-2A	9.91	59.16	30.93
Requirements for Ingredients (Inconel-690)	7.0~11.0	58.0>	27.0~31.0

$$[(1.77)\times(1.53)\text{-}1.0]\times 100 = 172\% \quad (8)$$

$$[(1.33)\times(1.24)\text{-}1.0]\times 100 = 65\% \quad (9)$$

is required due to the two design changes, which means that an explosion energy was required as much as 2.7 times greater than that in the (initial design of the) Palo Verde plant.

Fortunately, it is believed that the additional explosion energy requirement envisioned in the 1st design modification (From Palo Verde to OPR 3 & 4) was compensated by the margin of gunpowder explosion, which is indicated by the fact that the T/Ss in OPR 3 & 4 have been in service without any trouble to date. However, in case of OPR 5 & 6, the explosion energy design requirement remained the same while the groove depth as well as the T/S material was modified. Hence, it seems that the T/S was poorly fitted and loosened in the end, as the expansion energy requirement was greater than the explosion energy delivered by the gunpowder.

3.5 Why did the T/S in YGN #5-1A not become loosened?

We came to suspect that YGN #5-1A T/S, the only T/S that did not become loosened among the T/Ss of OPR 5 & 6, might be made of a different material as the T/Ss made of Inconel-600 in OPR 3 & 4 were not loosened while most of the T/Ss made of Inconel-690 in OPR 5 & 6 became loosened. Therefore, samples were taken from T/S of YGN #5-1A and T/S of UCN #6-2A and their metallic compositions analyzed to confirm whether the T/Ss were made of Inconel-690 and compliant with specifications.

As shown in Table 2 (the percentages were compensated as much as the ratio of impurities such as $CaCo_3$ and contaminants in the T/S.), T/S of YGN #5-1A was confirmed to be made of Inconel-690 and the Inconel-690 used was compliant with design specifications.

Then, how can we explain that the T/S in YGN #5-1A did not become loosened? This can be accounted for by statistical probability. The explosion energy and the T/S fitting energy requirement must not be universal, but distributed within a certain envelope in the neighborhood of the mean value. Statistically, the T/S rarely loosens as the probability of T/S loosening is very low if the explosion energy delivered by gunpowder is far greater than the T/S fitting energy requirement in Fig. 4.

Table 4. Comparison of Groove Depth Between YGN #5-1A and UCN #6-2A.

Position of Measurements	YGN #5-1A		UCN #6-2A
	Inside	Outside	Outside
1	3.6	NA	3.4
2	3.6	3.7	3.49
3	3.6	NA	3.47
4	3.8	3.7	3.40
5	3.7	NA	3.15
6	3.8	3.7	3.46
7	3.8	3.7	3.43

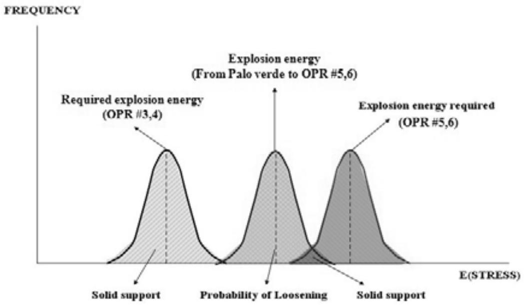

Fig. 4. Probability analysis of T/S expansion energy.

However, in case of OPR 5 & 6 where the T/S material was changed, the explosion energy delivered by gunpowder is somewhat smaller than the energy required for fitting the T/S solidly.

Therefore, most of the T/Ss are likely to become loosened. In other words, T/Ss (in OPR 5 & 6) whose expansion energy requirement has greater probable distribution than the explosion energy of gunpowder are more prone to loosen, while T/Ss (in YGN #5-1A) whose case is the other way around rarely become loosened.

Hence, most of the T/Ss in OPR 5 & 6 become loosened except for YGN #5-1A. This theory can provide a clear account of the T/S loosening mechanism that other mechanisms failed to explain to date. Furthermore, this theory is all the more convincing, as in the case of OPR 3 & 4 where only the grove depth was changed (2.48 mm → 3.3 mm), an additional explosion energy requirement was compensated by the margin of gunpowder and the T/Ss thereof have been in service without any trouble to date.

In order to prove this, a replica of YGN #5-1A T/S and UCN #6-2A T/S was compared. As shown in Table 4, the depth of T/S groove in YGN #5-1A was greater than UCN #6-2A even with the measurement errors. It means that YGN #5-1A corresponds to the rare probability case in Fig. 4.

Table 5. Measurements of thinning effect.

Position of Measurement	Components			
	Sample of UC #6-2A			
	1	2	3	Avg.
A	4.25	4.27	4.26	4.26
B	4.06	4.10	4.11	4.09
C	4.06	4.07	4.06	4.06
D	4.15	4.13	4.10	4.12
E	4.26	4.25	4.25	4.25

3.6 Analysis of acceptance criterion and thinning effect

After explosive expansion, the T/S fitting is checked according to the acceptance criterion. Given that most of the T/Ss accepted in OPR 5 & 6 have become loosened, it is now deemed that there is some problem with the T/S acceptance criterion. The current T/S acceptance criterion is $G-(D+2T)<0.005G$ [5] and T/Ss are required to satisfy the requirement of $0.995G<(D+2T)$, which means that, with all the nominal values of the other dimensions, the T/S is accepted if the gap between the T/S and SI nozzle is within 0.5% of the SI nozzle diameter after explosive expansion. But, we have to point out two flaws inherent in such an acceptance criterion.

First, the acceptance criterion described means that a gap between the T/S and SI nozzle within 0.5% of the SI nozzle diameter is tolerated unless there is any uncertainty in the inner diameters of the SI nozzle groove (G), T/S groove (D) and the T/S thickness (T) as shown in Table 6. If this is the case, the T/S and SI nozzle are bound to be unfixed and vibrate when subjected to minute external forces.

In conclusion, the acceptance criterion described does not tolerate any gap between the T/S and SI nozzle but rather tolerates the manufacturing and measurement errors of the T/S and SI nozzle. No gap should be tolerated to ensure that the T/S and SI nozzle are fitted together securely.

Second, this overlooks the fact that T/S thickness is reduced as T/S length is increased during explosive expansion. The thinning is due to both circumferential and longitudinal length increase. The T/S thinning effect was evaluated as shown in Fig. 5. Therefore, assuming that the original T/S thickness is 4.5 mm, the T/S becomes thinner by 0.1 mm as the longitudinal (arc) length is increased.

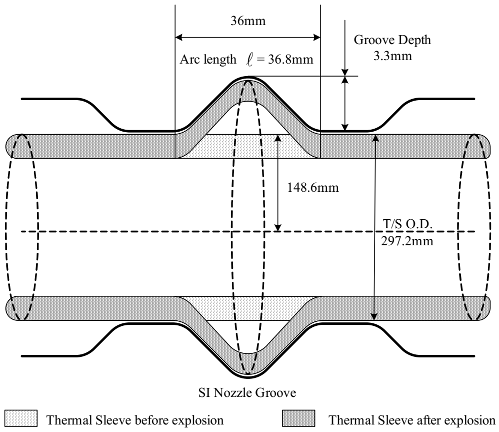

Fig. 5. Schematic drawing of T/S thinning effect.

$$4.5\,\text{mm} - \frac{36\,\text{mm}}{36.8\,\text{mm}} \times 4.5\,\text{mm} = 0.1\,\text{mm} \tag{10}$$

Also, additional thickness reduction by circumferential length increase can be derived as follow.

$$(R + d) \times t = RT \tag{11}$$

$$t = \frac{297.2\text{mm}/2}{(297.2\text{mm}/2) + 3.3\text{mm}} \times 4.5\,\text{mm} = 4.4\,\text{mm} \tag{12}$$

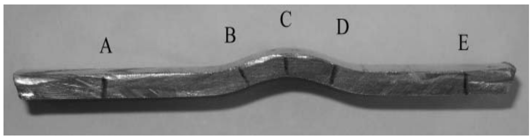

Fig. 6. T/S Sample in UCN #6-2A.

Table 6. Dimensions, theoretical gap and application of acceptance criterion in OPR (P : Pass, F : Fail).

NPP		G	D	T	Status	Theoretical Gap [G-(D+2T)]	Application of AC	
							Old AC=0.005G ≒1.56mm	New AC=-0.001G ≒-0.312mm
YGN #3	1A	311.67	303.48	4.50	Fitted	-0.81	P	P
	1B	311.76	303.21	4.50	〃	-0.45	P	P
	2A	311.68	303.30	4.25	〃	-0.12	P	F
	2B	311.66	302.95	4.25	〃	0.21	P	F
YGN #4	1A	312.10	303.55	4.22	〃	0.11	P	F
	1B	312.13	303.50	4.15	〃	0.33	P	F
	2A	312.18	303.50	4.31	〃	0.06	P	F
	2B	311.82	303.97	4.14	〃	-0.43	P	P
UCN #3	1A	311.80	303.26	4.30	〃	-0.06	P	F
	1B	311.80	303.50	4.29	〃	-0.28	P	F
	2A	311.84	303.45	4.23	〃	-0.07	P	F
	2B	311.83	303.50	4.30	〃	-0.27	P	F
UCN #4	1A	311.69	303.00	4.31	〃	0.07	P	F
	1B	311.74	303.05	4.29	〃	0.11	P	F
	2A	311.75	303.05	4.24	〃	0.22	P	F
	2B	311.66	303.30	4.20	〃	-0.04	P	F
YGN #5	1A	311.68	303.10	4.39	Fitted	-0.20	P	F
	1B	311.74	302.41	4.37	Loosened	0.59	P	F
	2A	311.76	302.40	4.44	〃	0.48	P	F
	2B	311.76	302.56	4.43	〃	0.34	P	F
YGN #6	1A	311.66	302.72	4.44	〃	0.06	P	F
	1B	311.70	302.67	4.38	〃	0.27	P	F
	2A	311.66	302.71	4.44	〃	0.07	P	F
	2B	311.64	303.04	4.47	〃	-0.34	P	P
UCN #5	1A	311.77	303.38	4.30	〃	-0.21	P	F
	1B	311.75	302.59	4.35	〃	0.46	P	F
	2A	311.72	303.07	4.30	〃	0.05	P	F
	2B	311.74	302.68	4.35	〃	0.36	P	F
UCN #6	1A	311.73	303.18	4.35	〃	-0.15	P	F
	1B	311.74	303.16	4.21	〃	0.16	P	F
	2A	311.73	303.13	4.29	〃	0.02	P	F
	2B	311.61	303.20	4.32	〃	-0.23	P	F

Where
R = Thermal Sleeve Outside Diameter
d = Depth of SI nozzle Groove
t = Thermal Sleeve Thickness after explosion
T = Thermal Sleeve Thickness before explosion.

To sum it up, total reduced thickness of T/S is about 0.2 mm.

In order to prove this, we collected the sample of the T/S that was forcefully removed in UCN #6-2A during test operation. And T/S of UCN #6-2A was cut for easy measuring. Then the T/S thickness was measured in 5 places from A to E (Fig. 6). As shown in Table 5, T/S thickness thinning effect corresponds between theoretical derivations and measured. It indicates that even if G-(D+2T)/2 equals zero, a δ (GAP) of as much as the decrease in T/S thickness is created. In other words, the acceptance criterion described in the above indicates that there is zero gap between the T/S and SI nozzle if G-(D+2T)/2 is zero, but a gap of 0.2 mm is formed effectively as T/S thickness decreases.

Therefore, the acceptance criterion must be revised scientifically in consideration of a decrease in T/S thickness, change in inner diameter of SI nozzle groove, actual measurement of T/S thickness and other statistical analysis of uncertainties, all following explosive expansion to ensure that the T/S is fitted solidly against the SI nozzle.

3.7 Analysis of quality control

As previously mentioned, to appraise T/S fitting according to acceptance criterion, G, D and T were measured before and after explosion. As above, a series of measurement processes related to explosion expansion is called "Quality Control" But lenient quality control means that even if the acceptance criterion is firm, we can't expect to fit the T/S perfectly. Thus, the quality control of T/S was analyzed as follows.

First, SI nozzle diameters, T/S thickness and roundness were measured by two points (0° 180° 90° 270°) before explosion. After explosion, these processes were repeated. Difference of roundness may have occurred of approximately 0.1~0.2 mm because the SI nozzle and T/S were not perfect circles. Thus, dimensions of G, D and T were varied as each measurement point. But, only one dimension was used for acceptance criterion. It means that [G-(D+2T)]/2 is different from point to point.

Table 7. Results of statistical procedure.

Classification		G_N	D_N	T
OPR #3,4,5,6	Mean Value	311.7656	303.1116	4.3222
	Standard Deviation (σ_s)	0.1341	0.3723	0.0955
OPR #3,4 (YG & UC #3,4)	Mean Value	311.8194	303.3481	4.2800
	Standard Deviation (σ_s)	0.1694	0.2629	0.1007
OPR #5,6 (YG & UC #5,6)	Mean Value	311.7119	302.875	4.3644
	Standard Deviation (σ_s)	0.0481	0.3130	0.0701

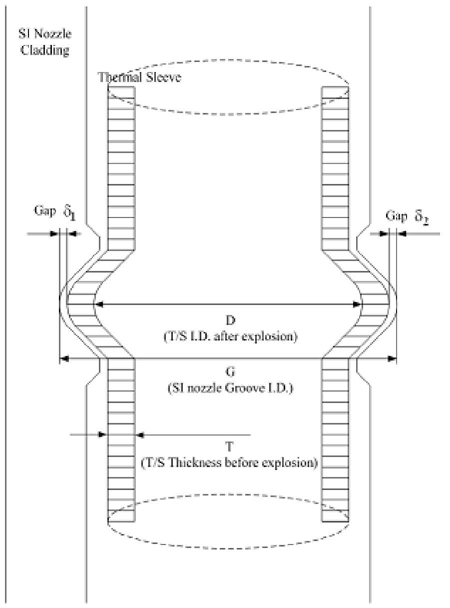

Fig. 7. Schematic of T/S dimensions.

To reduce the uncertainty in the measurement, the location and the number of measurements should be increased. Also the uncertainty should be incorporated into the acceptance criterion as a form of standard deviation based on the probability and confidence level.

Second, on measuring dimensions, to reduce the uncertainty the measuring locations should be coherent before and after explosion because the values might be different depending on the measuring locations.

3.8 Revision of acceptance criterion

Descriptions in the previous sections show that the acceptance criterion must be scientifically revised to incorporate the thinning effect and inherent uncertainties of measurements. Therefore, a statistical methodology was used as follows.

OPR had experimented with manufacturing the T/S 32 times, so the manufactured dimensions (G, D, T) of T/S that were already measured, have a specific distribution. In this section, therefore, statistical estimation was performed from manufactured dimensions of T/S. Before the statistical procedure, however, reasonable theoretical background must be established for a scientific acceptance criterion.

3.8.1 Statistical estimation and confidence interval

Generally, when the numbers of samples are small such as 32 samples of T/S data, 'Student T-Distribution' is very useful. So assume that dimensions of T/S (G, D, T) followed the 'Student T-Distribution'. And in modern applied nuclear industries, most confidence intervals and probabilities are stated at the 95% level.

Therefore, each actual value of dimension is expressed by

$$\text{Nominal Value (Mean value)} \pm N s_s \tag{13}$$

Where, N is multiplication number of standard deviation depending on confidence level.

3.8.2 Theoretical derivation and new acceptance criterion

As shown in fig 7, $\delta_1 + \delta_2$ can be represented as follows.

$$\delta_1 + \delta_2 = G - D - 2T' \tag{14}$$

$$T' = T - S \tag{15}$$

$$\delta_1 + \delta_2 = G - D - 2T + 2S \tag{16}$$

$$\sigma_T = \sqrt{\sigma_{s1}^{\ 2} + \sigma_{s2}^{\ 2} + 4\sigma_{s3}^{\ 2}} \tag{17}$$

To guarantee the solid support of T/S, the confidence interval would be 1.67. Therefore,

$$\delta_1 + \delta_2 \le G_N - (D_N + 2T_N) - 1.67\sigma_T + 2S \tag{18}$$

$$\frac{\delta_1 + \delta_2}{G_N} \le 1 - \frac{(D_N + 2T_N)}{G_N} - \frac{1.67\sigma_T}{G_N} + \frac{2S}{G_N} \tag{19}$$

3.8.3 Application of new acceptance criterion to opr data

If a new acceptance criterion is applied to OPR data, follows are calculated.

$$\sigma_T = 0.4394 \tag{20}$$

$$\delta_1 + \delta_2 \le -0.001G_N = -0.312\,\text{mm} \tag{21}$$

The criterion becomes more strict than old one, therefore almost of the explosion could not pass. There needs the effort to decrease uncertainty.

4. Discussions

If a new acceptance criterion is applied to OPR data, most of the explosion was failed. It may be unreasonable acceptance criterion. The reason is due to strict criteria. However, as shown in Table 7, the strict criteria were generated by the large uncertainty in the diameter (D) of SI Nozzle after explosion rather than the generation methodology. Therefore there needs to be an effort to reduce the diameter uncertainty. To do this, the number of measuring position should be increased. Also if the standard deviation of diameter (D) is calculated based on the data before and after material change(as shown in Table 7) the deviation is considerably reduced. In particular, the deviation before material change is quite small. The reason may be due to the solid support of T/S so that there is no room of diameter variation. However after the material change, T/S is not supported solidly and resulted in large uncertainty of the diameter. Therefore the strict quality control and enough explosive are necessary to reduce the diameter uncertainty and results in the reasonable acceptance criterion.

5. Conclusion and recomendations

We have arrived at the following conclusions after analyzing probable causes of T/S loosening in an OPR and looking for the T/S loosening mechanism:

A. It was ruled out that the T/S's became loosened due to simple SI flow, differences in metallurgical properties of T/S materials, T/S positioning error or asymmetric T/S expansion.

B. It was realized that despite two design revisions, the explosive energy requirement for the T/Ss in OPR 5 & 6 was not properly compensated, resulted in loosely fit T/Ss. In order to be solidly supporting, it is required to increase the explosive energy.

C. Acceptance criterion was not strict enough to discern loosely fit T/Ss. Therefore, acceptance criterion must be scientifically revised, including the T/S thinning effect.

D. After application of new acceptance criterion, most of the T/Ss failed to pass. Therefore, rigid quality control activities are needed.

E. Lenient quality control aggravated the inherent flaws in the acceptance criterion and quality control is not strict enough to minimize the measurement uncertainty. Also, process specification must be reorganized. Rigid quality control should be established to screen out the loose fittings.

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References

[1] J. S. Ryu, Thermal sleeve expansion procedure for P/P, Doosan Heavy Industries, (2000)
[2] Boiler and pressure vessel code-an international code, American Society of Mechanical Engineers, Section Ⅱ, Part-D, (1998) 588.
[3] O. S. Kim, The comparison of properties between inconel-690 and inconel-600, Doosan Heavy Industries, (2004).
[4] C. S. Kong, The report of primary piping mockuptest for SI nozzle thermal sleeve, Doosan Heavy Industries, (2004).
[5] C. S. Kong, Explosive expansion qualification report of primary piping for inconel 690 thermal sleeve material, Doosan Heavy Industries (2003).