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Economic Analysis on Shrunk-on Type Low Pressure Turbine Retrofit

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1. Introduction

There are many degradation mechanisms in vintage nuclear steam turbines. Among them, stress corrosion cracking (SCC) of low pressure turbines (LPTs) is one of the most critical aging issues. In particular, LPTs with shrunk-on type rotors are more susceptible to SCC as cracks can be initiated in the disk keyway regions as well as in bucket attachment areas. The best way to minimize the SCC risks in LPTs is to retrofit original LPTs with new designs which have more reliable structures to combat SCC. As large rotor forging technology became available in the 1980s, the monoblock type rotor which eliminates SCC risk in the disk keyway area became a commercially viable technology to address SCC risk. Other types of LPT rotor technology like welded drum or advanced shrunk-on also evolved to effectively cope with SCC issues. Most designs employed lowered material yield strength and peak dovetail stress in stress concentrated areas. In addition to reducing SCC risks, recent LPTs offer high thermal performance by adopting lager last stage blades (LSBs), so that nuclear power plants (NPPs) can achieve additional output (1~3 percent of unit capacity) through the LPT retrofit.

Many utilities have been replacing old LPTs with the advanced designs which improve not only SCC reliability but thermal performance. However LPT retrofit still requires a substantial capital investment, and the plant owners should perform an economic analysis prior to making a decision on the timing of LPT retrofit.

In Korea, seventy (70) LPTs are being operated at twenty-four (24) nuclear power plants (NPPs). Eight stations (Kori-1~4, Hanbit-1~2, and Hanul-1~2) have already replaced their LPTs. Considering the operation age of remaining LPTs in Korea, the next targets for retrofit will be the twelve (12) shrunk-on type LPTs at four plants (Hanbit-3~4, Hanul-3~4). In this study, we will review the inspection status of shrunk-on type LPTs in Korea, and perform economic analysis on LPT retrofit based on four alternative cases.

2. SSC Issues in LPT

SCC is a prevalent aging mechanism of low pressure turbine rotors. Low alloy material (Ni-Cr-Mo-V) has high material yield strength and stress intensity particularly in the keyway or rim attachment areas. This can cause SCC issues under the wet steam operational environment. There are two major SCC risks in LPTs: SCC in the disk keyway (wheel) and SCC at the rim areas (blade attachments). Considering turbine geometry, it is significant design challenge to eliminate SCC risk in the LPT rim attachment region. However, for the case of SCC concern in the disk keyway area, this can be minimized or eliminated by adopting advanced LPT rotor technology. Currently, there are three types of turbine rotor designs in the nuclear market as follows;

- *Ruggedize: Ruggedized (massive) disks are shrunk-on to the shaft*
- *Monoblock: Disks are machined as integral parts from an integral shaft-disk rotor forging*
- *Welded Drum: Disks are welded at their outer circumference to create a drum-like rotor [1]*

Operating performance of these rotor designs show more reliable performance on SCC issues by eliminating the disk keyway area. Fig. 1 shows SCC concentration areas for historical design shrunk-on type LPT rotors.

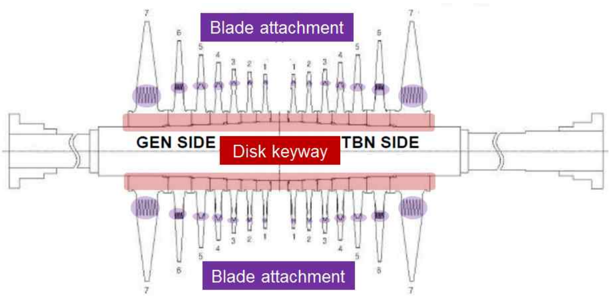

Fig. 1. Structure of shrunk-on type LPT rotor (OPR1000)

SCC in vintage LPT rotors of the shrunk-on type can be minimized through rigorous secondary side chemistry controls. However, it is difficult to avoid. Therefore, it is critical to monitor LPT rotor degradation and to set up a long term maintenance plan including decision points for LPT retrofit based on non-destructive evaluation (NDE) inspection results.

2.1 NDE for Shrunk-on LPT in Korea

Korea Hydro & Nuclear Power (KHNP) has been operating twelve (12) shrunk-on type LPTs in four PWR plants since 1995. Considering the large uncertainty on

SCC risk, those shrunk-on type LPT rotors need to be rigorously inspected during outages.

2.1.1 Inspection interval

PWRs in KHNP have 18-month refueling cycle, and most major maintenance including turbine NDE is performed during outages. Considering the outage period and workload, normally a single turbine section is disassembled each outage. As a result, each turbine section, high pressure turbine (HPT), LPT-1, LPT-2, and LPT-3, is inspected every six years. General Electric (GE), the original equipment manufacturer (OEM) of the OPR1000 type, also recommends a six-year NDE interval for the shrunk-on type LPTs. Currently, KHNP performs NDE for those LPTs every six (6) years since 2008. Table I shows the recently performed NDE schedule.

Table I: NDE status of shrunk-on type LPTs

Unit	LPT 1	LPT 2	LPT 3
Hanbit-3	‘11	‘15	‘11
Hanbit-4	‘14	‘11	‘14
Hanul-3	‘13	‘11	‘14
Hanul-4	‘09	‘11	‘10

2.1.2 Applied technology for SCC inspection

Two typical NDE technologies are used for inspecting SCC in LPTs. For the whole external areas of rotors, magnetic particle testing (MT) is conducted to detect surface or near surface cracks. Ultrasonic testing (UT) is required to detect any internal cracks in the disk keyway area and rim attachment areas for each LPT stage. Advanced UT technology, phased array (PA) UT, has been developed and commercialized in the nuclear industry. With this technology, the inspection time and accuracy of NDE for the disc and bucket dovetail areas have been considerably improved. Table II and Fig. 2 indicate the applied NDE technologies and inspection regions.

Table II: Applied NDE technologies and inspection regions

NDE	Region	Method
MT	All External	-
UT-1	Disc Key, Hub, and Internal	P.E. [1] TOFD [2]
UT-2	Disc/Bucket dovetail	P.A.
UT-3	Dovetail Finger Pin	P.E. TOFD

1 - Pulse-echo Technique
2 - Time of Flight Deflection Technique

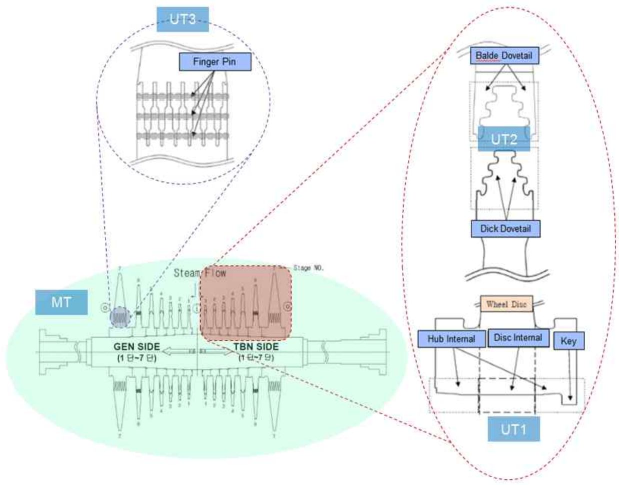

Fig. 2. Applied NDE technology and region

2.1.3 Inspection results

KHNP has been conducting NDE testing for the twelve (12) shrunk-on type PWR LPTs since 2008. No significant SCC cracks have been reported, but most of the inspected LPTs had some pitting indications in stress concentrated areas.

Table III shows one of the UT inspection results (for LPT at Hanbit-3) recently performed NDE in January 2015. The LPTs at Hanbit-3 have an operating history over 150,000 hours since initial operation on March 1st, 1995. It is one of the oldest LPTs among the shrunk-on type LPT fleet in KHNP.

Table III. NDE (UT) results for HB-3 LPT-2 (’15)

(unit: mm)

Location	Stage		Indication		Threshold
			Inlet	Outlet	
Disk Hub Internal	TBN	LP1	-	0.4	1.61
	TBN	LP2	0.2	-	1.35
	GEN		0.3	-	
	TBN	LP5	0.2	-	1.24
	TBN	LP6	0.2	-	1.08
	GEN		**0.7**	-	
Wheel Dovetail	GEN	LP1	-	0.2	1.07
	GEN	LP2	0.6	0.5	1.05
Bucket Dovetail	TBN	LP2	0.3	-	1.50
	GEN		0.3	-	

*Source: ENESG, “Hanbit-3 LPT-C NDE Report,” 2014.

Several pitting indications have been detected (e.g. disk hub internal, wheel and bucket dovetail). Threshold sizes to indicate ‘crack initiation’ have been calculated for each stage of the LPTs. Generally, indications below the threshold size do not cause concern relative to SCC issues. All the detected indications from the twelve (12) shrunk-on type LPTs were below the threshold size. The largest indication (0.7mm) was found on the disk hub internal area but is still below than the threshold size (1.08mm). Therefore, it is assumed that no SCC cracks have been detected to date based on NDE results.

Although NDE results for the shrunk-on type LPT fleet in Korea are encouraging, possibility remains for future failures caused by the SCC mechanism. NDE indications can develop into cracks in the future as operating time is increased. Therefore, they need to be evaluated and monitored thoroughly by the periodic NDE inspection program.

2.2 Status of LPT Retrofit in Korea

The original design life for LPT was historically as about 30 ~ 40 years. However, many utilities confirmed through the in-service experience that there were significant differences between design and actual lifespans. According to the report of KHNP Central Research Institute (CRI), many old shrunk-on type LPTs manufactured prior to 1990 experienced early replacement due to SCC issues and their average lifespan was about 20 years. In this experience, it has been recognized that poor control of secondary side water chemistry may have played a significant role. Improved chemistry, such as outlined in EPRI guidelines [2], is expected to significantly reduce in LPT rotors SCC progression.

In Korea, twenty-four (24) commercial NPPs have been operation starting in 1978. The first LPT retrofit was Kori-1 in 1997 after nineteen (19) years of operation. A total of eight units among the twenty-four (24) units have retrofit OEM LPT accounting for 33.3% of the installed number. The average lifetime and power upgrade of those replaced LPTs was 19.6 years and 23.4 MWe, respectively. Table IV shows the retrofit history of LPTs in Korea.

Table IV. Retrofit history of LPTs in Korea

Unit	C.O. [1]	Retrofit	Lifespan	Power Up
Kori-1	‘78	‘97	19 Y	18.2 MWe
Kori-2	‘83	‘98	15 Y	26.4 MWe
Kori-3	‘85	‘98	13 Y	17.5 MWe
Kori-4	‘86	‘97	11 Y	16.2 MWe
Hanul-1	‘88	‘12	24 Y	20.5 MWe
Hanul-2	‘89	‘11	22 Y	23.8 MWe
Hanbit-1	‘86	‘13	27 Y	31.2 MWe
Hanbit-2	‘87	‘13	26 Y	33.6MWe

1 - Commercial Operation

3. Economic Analysis of LPT Retrofit

In general, retrofit of OEM LPT rotors requires enormous investment. Therefore, the plant owner should make an investment decision based on an economic assessment. In other words, LPT retrofit projects should be carried out when the benefits coming from retrofit is large enough to offset the substantial cost of the investment. The primary benefit of the retrofit is the expected reduction of future SCC risk by adopting advanced LPT rotor design. In addition, since new LPTs have more confidence on preventing SCC issues, industry experience has shown that maintenance cost can be reduced by extending the LPT inspection interval up to 100,000 hours. In addition, there is a potential power upgrade derived from improved thermal performance of the new LPT design. This additional electricity revenue from the additional power output will be the greatest direct payback on the substantial investment of the LPT retrofit project.

3.1 Scenarios

The target group for economic evaluation is the twelve (12) shrunk-on type PWR LPTs in Korea with over twenty (20) years of operating history. Table V lists general information on the LPT fleet examined in the economic analysis for LPT retrofit.

Table V. Shrunk-on type LPTs (OPR1000)

Unit	C.O. [1]	# of LPT Cylinders	Power	LSB
Hanbit-3	‘95	3	1000MWe	43”
Hanbit-4	‘96			
Hanul-3	‘98			
Hanul-4	‘99			

1 - Commercial Operation

For the analysis, a 60 year operating term including 20 years of continued operation has been assumed. Based on 60 years of operation, an economic evaluation for the four alternative cases is outlined below;

A. *No LPT retrofit during 60 years of operation*
B. *LPT retrofit after 30 years of operation*
C. *LPT retrofit after 40 years of operation*
D. *LPT retrofit after 50 years of operation*

Three LPTs at Hanbit-3 (HB-3) has been selected for the economic evaluation since they have the most operating hours among the twelve (12) shrunk-on type PWR LPTs in Korea. Data from the latest retrofit case Hanbit-2 (HB2) in 2013, will be referenced because those LPTs have a similar design to the evaluation targeted LPTs at HB-3 as shown Table VI below.

Table VI. Design data for HB-2 and HB-3

Unit	Power (MWe)	Original Type	LSB	OEM
HB-2	996	Shrunk-on	44"	WH
HB-3	1000	Shrunk-on	43"	GE

3.2 Methodology

A net present value (NPV) method has been adopted for the economic evaluation and will consider following four financial factors;

- *Maintenance cost (Overhaul + NDE)*
- *Capital investment cost (Retrofit)*
- *Loss due to performance degradation*
- *Gain due to performance upgrade*

Maintenance, maintenance cost consists of two major parts, the overhaul (O/H) maintenance cost and NDE cost. In order to apply reliable values, we have used average expenses which occurred during five outages at HB-3 (2007 to 2013). Since we can extend the O/H interval for LPTs from 18M to 36M after replacing old LPTs with new ones, the maintenance cost will be reduced by half after all.

Capital, the retrofit cost for three LPTs at HB-2, $95.4M in 2013, has been applied for the analysis. Since 2015 is the starting point of the economic assessment, we need to recalculate the retrofit cost after applying 3% of inflation rate for two years. The scope of retrofit will be the section replacement replacing three LPT rotors, inner casings and seals with a new design, which not only reduces SCC susceptibility but achieves a high thermal performance by adopting advanced blade profiles.

Degradation, as the operation years of LPT increase, some components like diaphragms, or blades will experience aging mechanisms. This can cause degradation issues and reduce power up to 0.5% of total output. We assume that 0.1% power loss occurs due to the erosion of diaphragms and blades after a 25-yr of operating period.

Uplift, retrofit LPTs adopting advanced design features will generate additional output through the performance upgrade. The expected power gain due to the retrofit is 23MWe, and it is the mean value of eight retrofit cases of KHNP for the past 10 years. Table VII shows the costs and power values that we apply for the analysis.

Table VII. Input values for economic evaluation

Cost (unit : U.S. M. $)			Power (unit : MWe)	
O/H	NDE	Retrofit	Loss	Gain
0.32/OH	0.27/OH	101.13	1/year	24/year

3.3 Results

In order to compare the analysis results of the four alternative cases, we compute the NPVs of each financial factor first, and then sum all of them to get the total NPV for alternative cases as shown below.

$$NPV_{(total)} = NPV_{(gain)} - NPV_{(loss)} - NPV_{(O\&M)} - NPV_{(retrofit)}$$

The NPVs of power gain and loss factors have been calculated based on the average nuclear electricity sales price (49.95$/MWh) and capacity factor (90%) for Korea in 2014. A 5% discount rate is assumed along with a 3% inflation rate for all NPVs computations.

Table VIII shows the results of the economic evaluation for the four alternative cases. The Case-A scenario, operating NPP without LPT retrofit for 60 years, has a minus total NPV value since there is no additional financial benefit from power upgrade. The Case-B scenario, performing LPT retrofit in 2024 after 30 years of operation and operating until 2054, shows the largest gain and therefore, it can be the best option among the four alternatives. The Case-C scenario also creates positive total NPV value but projected revenue is only one third of Case-B. The Case-D scenario, conducing LPT retrofit after 50 years operation, results in a minus total NPV value due to the small remaining operation years after the retrofit.

Table VIII. Computed NPV values for the four alternatives

Case	NPV (unit : U.S. million dollars)				
	O&M	Retrofit	Loss	Gain	Total
A	10.99	0.00	9.46	0.00	-20.45
B	**7.14**	**84.74**	**1.75**	**180.45**	**86.83**
C	8.65	69.51	4.77	109.79	26.86
D	9.88	57.03	7.25	51.81	-22.34

4. Conclusions

Now that operation age of twelve (12) shrunk-on type PWR LPTs in Korea has reached about twenty (20) years, a program needs to be considered to manage retrofit projects as a of long term maintenance. In this paper, the inspection status of those LPTs was reviewed along with an economic assessment on LPT retrofit based on the four alternative scenarios.

To date, NDE results for the shrunk-on type LPT fleet in Korea have been quite positive (i.e. indications have been below the threshold size). However, the current NDE intervals should be maintained to closely monitor those indications which can develop into SCC cracks in the future.

In addition, retrofit of LPTs should be considered to minimize the probability of future failure. According to the simplified economic analysis here, revenue can be maximized for the case LPT retrofit implementation after thirty (30) years of operation assuming sixty (60) years of overall lifespan

This paper outlines the salient elements required for establishing a retrofit plan for shrunk-on disk type LPT rotors in the OPR1000 fleet. Other factors to be considered include the following: (i) procurement plans to maximize the number of qualified vendors, (ii) decisions points to adjust and modify the plan as operating experience accrues, and (iii) oversight of non-OEM vendors related to critical vendor analyses such as torsional vibration and turbine missile.

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