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Technical Note

The application study of preventive maintenance during normal operation for APR1400 nuclear power plants considering risk

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ABSTRACT

Preventive Maintenance(PM) for safety component during power operation at nuclear power plants, On-Line Maintenance(OLM) refers to intentionally entering the Limited Condition of Operation(LCO) specified in the Technical Specification(TS) for safety-related systems and components in order to perform preventive maintenance within the Allowed Outage Time (AOT). This study assessed the feasibility of conducting OLM at the domestic APR1400 nuclear power plant. It focused on preventive maintenance duration and risk perspectives. A total of 78 FEGs were developed for 4450 facilities, considering system functions and preventive maintenance scope during output operation for eight safety-related systems. Additionally, maintenance items included in FEGs were selected, designated as targets for OLM, and their maintenance durations were evaluated and compared with AOT for each maintenance item. As a result, the Auxiliary Feedwater and Essential Chilled Water systems were identified as systems allowing OLM. Furthermore, utilizing the Risk Monitoring System (RIMS), the increased risk value due to the unavailability of target equipment during preventive maintenance was analyzed to determine whether it falls within the acceptable range.

Regarding the temporary risk increase caused by OLM, it was observed that in all systems, it falls within Zone III according to NUMARC93-01 standards, allowing for normal equipment arrangement for OLM. However, according to the risk increase standards rate in domestic nuclear power plants, when maintaining the A-train in four systems including Component Cooling Water, they are all evaluated as 'Orange,' indicating that measures for risk mitigation are necessary for OLM to be feasible. When considering extending AOT up to 1.6 times the maintenance time, the risk increase falls within Zone III according to permissible change in risk standards, indicating that AOT extension might be feasible based solely on risk changes. To apply OLM within the permissible risk management scope in domestic nuclear power plants, regulatory policies need to allow voluntary LCO entry for preventive maintenance, necessitating clear determination by regulatory agencies using risk-informed policies. While OLM seems viable concerning maintenance duration and quantitative risk aspects, for inducing regulatory policy changes, comprehensive OLM guidelines are necessary, including risk management strategies.

1. Introduction

On-Line Maintenance(OLM), Preventive Maintenance(PM) for safety component during power operation at nuclear power plants, refers to intentionally entering the Limited Condition of Operation(LCO) specified in the Technical Specification(TS) for safety-related systems and components in order to perform preventive maintenance within the Allowed Outage Time (AOT) [1]. Therefore, if preventive maintenance cannot be completed within the specified AOT stated in the TS., actions such as changing the operating mode, reducing power, or shutting down the power plant as specified must be complied with. Currently, domestic nuclear power plants are in a state where conducting OLM is impossible. This is because the TS was changed, due to the demand of the regulatory agency in 2014, to prevent entry into LCO artificially in order to perform OLM.

However, nuclear plants overseas, like those in the United States, have been performing OLM by securing appropriate maintenance duration through methods such as extending the AOT using risk-

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informed method, starting from the early 2000s [2]. In the United States, for the first time in the 1990s, the allowable outage time for safety injection systems was extended using risk information. Specifically, for the Safety Injection Tank (SIT), it was extended from 1 h to 24 h, and for the Low-Pressure Safety Injection (LPSI) system, it was extended from 72 h to 7 days [3,4]. Furthermore, recently, at the Wolf Creek nuclear power plant, the allowable outage time for emergency diesel generators was extended to 14 days [5]. Similarly, in domestic nuclear power plants, there are cases where the inspection intervals and allowable outage times for inverters have been extended using risk information, and efforts are being made to gradually expand the scope of such systems. Especially, U.S. nuclear plants have been applying OLM consistently after risk-informed approaches were introduced to the industry through the Maintenance Rule, 10CFR50.65.10 [6]. The Maintenance Rule(MR), Published in July 1991, with an effective date of July 1996, titled Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants was published by the NRC. This rule was developed to have an established regulatory framework to provide the means for evaluating the administrative effectiveness of nuclear power plant licensees' maintenance programs. The NRC's overall objective is that structures, systems, and components important to nuclear power plant safety be maintained properly so that plant equipment perform its intended safety functions reliably when required. The Electric Power Research Institute (EPRI) in the U.S. has analyzed that proactive OLM enhances the reliability of safety component, improves the safety of power plants, and contributes to increased efficiency in maintenance workload and manpower allocation for planned and OLM, thus enhancing the utilization rate of power plants [7]. Since 2003, domestic nuclear power plants have voluntarily introduced maintenance regulations to enhance equipment reliability and safety. Unlike in the United States, this operation is voluntary for operators rather than a legal requirement.

In 2010, domestic nuclear power plants performed pilot preventive maintenance during power operation on the essential chilled water system of the Westinghouse-type reactor, Gori-3, with the goal of enhancing the plant's equipment reliability, approved by the regulatory agency. At that time, a study on "Development of Safety Impact Assessment Technology for OLM [1]" conducted by the Korean regulatory body in 2012 also suggests that OLM is beneficial in terms of nuclear power plant safety and economy, and that legislation of MR along with regulatory technology requirements for maintenance risk management is a prerequisite for the establishment of OLM. In addition, in relation to the implementation of OLM, the evaluation of KHNP's work control system, MR, and on -line risk monitoring program concluded that it has the capability to perform OLM. However, discussions regarding this OLM have been completely suspended since 2011 following the Fukushima nuclear disaster.

However, recently, KHNP have begun discussions with regulatory agencies, based on KHNP's operational experience with maintenance regulations, aiming at enhancing safety, securing a foundation for overseas exports, and improving capacity factor, and have established OLM implementation plans.

This paper presented the method and results of selecting target equipment for preventive maintenance during normal operation for major safety systems. Additionally, it evaluated the change in risk associated with OLM of these equipment, comparing it with domestic and international standards, thereby assessing the feasibility of implementing OLM in domestic nuclear power plants in the future.

2. Methods

2.1. Preventive Maintenance(PM) process and functional equipment groups (FEGs)

In domestic nuclear power plants, the preventive maintenance targets are selected by evaluating the functional importance of all equipment. Maintenance items are generated according to Preventive Maintenance Template(PMT) that provide information on failure parts, failure modes, and causes of performance degradation by equipment type, along with suitable tasks. Maintenance items are created by job category to efficiently manage maintenance and inspection items applicable to target equipment, aiming for systematic preventive maintenance execution.

These maintenance items refer to the preventive maintenance target items that are developed by linking task lists containing information such as work details, required resources (labor, materials, technical documents, measurement, and testing equipment). Depending on the preventive maintenance tasks, multiple maintenance items can be created for a single piece of equipment. In domestic nuclear plants, currently, most preventive maintenance tasks like disassemble and inspections of safety-related component are conducted during planned outage periods. Only inspection-focused preventive maintenance tasks, such as visual inspections, are carried out during power operation. Therefore, to implement OLM for safety-related component, it's essential to evaluate if the maintenance items currently being conducted during planned outage periods can also be performed OLM. To accomplish this, an evaluation of Functional Equipment Groups(FEGs) were conducted for the major safety-related systems. FEGs involve selecting representative equipment within each system, extending its scope to include supporting equipment that doesn't impact functionalities in other systems or subsystems [8]. It is utilized for tasks such as work planning, maintenance risk assessment, issuing work permits, and performing tasks. In this study, among safety-related systems, 9 systems were selected as targets for OLM, as illustrated in Table 1. Through analysis of system functionalities, FEGs were developed.

FEGs were designed to encompass representative equipment for each system from the perspective of performing OLM. This included the maximum range that functionally supports the representative equipment without impacting other systems, along with equipment supporting the functionality of the representative equipment (Fig. 1).

In Fig. 1, the work management unit FEG could be composed around a pump, involving components like the pump motor, breakers, inlet/outlet air-operated valves, outlet check valves, recirculation valves, pump room cooling system (cooling fans, breakers, cooling coils), and pressure instruments (PIs). PI-01, being field measuring instruments not influencing the functionality of the FEG, were excluded. Breakers and the pump room cooling system, although belonging to different systems than the pump, were classified under related FEGs as they influence the FEG's functionality. Main FEGs refer to systems composed solely of equipment within the target system, while "related FEGs" denote devices that do not belong to the target system but impact the functionality of the key equipment within the target system. Furthermore, to mitigate risks associated with duplicate management of equipment across maintenance areas, a single piece of equipment cannot belong to more than two FEGs. Facilities positioned on the boundaries of FEGs for work

Table 1
The Safety-related system and its Technical Specification (TS) requirements at power operation [9].

System Name	LCO requirement	AOT (hr)
Safety Injection	1 train or 2 train inoperable	72
Shutdown Cooling	NA	NA
Containment Spray	1 train inoperable	72
Component Cooling Water	1 train inoperable	72
Essential Service Water	1 train inoperable	72
Aux. Feedwater Pump	1 train inoperable	168
Turbine	2 train inoperable	72
Auxiliary Feedwater	1 Pump or 1 flow path inoperable	168
	1 train inoperable	72
	1 Pump or 1 flow path inoperable each train	72
Emergency Diesel Generator	1 train inoperable	72
Essential Chilled Water	1 train inoperable	72

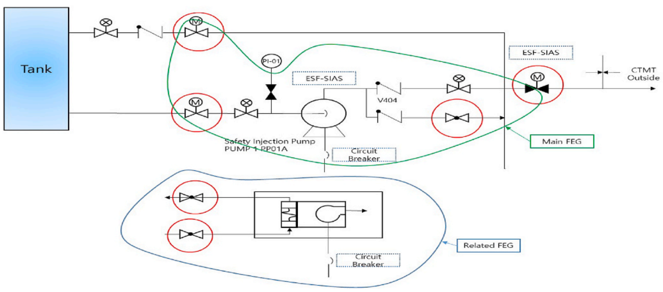

Fig. 1. Functional equipment group Description example.

line-up purposes during preventive maintenance tasks were categorized as boundary facilities. Furthermore, maintenance items included in each FEG were initially selected, prioritizing them as targets for OLM. The naming of FEGs was done based on the following criteria: If the FEG name is AAABBBCCC-DD, here, AAA represents the PBS(Physical Breakdown Structure) Number indicating the system, BBB is the equipment type code of the representative equipment (Table 2), CCC signifies the number and trains of the representative equipment, and DD denotes the unit number.

2.2. Risk management program

2.2.1. Risk Monitoring System (RIMS)

RIMS quantifies real-time changes in risk, such as Core Damage Frequency(CDF) and Large Early Release Frequency(LERF) of radioactive materials, considering operational availability changes due to tests and maintenance of power plant facilities. It's a software that quantifies risk changes using a risk monitoring model (as-operated PSA model considering power plant arrangement changes) and possesses functionalities depicted in Fig. 2 [10].

RIMS, developed in 2014, utilizes an operational Probabilistic Safety Assessment(PSA) model to monitor internal events concerning full power operation, using CDF and LERF in the reactor building as risk indicators. The PSA model comprises a total of 20 selected initial events, encompassing a total of 266 sequences of core damage events resulting from these initial events. The baseline CDF and LERF for these events are at levels of 1.06E-6 per year and 5.14E-8 per year, respectively [11].

2.2.2. Temporary risk increases

The risk criteria for temporary changes were developed by EPRI [12]. The increase of CDF for more than an order of magnitude was prevented by limit 1E-3/Ry, which should never be exceeded. This means that configuration-specific risk levels in excess of 1E-3/Ry should be carefully considered before voluntarily entering such conditions. With proper planning and control, risk levels should not exceed 1E-3/Ry. And in the industry guidelines for monitoring maintenance efficiency in U.S. nuclear power plants, referencing EPRI [12], criteria for risk based on temporary arrangement changes due to maintenance are presented as shown in Table 3 [13].

These criteria are based on the overall incremental impact of the temporary condition on risk. It is based on the risk rate (i.e. CDF or LERF) and duration. Plants should consider factors of duration in setting the risk management thresholds. This may be either the duration of a particular out-of-service condition, or a specific defined work interval (e.g. shift, week, etc). The product of the incremental CDF (or LERF) and duration is expressed as a probability (e.g., incremental core damage probability – ICCDP, incremental large early release probability – ICLERP).

In domestic nuclear power plants, risk management based on equipment arrangement during maintenance planning during power operation is also conducted, and the management criteria are as shown in Table 4 [14]. If the risk level is categorized as orange or red, the respective maintenance plan undergoes reassessment, or in some cases, approval might not be feasible. However, unavoidable single maintenance activities are permitted, but in such cases, there's a necessity to establish risk reduction measures and recovery plans.

2.2.3. Permanent risk increases

In the U.S.'s R.G. 1.174, they divide the risk areas into three categories based on the comparison of the plant's baseline risk (CDF and LERF, among others) and the risk increase due to Current Licensing Basis (CLB) changes (ΔCDF and ΔLERF). They present different acceptance criteria for each risk area [15]. The criteria for CLB changes are as presented in Table 5.

Region I states that CLB changes are generally not permitted. In Region II, consideration for CLB changes might be possible only for nuclear power plants with Base CDF and LERF each below 1.0E-04/Ry and 1.0E-05/Ry, respectively, where risk changes are considered minimal. Region III indicates very minimal risk increases, allowing flexibility in CLB changes without requiring Total CDF calculations. However, for power plants with a baseline CDF above 1.0E-04/Ry, exploring options to reduce the current total CDF is recommended instead of CLB changes. Domestic regulatory agencies also reference the U.S.'s R.G. 1.174, presenting similar guidelines as shown in Fig. 3 [16]. Any region where the change value (ΔCDF) exceeds 1.0E-5/Ry from any baseline CDF or where the change value (ΔLERF) exceeds 1.0E-6/Ry from any baseline LERF is considered unacceptable. Any region where ΔCDF is less than 1.0E-6/Ry from any baseline CDF or where ΔLERF is less than 1.0E-7/Ry from any baseline LERF is considered acceptable. However, for baseline CDF below 1.0E-6/Ry or baseline LERF below 1.0E-7/Ry, only changes below these respective baseline risk values are set as the "acceptable area. Moreover, regions between the "acceptable area" and "unacceptable area" for any baseline risk scale value larger than 1.0E-4/Ry for CDF or larger than 1.0E-5/Ry for LERF become the "detailed assessment area, " even if ΔCDF is smaller than 1.0E-6/Ry or ΔLERF is smaller than 1.0E-7/Ry. Similarly, if the baseline LERF is larger than 1.0E-5/Ry, even if ΔLERF is smaller than 1.0E-7/Ry, it falls into the "detailed evaluation region. In cases where the "detailed assessment area" applies, measures to reduce the baseline risk value and in-depth analysis are typically required.

Table 2
The Equipment type code for FEGs.

Equipment Type	Code	Equipment Type	Code
Train	TRN	Pump	PP
Chiller	CH	Condensate Pump	CP
Heat Exchanger	HE	Turbine	TA
Filter	FT	Tank	TK
Diesel	DG	–	–

3. Results and discussion

3.1. Functional equipment groups (FEGs) for OLM

The FEG results for the target system are presented in Table 6. FEGs were established by distinguishing between individual equipment units or trains, considering the scope of maintenance during operation for each system. Maintenance items for the devices included in each FEG were also coordinated.

Considering the main functions and equipment configuration of each system, including the safety injection system, a total of 78 FEGs were developed for 4450 target system facilities, confirming 842 related preventive maintenance items.

The essential chilled water system designates the cooling unit and pumps as representative facilities. For the cooling of these representative facilities, functional equipment groups were established for 461 systems (primary component cooling water system) and for power supply, involving 823 systems (1E class 4.16 kV) and 827 systems (1E

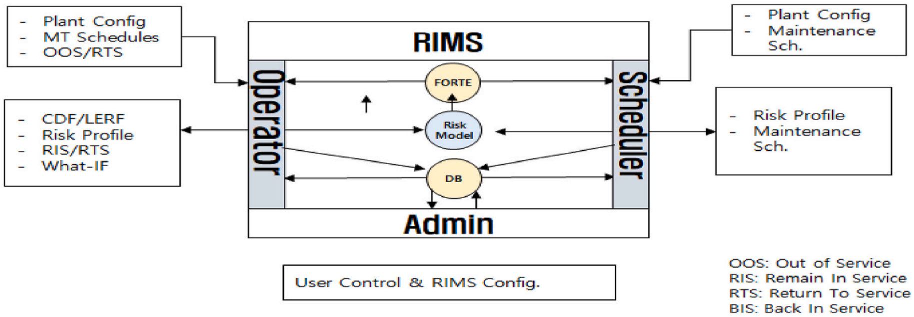

Fig. 2. Rims Conceptual framework.

Table 3
Action thresholds based on risk for maintenance (NUMARC 93–01).

Region	ICCDP	ICLERP	Action
I	>1.0E-05	>1.0E-06	- Configuration should not normally be entered voluntarily
II	1.0E-06–1.0E-05	1.0E-07–1.0E-06	- Assess non-quantifiable factors and establish risk management actions
III	<1.0E-06	<1.0E-07	- Normal work control

Table 4
Action thresholds based on risk for maintenance.

Risk Color	Threshold (CDF or LERF)	Action
Green	<2 times the zero maintenance risk	- Proceed normally
Yellow	≥2 times the zero maintenance risk	- Invoke contingency actions or restrict out of service time - Notify of the plant safety level
Orange	≥10 times the zero maintenance risk	- Invoke contingency actions or restrict out of service time - Plan for the restoration of risk important equipment - Notify of the plant safety level
Red	≥20 times the zero maintenance risk	- Invoke contingency actions or restrict out of service time - Hasten the restoration of risk important equipment - Notify of the plant safety level

Table 5
Acceptance criteria for change of current licensing basis (R.G. 1.174).

Region	ΔCDF	ΔLERF
I	ΔCDF ≥1.0E-05/Ry	ΔLERF≥ 1.0E-06/Ry
II	1.0E-06/Ry < ΔCDF <1.0E-05/Ry	1.0E-07/Ry < ΔLERF <1.0E-06/Ry
III	ΔCDF ≤1.0E-06/Ry	ΔLERF≤ 1.0E-07/Ry

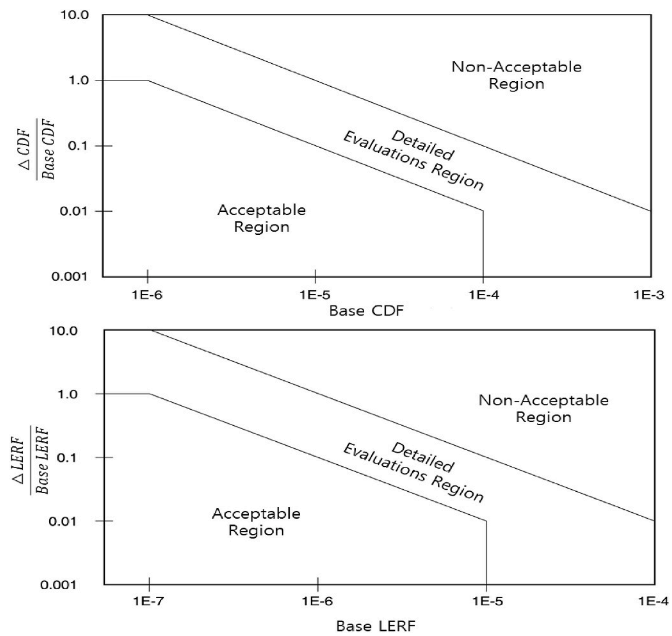

Fig. 3. Acceptance criteria for CDF & LERF

class 480V). The Essential chilled Water System was designed in two trains. Each train consists of two chilled water pumps, chillers, one makeup pump, a compressed tank, an air separator, and a chemical additive tank as the primary equipment. The FEGs for this system was structured into a total of 16 groups (eight per train), considering redundancy, capacity, the potential for OLM based on train or equipment. Equipment eligible for preventive maintenance during operation includes major equipment within the boundaries of the FEG, along with valves, breakers, and instrumentation and control systems. The Essential Chilled Water Pumps, operating at 100 % capacity, enable the maintenance of standby pumps without impacting the system's normal operation within the boundaries of the FEG. Consequently, the FEG was named as 633PP01A-S3, 633PP02A-S3, 633PP01B–S3, 633PP02B–S3. Similarly, for the Essential Chillers operating at 100 % capacity, the FEG was structured as 633CH01A-S3, 633CH02A-S3, 633CH01B–S3, 633CH02B–S3. The essential chilled water makeup pumps operate at 100 % capacity each. When OLM is carried out on these pumps, the supply of water to the essential chilled water compression tank can be sourced from the Make-up Demineralizer System, thus not affecting the system's normal operation. Therefore, the FEGs were named as 633PP03A-S3, 633PP03B–S3. And the replenishment of the essential chilled water compression tank is supplied by utilizing the essential chilled water makeup pumps from the auxiliary feedwater storage tank from Auxiliary Feedwater Storage and Transfer System. Additionally, it can also be sourced from the Make-up Demineralizer System. The Make-up Demineralizer System functions to supply filtered makeup water (demineralized water) to the auxiliary water storage tank and various equipment during all operational modes including startup, power production, high-temperature shutdown, normal shutdown, nuclear fuel reloading, and regular operation. The Heating, Ventilation, and Air conditioning(HVAC) system, in the safety-related equipment room, supplied by the Essential Chilled Water System, is designed in two trains. Even if one series malfunctions, it sufficiently cools the safety-related equipment room. By considering the possibility of preventive maintenance during operation of one train of the Essential Chilled Water System without affecting the system's normal operation, FEGs were named as 633TRN01A-S3, 633TRN01B–S3. To cover the possibility of performing preventive maintenance during operation for individual Essential Chilled Water Pumps and Chillers within one train rather than the entire train, FEGs were added, named as 633CP01A-S3, 633CP02A-S3, 633CP01B–S3, 633CP02B–S3. In the same manner, FEGs for the remaining seven systems were developed.

Table 6
The development results of functional equipment groups for each system.

System Name	FEG NAME	The number of Components			Outage Time for PM(hr)
		Total	Major	Boundary	
Safety Injection/ Shutdown Cooling	441TRN01A-S3	320	4	63	70
	441PP01A-S3	46	1	6	
	441PP02A-S3	37	1	7	
	441 PP02C–S3	35	1	7	
	441HE01A-S3	42	1	25	
	441TRN01B–S3	334	4	70	
	441PP01B–S3	46	1	6	
	441PP02B–S3	37	1	7	
	441PP02D-S3	35	1	7	
	441HE01B–S3	43	1	25	
Containment Spray	442TRN01A-S3	112	3	7	98
	442PP01A-S3	60	1	4	
	442HE01A-S3	36	1	9	
	442HE02A-S3	12	1	3	
	442TRN01B–S3	112	3	7	
	442PP01B–S3	60	1	4	
	442HE01B–S3	35	1	9	
	442HE02B–S3	12	1	3	
Component Cooling Water	461TRN01A-S3	326	7	9	110
	461PP01A-S3	66	1	2	
	461PP02A-S3	66	1	2	
	461PP03A-S3	19	1	3	
	461HE01A-S3	19	1	2	
	461HE02A-S3	19	1	2	
	461HE03A-S3	19	1	2	
	461TK02A-S3	13	1	2	
	461TRN01B–S3	329	7	9	
	461PP01B–S3	66	1	2	
	461PP02B–S3	66	1	2	
	461PP03B–S3	19	1	3	
	461HE01B–S3	19	1	2	
	461HE02B–S3	19	1	2	
	461HE03B–S3	19	1	2	
	461TK02B–S3	13	1	2	
Essential Service Water	462TRN01A-S3	213	5	1	84
	462PP01A-S3	60	1	2	
	462PP02A-S3	60	1	2	
	462FT01A-S3	10	1	3	
	462FT02A-S3	10	1	3	
	462FT03A-S3	10	1	3	
	462TRN01B–S3	213	5	1	
	462PP01B–S3	59	1	2	
	462PP02B–S3	61	1	2	
	462FT01B–S3	10	1	3	
	462FT02B–S3	10	1	3	
	462FT03B–S3	10	1	3	
Aux. Feedwater Pump Turbine	527TA01A-S3	145	1	4	112
	527TA01B–S3	145	1	4	
Auxiliary Feedwater	542TRN01A-S3	242	2	6	36
	542PP01A-S3	68	1	3	
	542PP02A-S3	99	1	3	
	543TK01A-S3	55	1	15	
	542TRN01B–S3	238	2	6	
	542PP01B–S3	68	1	3	
	542PP02B–S3	99	1	3	
	542TK01B–S3	53	1	15	
Emergency Diesel Generator	591DG01A-S3	332	3	–	177
	591TK40A-S3	23	1	2	
	591TK41A-S3	23	1	2	
	591DG01B–S3	331	3	–	
	591TK40B–S3	23	1	2	
	591TK41B–S3	24	1	2	
Essential Chilled Water	633TRN01A-S3	224	15	15	97
	633CP01A-S3	68	7	3	
	633CH01A-S3	48	6	2	
	633PP01A-S3	27	1	3	
	633CP02A-S3	68	7	3	
	633CH02A-S3	48	6	2	
	633PP02A-S3	27	1	3	
	633PP03A-S3	15	1	2	
	633TRN01B–S3	224	15	15	
	633CP01B–S3	68	7	3	
	633CH01B–S3	48	6	2	
	633PP01B–S3	27	1	3	
	633CP02B–S3	68	7	3	
	633CH02B–S3	48	6	2	
	633PP02B–S3	27	1	3	
	633PP03B–S3	15	1	2	

The outage time for PM is the time taken from preparation to cleanup for the maintenance items within each FEG was calculated, considering the longest duration as the representative maintenance time. When comparing these maintenance durations with AOT alone, it can be confirmed that the systems capable of OLM are Safety Injection, Auxiliary Feedwater, and Essential Chilled Water System. However, it is known that in most overseas nuclear power plants conducting OLM, around 60 % of AOT is used as maintenance duration to ensure safety integrity [17]. Considering this, it can be understood that the systems capable of OLM are Auxiliary Feedwater and Essential Chilled Water System. Additionally, due to the design characteristics of the APR1400 nuclear reactor, the Shutdown Cooling System is not subject to the application of LCO during power operation, indicating its suitability for OLM.

3.2. *Risk analysis for OLM*

Base line CDF and LERF are 1.06E-06/Ry and 5.14E-08/Ry, respectively, calculated using formulas 1) and 2) for ICCDP and ICLERP.

$$\Delta\mathrm{CDF}(\mathrm{or}\Delta\mathrm{LERF}) = CDF_{OOS}(or\ LERF_{OOS}) - CDF_{Baseline}(or\ LERF_{Baseline}) \quad (1)$$

$$\mathrm{ICCDP}(\mathrm{or\ ICLERP}) = \Delta\mathrm{CDF}(\mathrm{or}\Delta\mathrm{LERF}) \times \mathrm{Outage\ time(period)\ for\ PM} \quad (2)$$

Table 7 represents the calculated ICCDP and ICLERP based on the maintenance time for each system. CDF_{OOS} ($LERF_{OOS}$) indicates the change in risk when the major equipment of the corresponding FEG becomes unavailable. PSA involves identifying all initiating events that can occur at a nuclear power plant, evaluating the comprehensive risk based on event-specific scenarios and impacts. For this purpose, the PSA model includes modeling of key equipment by system. Therefore, CDF_{OOS} ($LERF_{OOS}$) evaluates the risk for each FEG by finding the equipment included in the FEG in the PSA model and changing the status of that equipment to unavailable. If the equipment for each FEG is not reflected in the PSA model, the risk cannot be evaluated, hence marked as "Not Applicable (NA)" in Table 7.

The analysis results show that for all systems, they fall within Zone III of the NUMARC93-01 criteria, indicating that the normal arrangement of the equipment is possible for OLM.

Table 8 shows the calculated increase rates of CDF (LERF) according to the increase in CDF_{OOS} ($LERF_{OOS}$) divided by $CDF_{Baseline}$ ($LERF_{Baseline}$) based on the criteria of domestic nuclear power plants. Some FEGs within the Component Cooling Water, Essential Service Water, Auxiliary Feedwater Pump Turbine, Auxiliary Feedwater, Emergency Diesel Generator, and Essential Chilled Water systems were evaluated to exceed the green range. Specifically, despite all A-train maintenance in the Component Cooling Water, Essential Service Water, and Essential Chilled water systems being evaluated as Orange, they were Yellow in the B-train. Furthermore, the Auxiliary Feedwater Pump Turbine A train and Emergency Diesel Generator A, B were all evaluated in the Yellow range. And maintenance for the A-train of the Auxiliary Feedwater System was evaluated in the Orange range, while Auxiliary Feedwater Pump A was evaluated in the Yellow range.

As a result, the four A-trains of the four systems evaluated as 'Orange' appeared to have difficulties in performing OLM regardless of

Table 7
ICCDP & ICLERP for OLM by NUMARC 93-01 criteria.

System Name	FEG Name	CDF_{OOS}	$LERF_{OOS}$	ICCDP	ICLERP	Region
Safety Injection/Shutdown Cooling	441TRN01A-S3	1.71E-06	5.53E-08	5.20E-09	3.13E-11	III
	441PP02A-S3	1.32E-06	5.27E-08	2.06E-09	1.09E-11	III
	441 PP02C–S3	1.30E-06	5.26E-08	1.92E-09	9.98E-12	III
	441TRN01B–S3	1.73E-06	5.67E-08	5.34E-09	4.29E-11	III
	441PP02B–S3	1.32E-06	5.27E-08	2.06E-09	1.06E-11	III
	441PP02D-S3	1.31E-06	5.26E-08	2.00E-09	1.02E-11	III
	441PP01A-S3	1.11E-06	5.18E-08	3.92E-10	3.37E-12	III
	441HE01A-S3	1.09E-06	5.18E-08	2.56E-10	3.35E-12	III
	441PP01B–S3	1.12E-06	5.18E-08	4.92E-10	3.38E-12	III
	441HE01B–S3	1.09E-06	5.18E-08	2.69E-10	3.36E-12	III
Containment Spray	442TRN01A-S3	1.13E-06	5.14E-08	8.04E-10	1.72E-13	III
	442PP01A-S3	1.08E-06	5.14E-08	2.57E-10	4.14E-15	III
	442HE01A-S3	1.13E-06	5.14E-08	8.04E-10	1.72E-13	III
	442HE02A-S3	1.08E-06	5.14E-08	2.57E-10	4.14E-15	III
	442TRN01B–S3	1.12E-06	5.14E-08	6.82E-10	1.72E-13	III
	442PP01B–S3	1.07E-06	5.14E-08	1.56E-10	4.14E-15	III
	442HE01B–S3	1.12E-06	5.14E-08	6.82E-10	1.72E-13	III
	442HE02B–S3	1.07E-06	5.14E-08	1.56E-10	4.14E-15	III
Component Cooling Water	461TRN01A-S3	1.77E-05	1.77E-07	2.09E-07	1.58E-09	III
	461PP01A-S3	1.10E-06	5.16E-08	4.50E-10	2.33E-12	III
	461PP02A-S3	1.10E-06	5.15E-08	5.40E-10	1.83E-12	III
	461PP03A-S3	NA	NA	NA	NA	NA
	461HE01A-S3	1.11E-06	5.17E-08	5.69E-10	3.82E-12	III
	461HE02A-S3	1.11E-06	5.17E-08	5.69E-10	3.82E-12	III
	461HE03A-S3	1.07E-06	5.14E-08	8.92E-11	4.65E-15	III
	461TK02A-S3	NA	NA	NA	NA	NA
	461TRN01B–S3	6.64E-06	1.08E-07	7.01E-08	7.09E-10	III
	461PP01B–S3	1.07E-06	5.15E-08	1.66E-10	1.24E-12	III
	461PP02B–S3	1.09E-06	5.15E-08	3.18E-10	1.13E-12	III
	461PP03B–S3	NA	NA	NA	NA	NA
	461HE01B–S3	1.11E-06	5.14E-08	5.75E-10	9.46E-13	III
	461HE02B–S3	1.11E-06	5.14E-08	5.75E-10	9.46E-13	III
	461HE03B–S3	1.07E-06	5.14E-08	8.92E-11	4.65E-15	III
	461TK02B–S3	NA	NA	NA	NA	NA
Essential Service Water	462TRN01A-S3	1.47E-05	1.51E-07	1.30E-07	9.55E-10	III
	462PP01A-S3	1.14E-06	5.19E-08	7.82E-10	4.77E-12	III
	462PP02A-S3	1.17E-06	5.19E-08	1.03E-09	5.18E-12	III
	462FT01A-S3	1.08E-06	5.15E-08	1.60E-10	1.12E-12	III
	462FT02A-S3	1.08E-06	5.15E-08	1.60E-10	1.12E-12	III
	462FT03A-S3	1.07E-06	5.14E-08	6.81E-11	3.55E-15	III
	462TRN01B–S3	3.04E-06	9.43E-08	1.90E-08	4.12E-10	III
	462PP01B–S3	1.08E-06	5.16E-08	2.27E-10	2.37E-12	III
	462PP02B–S3	1.10E-06	5.16E-08	3.38E-10	2.57E-12	III
	462FT01B–S3	1.07E-06	5.14E-08	1.19E-10	2.43E-13	III
	462FT02B–S3	1.07E-06	5.14E-08	1.19E-10	2.43E-13	III
	462FT03B–S3	1.07E-06	5.14E-08	6.81E-11	3.55E-15	III
Aux. Feedwater Pump Turbine	527TA01A-S3	2.95E-06	1.21E-07	2.42E-08	8.86E-10	III
	527TA01B–S3	1.47E-06	5.88E-08	5.24E-09	9.54E-11	III
Auxiliary Feedwater	542TRN01A-S3	1.56E-05	7.86E-07	5.98E-08	3.02E-09	III
	542PP01A-S3	2.76E-06	1.20E-07	6.98E-09	2.81E-10	III
	542PP02A-S3	1.30E-06	6.30E-08	9.90E-10	4.79E-11	III
	542TRN01B–S3	1.81E-06	6.40E-08	3.08E-09	5.18E-11	III
	542PP01B–S3	1.47E-06	5.88E-08	1.68E-09	3.07E-11	III
	542PP02B–S3	1.08E-06	5.16E-08	8.67E-11	9.55E-13	III
Emergency Diesel Generator	591DG01A-S3	2.73E-06	9.44E-08	3.38E-08	8.70E-10	III
	591TK40A-S3	NA	NA	NA	NA	NA
	591TK41A-S3	NA	NA	NA	NA	NA
	591DG01B–S3	2.87E-06	9.51E-08	3.66E-08	8.84E-10	III
	591TK40B–S3	NA	NA	NA	NA	NA
	591TK41B–S3	NA	NA	NA	NA	NA
Essential Chilled water	633TRN01A-S3	1.47E-05	1.48E-07	1.51E-07	1.07E-09	III
	633CP01A-S3	1.22E-06	5.24E-08	1.72E-09	1.11E-11	III
	633CH01A-S3	1.17E-06	5.21E-08	1.19E-09	7.70E-12	III
	633PP01A-S3	1.12E-06	5.17E-08	6.18E-10	3.44E-12	III
	633CP02A-S3	1.35E-06	5.29E-08	3.21E-09	1.65E-11	III
	633CH02A-S3	1.29E-06	5.25E-08	2.54E-09	1.28E-11	III
	633PP02A-S3	1.13E-06	5.17E-08	7.66E-10	3.71E-12	III
	633PP03A-S3	NA	NA	NA	NA	NA
	633TRN01B–S3	3.01E-06	9.22E-08	2.16E-08	4.52E-10	III
	633CP01B–S3	1.10E-06	5.19E-08	4.68E-10	5.35E-12	III
	633CH01B–S3	1.09E-06	5.17E-08	3.45E-10	3.69E-12	III
	633PP01B–S3	1.08E-06	5.15E-08	2.03E-10	1.67E-12	III
	633CP02B–S3	1.22E-06	5.19E-08	1.72E-09	5.35E-12	III
	633CH02B–S3	1.19E-06	5.21E-08	1.48E-09	8.13E-12	III
	633PP02B–S3	1.09E-06	5.15E-08	3.29E-10	1.93E-12	III
	633PP03B–S3	NA	NA	NA	NA	NA

Table 8
The rate of CDF & LERF change for OLM by APR1400 Criteria.

System Name	FEG Name	$CDF_{OOS}/CDF_{Baseline}$	$LERF_{OOS}/LERF_{Baseline}$	Region
Safety Injection/ Shutdown Cooling	441TRN01A-S3	1.61	1.08	Green
	441PP02A-S3	1.24	1.03	Green
	441 PP02C–S3	1.23	1.02	Green
	441TRN01B–S3	1.63	1.10	Green
	441PP02B–S3	1.24	1.03	Green
	441PP02D-S3	1.24	1.02	Green
	441PP01A-S3	1.05	1.01	Green
	441HE01A-S3	1.03	1.01	Green
	441PP01B–S3	1.06	1.01	Green
	441HE01B–S3	1.03	1.01	Green
Containment Spray	442TRN01A-S3	1.07	1.00	Green
	442PP01A-S3	1.02	1.00	Green
	442HE01A-S3	1.07	1.00	Green
	442HE02A-S3	1.02	1.00	Green
	442TRN01B–S3	1.06	1.00	Green
	442PP01B–S3	1.01	1.00	Green
	442HE01B–S3	1.06	1.00	Green
	442HE02B–S3	1.01	1.00	Green
Component Cooling Water	461TRN01A-S3	16.67	3.45	Orange
	461PP01A-S3	1.03	1.00	Green
	461PP02A-S3	1.04	1.00	Green
	461PP03A-S3	NA	NA	NA
	461HE01A-S3	1.04	1.01	Green
	461HE02A-S3	1.04	1.01	Green
	461HE03A-S3	1.01	1.00	Green
	461TK02A-S3	NA	NA	NA
	461TRN01B–S3	6.27	2.10	Yellow
	461PP01B–S3	1.01	1.00	Green
	461PP02B–S3	1.02	1.00	Green
	461PP03B–S3	NA	NA	NA
	461HE01B–S3	1.04	1.00	Green
	461HE02B–S3	1.04	1.00	Green
	461HE03B–S3	1.01	1.00	Green
	461TK02B–S3	NA	NA	NA
Essential Service Water	462TRN01A-S3	13.84	2.94	Orange
	462PP01A-S3	1.08	1.01	Green
	462PP02A-S3	1.10	1.01	Green
	462FT01A-S3	1.02	1.00	Green
	462FT02A-S3	1.02	1.00	Green
	462FT03A-S3	1.01	1.00	Green
	462TRN01B–S3	2.87	1.84	Yellow
	462PP01B–S3	1.02	1.00	Green
	462PP02B–S3	1.03	1.01	Green
	462FT01B–S3	1.01	1.00	Green
	462FT02B–S3	1.01	1.00	Green
	462FT03B–S3	1.01	1.00	Green
Aux. Feedwater Pump Turbine	527TA01A-S3	2.78	2.35	Yellow
	527TA01B–S3	1.39	1.15	Green
Auxiliary Feedwater	542TRN01A-S3	14.73	15.29	Orange
	542PP01A-S3	2.60	2.33	Yellow
	542PP02A-S3	1.23	1.23	Green
	542TRN01B–S3	1.71	1.25	Green
	542PP01B–S3	1.39	1.15	Green
	542PP02B–S3	1.02	1.00	Green
Emergency Diesel Generator	591DG01A-S3	2.58	1.84	Yellow
	591TK40A-S3	NA	NA	NA
	591TK41A-S3	NA	NA	NA
	591DG01B–S3	2.71	1.85	Yellow
	591TK40B–S3	NA	NA	NA
	591TK41B–S3	NA	NA	NA
Essential Chilled water	633TRN01A-S3	13.82	2.89	Orange
	633CP01A-S3	1.15	1.02	Green
	633CH01A-S3	1.10	1.01	Green
	633PP01A-S3	1.05	1.01	Green
	633CP02A-S3	1.27	1.03	Green
	633CH02A-S3	1.22	1.02	Green
	633PP02A-S3	1.07	1.01	Green
	633PP03A-S3	NA	NA	NA
	633TRN01B–S3	2.84	1.79	Yellow
	633CP01B–S3	1.04	1.01	Green
	633CH01B–S3	1.03	1.01	Green
	633PP01B–S3	1.02	1.00	Green
	633CP02B–S3	1.15	1.01	Green
	633CH02B–S3	1.13	1.01	Green
	633PP02B–S3	1.03	1.00	Green
	633PP03B–S3	NA	NA	NA

maintenance time. However, among the total 68 FEGs, it is assessed that 94 % of the FEGs are either in the 'Green' or 'Yellow' zones, indicating the feasibility of conducting OLM(particularly noteworthy is that the 'Green' zone encompasses 84 % of the total).

The licensee has to establishe the TS, in which maximum unavailability time spans are specified for safety related systems and components. If these time spans are exceeded the reactor has to be shut down. Within this framework of unavailability time spans the TS may also specify requirements for temporarily taking individual trains of safety systems out of service for maintenance purposes. In Hungary, for example, one train (out of three) of the electrical safety supply is allowed to be out of service for maximum 24 h provided that the availability of the other two trains is certified. In Spain, one NPP, for example, performs OLM only in those systems that the allowable outage time is at least 72 h. Additionally, the actual maximum unavailability time span is only 60 % of that defined in Technical Specification[17]. Since there is no established strategy for implementing On-Line Maintenance in domestic nuclear power plants, the risk assessment simply assumed an extension of AOT equivalent to 1.6 times the maintenance time. In other words, instead of extending AOT by only the necessary maintenance time, we assumed a 160 % extension to secure safety margins.

Table 9 presents the increase in risk when extending AOT up to 1.6 times the PM time considering OLM. The increase in risk was calculated using formulas 3) and 4).

$$\Delta CDF_{AVG} = \left(\frac{t_{OOS}}{T_{Cycle}}\right) \times CDF_{OOS} + \left(1 - \frac{t_{OOS}}{T_{Cycle}}\right) \times CDF_{Baseline} - CDF_{Baseline} \tag{3}$$

Table 9
The Average Risk Increasement according to the AOT extension.

System Name	FEG Name	AOT (hr)	ΔCDF_{AVG}.	$\Delta LERF_{AVG}$	Risk Criteria Region
Safety Injection/ Shutdown Cooling	441TRN01A (SI)–S3	112	8.31E-09	5.02E-11	III
	441TRN01B (SI)–S3	112	8.54E-09	6.86E-11	III
Containment Spray	442TRN01A-S3	157	1.29E-09	2.75E-13	III
	442TRN01B–S3	157	1.09E-09	2.75E-13	III
Component Cooling Water	461TRN01A-S3	176	3.34E-07	2.53E-09	III
	461TRN01B–S3	176	1.12E-07	1.13E-09	III
Essential Service Water	462TRN01A-S3	134	2.09E-07	1.53E-09	III
	462TRN01B–S3	134	3.04E-08	6.59E-10	III
Aux. Feedwater Pump Turbine	527TA01A-S3	179	3.87E-08	1.42E-09	III
	527TA01B–S3	179	8.38E-09	1.53E-10	III
Auxiliary Feedwater	542TRN01A-S3	58	9.57E-08	4.83E-09	III
	542TRN01B–S3	58	4.93E-09	8.28E-11	III
Emergency Diesel Generator	591DG01A-S3	283	5.40E-08	1.39E-09	III
	591DG01B–S3	283	5.85E-08	1.42E-09	III
Essential Chilled water	633TRN01A-S3	155	2.41E-07	1.72E-09	III
	633TRN01B–S3	155	3.45E-08	7.23E-10	III

$$\Delta LERF_{AVG} = \left(\frac{t_{OOS}}{T_{Cycle}}\right) \times LERF_{OOS} + \left(1 - \frac{t_{OOS}}{T_{Cycle}}\right) \times LERF_{Baseline} - LERF_{Baseline} \quad (4)$$

When extending AOT to 1.6 times the necessary maintenance time (outage time for PM), all systems fall within Zone III of the change-permitted risk criteria, indicating the feasibility of extending AOT when considering only the risk change.

4. Conclusion

To assess the feasibility of OLM for safety-related systems in the APR1400 nuclear power plant, FEGs were developed for each system. Subsequently, the risk changes associated with preventive maintenance for each FEG were evaluated. The FEGs were developed by analyzing the functions of each system, categorizing the equipment or trains by system, considering the scope of OLM. In total, 78 FEGs were developed for 4450 facilities within the target systems, with a total of 842 associated preventive maintenance items. The systems identified for OLM based on comparing the required maintenance time with AOT were Safety Injection, Auxiliary Feedwater, and Essential Chilled Water. However, considering the use of only 60 % of AOT as maintenance time, the systems assessed for OLM were Auxiliary Feedwater and Essential Chilled Water. Additionally, the Shutdown Cooling system was deemed feasible for OLM due to its design characteristics not subject to LCO during operation in the APR1400 design. For the remaining systems, it appeared that AOT extensions were necessary to conduct OLM. Furthermore, in cases where the system design includes redundancy with two or more trains, if maintenance during power operation is conducted on the remaining trains while one train remains operational, it is considered not subject to LCO. Therefore, it is presumed that OLM would be possible in such scenarios. The transient risk increase due to preventive maintenance was within Region III according to the NUMARC93-01 standard across all systems, indicating the ability to arrange equipment properly for preventive maintenance during operation. However, based on the CDF (LERF) increase rate criteria in domestic nuclear power plants, the A-train maintenance of Component Cooling Water, Essential Service Water, Essential Chilled Water, and Auxiliary Feedwater Systems was evaluated as Orange, requiring risk reduction measures for preventive maintenance during operation.

Considering the preventive maintenance time during power operation and extending the current AOT up to 1.6 times the maintenance duration, the increase in risk falls within Zone III of the allowable risk change criteria. Judging solely based on the change in risk, it appears that extending the AOT might be permissible. OLM allows for a decentralized distribution of maintenance resources, focusing on the planned outage period. This decentralization improves maintenance quality, securing the reliability of critical components related to safety. Ultimately, it is possible to continusly improve both the safety and capacity factor of nuclear power plants. For timely execution of preventive maintenance during operation in domestic nuclear power plants, a clear and reasonable regulatory policies based on risk information by regulatory authorities are impotant. Additionally, efforts from the operator's perspective, such as systematic work management and the establishment of risk mitigation plans in advance, are necessary.

CRediT authorship contribution statement

Jung-Wun Kim: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization, Writing – original draft, Methodology, Data curation, Conceptualization. **YoungJu Lee:** Writing – review & editing, Project administration, Formal analysis. **Weon Gyu Shin:** Writing – review & editing, Methodology.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

The authors(Jung-Wun Kim, Young-Ju Lee, Weon Gyu Shin) declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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