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Determination of Performance Indicator Thresholds Based on Typical PSA Results

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Abstract

Typical probabilistic safety assessment (PSA) results were used to estimate the performance indicator (PI) thresholds of unplanned reactor scram (URS) and safety system unavailability (SSU) for Korean nuclear power plants (NPPs). The changes in core damage frequency (ΔCDFs) of 10^{-6}/yr, 10^{-5}/yr, and 10^{-4}/yr were adopted as the risk criteria in setting up the PI thresholds. The PI thresholds for the URS were estimated using information pertaining to the initiating event frequencies, the CDF, and the CDF contribution of each initiating event. The PI thresholds of the SSU were estimated using information on the unavailability, the Fussell-Vesely importance, and the CDF.

Key Words : performance indicator thresholds, unplanned reactor scram, safety system unavailability, probabilistic safety assessment, core damage frequency

1. Introduction

Most of the nuclear industries and regulatory bodies throughout the world have developed and used quantitative performance indicators (PIs) to enhance the performance of nuclear power plants (NPPs), to satisfy the rights of the public to be aware of the plant safety status, and to implement an effective and efficient regulatory oversight on NPP operations [1,2]. As risk informed regulations and applications (RIR&A) become active throughout the world, PIs have become the basis for performance-based and risk-informed regulation [3]. However, as conventional PIs cannot properly reflect design characteristics, operational experiences, and risk information for individual NPPs, the U.S. Nuclear Regulatory Commission (USNRC) [4-6] and the European Union [7] are actively studying methods of developing risk-based PIs using the results from probabilistic safety assessments (PSAs).

The determination of the PI thresholds is generally dependent on the PI users' philosophy for their usage. The USNRC defined PI thresholds in consideration of risk and regulatory responses to different levels of licensee performance [8]. The USNRC classifies the licensee's performance levels into four color-coded categories: Green, White, Yellow, and Red [3, 8-10].

The PIs related to Level 1 PSA in the USNRC Reactor Oversight Process (ROP) involve initiating events and mitigating systems. The Green/White thresholds for these PIs were developed by analyzing the operational data of NPPs [8]. The White/Yellow and Yellow/Red thresholds were established using insights from PSA sensitivity analyses [8]. The various PI thresholds were then finally determined from an integrated perspective using engineering judgments.

The Korea Institute of Nuclear Safety (KINS) PIs are used to inform the public of the safety status and trends of Korean NPPs [11]. Table 1 shows the safety PIs being used by the KINS. As with the ROP PIs of the USNRC, the performance levels of each PI shown in Table 1 are classified into four categories: Green, Cyan, Yellow, and Orange. Every three months, the performance levels of safety PIs for Korean NPPs are displayed as one of these four colors on the KINS website [11, 12].

The KINS PIs directly relevant to Level 1 PSA are the ones associated with unplanned reactor scram (URS) and safety system unavailabilities (SSU). The safety systems related to the SSU PIs are the high pressure safety injection system (HPSIS), auxiliary feedwater system (AFWS), and emergency diesel generator (EDG) [11, 12]. Table 2 shows the thresholds of the URS and SSU PIs of the KINS according to the performance levels. The Green/Cyan threshold for the URS PI was set up based on Korean NPP operating experience. The thresholds for the SSU PI were established mainly in consideration of the plant's technical specifications. The Cyan/Yellow and the Yellow/Orange thresholds for the URS and SSU PIs were determined based on the corresponding

Table 1. Safety Performance Indicators of the KINS

Safety Performance Evaluation Area	Category	Performance Indicators	Remarks
Reactor Safety	Safety Operation	Unplanned Reactor Scram	
		Unplanned Power Reduction	
	Mitigating Systems	Safety Injection System Availability	
		Emergency Diesel Generator Availability	
		Auxiliary Feedwater System Availability	
	Safety Barrier	Fuel Reliability	
		Primary Coolant Leakage	
		Containment Leakage	Under development
		Emergency Preparedness	
Radiation Safety	On Site	Radiation Collective Dose	
	Off Site	Public Dose	

Table 2. PI Thresholds of the URS and SSU Used by the KINS

Performance Level	Color	URS Thresholds#	SSU Thresholds		
			HPSIS	AFWS	EDG
Superior	Green	< 3*	$<1.5\times10^{-2}$***	$<1.5\times10^{-2}$***	$<2.5\times10^{-2}$***
Good	Cyan	< 6**	$<5.0\times10^{-2}$**	$<5.0\times10^{-2}$**	$<5.0\times10^{-2}$**
Average	Yellow	< 20**	$<10^{-1}$**	$<10^{-1}$**	$<10^{-1}$**
Caution	Orange	> 20**	$>10^{-1}$**	$>10^{-1}$**	$>10^{-1}$**

#: one year base
*: Based on the operating experiences of the Korean NPPs
**: Based on the ROP PI thresholds of the US NRC
***: Based on the technical specifications of the Korean NPPs

values from the ROP program of the USNRC. Meanwhile, a recent state-of-the-art report of the KINS on Korean PIs [10] indicates that, in the future, PSA would be utilized to determine the PI thresholds for all Korean NPPs.

In light of these circumstances, we carried out a pilot study to estimate the thresholds for the URS and SSU PIs for two representative Korean NPPs. In the previous studies presented in SECY 99-007 [8] and NUREG-1753 [4], the thresholds for the URS PIs were determined based on conditional core damage probabilities, while those for the SSU PI were determined by changing the probabilities of the basic events for system fault trees in the PSA models. In this study, the thresholds for the URS and the SSU PI were determined based on typical PSA results without additional works for PSA models. The thresholds for the URS PI were estimated using information on the initiating event frequencies, the CDF, and the CDF contributions of each initiating event. On the other hand, the thresholds for the SSU PI were estimated using information on the component unavailability, the Fussell-Vesely (FV) importance, and the CDF. This study presents an assessment of PI thresholds for Korean NPPs and discusses related problems and proposed resolutions for improvement.

2. Methodology

2.1. Criteria for Establishing PI Thresholds

Two different approaches can be used in setting up criteria for PI thresholds; approaches are based on either absolute or relative changes in the plant risk impact (e.g., core damage frequency) or the system unavailabilities. In this study, absolute criteria were adopted because the use of relative criteria may result in an inconsistency in regulatory affairs, which can confuse the public and the licensees of the NPPs.

For the sake of illustration, the base CDFs for plants A and B are assumed to be 10^{-4}/yr and 10^{-5}/yr, respectively. If we adopt the relative approach, a 10% change in the CDF for plant A and a 20% change in the CDF for plant B is 10^{-5}/yr and 2.0×10^{-6}/yr, respectively. The correspondingly increased CDFs for plants A and B are 1.1×10^{-4}/yr and 1.2×10^{-5}/yr, respectively. Even though the incremental CDF for plant B is smaller than that for plant A, plant B might be inspected more by the regulatory body than plant A because the relative value of the change in the CDF for plant B (i.e., 20%) is higher than that for plant A (i.e., 10%). Therefore, the absolute approach based on

ΔCDF (= the CDF after the change - the CDF before the change) [4, 13], which has been widely used for risk-informed decision-making, was also adopted in this study in setting up the criteria for PI thresholds. The values corresponding to the changes in plant performance equivalent to 10^{-6}/yr, 10^{-5}/yr, and 10^{-4}/yr [4, 13] in ΔCDF were adopted as Green/Cyan, Cyan/Yellow, and Yellow/Orange thresholds, respectively.

2.2. Method for URS PI Thresholds

The unplanned reactor scram (URS) is defined as the number of unplanned scrams, both automatic and manual, during the previous four quarters, while critical per 7000 hours [8]. Examples of the types of scrams included are those that result from unplanned transients, equipment failures, spurious signals, human errors, or those directed by abnormal, emergency, or annunciator response procedures. Manual scrams of NPPs for planned maintenance are not included.

An internal initiating event in a PSA is defined as any event that perturbs the steady state operation of the NPP. According to the definition of the URS, the summation of all the internal initiating events considered in a PSA can be assumed to be the URS. External events such as fire, flooding, and seismic events are excluded because their occurrence frequencies are so low when compared with internal initiating events. The thresholds for the URS PI can be estimated through the calculation of changed initiating event frequencies corresponding to the plant specific (CDF equal to 10^{-6}/yr, 10^{-5}/yr, and 10^{-4}/yr.

Our equation for setting up the thresholds of the URS PI uses information on the initiating event frequencies, the CDF, and the CDF contribution of each initiating event. The internal CDF events for a NPP, calculated from the summation of the CDFs for each internal initiating event, can be expressed as:

$$CDF = \sum_{i=1}^{n} CDF_i = \sum_{i=1}^{n} f_i \times CP_i \qquad (1)$$

where, CDF : Core damage frequency for all the internal initiating events

f_i : Frequency of the initiating event 'i'

CDF_i : Core damage frequency for the initiating event 'i'

CP_i : Conditional probability that core damage will occur given the initiating event 'i'

If the CDF change depends on a change in only the initiating event frequencies, as in the SECY 99-007 (Appendix H) approach [8], the CDF after the change and the (CDF are represented as:

$$\begin{aligned} CDF' = CDF + \Delta CDF &= \sum_{i=1}^{n} f_i' \times CP_i \\ &= \sum_{i=1}^{n} (f_i + \Delta f_i) \times CP_i \end{aligned} \qquad (2)$$

$$\Delta CDF = \sum_{i=1}^{n} \Delta CDF_i = \sum_{i=1}^{n} \Delta f_i \times CP_i \qquad (3)$$

where, CDF' : The CDF after the change

f_i' : The changed frequency of initiating event 'i'

$\Delta CDF = CDF' - CDF$

$\Delta f_i = f_i' - f_i$

In Appendix H of SECY 99-007 [8], it was assumed that the initiating event frequencies are increased by the same percentage change. Thus, we adopted this same approach in our proposed method. All the initiating events are assumed to increase by the same percentage change according to the increase in ΔCDF. In addition, a new constant 'α' is introduced to represent the same changing rate for each initiating event. Then, ΔCDF and f_i' can be expressed as follows:

$$\Delta CDF = \sum_{i=1}^{n} \Delta f_i \times CP_i = \alpha \sum_{i=1}^{n} f_i \times CP_i = \alpha \times CDF \quad (4)$$

$$f_i' = f_i + \Delta f_i = (1+\alpha) \times f_i \quad (5)$$

where, $\alpha = (\Delta f_i) / f_i = \Delta CDF/CDF$

As the ΔCDF values in Eq. (4) are fixed (i.e., 10^{-6}/yr, 10^{-5}/yr, or 10^{-4}/yr) and the CDF is known, the changing rate of the initiating event, α, and the changed initiating event frequency, f_i', can be estimated. Hence, the URS can be estimated from the summation of the changed initiating event frequencies in Eq. (5). However, the initiating event frequencies in Eq. (5) are generally estimated based on calendar-years. On the other hand, the URS is based on critical reactor-years. Therefore, the URS assessed from Eq. (5) should be adjusted to incorporate the plant availability factor.

As some initiating events seldom occur during a plant's lifetime, they may be excluded from the CDF calculation, as in the approach presented in Appendix H of SECY 99-007 [8]. In this case, the total internal CDF is changed depending on the CDF contribution of each initiating event. From Eqs. (4) and (5), the thresholds for the URS PI can be estimated using information on the initiating event frequencies, the CDF contribution for each initiating event, and the CDF.

2.3 Method for SSU PI Thresholds

The SSU PI unavailability is defined as the average of the unavailabilities of the individual trains that comprise the system, provided that only the successful operation of any single train is required for system success [11]. The unavailability of each train is the ratio of its unavailable hours to the hours it was required to be operable. The train's total unavailable hours is the sum of the time associated with the train test, as well as planned and unplanned maintenance activities that render the train unavailable, and also the fault exposure time [11]. The fault exposure time is an estimate of the time the train was unavailable due to a failure before that failure became known. It is not easy to estimate the fault exposure time using plant documentation (e.g., trouble reports, maintenance logs, operator reports, etc.) because failures are typically detected only during periodic tests and the time of the failure occurrence is often unknown. Several previous studies [4, 8] estimated the thresholds of the SSU PI by increasing the probabilities of the basic events modeled in the system fault trees. Iterative works were performed to estimate the unavailabilities of safety systems corresponding to the plant-specific (CDF of 10^{-6}/yr, 10^{-5}/yr, and 10^{-4}/yr. In this study, the component unavailability, the Fussell-Vesely (FV) importance measure, and the CDF were used to determine the SSU PI thresholds.

In order to derive an expression for SSU PI thresholds, let us express the FV and Birnbaum (BB) importance measures for event 'i' as follows [14]:

$$FV(i) = [R_o - R_i(-)] / R_o \quad (6)$$

$$BB(i) = R_i(+) - R_i(-) \quad (7)$$

where, R_o : base risk,
$R_i(+)$: risk when basic event i fails
$R_i(-)$: risk when basic event i succeeds

The FV importance is a measure of the fractional contribution of the basic event to the overall risk. The BB importance is an interval risk importance measure that is completely dependent on the structure of the system model and is independent of basic event probability.

The CDF can be represented as a risk equation [15, 16]:

$$CDF(B_i) = AxB_i + Y \quad (8)$$

Here, $A \times B_i$ represents the cutsets containing a *specific basic event 'i' of component 'B'*, *while* the remaining cutsets that do not include basic event 'i' are represented by Y. Hereafter, symbols such as 'B_i' in Eq. (8) are used to denote either a Boolean event or its probability or frequency, depending on context [17].

Let us calculate the importance of FV and BB for a specific basic event 'i' of component 'B' in Eq. (8) to express the performance (i.e., unavailability) change of a basic event 'i' in terms of the importance measures. The FV and BB importance measures in Eq. (6) and Eq. (7) can be represented using the risk measure of core damage frequency and Eq. (8) as follows:

$$FV(B_i)=\{CDF_o - CDF_i(-)\} / CDF_o=A \times B_i / CDF_o \quad (9)$$

$$BB(B_i)= \{CDF_i(+) - CDF_i(-)\} = A \quad (10)$$

where, CDF_o : base CDF
$CDF_i(+)$: CDF when basic event 'i' of component 'B' fails
$CDF_i(-)$: CDF when basic event 'i' of component 'B' succeeds

It should be noted that, unless $FV(B_i)$ in Eq.(9) is larger than about 0.2, $FV(B_i)$ is proportional to the unavailability for the basic event 'i' [15]. Let the CDF' (= $CDF+\triangle CDF_i$) be the changed CDF, corresponding to the performance change of a specific basic event '*i*', and the B_i' (= $B_i+\triangle B_i$) be the changed basic event unavailability. Then, the CDF′ and $\triangle CDF_i$ are represented as follows [17, 18]:

$$\begin{aligned} CDF' &= AxB_i' + Y = Ax(B_i+ \triangle B_i) +Y \\ &= AxB_i+ Y + Ax\triangle B_i = CDF + \triangle CDF_i \end{aligned} \quad (11)$$

$$\begin{aligned} \triangle CDF_i &= A x\triangle B_i = BB(B_i)x\triangle B_i \\ &=FV(B_i)xCDFx\triangle B_i /B_i \end{aligned} \quad (12)$$

From Eq. (12), the following expression can be obtained for Bi′ :

$$B_i' = B_i+\triangle B_i = B_i+ (B_i/FV(B_i))x(\triangle CDF_i/CDF) \quad (13)$$

The typical results of a PSA provide us with information on the FV importance for basic events included in the PSA model, but not for components. Thus, the FV importance and the component unavailability are to be estimated using information on the associated basic events. As the failure logic of a component in a PSA consists of 'OR' ed basic events for the component failure modes (e.g., 'fail to start', 'fail to run', etc.), the changed component unavailability B' can be represented as follows:

$$\begin{aligned} B' &= \sum_{i=1}^{n} B'_i = \sum_{i=1}^{n} [B_i+\triangle B_i] = B+\triangle B \\ &= B+ (B/FV(B))x(\triangle CDF/CDF) \end{aligned} \quad (14)$$

where, $\triangle CDF = \sum_{i=1}^{n} \triangle CDF_i,$
$\triangle B = \sum_{i=1}^{n} \triangle B_i,$
$FV(B) = \sum_{i=1}^{n} FV(B_i),$

Eqs. (13) and (14) assume that the unavailability of a basic event or component is proportional to the FV importance value. However, there is no exact proportionality between the unavailability and the FV importance value because of the asymmetry and nonlinearity of PSA logic structures that result from recovery analysis, restrictions on the unavailability of multiple safety system components as imposed by the plant technical specifications, the potential modeling of components in both initiating event fault trees and mitigating system fault trees, and so on. Since the PI thresholds of the URS and SSU applicable to all Korean NPPs should be determined based on information from the sensitivity study results for several Korean NPPs [8, 11], it is assumed that an exact calculation of PI thresholds for each NPP is not required. Therefore, Eqs. (13) and (14) can be used as the basic framework for establishing the SSU PI thresholds, despite the aforementioned shortcomings.

3. Applications

3.1. Estimation of PI Thresholds for the Unplanned Reactor Scram

The methodology presented in Section 2 was applied to two representative Korean NPPs. The CDFs of the two selected Korean NPPs are similar. In Appendix H of SECY 99-007 [8], rare but risk-significant initiating events were not considered in calculating CDFs using Eq. (4). In this study, however, the following three cases were considered in the CDF calculation: 1) all the initiating events are changed; 2) initiating events with frequencies above 5.0×10^{-3}/yr are changed; 3) several selected initiating events, as in the SECY 99-007 approach, are changed. The initiating event frequency of 5.0×10^{-3}/yr was chosen as a criterion because Korean NPPs are typically in operation for more than 100 reactor-years. Thus, this criterion represents events that could occur more than once during a cycle of 100 reactor-years. The URS thresholds for Korean K1 and K2 NPPs for the three cases mentioned above were estimated using Eqs. (4) and (5). Table 3 shows the estimated URS thresholds along with those currently used by the KINS. The URS shown in the third column of Table 3 was estimated from the summation of all the initiating event frequencies for the aforementioned three cases while considering plant availability factors. From Table 3, the following for the URS thresholds can be noted:

- The Green/Cyan thresholds of the K1 and K2 NPPs estimated from the methodology proposed here, which is based on typical PSA results, are lower than those being used by the KINS.
- The URS thresholds in the fourth, fifth, and sixth column of Table 3 show that the more initiating events are considered in the CDF calculation, the lower the thresholds become.
- In cases where all or some of the initiating

Table 3. URS PI Thresholds for the Korean K1 and K2 NPPs

Initiating events considered in the CDF Evaluation	Plant	URS* estimated from Iniating Event	Thresholds* Estimated from Typical PSA Results			Thresholds Used by the KINS [11,12]		
			G/C**	C/Y**	Y/O**	G/C**	C/Y**	Y/O**
1) All IEs	K1	1	1.12	2.19	12.96	3	6	20
	K2	1.22	1.38	2.8	17			
2) IEs above 5.0E-3/yr	K1	0.991	1.82	9.28	84			
	K2	1.208	1.57	4.84	37.5			
3) SECY 99-007 approach (except LOCA, LOOP, SGTR, supporting system failures)	K1	0.967	2.17	13	122			
	K2	0.848	2.33	15.7	149			

*: Plant availability factor assumed to be 80%

**: G/C - Green/Cyan, C/Y- Cyan/Yellow, and Y/O- Yellow/Orange

Table 4. SSU PI Thresholds for the K1 and K2 NPPs Using Basic Event Unavailabilities

System	Plant	Basic Event Unavailability	FV Importance	Thresholds Estimated from Typical PSA Results**			Thresholds Used by the KINS [11,12]		
				G/C*	C/Y**	Y/O**	G/C**	C/Y**	Y/O*
High Pressure Safety Injection System	K1	1.55×10^{-2}	7.12×10^{-4}	Not reached	Not reached	Not reached	1.5×10^{-2}	5.0×10^{-2}	10^{-1}
	K2	2.5×10^{-4}	7.0×10^{-4}	5.05×10^{-2}	5.03×10^{-1}	Not reached			
Auxiliary Feedwater System	K1	3.2×10^{-3}	1.74×10^{-2}	2.55×10^{-2}	2.26×10^{-1}	Not reached	1.5×10^{-2}	5.0×10^{-2}	10^{-1}
	K2	1.07×10^{-3}	2.22×10^{-3}	6.95×10^{-2}	6.85×10^{-1}	Not reached			
Emergency Diesel Generator	K1	4.90×10^{-3}	2.5×10^{-2}	2.84×10^{-2}	2.4×10^{-1}	Not reached	2.5×10^{-2}	5.0×10^{-2}	10^{-1}
	K2	1.42×10^{-3}	5.0×10^{-4}	4.01×10^{-1}	Not reached	Not reached			

*: G/C - Green/Cyan, C/Y- Cyan/Yellow, and Y/O- Yellow/Orange**: The lowest values adopted

events are taken into account in the CDF calculation, as in the SECY 99-007 approach, the thresholds for the K2 NPP are higher than those for the K1 NPP. However, where only the initiating events with a frequency above 5.0×10^{-3}/yr are included, the thresholds for the K2 NPP are lower than those for the K1 NPP. These results may come from differences in the initiating event analysis methods. For example, the K1 NPP considers a steam generator tube rupture (SGTR) event with a frequency above 5.0×10^{-3}/yr as an initiating event, but the K2 NPP does not.

- As the current Green/Cyan threshold of the KINS is higher than the Green/Cyan thresholds for the two NPPs in this study, the threshold should be changed if the thresholds are determined using only a PSA.

As shown in Table 3, if the SECY 99-007 approach is used for the CDF calculation, the Yellow/Orange thresholds for the URS PI of the two NPPs become unrealistically high in comparison with the other two cases. Meanwhile, the case where all the initiating events were assumed to contribute to the CDF calculation provides us with reasonable thresholds for the URS PI as compared with the other two cases shown in Table 3. Thus, establishing the URS PI thresholds in consideration of all the initiating events is the best approach. As mentioned earlier in this paper, the setting up of the PI thresholds should be consistent with the PI users' philosophy for their use. The PIs may not be actively used if the PI thresholds are determined solely by quantitative analyses.

The study results indicate that significantly different URS thresholds are obtained depending on the analysis method of the initiating events, even if the base CDF values for the two NPPs are similar. In order to resolve this problem, it appears that a unified method to analyze initiating events should be used in the PSAs for all Korean NPPs. Furthermore, the PSA models for representative Korean reactor types should be used for setting up URS thresholds that are applicable to all Korean NPPs.

Table 5. SSU PI Thresholds for the K1 and K2 NPPs Using Component Unavailabilities

System	Plant	Component Unavailability	FV Importance	Thresholds** Estimated from Typical PSA Results			Thresholds Used by the KINS [11,12]		
				G/C*	C/Y*	Y/O*	G/C*	C/Y*	Y/O*
High Pressure Safety Injection System	K1	2.05×10^{-2}	1.04×10^{-3}	Not reached	Not reached	Not reached	1.5×10^{-2}	5.0×10^{-2}	10^{-1}
	K2	2.26×10^{-3}	6.89×10^{-2}	6.87×10^{-3}	4.84×10^{-2}	4.64×10^{-1}			
Auxiliary Feedwater System	K1	8.03×10^{-3}	1.06×10^{-1}	1.71×10^{-2}	9.89×10^{-2}	9.17×10^{-1}	1.5×10^{-2}	5.0×10^{-2}	10^{-1}
	K2	1.91×10^{-2}	1.22×10^{-1}	4.12×10^{-2}	2.4×10^{-1}	Not reached			
Emergency Diesel Generator	K1	1.47×10^{-2}	2.34×10^{-1}	2.21×10^{-2}	8.94×10^{-2}	7.62×10^{-1}	2.5×10^{-2}	5.0×10^{-2}	10^{-1}
	K2	3.72×10^{-1}	2.61×10^{-1}	5.72×10^{-1}	Not reached	Not reached			

* : G/C - Green/Cyan, C/Y- Cyan/Yellow, and Y/O- Yellow/Orange

** : The lowest values adopted

3.2. Estimation of PI Thresholds for Safety System Unavailabilities

As the current SSU PI for Korean NPPs includes unavailability due to not only planned and unplanned maintenance but also to the fault exposure time, it does not have a one-to-one correspondence with a parameter in PSAs. In PSAs, the unavailability parameter due to planned and unplanned maintenance typically represents only the ratio of time when the train is out of service to the time it is required to be available. It is generally modeled into a major component in the system train. The fault exposure time may be incorporated into reliability parameters for a PSA component. If the unavailability parameter due to only planned and unplanned maintenance (hereafter referred to as 'basic event unavailability') was used in Eq. (13) in setting up the SSU PI thresholds, it would likely underestimate the performance thresholds of the SSU PI somewhat because unavailability due to fault exposure time is not considered in Eq. (13). Therefore, in this study, the component unavailability of Eq. (14), estimated from the summation of the unavailabilities of all the basic events for the major component, was also used in estimating the thresholds of the SSU PI for the K1 and K2 NPPs. The FV importance of any train in the SSU PI systems is assumed to be equal to that of a major component in the same train.

Table 4 shows the SSU PI thresholds for the K1 and K2 NPPs using the basic event unavailabilities in Eq. (13). Table 5 shows those using the component unavailabilities in Eq. (14). The meaning of 'not reached' in Tables 4 and 5 is that the $\triangle$CDF calculated for the case where any train of the relevant system is unavailable is less than the corresponding $\triangle$CDF equal to 10^{-6}/yr, 10^{-5}/yr, or 10^{-4}/yr. The estimated PI threshold of each train for the SSU PI systems equivalent to the ΔCDF (10^{-6}/yr, 10^{-5}/yr, and 10^{-4}/yr) is different because of the asymmetry and nonlinearity of PSA logic structures mentioned above in Section 2.3. The lowest values among the SSU PI thresholds estimated from Eqs. (13) and (14) were adopted as the SSU PI thresholds for conservatism. Sample calculations were performed to verify whether these equations are appropriate as a basis for setting up the SSU PI thresholds. Approximate ΔCDFs equivalent to the selected thresholds of Tables 4 and 5 were obtained through the sample calculations.

The study results on the estimation of the SSU PI thresholds show that:

- The thresholds estimated from the basic unavailabilities in Table 4 are higher when compared with those of the current KINS SSU PI. Meanwhile, the thresholds based on the component unavailabilities in Table 5 are different depending on the NPPs and the specific safety systems.
- The higher the unavailability, the lower the thresholds. However, the Green/Cyan threshold for the emergency diesel generator (EDG) of the K2 NPP is high, as shown in Table 5, because the component unavailability of the EDG for the K2 NPP is relatively high.
- The Cyan/Yellow and Yellow/Orange thresholds for the SSU PI of the two NPPs are slightly higher than the corresponding KINS thresholds. Thus, the current KINS SSU PI thresholds are set up somewhat conservatively.
- The high pressure safety injection system (HPSIS) PI thresholds of the KINS are very conservatively set up compared to those of the K1 NPP. Meanwhile, the HPSIS Green/Cyan threshold of the KINS is optimistically determined compared to that of the K2 NPP.

From Tables 4 and 5, the SSU PI thresholds for the HPSIS of the K1 NPP were estimated as 1. In other words, even if any train of the HPSIS for the K1 NPP is unavailable during a power operation, the ΔCDF is not reached for 10^{-6}/yr, 10^{-5}/yr, or 10^{-4}/yr. This indicator is called an insensitive indicator. The PI threshold for the insensitive indicator cannot be estimated. One of the proposed solutions for avoiding the insensitive indicator is to adopt a performance-based approach in setting up the PI thresholds [6].

As mentioned above, the unavailability definition of the current SSU PI for the KINS differs from that of the PSA and the maintenance rule (MR) [11, 19]. To determine the appropriate thresholds of the SSU PI for the Korean NPPs using typical PSA results, it is necessary that the SSU PI and the PSA both use the same definition for the unavailability. It is also necessary to incorporate the reliability into the PI. The use of a unified definition for the unavailability and unreliability among the PI, the PSA, and the MR will save resources in industries and regulatory bodies for Korean NPPs [1, 2, 18, 19].

4. Concluding Remarks

Typical PSA results were used for estimating the PI thresholds of the URS and the SSU for the Korean NPPs. Two representative Korean NPPs were selected for this study. The ΔCDFs of 10^{-6}/yr, 10^{-5}/yr, and 10^{-4}/yr were adopted as the criteria for setting up the PI thresholds. The PI thresholds for the URS were estimated using information on the initiating event frequencies, the CDF contribution of each initiating event, and the CDF. The PI thresholds of the SSU were estimated using information on the unavailability, the Fussell-Vesely importance, and the CDF.

This study points out that the PI thresholds for the URS and the SSU can be estimated using typical PSA results without additional works for PSA models. The major study results in the estimation of PI thresholds for the two Korean

NPPs are: 1) the Green/Cyan thresholds for the URS PI as estimated from the approach proposed here are lower than those currently used by the KINS; and 2) the Cyan/Yellow and Yellow/ Orange thresholds for the SSU PI based on typical PSA results are higher than the corresponding KINS thresholds. In order to establish the PI thresholds based on PSAs, it is recommended that the PSA models for all representative Korean reactor types be used.

Thus far, more than 10 PSA projects for Korean NPPs have been completed and several PSA projects are underway. However, there are no databases for component failure events or initiating events for all Korean NPPs. These databases are essential for not only PI development and PSA guality, but also for risk informed regulations and applications (RIR&A) for the Korean NPPs. Therefore, it is necessary to systematically study the system and component reliability characteristics and initiating events for all Korean NPPs. For the active development and usage of risk-based PIs, PSA requirements for PIs as well as the relationship between the SSU PI thresholds and the performance criteria for the unavailability/unreliability as employed in the MR should be studied [1, 2].

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