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Original Article

IDENTIFICATION OF HUMAN-INDUCED INITIATING EVENTS IN THE LOW POWER AND SHUTDOWN OPERATION USING THE COMMISSION ERROR SEARCH AND ASSESSMENT METHOD

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ABSTRACT

Human-induced initiating events, also called Category B actions in human reliability analysis, are operator actions that may lead directly to initiating events. Most conventional probabilistic safety analyses typically assume that the frequency of initiating events also includes the probability of human-induced initiating events. However, some regulatory documents require Category B actions to be specifically analyzed and quantified in probabilistic safety analysis.

An explicit modeling of Category B actions could also potentially lead to important insights into human performance in terms of safety. However, there is no standard procedure to identify Category B actions. This paper describes a systematic procedure to identify Category B actions for low power and shutdown conditions. The procedure includes several steps to determine operator actions that may lead to initiating events in the low power and shutdown stages.

These steps are the selection of initiating events, the selection of systems or components, the screening of unlikely operating actions, and the quantification of initiating events. The procedure also provides the detailed instruction for each step, such as operator's action, information required, screening rules, and the outputs.

Finally, the applicability of the suggested approach is also investigated by application to a plant example.

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1. Introduction

Human induced-initiating events, also called Category B actions in human reliability analysis (HRA), are operator actions that may lead directly to initiating events in probabilistic safety assessment (PSA) [1]. Category C actions are mitigating actions after an initiating event occurs, whereas Category A actions are operator actions—in maintenance, testing, or calibration—that can disable the actuation of safety systems after an initiating event occurs. Most conventional PSAs typically assume that the frequency of initiating events already includes human-induced initiating events. Sometimes, human-induced initiating events may not be dealt with in the full power PSA because of their infrequent occurrence.

Category B actions need to be more strongly highlighted in the low power and shutdown states. Many events initiated by human actions have been reported to occur during low power and shutdown [2]. A regulatory document in Switzerland recommends Category B actions to be specifically analyzed and quantified in the PSA [3]. In addition, a Nuclear Regulatory Commission report, NUREG-1792, also stresses that an explicit modeling of Category B actions could potentially lead to important insights into human performance in terms of safety [4]. However, no standard procedure to identify and quantify Category B actions is available for the low power and shutdown states.

According to the Operational Performance Information System (OPIS) database [5], 21 events that were caused by human error in Westinghouse-type plants in the low power and shutdown condition have been reported to the Korean regulator since 1991. Among these 21 events, 19 events (about 90%) were caused by error of commission (EOC), whereas only two events were due to error of omission. The EOC figure is especially notable in the low power and shutdown condition because a number of tasks including lowering/raising power, maintenance, testing, and calibration are carried out by the operators.

This paper suggests a procedure to identify and quantify human-induced initiating events, i.e., Category B actions, during the low power and shutdown states in nuclear power plants (NPPs) using the Commission Error Search and Assessment (CESA) method. With the modification of the CESA method, the procedure includes several steps to identify and quantify Category B actions, such as defining plant operating state (POS), selecting types of major initiating events, analyzing the operator actions, screening unlikely operator actions, and quantifying operator actions. To investigate the feasibility of the approach, this paper also applies the approach to an example plant, i.e., the Optimized Power Reactor 1000 (OPR1000).

2. Development of a procedure for identifying Category B actions

2.1. CESA

The CESA method, developed by the Paul Scherrer Institute, Switzerland, is suggested to identify potentially risk-significant EOCs in the mitigating actions, also called Category C actions [6,7]. The CESA's basic concept is to analyze the key actions required in the operating procedures. The method consists of four steps required to investigate EOC events that take place between human actions and procedures. Fig. 1 shows the basic structure of the CESA method.

The objective of Step 1 is to define and catalog possible operator actions to be considered as potential causes of system failure. As a final product of this step, a catalog of actions that are required in procedural responses to plant scenarios is established. This is done by reviewing the procedures that guide the operators in their responses to plant trips and to the initiating events. The result of Step 1 is a list of actions that could be carried out as operator responses to plant trips and the initiating events. The subsequent CESA search focuses on the actions included in the catalog to determine the conditions under which the performance of these actions is inappropriate.

The aim of Step 2 is to define EOC events; these are defined as operator actions that may contribute to failures of PSA top events. A first screening is performed in this step by focusing on the PSA top events, which have a Risk Achievement Worth (RAW) value above a given threshold. The catalog of candidate actions from Step 1 is compared against the fault trees for the PSA top events.

Next, this set of EOC events is reduced by considering the case-by-case basis of the consequences of contributing candidate actions on the PSA top event as expressed by the fault tree structure. The result of Step 2 is a more manageable number of EOC events for which specific scenarios will be subsequently identified. The level of screening is determined by the RAW threshold used, which prioritizes EOC events.

Specific EOC scenarios are identified in Step 3; these scenarios are defined in terms of specific accident sequences. The search is prioritized by analyzing the top PSA sequences, i.e., those with the largest contribution to the core damage frequency (CDF; Fussell–Vesely importance). As in Step 2, a threshold (e.g., the Fussell–Vesely importance or RAW) is defined to determine the level of screening. The identified accident sequences with potential EOC contributions are next grouped into sequences with similar performance contexts.

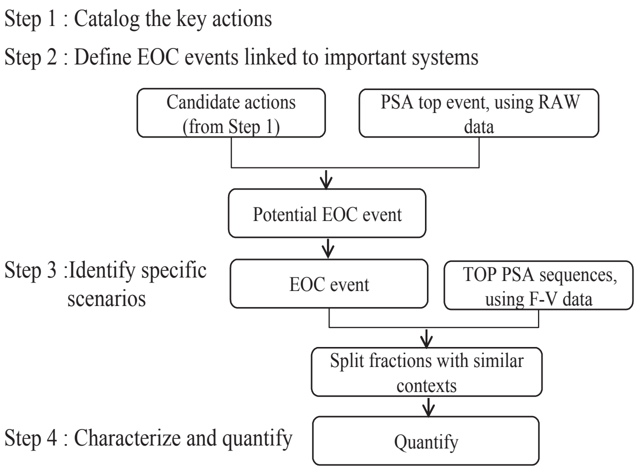

Fig. 1 – Basic structure of Commission Error Search and Assessment (CESA) method.

The result of Step 3 is a set of scenario-specific EOC split fractions in which each split fraction is an EOC event in a specific accident sequence or a set of sequences with similar performance conditions.

In Step 4, qualitative and quantitative analyses are performed to determine the risk impact of the identified EOC situations and to provide insights into reducing the risk contributions of these EOCs. The risk impact of the EOC split fractions then basically consists of the additional frequency of the sequences (cut sets) calculated using the EOC split fraction probability. This calculation accounts for the integration of the EOC split fraction into the accident sequence context. In many sequences, core damage only results when the EOC is combined with subsequent hardware failures and operator action failures.

In the quantification of an EOC split fraction, within the EOC paths, dependencies have to be considered. Similarly, dependency has to be analyzed in accident sequences in which the EOC is combined with preceding or subsequent operator action failures (these could be errors of omission and EOCs).

2.2. *Procedure for identifying Category B actions*

This study suggests a procedure to identify Category B actions during the low power and shutdown states using the CESA method. In order to apply the CESA method for this purpose, it is necessary to modify it, for several reasons. First, the CESA method was originally intended to identify risk-important EOCs of mitigating actions (i.e., Category C actions) in emergency operating procedures. However, human-induced initiating events are more often related to other procedures such as general operating procedures, abnormal operating procedures (AOPs), and maintenance procedures. Second, the importance measures of PSA (e.g., the Fussell–Vesely and RAW values) are not available for prioritizing the EOCs that introduce initiating events. The importance measure values evaluate the importance of failures and human errors that are modeled in the PSA. However, human errors that may introduce initiating events are normally not included in the PSA model. Thus, other criteria need to be developed to prioritize or screen out Category B actions. In this light, this study suggests a modification of the CESA method to identify Category B actions in the low power and shutdown state. The procedure consists of six steps, as shown in Fig. 2.

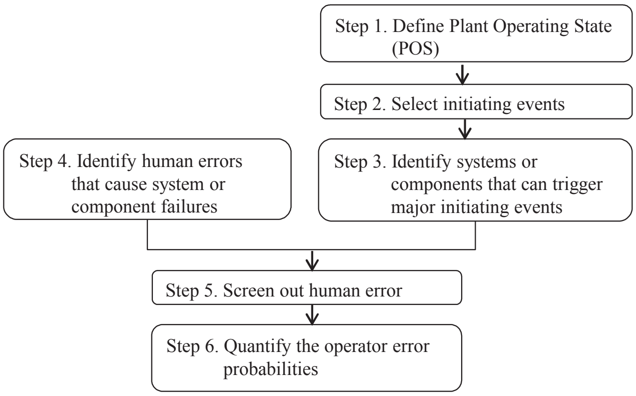

Fig. 2 – Basic structure for proposed procedure.

2.2.1. *Step 1: Define POS*

The first step defines the POS in the low power and shutdown condition. POS is a discrete NPP condition during low power and shutdown state; it is based on the reactor coolant system parameters (e.g., pressure and temperature) and other physical plant conditions. POS is characterized in terms of time after shutdown and the duration of the phases as estimated from plant experience [8]. Even if there is no standard format, POS can be separated into 15 states based on the reactor coolant system parameters and the physical plant conditions [9]. Plant configuration, operator actions, and consequence of operator errors become different depending on the POS. Using the same definition of POS as that used in the PSA has advantages in terms of consistency.

2.2.2. *Step 2: Select initiating events*

The second step is to select important initiating events for the POSs of interest. The following information is used to select the initiating events: (1) contribution of initiating events to the CDF in the low power and shutdown PSA; (2) plant-specific experience about human-induced initiating events; and (3) survey of Category B actions reported from other similar NPPs.

The initiating events that have a large contribution to the CDF are selected. The initiating events can be identified from the PSA results. Plant-specific experiences are also useful because they show vulnerabilities of the plant. If a plant has any experiences of human-induced initiating events, the initiating events are selected for further analysis. The experiences from other NPPs need to be considered. Reported events from similar types of plants or reference plants are reviewed and selected if it is considered that it may happen in the plant of interest. The result of this step is a list of the important initiating events to be analyzed in the next step.

2.2.3. *Step 3: Identify systems or components that can trigger major initiating events*

The third step identifies systems or components that may trigger the initiating events selected in the previous step. The information from AOPs and the piping and instrumentation diagrams (P&IDs) can be used in this step. If the plant has an AOP for an initiating event, the AOP may provide potential causes of the event. For instance, the AOP for the Optimized Power Reactor 1000 MW (OPR1000, Republic of Korea) directly address three potential causes for the loss of shutdown cooling system (SCS), i.e., loss of SCS pump, loss of flow line, or loss of cooling capacity. P&IDs also provide useful information to identify systems and components. This includes information on connections or relations between systems or components. The diagram helps provide a logical understanding of the idea that a failure of the system or of a component can lead to an initiating event. Using this information, this step creates a list of systems or components whose failures could cause an initiating event.

2.2.4. *Step 4: identify human errors that cause system or component failures*

Step 4 identifies human errors that may lead to system or component failures selected in Step 3. At first, operating procedures (e.g., general operating procedures and system operating procedures) are investigated to determine the operator's actions as they are related to the systems or components selected in the previous step. Then, this step identifies EOCs in the action that can cause system or component failures. Table 1 provides examples of EOCs that can be considered in this step. Finally, the result of this step is a list of EOCs that can lead to the initiating events identified in Step 2.

2.2.5. *Step 5: screen out human error*

This step eliminates EOCs that may have a very low frequency of occurrence. This can reduce the effort spent on quantifying those EOCs in the next step. Step 5 applies the screening criteria to the EOCs resulting from the previous step. This study suggests four criteria for the screening. (1) If there is a compelling indication of operator error in the main control room and if there is sufficient time to recover from the error before it introduces an initiating event, the EOC can be screened out. (2) If the next shift can detect an error by checking the status of systems or components, and if this checking activity is compulsory according to the procedures, and there is sufficient time to recover from the error before it introduces an initiating event, then the EOC can be eliminated. (3) If an EOC can be automatically recovered from or may not lead to an initiating event due to the plant configuration in the POS (e.g., the system or component is bypassed or disabled in a specific POS), then the EOC can be eliminated from further analysis. (4) If a specific aid (e.g., tags attached to valves or components) is implemented to prevent operator error and, as a result, the EOC is unlikely to occur, then the EOC can be screened out.

2.2.6. *Step 6: quantify the operator error probabilities*

Step 6 estimates human error probabilities (HEPs) for the EOCs selected in the previous step. Finally, HEP will be a part of the frequency of the initiating event. This step follows the CESA quantification method. The quantification of CESA consists of six steps as follows: (1) define the EOC opportunity; (2) estimate the reliability index under the nominal scenario context; (3) determine the prior value of the total EOC probability; (4) evaluate PSA impact; (5) identify adverse contexts and determine their probabilities; and (6) evaluate adverse contexts and determine the final value of the total EOC probability.

The quantification method of CESA includes relatively complicated steps, compared with other HRA methods. Thus, the detailed explanation would be out of scope in this paper. The details of the quantification method are provided by Reer [10].

Table 1 – Examples of errors of commission (EOCs).

Error type	Specific effect
Action of wrong control	Selection wrong control Operate wrong direction
Communication	Wrong command or information (via voice or writing)
Action at wrong time	Error of sequence Error of timing

3. Application

This paper applies the suggested approach to the identification of human-induced initiating events during an outage period of the OPR1000.

3.1. *Step 1: Develop the POS*

The first step defines the POS of the OPR1000. This step may use a definition of POS from the literature, such as NUREG/CR-6144 [8] or IAEA-TECDOC-1144 [11]. For consistency of the PSA, this study uses the same definition as that in the PSA for the OPR1000, as shown in Table 2 [12]. Fifteen POSs are defined in the PSA report. To demonstrate the feasibility of the approach, a range from POS 3 (i.e., “Cooldown with Shutdown Cooling System”) to POS 7 (i.e., “Withdraw Fuel”) is chosen for further analysis.

3.2. *Step 2: Select the initiating event during low power and shutdown state*

Step 2 selects the important initiating events in the POS chosen in Step 1. According to the PSA report for OPR1000, as shown in Fig. 3, two initiating events (i.e., a loss of coolant accident and a loss of shutdown cooling) contribute to > 90% of CDFs.

This study also reviewed plant-specific experiences from the KEPCO International Nuclear Graduate School OPIS database for the period of 1978 to 2013. Several human-induced initiating events have been reported, such as loss of offsite power, loss of coolant accident, and station blackout, as shown in Table 3. In OPR1000 plants, there was one case of loss of offsite power at Hanbit Unit 5. This study chooses the loss of shutdown cooling as an initiating event because it was identified to have the largest contribution to the CDF,

Table 2 – POS of modification results.

POS	Description
1	Low power operation and RX shutdown
2	Cooldown with SGs
3	Cooldown with SCS
4	Drain RCS to midloop
5	Midloop operation
6	Fill for refueling
7	Withdraw fuel
8	Drain RCS to maintenance
9	Reload fuel
10	Drain RCS to Midloop after reloading fuel
11	Midloop operation
12	Refill RCS completely
13	RCS heat-up with RCPs
14	RCS heat-up with SGs
15	RX startup and low power operation

POS, plant operating state; RCPs, reactor coolant pumps; RCS, reactor coolant system; RX, reactor; SCS, shutdown cooling system; SG, steam generators.

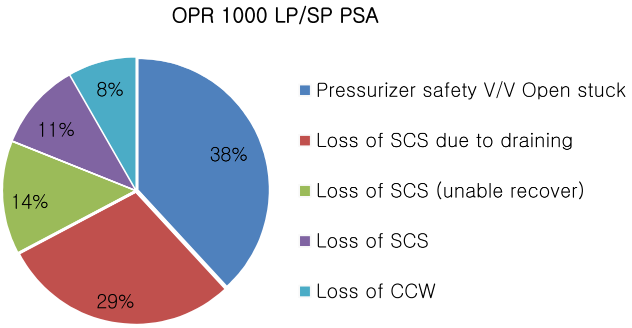

Fig. 3 – Initiating event during low power and shutdown.

although there has been no plant-specific experience of this type of error.

3.3. *Step 3: Identify systems or components*

This step identifies the systems or components that may trigger the loss of shutdown cooling. The AOP of the OPR1000 indicate that the loss of SCS can be caused by three problems: loss of the low pressure safety injection pump, loss of the flow line, and loss of cooling capacity. The SCS shares pumps with the low pressure safety injection system in the OPR1000. This study also investigates the P&IDs to see the relationship between systems, which may influence the failure of SCS. Fig. 4 shows a simplified P&ID to indicate the connections between the SCS and the other systems. After reviewing the AOP and P&IDs, four systems that may initiate the loss of shutdown cooling are identified as follows: (1) Pressurizer; (2) Safety Injection System; (3) Component Coolant Water System; and (4) Chemical Volume and Control System.

3.4. *Step 4: Identify potential human actions that can cause system failure*

This step identifies the operator actions and errors that may trigger the failure of the systems selected in the previous step. This study reviewed the general operating procedures, system operating procedures, and AOPs. Then 16 operator actions performed on the selected systems and the EOCs that may lead to the failure of systems were identified. Table 4 summarizes the operator actions and EOCs that may initiate the loss of shutdown cooling detailed in POSs 3–7.

3.5. *Step 5: Screen out the selected actions*

This step applies the screening criteria to reduce the number of EOCs. Ten EOCs are eliminated from the 16 EOCs of the previous step and the rest six remains. For instance, the action "Perform rack-out of HPSI circuit breaker" is removed based on the fourth criterion mentioned in section *Step 5: screen out human error* because the operator must attach a tag to the circuit break for this action. Thus, 10 EOCs are eliminated in

Table 3 – Plant experience of initiating event during low power and shutdown state.

Event	Description	Date
LOCA	SI signal actuated due to pressurizer safety valve opening	May 25, 2008 Kori-3
LOOP	LOOP signal and EDG start signal occurred due to human error	Apr 4, 2011 Kori-3
	EDG started automatically due to loss of voltage for C-1E bus	Dec 12, 2010 Hanbit-5
	Loss of offsite power occurred	Jun 19, 2004Wolsong-2
SBO	LOOP occurred and EDG failed to start	Feb 9, 2012 Kori-1

EDG, emergency diesel generator; LOCA, loss of coolant accident; LOOP, loss of offsite power; SBO, station blackout.

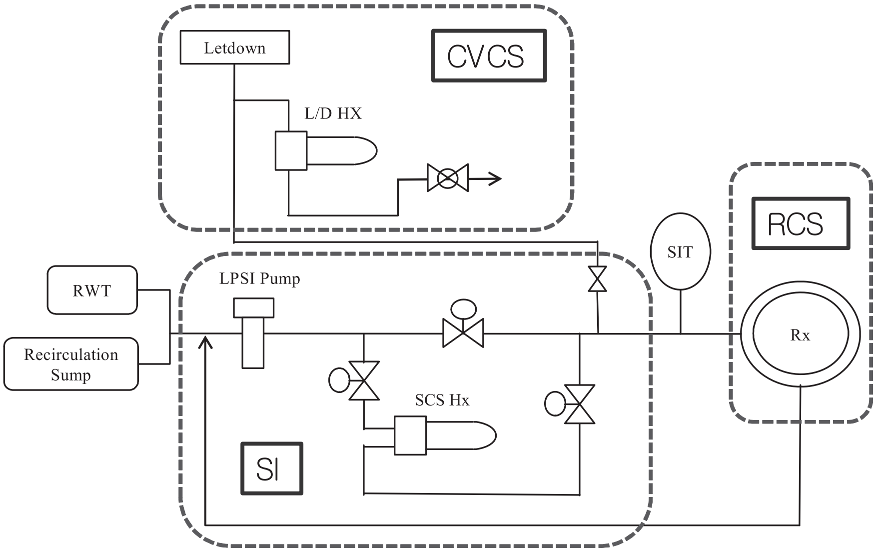

Fig. 4 – Simplified piping and instrumentation diagram (P&ID) for shutdown cooling system.

Table 4 – Potential operator actions and EOCs in POSs 3–7.

Cause	System or component	Procedures (ID)	Step/activity	Operator action	EOC type
Loss of pump	SI	Operating procedure (3005)	5.37.1 Request I&C team to bypass ESFAS signal	Perform bypass signal	Selection of wrong control
		Operating procedure (3005)	5.37.2 HPSI Circuit Breaker rack-out	Perform rack-out for specific component	Selection of wrong pump owing to miscommunication
		Operating procedure (3005)	5.37.3 CSP Circuit Breaker rack-out	Perform rack-out for specific component	Selection of wrong pump owing to miscommunication
		System procedure (3441B)	6.1.6 Perform pump start-up check	Perform vent activity	Selection of wrong control
		System procedure (3441B)	6.2.6 4) Perform pump start-up check	Perform vent activity	Selection of wrong control
	CVCS	Operating procedure(3006)	5.2.22 Control the level of RCS using controller	Control the controller	Operation of wrong direction
Loss of flow line	SI	Operating procedure (3005)	5.30 Bypass low pressure of PZR signal	Bypass CPC trip function	Error of timing
		System procedure(3441B)	6.4 Change line for purification	Open/close valve	Error of sequence
	CVCS	Operating procedure (3005)	5.41.10 IA Cooling source change	Open/close valve	Selection of wrong control
		Operating procedure(3005)	5.45.3 3) Let down flow control using flow controller	Adjust controller demand	Operation of wrong direction
		Operating procedure(3005)	5.45.4 2) Let down flow control using flow controller	Adjust controller demand	Operation of wrong direction
		System procedure (3441B)	6.3.1 4) Purification low control using flow controller	Adjust controller demand	Operation of wrong direction
	PZR	Operating procedure (3005)	5.42.1 PZR spray valve open to reduce RCS pressure	Adjust controller demand	Operation of wrong direction
		Operating procedure (3005)	5.42.2 Adjust the number of PZR heaters	Turn heater on/off	Selection of wrong control
		Operating procedure (3005)	5.45.3 1) PZR spray valve open to reduce RCS pressure	Adjust controller demand	Operation of wrong direction
		Operating procedure (3005)	5.45.3 2) Adjust the number of PZR heaters	Turn heater on/off	Selection of wrong control

CPC, Core Protection Calculator; CSP, Containment Spray Pump; CVCS, Chemical Volume and Control System; EOC, error of commission; ESFAS, Engineered Safety Feature Actuation System; HPSI, High Pressure Safety Injection; I&C, Instrumentation & Control; IA, Instrument Air; PZR, pressurizer; RCS, reactor coolant system; SI, Safety Injection System.

Table 5 – Eliminated EOCs in Step 5.

Cause	System or component	Procedures (ID)	Step/activity	Operator action	Screening criteria
Loss of pump	SI	Operating procedure (3005)	5.37.1 Request I&C team to bypass ESFAS signal	Perform bypass signal	3
		Operating procedure (3005)	5.37.2 HPSI Circuit Breaker rack-out	Perform rack-out for specific component	4
		Operating procedure (3005)	5.37.3 CSP Circuit Breaker rack-out	Perform rack-out for specific component	4
	CVCS	Operating procedure (3006)	5.2.22 Control the level of RCS using controller	Control the controller	1
Loss of flow line	SI	Operating procedure (3005)	5.30 Bypass low pressure of PZR signal	Bypass CPC trip function	3
	CVCS	Operating procedure (3005)	5.41.10 IA Cooling source change	Open/close valve	1
	PZR	Operating procedure (3005)	5.42.1 PZR spray valve open to reduce RCS pressure	Adjust controller demand	1
		Operating procedure (3005)	5.42.2 Adjust the number of PZR heaters	Turn heater on/off	1
		Operating procedure (3005)	5.45.3 1) PZR spray valve open to reduce RCS pressure	Adjust controller demand	1
		Operating procedure (3005)	5.45.3 2) Adjust the number of PZR heaters	Turn heater on/off	1

CPC, Core Protection Calculator; CVCS, Chemical Volume and Control System; EOC, error of commission; ESFAS, Engineered Safety Feature Actuation System; HPSI, High Pressure Safety Injection; IA, Instrument Air; I&C, Instrumentation & Control; PZR, pressurizer; RCS, reactor coolant system SI, Safety Injection System.

Table 6 – Selected EOCs in Step 5.

Major Accident	System or component	Procedures	Step/activity	Operator action	EOC type
Loss of pump	SI	System procedure (3441B)	6.1.6 Perform pump start-up check	Perform vent activity	Selection of wrong control
	SI	System procedure (3441B)	6.2.6 4) Perform pump start-up check	Perform vent activity	Selection of wrong control
Loss of flow line	SI	System procedure (3441B)	6.4 Change line for purification	Open/close valve	Error of sequence
	CVCS	Operating procedure (3005)	5.45.3 3) Let down flow control using flow controller	Adjust controller demand	Operation of wrong direction
	CVCS	Operating procedure (3005)	5.45.4 2) Let down flow control using flow controller	Adjust controller demand	Operation of wrong direction
	CVCS	System procedure (3441B)	6.3.1 4) Purification flow control using flow controller	Adjust controller demand	Operation of wrong direction

CVCS, Chemical Volume and Control System; EOC, error of commission; RCS, reactor coolant system; SI, Safety Injection System.

Table 7 – HEPs of six EOCs.

Cause	Step/Activity	EOCs	HEPs (/demand)	Frequency (/year)
Loss of pump	6.1.6 Perform pump start-up check	Selection of wrong control	3×10^{-3}	2×10^{-3}
	6.2.6 4) Perform pump start-up check	Selection of wrong control	3×10^{-3}	2×10^{-3}
Loss of flow line	6.4 Change line for purification	Error of sequence	4×10^{-2}	2.67×10^{-2}
	5.45.3 3) Let down flow control using flow controller	Operation of wrong direction	3×10^{-4}	2×10^{-4}
	5.45.4 2) Let down flow control using flow controller	Operation of wrong direction	3×10^{-4}	2×10^{-4}
	6.3.1 4) Purification flow control using flow controller	Operation of wrong direction	4×10^{-2}	2.67×10^{-2}
Total (POSs 3–7)			8.7×10^{-2}	5.78×10^{-2}

EOCs, errors of commission; HEPs, human error probabilities; POS, plant operating state.

this step. Table 5 shows the eliminated EOCs and the criteria applied. The result of Step 5 is the identification of the final six EOCs that will be quantified in the next step as shown in Table 6.

3.6. *Step 6: Quantify HEPs*

This step estimates the HEP for the six EOCs using the CESA quantification method. The CESA quantification method mainly consists of two stages [10]. The first stage is to evaluate nominal scenario conditions and quantify the HEP under the given conditions. The estimated HEP is multiplied with the recovery factor for quantification. However, recovery actions are not taken into account in this study because these EOCs immediately initiate the loss of shutdown cooling. Then, the second stage comprises the search for adverse contexts (i.e., conditions worse than nominal) and the estimation of the final HEPs. The HEPs of the six EOCs during POSs 3–7 are calculated as shown in Table 7. The HEPs are also converted to the annual frequencies for use as an initiating event frequency. It is assumed that the overhaul is carried out every 18 months and the action is taken once per overhaul.

4. Discussion

The PSA of the OPR1000 assigns 1.89×10^{-6} as the frequency of loss of shutdown cooling for POSs 3–7. The approach of this study estimates the probability of human errors that may initiate a loss of shutdown cooling to be 5.78×10^{-2} for the same period. Two possible reasons can be considered for the reason for the probability of human-induced events being higher than the frequency of the initiating event used in the PSA. One is that the current PSA may not sufficiently take into account the probability of human-induced initiating events in the low power and shutdown condition. The operating experiences from the OPIS and from this study commonly indicate that human induced-initiating events in the low power and shutdown condition are more probable than the estimate given in the PSA. However, the current PSA simply assumes that the frequency of initiating events includes cases caused by human error. The other reason for this discrepancy of probability is that the CESA quantification method may overestimate the probability of human error for Category B actions. Similar to other HRA methods, the CESA quantification method focuses on Category C actions, i.e., mitigating actions. In the analysis of Category C actions, many HRAs divide operator actions into diagnosis and execution, and quantify these two types of actions separately. However, diagnosis action may be trivial or eliminated because there are no abnormal indications in the low power and shutdown condition. Thus, the error probability of the diagnosis step needs to be excluded in the analysis of Category B actions. Another reason for the overestimation is that the CESA method has no way to credit actions performed by independent checkers. To reduce HEPs, the OPR1000 allocates an independent checker who observes and monitors important operator actions simultaneously. These checkers may detect operator errors before they are committed. This independent checking is different from recovery, which happens after a human error, which is credited by most HRA approaches. If this independent checking is credited in the analysis, the error probability of Category B actions would seem to decrease.

In conclusion, this paper suggests an approach based on the CESA method to identify human-induced initiating events during the low power and shutdown state. This approach can be used to systematically identify Category B actions. This paper also applied the approach to identify a loss of shutdown cooling accident caused by human error at POSs 3–7 for OPR1000. The final probability of initiating events can be used to update the current frequency of initiating events during low power and shutdown PSA.

Conflict of interest statement

There is no conflicts of interest regarding this manuscript.

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