Analysis of Human-Induced Initiating Events in the LOOP Scenario

Awwal Mohammed Arigi[a], Jooyoung Park[a], and Jonghyun Kim*[a]
[a] Department of Nuclear Engineering, Chosun University, Gwangju, Republic of Korea

Abstract: Human errors have been identified in various studies as real and potential contributors to nuclear power plant incidents. Human errors can be either considered as errors of omission (EOO) or errors of commission (EOC). EOCs account for a significant portion of the human-induced initiating events (which are category-B actions). This study attempts to analyze human-induced initiating events, particularly those in the loss of offsite power (LOOP) scenario of an advanced pressurized water reactor (PWR) plant. The current issues in probabilistic safety analysis (PSA) for many countries includes the multi-unit PSA/HRA. The LOOP is identified as a dominant scenario affecting multiple units simultaneously and thus selected for a case study. This work suggests the use of a search scheme similar to other known methods for identifying EOCs. The use of risk importance measures from single point vulnerability fault trees is suggested to select the important systems. Thereafter, the important human actions and human-induced initiators are identified based on maintenance and test procedures. The quantification method suggested is a modified cause-based decision tree (CBDT) method where the failures due to the system information-to-operator interface and the operator-to-procedure interface are considered.

Keywords: PSA, Human error, Human reliability analysis, Human-induced initiator.

1. INTRODUCTION

Probabilistic safety analysis (PSA) have long been established as a veritable part of assuring the safety of nuclear power plants (NPPs). Human reliability analysis (HRA) and in particular, Human error probabilities (HEPs) can serve as input to the overall plant PSA. Meanwhile, human errors have been identified in various studies as real and potential contributors to nuclear power plant incidents.

Human errors can be either considered as errors of omission (EOO) or errors of commission (EOC). In the years before the early 90's, PSAs of nuclear power plants focused on the EOOs with reference to the operators' use of emergency operating procedures (EOPs) or abnormal operating procedures (AOPs) after an initiating event has occurred [1]. Thereafter, attention shifted to analyzing the EOCs but mostly focused on category-A (pre-initiator) human actions and category-C (post-initiator) human actions. Most of the literature on human reliability analysis (HRA) also consider only pre-initiators (latent errors) and post-initiators (during event response) [2]. In fact, according to reference [3] more recently, in some situations both the pre-initiators and human-induced initiators were not regarded as EOCs and only those operator actions that act to aggravate an ongoing scenario were considered. Meanwhile, the category-B actions which are human interactions that initiate a scenario are seldom explicitly identified in PSAs and analyzed in terms of specific causes [4].

The EOCs account for a significant portion of the human-induced initiating events (which is category-B actions). According to the Operational Performance Information System (OPIS) database, 21 events that were caused by human error in Westinghouse-type plants in the low power and shutdown condition were reported to the Korean regulator in the period 1991-2014. Among these, 19 events (about 90%) were caused by EOC, but only two events were due to EOO [5].

According to the committee on safety of nuclear installations (CSNI) [4], the category-B actions which are human actions that initiate a scenario are rarely explicitly identified in probabilistic safety assessments (PSAs) and analyzed in terms of specific causes for nuclear power plant incidents. It is often assumed in conventional PSAs that the experience-based frequencies of initiating events already reflect these type of human actions. However, this assumption may not be satisfactory because experience has shown that human interactions may contribute to both a specific type of initiator (e.g.

**Corresponding author: jonghyun.kim@chosun.ac.kr*

loss of coolant accidents) and the failure of a subsequently required safety function otherwise called latent error (e.g. safety injection) [4]. More importantly, some regulatory documents recommend that the human-induced initiators be specifically identified and quantified for PRA [6].

In spite of the importance of human-induced initiators, there is yet to be a standard and acceptable method to specifically analyze them. All of the HRA methods currently available are developed to analyze either pre-initiators or post-initiators. However, an attempt has been made previously to analyze human-induced initiating events [5]. The work highlighted the fact that other HRA methods used for EOC identification are unsuitable for identifying category-B actions for reasons such as unsuitability of the kind of procedures and PSA importance measures suggested. However, the research only focused on analyzing the human-induced initiators during the low power and shutdown plant operating states. It also inferred that the method used may be inadequate for quantification. Hence, there is a need to develop other methods for analyzing category-B actions.

This study attempts to analyze (identify and quantify) human-induced initiating events, particularly those in the loss of offsite power (LOOP) scenario of an advanced pressurized water reactor (PWR) NPP. The current issues in PRA for many countries includes the multi-unit PRA/HRA. The LOOP is identified as a dominant scenario affecting multiple units simultaneously. Thus, this scenario is selected for a case study such that the method developed could be applicable to both the single- and multi-unit cases. The second section of this paper discusses the offsite power system and the LOOP event. The development process for analyzing the category B actions in the LOOP case is addressed in the third section, before discussion and a conclusion respectively in the last two sections.

2. THE LOSS OF OFFSITE POWER EVENT

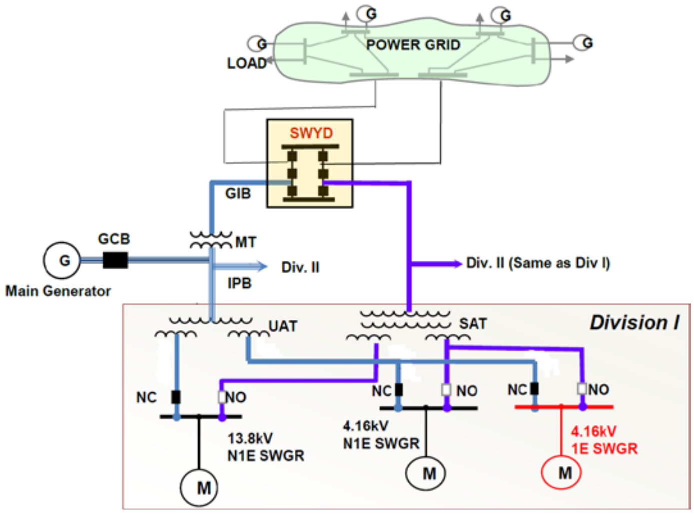
2.1. Definition of LOOP Event

A loss of offsite power (LOOP) event is the simultaneous loss of electrical power to all unit safety buses (class 1E buses) and requiring all emergency power generators to start and supply power to these safety buses. The non-essential buses may also be de-energized as a result of this [7]. A LOOP can occur when the switchyard that is connected to the plant or electric grid fails. An emergency diesel generator (EDG) and an alternate alternating current diesel generator (AAC-DG) are installed to mitigate LOOP and station blackout (SBO) events. LOOP is a special common cause initiating event because it not only causes a reactor shutdown but it may disable one or more of the mitigating systems.

2.2. The Offsite Power Electrical System

The off-site power system is composed of the transmission system (grid) and switchyard connecting the plant with the grid. The off-site power system will ideally provide AC power to the plant during all modes of a NPP operation. It also provides transmission lines for out-going power to the transmission grid. There are two transmission lines from different remote substations connected to the switchyard. The electrical system supplies power to the plant safety-related and non-safety systems to ensure their availability under normal and postulated accident conditions. An electrical power system of a nuclear power plant is shown in figure 1. The IPB (Isolated Phase Bus), GCB (Generator Circuit Breaker) and GIB (Gas Isolated Bus) are important parts of the electrical power supply system.

Figure 1: Electrical power system configuration of a NPP [8]



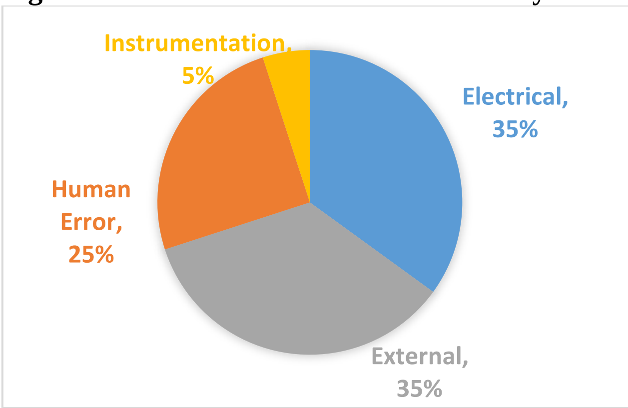
The unit auxiliary transformer (UAT) and standby auxiliary transformer (SAT) are sized to provide the full load requirements of the main buses in their respective load group. The main transformer (MT) transfers a generated power in the NPP to the offsite power system and permits the offsite power source to supply power to the onsite loads. The switchyard functions as a link between the various onsite transformers and the offsite electrical grid system. The switchyard (SWYD) systems and components include bus-lines (for walking and climbing inspections), high-voltage circuit breakers, high-voltage instrument transformers, high-voltage switches, high-voltage bus, high-voltage insulators, batteries, battery chargers, protective relaying, instrumentation and metering, panel boards, among others.

2.3. LOOP Events Review

The LOOP event can be categorized as plant centered, switchyard centered, grid related or weather related [7]. The plant centered LOOP event is one in which the design and operational characteristics of the NPP unit itself play the major role in the cause and duration of the LOOP. Plant-centered failures typically involve hardware failures, design deficiencies, human errors, and localized weather-induced faults. The switchyard centered LOOP event is one in which the equipment or human-induced failures of equipment in the switchyard play the major role in the loss of offsite power. Grid related LOOP events are failures that occurs in the interconnected transmission grid which is outside the direct control of plant personnel. It is also classified as grid related if the transmission lines fail from voltage or frequency instabilities, overload, or other causes that require restoration efforts or corrective action by the transmission operator. Weather related LOOP events are caused by severe or extreme weather which is widespread, not just centred on the site, and it may be capable of major interruption in plant operations.

A broad review of NPP LOOP in four databases including operating experiences in Europe and the United States of America was conducted in the year 2016 [9]. The results show that most of the LOOP events occurred during at power mode, the main contributors were switchyard centered, and plant centered events. Additionally, their root causes were mainly human failure during testing, inspection or maintenance activities. A review of the of the LOOP events in Korean NPPs for the period 1978-2017 based on the OPIS database [10] gives the result shown in figure 2. The human errors were found to contribute as large as 25% to LOOP incidents.

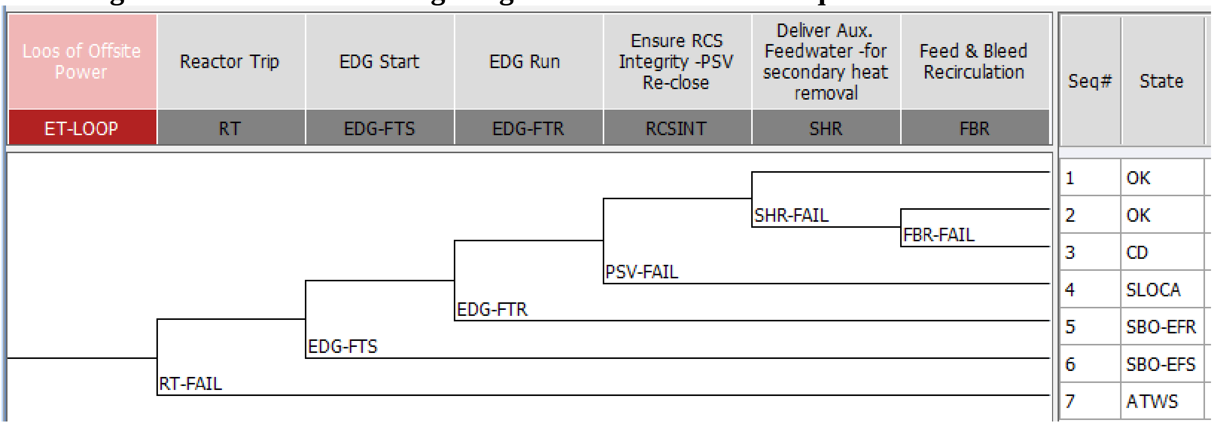
Figure 2: LOOP Events in Korean NPPs by Cause



2.4. Consequence of LOOP

The LOOP is an initiating event that is often given high priority in the nuclear power plant (NPP) safety analysis. It can lead to a station blackout (SBO) when the safety-class emergency diesel power generators fail to start. Figure 3 shows the general event sequence as a result of a LOOP event in a PWR plant. This shows that other transients like small break loss of coolant accident (SBLOCA), SBO, anticipated transient without scram (ATWS) or even core damage (CD) might potentially occur as a consequence of any LOOP event.

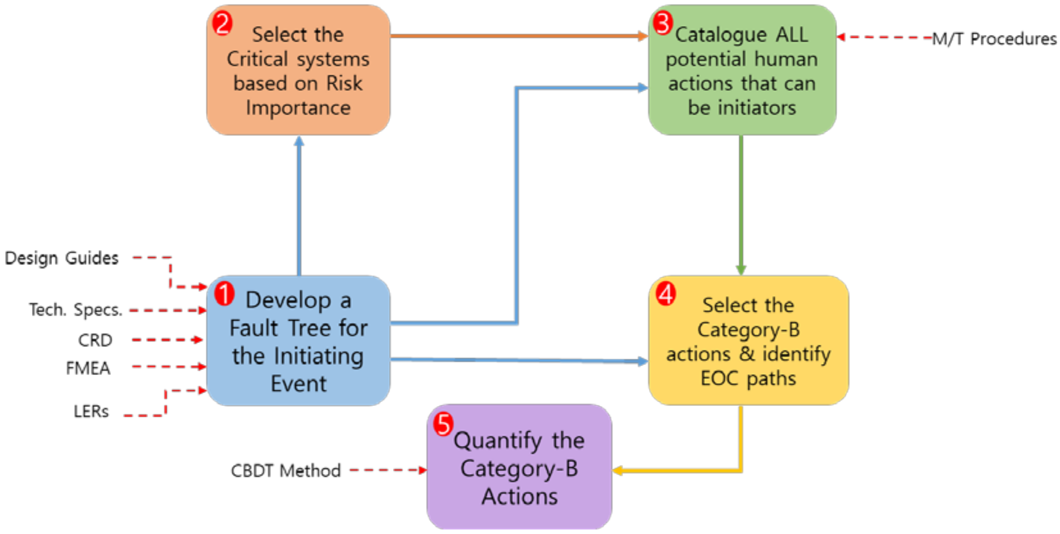
Figure 3: Event tree showing the generic PWR accident sequence for a LOOP event



3. DEVELOPMENT OF A PROCESS FOR ANALYZING HUMAN-INDUCED INITIATORS

This section introduces a systematic process for analyzing the human induced events and describes each step of the process while considering the LOOP scenario. It is assumed that the analyst would have decided on the initiating event for which category-B actions would be analyzed. In the case of this study, the initiating event considered is the LOOP. The process for the analysis (identification and quantification) includes five major steps. They are: developing a fault tree for the initiating event; selecting the critical systems based on risk importance; cataloguing all potential human actions that can be initiators; selecting those that are category-B actions and identifying the EOC paths for those human actions; and quantifying the category-B actions. Figure 4 shows the process of analysing human-induced initiators and the steps are described in the ensuing subsections.

Figure 4: A process for analysing human-induced initiators



3.1. Step 1: Develop a fault tree for the initiating event

The first step of the process is to develop a fault tree (FT) for the LOOP event. As shown on figure 4, there are several inputs to facilitate the execution of this step. The plant specific design guides or general design criteria (GDC) are evaluated with specific reference to electrical systems. For example, GDC 17 "Electrical Power systems" and GDC 18 "Inspection and testing of electrical power systems" may specify important insights for relevant systems. Important system functions may be identified.

Tech. Specs. (Technical Specifications) includes detailed requirements for system functions including limiting conditions of operation (LCOs), safety limits, design feature, surveillance, and etcetera. Conditions, where human actions (and types) are needed, can also be identified.

Failure modes and effect analysis (FMEA) are the failure modes of each component and their effect on the related systems involved in a LOOP event should be analyzed.

The component reliability data (CRD) contain the failure rates of each component and may be provided by the manufacturer of each component of the systems involved. The failure rate of the component may determine if they are included in the FMEA.

Licensee Event Reports (LERs) are event reports provided by the licensee to the regulators. In the case of Korea, the Korea Institute of nuclear safety (KINS) reviews and provides these in the OPIS database. They can help to identify some SSCs and even scenarios for human action on those SSCs.

The FT cutsets will help to identify the important systems which may lead to the LOOP. Such systems are to be further investigated. A part of cutsets derived from the LOOP FT is shown on figure 5. It should be noted that while the main idea of developing the LOOP FT in step 1 is to derive the importance measures from the cutsets (which is the input for step 2), other insights may be gotten from the inputs to step 1. These insights can serve as inputs to other stages of the process (steps 3 and 4).

Figure 5: A snapshot of some cutsets derived from the FT for LOOP event

Value	FV	Basic Event #1	Basic Event #	Basic Event #3
1.19E-04	0.011947	SPURIOUS OPERATION OF RELAY 351A FOR UNIT AUXILIARY TRANSFORMER 01M PHASE B		
1.19E-04	0.011947	SPURIOUS OPERATION OF RELAY 351B FOR UNIT AUXILIARY TRANSFORMER 01N PHASE B		
1.19E-04	0.011947	SPURIOUS OPERATION OF UNDER FREQUENCY RELAY FOR GENERATOR		
1.19E-04	0.011947	SPURIOUS OPERATION OF GROUND OVER VOLTAGE RELAY FOR GENERATOR		
7.64E-05	0.007702	EXCITATION TRANSFORMER 01 FAILS TO OPERATE		
7.64E-05	0.007702	UNIT AUXILIARY TRANSFORMER 01N FAILS TO RUN		
4.25E-05	0.004523	SPURIOUS OPERATION OF GENERATOR CIRCUIT BREAKER PNEUMATIC POLE		
4.25E-05	0.004523	SPURIOUS OPENING OF GENERATOR FIELD BREAKER X01		
1.87E-05	0.001875	CURRENT TRANSFORMER 01 FAILS TO OPERATE		
1.21E-05	0.001008	FAILURE OF ISOLATED PHASE BUS DUCT		
7.10E-06	0.000715	TRIP OF MAIN TRANSFORMER 01M SUDDEN PRESSURE RELAY		
7.10E-06	0.000715	TRIP OF MAIN TRANSFORMER 01N SUDDEN PRESSURE RELAY		
7.10E-06	0.000715	SPURIOUS OPERATION OF RELAY 387A FOR UNIT AUXILLIARY TRANSFORMER 01M		
4.66E-06	0.000487	FAILURE OF INDEPENDENT PHASE BUS FORCED AIR COOLING UNIT 01		
3.82E-06	0.000353	POTENTIAL TRANSFORMER FOR MAIN GENERATOR EXCITER FAILS TO OPERATE		

3.2. Step 2: Select the critical systems based on risk importance

The cutsets, their probabilities, and Fussell-Vesely (FV) importance derived from step1 serve as input to step 2 of the analysis process. The selection of the critical systems for further analysis is necessary in order for this process to be practical and ensure the realization of the objectives of this study. The selection of the critical systems involved: 1) the selection of the top 54 cutsets as they constitute above 99% contribution to the top event frequency and 2) Only single cutsets are selected as they represent the single failures. Moreover, the eliminated cutsets have very low failure probability and as such, a negligible effect on the overall plant core damage frequency (CDF).
These selected cutsets are then grouped according to the relevant systems. An example of these grouping is shown on table 1. However, there are five systems identified at this stage of the process: the unit auxiliary transformer (UAT), the switchyard, the generator circuit breaker (GCB), the Main generator, and the component cooling water (CCW) pump switch connected to the 4.16KV safety class 1E switchgear.

Table 1: Example of the grouping of cutsets

Cutset	Description	System
RL351A-01M-UAT	Spurious operation of relay 351A phase bus for unit auxiliary transformer 01M	Unit Auxiliary Transformer
RL151-01M-UAT	Spurious operation of relay 151 for unit auxiliary transformer 01M	
RL151-01N-UAT	Spurious operation of relay 151GNB for unit auxiliary transformer 01N	
RL381-MG	Spurious operation of under frequency relay 381 for generator	Generator
RL359-MG	Spurious operation of ground over voltage relay 359 for generator	
FB-01-MG	Generator field breaker 01 spurious opening	
RL587U-CT2B-SWYD	Spurious operation of unit overall differential relay 587U of switchyard circuit bus 2 for phase B	Switchyard
RL587G-CT2B-SWYD	Spurious operation of ground differential relay 587G for switchyard circuit bus 2 for phase B	
RL587U-CT2A-SWYD	Spurious operation of unit overall differential relay 587U of switchyard circuit bus 2 for phase A	

3.3. Step 3: Catalogue all potential human actions that can be initiators

The identified systems, structures, and components (SSCs) in step 2 should inform the type of the maintenance and testing (M/T) procedures to be used at this stage (step 3). As mentioned in section 2 of this paper, the root causes of plant centered and switchyard centered LOOP events due to human errors often occur during testing, inspection, and maintenance activities. It is also not plausible that human-induced initiators can occur while operators are using the emergency operating procedures or the abnormal operating procedures. Therefore, the M/T procedure is suggested as another input to step 3 of the process. The M/T procedures can show most of the procedural stages at which human actions are needed. All these human actions need to be identified and cataloged in a logical order at this stage.

The action or decision points while following the procedure are especially considered to search for any possible error by the maintenance personnel. These may include errors like too little action, too much action, incorrect action, repeated action, selection of wrong object, wrong directives, and etcetera. The catalog should include the procedure step number, step title, action type, component, and system.

3.4. Step 4: Select the category-B actions and identify EOC paths

Selection of potential category-B actions can be achieved in step 4 by utilizing the results and insights from both step 1 and 3. The selection of the final list of category-B actions for further analysis can be a sort of iterative process as the design guides, technical specifications or FMEA for some of the systems and components may need to be revisited. This is to assure of the potential for those human errors to lead to the failure of the systems or the potential for those errors to occur in the first place. This step also involves the identification of the error of commission (EOC) paths for the potential human actions derived from the previous step. The results of the various steps need to be harmonized at this stage in order to derive an acceptable EOC path. The EOC paths for the identified category-B actions need to be clearly specified as this would aid the next step of quantification (step 5).

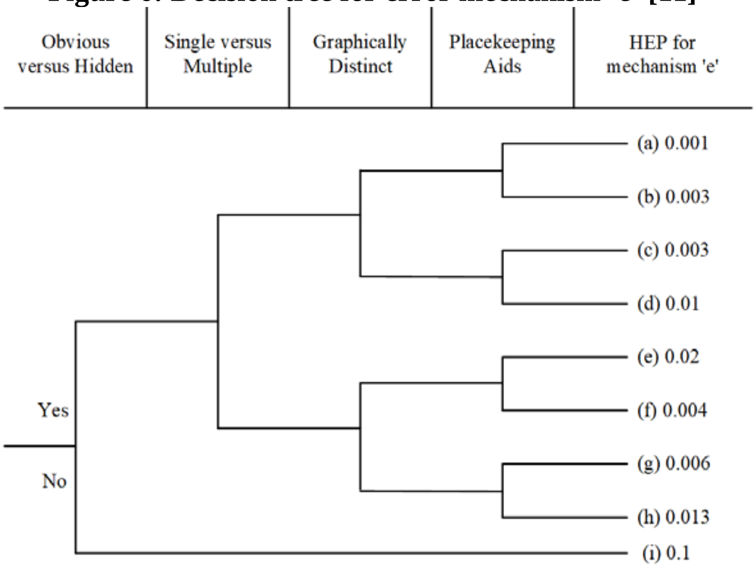
3.5. Step 5: Quantify the category-B actions

This is the final step in the analysis of category-B actions. The quantification of category-B actions is essential in that it gives a valuable input to estimate the initiating event frequency. The cause-based decision tree (CBDT) method of human error quantification is suggested for this analysis.

The CBDT method was developed by the electric power research institute (EPRI) [11] to quantify EOCs albeit post-initiators. This method was developed to identify specific causes of human error and also evaluate the impact of performance shaping factors (PSFs). This approach assumes situation-specific failure modes and each one includes four error mechanisms. However, the modified version proposed in this study will adopt the two failure modes in a different form. Failure mode 1 will address the failure of the system information-to-operator interface while Failure mode 2 will address failures with regards to the operator-to-procedure guideline interface as follows:

- Failure mode 1: Failure of the system information-operator interface
  - Error mechanism ‘a’: Availability of information
  - Error mechanism ‘b’: Failure of attention
  - Error mechanism ‘c’: Misread/miscommunicate data
  - Error mechanism ‘d’: Information misleading
- Failure mode 2: Failure of the operator-procedure guideline interface
  - Error mechanism ‘e’: Skip a step in the procedure
  - Error mechanism ‘f’: Misinterpret instruction
  - Error mechanism ‘g’: Misinterpret decision logic
  - Error mechanism ‘h’: Deliberate violation

Figure 6: Decision tree for error mechanism ‘e’ [11]



Each error mechanism estimates error probability using a decision tree. Figure 6 shows the example of a decision tree for error mechanism ‘e’. The final HEP for each human-induced initiator is calculated by the sum of all the HEPs from each of the error mechanisms.

4. DISCUSSION

The CBDT method is recommended for several reasons among them are; (1) CBDTM does not do human error identification and was developed specifically for quantification of human errors; (2) CBDTM is simple and traceable such that an independent reviewer could easily trace back the resultant HEPs; (3) It has a comprehensive technical basis and explicitly considers organizational process factors; (4) the PSFs used are very sensitive, indicating the importance of the PSFs used in this method. One of the disadvantages of CBDTM is that it does not consider time factor. However, time is not normally a priority in quantifying human-induced initiating events while utilizing the M/T procedures.

Although the CBDT method is not meant for category B actions and it is mainly developed for MCR operator actions, there is currently no standard method developed for analyzing category B actions. Moreover, the authors opine that the CBDT method may serve well for quantification in this case because it also involves procedure-based tasks and the PSFs used also serve well for the M/T procedures.

Similarly, the identification part of the suggested methodology follows a search scheme like some other methods including commission error search and assessment (CESA) and a technique for human error analysis (ATHEANA). However, this proposed method is different for several reasons

- It is proposed for category-B actions which are human-induced initiators
- It follows a Scenario-system-action search scheme
- It suggests the use of maintenance procedures
- It recommends the use of a modified CBDT method for quantification.

5. CONCLUSION

This work shows an analysis of human-induced initiating events, particularly for the LOOP scenario of a PWR NPP. The procedure suggested the use of a search scheme similar to those of other well-known methods previously used for identifying EOCs. However, the use of risk important measures from the fault tree of a pre-selected initiating incident is suggested to select the important systems. Thereafter, important human actions are catalogued and subsequently, human-induced initiators are selected based on maintenance and test procedures as against other EOC analysis methods that apply the AOPs or EOPs. The quantification method suggested is a modified CBDT method with a system information-to-operator interface and the operator-to-procedure interface. The probability of performing an unsafe action is assigned using decision trees considering several factors including the availability of procedural rules, operator training and experience, availability of information, operator workload, and interpretation of logic. This development of a human-induced initiator analysis method is on-going and a complete verification of the method will be completed in the near future. The HEPs obtained from this analysis procedure will add to the completeness of the NPP PSAs.

Acknowledgements

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea (No. 1705001).

References

[1] J. Julius, E.J., G.W. Parry, A.M. Mosleh. "*A procedure for the analysis of errors of commission in a Probabilistic Safety Assessment of a nuclear power plant at full power"*, Reliability Engineering and System Safety, **50**: p. 189-201, (1995).

[2] D.I. Gertman, et al., "*Review of findings for human error contribution to risk in operating events"*, INL, U.S. NRC: Washington, D.C. 20555 (2001).

[3] B. Reer. "*Outline of a Method for Quantifying Errors of Commossion -Rev. 1*.", Paul Scherrer Institut (2014).

[4] S. Hirschberg. "*Human Reliability Analysis in Probabilistic Safety Assessment for Nuclear Power Plants"*, in Technical Opinion Papers, OECD/NEA, Organization for Economic Co-operation and Development / Nuclear Eergy Agency, (2004).

[5] Y. Kim and J. Kim. "*Identification of human-induced initiating events in the low power and shutdown operation using the Commission Error Search and Assessment method"*, Nuclear Engineering and Technology, **47**(2): p. 187-195, (2015).

[6] ENSI. "*Probabilistic Safety Analysis (PSA): Quality and Scope"*, Swiss Federal Nuclear Safety Inspectorate (ENSI), (2009).

[7] S.A. Eide, et al. "*Reevaluation of Station Blackout Risk at Nuclear Power Plants"*, INL, U.S. Nuclear Regulatory Commission: U.S. NRC,Office of Nuclear Regulatory Research, Washington DC, (2005).

[8] S. H. Kim, W.S. Jeung. "*Introduction of Electrical System Simulation and Analysis Used in Korean Nuclear Power Plants"*, in Proceedings of *ROBELSYS* Conference. 2014. Paris, France, OECD-NEA, (2015).

[9] A. Volkanovski, et al. "*Analysis of loss of offsite power events reported in nuclear power plants"*, Nuclear Engineering and Design, **307**: p. 234-248 (2016).

[10] *Operational Performance Information System for Nuclear Power Plants*. Accessed: January 2018; Available from: http://opis.kins.re.kr/opis?act=KEOPISMAIN.

[11] G.W. Parry, "*An Approach to the Analysis of Operator Actions in Probabilistic Risk Assessment"*, EPRI, (1992).