http://dx.doi.org/10.5516/NET.04.2012.510

OPERATOR BEHAVIORS OBSERVED IN FOLLOWING EMERGENCY OPERATING PROCEDURE UNDER A SIMULATED EMERGENCY

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Invited September14, 2011
Received November 24, 2011
Accepted for Publication February 27, 2012

A symptom-based procedure with a critical safety function monitoring system has been established to reduce the operator's diagnosis and cognitive burden since the Three-Mile Island (TMI) accident. However, it has been reported that a symptom-based procedure also requires an operator's cognitive efforts to cope with off-normal events. This can be caused by mismatches between a static model, an emergency operating procedure (EOP), and a dynamic process, the nature of an on-going situation. The purpose of this study is to share the evidence of mismatches that may result in an excessive cognitive burden in conducting EOPs. For this purpose, we analyzed simulated emergency operation records and observed some operator behaviors during the EOP operation: continuous steps, improper description, parameter check at a fixed time, decision by information previously obtained, execution complexity, operation by the operator's knowledge, notes and cautions, and a foldout page. Since observations in this study are comparable to the results of an existing study, it is expected that the operational behaviors observed in this study are generic features of operators who have to cope with a dynamic situation using a static procedure.

KEYWORDS : Operational Behavior, Emergency Operating Procedure (EOP), Simulated Emergency Operation

1. INTRODUCTION

An emergency operating procedure (EOP) has been developed to recover or restore the off-normal status of a plant to a safe condition. For this, after the Three-Mile Island (TMI) accident, a symptom-based procedure with a critical safety function monitoring system has been established to reduce the operator's diagnosis and cognitive burden.

However, it has been reported that a symptom-based procedure also requires an operator's cognitive efforts in coping with off-normal events. This can be caused by a mismatch between a static model (i.e. prescribed tasks in EOPs) and a dynamic process (i.e. the nature of an on-going situation) [1]-[3]. From the existing human reliability analysis (HRA) method, the effect of procedures on human performance has been recognized as one of the most important performance shaping factors (PSF) [4]-[6].

The purpose of this study is to share the evidence of the mismatches that may result in an excessive cognitive burden in conducting EOPs. For this purpose, we analyzed the emergency training records collected from a full scope simulator of a Westinghouse 3-loop pressurized water reactor (PWR).

2. DATA COLLECTION AND ANALYSIS

2.1 Scenario

The simulated scenario for this study is a steam generator tube rupture (SGTR) immediately following a main steam line break (MSLB). An MSLB is a large break in a main steam line piping. In this study, we consider a piping break inside the containment. An MSLB is characterized as a cooldown event due to an increased steam flow rate, which causes excessive energy removal from the SG and reactor coolant system (RCS). This results in a decrease in temperature and pressure in both the RCS and SG. After a reactor trip as a consequence of an MSLB, the depressurization of the affected SG induces the actuation of a main steam isolation signal (MSIS). This closes the main steam isolation valves (MSIVs), isolating the unaffected SG from a blowdown and closes the main feedwater isolation valves (MFIVs), terminating the main feedwater flow to both SGs.

An SGTR applies to the rupture of one or more tubes in one SG, causing a primary coolant to leak into the secondary system. If the leakage exceeds the capacity of the chemical and volume control system (CVCS), the reactor coolant inventory will continue to decrease and eventually lead to an automatic reactor trip. N-16 radiation detectors located on each SG provide an early positive indication of a tube rupture and identify the ruptured SG.

2.2 Related Procedures

“EOPs are plant procedures that direct operators' actions necessary to mitigate the consequences of transients and accidents that have caused plant parameters to exceed reactor protection system set points or engineered safety feature set points, or other established limits [7].” They are developed based on technical guidelines which serve as the technical basis for EOPs and a writer’s guideline which is used to ensure that the EOPs are clearly and explicitly written and organized. Figure 1 shows an example of the structure of an EOP. An EOP consists of two columns. The left-hand column describes the action/expected response while the right-hand column is for the response not obtained (RNO). The action/expected response is comprised of steps. Each step consists of a step heading, substep, and detailed action. When an action/expected response is completed, operators conduct the following step, however, when it is not satisfied, they must perform the related RNO and then return to the next step in the left-hand column.

The participating operators use EOPs developed by the Westinghouse Owners Group [8]. Here are the summaries of the EOPs used for the simulated scenario:

- E-0 (Reactor trip or Safety injection): Provides actions to verify the proper response of automatic protection systems following manual or automatic actuation of a reactor trip or safety injection
- E-2 (Faulted SG isolation): Provides actions to identify and isolate a faulted SG
- E-3 (SGTR): Explains actions to terminate the leakage

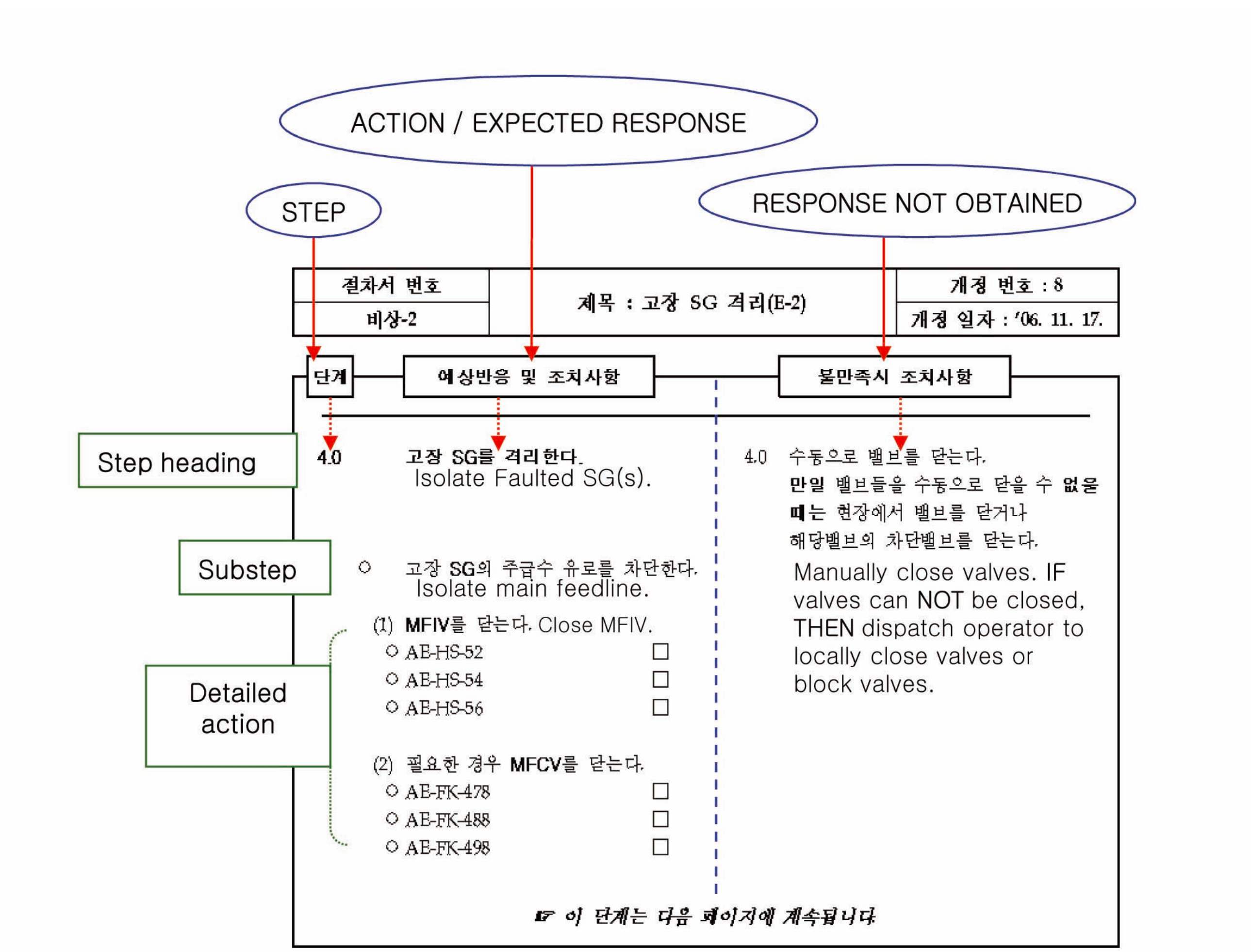

Fig. 1. Example of EOP Structure (E-2)

of reactor coolant into the secondary system following a SGTR

- ECA-3.1 (SGTR with loss of reactor coolant subcooled recovery desired): Explains actions to cool down and depressurize the RCS to cold shutdown conditions while minimizing the loss of RCS inventory and voiding in the RCS

An MSLB and nearly coincident SGTR will cause an immediate reactor trip. After entering E-0, operators move on to E-2, E-3, and ECA-3.1 sequentially. Table 1 shows the conditions of EOP transitions.

2.3 Data Collection

We collected data on nine simulated emergency operation training teams for the scenario at a Westinghouse 3-loop PWR. All the operators were male and their mean age was 39.7 years with a standard deviation of 5.5 years. The audio/video recordings of the simulated emergency operation, process parameter trend data, operation log file that lists operator's component manipulation action, and the human machine interface (HMI) lists with the associated images were collected.

Table 1. EOP Transfer Conditions for MSLB & SGTR

From	Step	Transfer Condition	To
E-0	22.0	If any SG pressure decreases in an uncontrolled manner or any SG is completely depressurized	E-2
E-2	6.0	When secondary radiation is abnormal	E-3
E-3	3.0	If any ruptured SG cannot be isolated from at least one intact	ECA-3.1
	5.0	If ruptured SG pressure is less than the setpoint	
	6.0	If no intact SG is available for RCS cooldown	
	8.0	If the PZR PORV cannot be isolated by closing its bloc valve	
	14.0	If the minimum delta P between the ruptured and intact SGs cannot be maintained	
	15.0	If the RCS subcooling is less than required	
	18.0	When the RCS pressure does not increase after closing the PZR PORV and block valve	

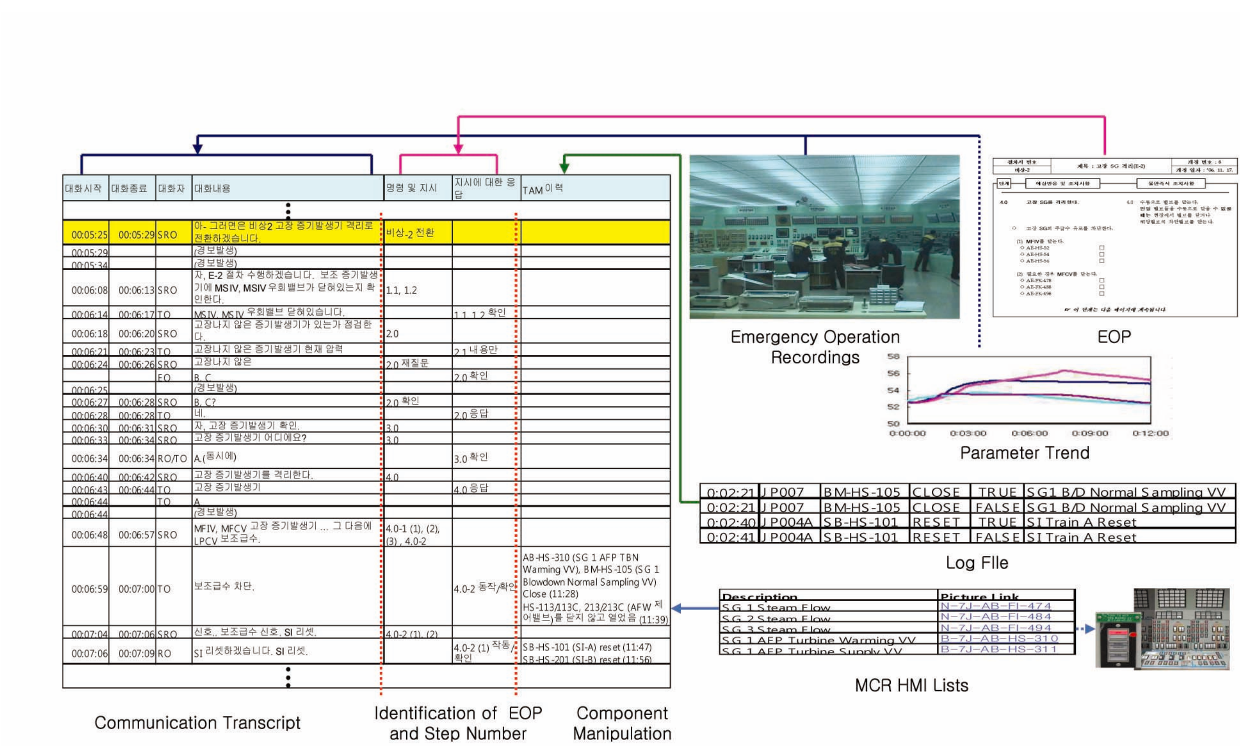

Fig. 2. Consolidated Transcript with Collected Data

After collecting the data, we developed communication transcripts based on the audio/video recordings of the simulated emergency operation. For each conversation such as instructions and responses, we identified the related EOP and step number and added information about the operators' component manipulation with the operation log file. We referred to the process parameter trend data and HMI list data when necessary.

2.4 Analysis

Based on the consolidated transcripts of the simulated emergency operation, human reliability analysis experts, human factor specialists, and plant operation specialists performed a data analysis to obtain evidence of mismatches that may result in an excessive cognitive burden in conducting EOPs. We developed a checklist to observe how operators actually carry out the related EOP steps. We developed two kinds of checklists, one for a shift supervisor (SS) and one for a board operator (BO). The SS group consists of a senior reactor operator (SRO) and a shift technical advisor (STA), and the BO group consists of a reactor operator (RO), a turbine operator (TO), and an electrical operator (EO). An SRO performs a plant operation by procedures. He/she must follow and confirm the procedural instructions and verify if each step of an EOP is conducted appropriately. The role of the STA is to check the critical safety functions when action is required during an EOP operation. BOs should perform component manipulation and monitoring after reporting to an SS and follow the instructions of the SRO and STA. Table 2 shows the checklist applied to both the SS and BO groups. For the SS's checklist, we focused on their mission that they should select an appropriate EOP, instruct the EOP sequentially, and make a valid decision for a step that requires a decision. To write the checklist for BOs, we put a high value on compliance with the order of SSs.

3. RESULTS

Our results indicate that there are common operational behaviors in conducting EOPs, which may result from a mismatch between the static model ('snap-shot' description in EOPs) and the dynamic process (the nature of the ongoing status). The operational behaviors are summarized below. They may be critical for safety or not. In spite of their potential risk, nine simulated emergency operation training teams involved in the analysis completed their missions successfully.

3.1 Continuous Steps

During a simulated emergency operation for the above scenario, operators are usually faced with eight to twelve kinds of steps that require continuous monitoring or component manipulation during the related EOP operation. Those steps are called continuous steps. While there are

Table 2. EOP Operation Checklist

Group	Checklist Items
SS	• Did the SS select a proper EOP? • Did the SS follow the EOP in the order of the step number? • Did the SS order all contents of each step? • Did the SS order a work beyond the EOP? • Did the SS discriminate monitoring work from manipulation work? • Did the SS make an appropriate decision for an RNO entry or a transfer to another EOP? • Did the SS use a proper communication?
BO	• Did the BO follow the SS's instruction exactly? • Did the BO report to the SS after following SS's instruction? • Did the BO conduct a work the SS didn't instruct? • Did the BO use a proper communication?

the continuous steps in performing an EOP, operators seldom perform or confirm the associated actions once they pass the continuous steps.

Observations: Step 1.0 of E-3 is to check if the reactor coolant pumps (RCPs) should be stopped based on a RCP trip parameter (RCS pressure). Seven teams stopped RCPs during an E-0 operation. For the remaining teams, since the RCS pressure did not meet the set point, they did not stop the RCP during this step. Although the step is one of the continuous steps, all SSs did not instruct the continuous monitoring of the trip parameter. As a result, they did not stop RCPs even when the RCS pressure met the set point within a few minutes after leaving the step during the EOP operation.

Step 8.0 of the ECA-3.1 requires checking if residual heat removal (RHR) pumps should be stopped based on the RCS pressure. Some teams did not stop the pumps since the RCS pressure did not meet the set point at that time. Even when the RCS pressure met the set point after they left step 8.0, no team stopped the pumps.

3.2 Improper Description

Doe to an improper description, operators are sometimes confused in judging whether they should go to an RNO that is at the right-hand side of an EOP.

Observations: Step 12.3 of the ECA-3.1 requires dumping steam into the condenser from intact SGs to initiate an RCS cooldown. The RNO associated with the step requires dumping steam manually or locally from intact SGs by using an SG pressure operated relief valve (PORV). Some SSs hesitated in deciding whether to open MSIVs or SG PORVs. One SS instructed the TO to open the closed MSIV near intact SGs and to dump steam into the condenser, while the others instructed the TOs to enter the RNO using a SG PORV because all of the MSIVs were already closed due to the MSLB. There is no description of what to do for steam dumping when the MSIVs are closed.

Step 22.0 of E-0 is to check if SGs are not faulted. When either there is any SG with a pressure decreasing in an uncontrolled manner, or there is any SG that is completely depressurized, the SS should follow the related RNO. In this step, however, some SSs were confused in determining what an uncontrolled manner is since there is no detailed description about a decrease in an uncontrolled manner. Therefore, they spent time going to the next step even though the TOs answered that there was one SG with decreasing pressure in an uncontrolled manner.

Step 17.4 of the ECA-3.1 is to establish conditions for starting an RCP. This step requires verifying if the flow rate of the component cooling water (CCW) to the RCP motors and to the RCP thermal barriers are greater than set points. Unfortunately, there are no RNOs for a situation in which the CCW flow is blocked. Some ROs manipulated related components based on their knowledge to provide CCW flow to the RCP motors and RCP thermal barriers.

3.3 Parameter Check at a Fixed Time

BOs sometimes check a parameter at a fixed time only when they enter the relevant step that requires the parameter checking during an EOP operation. The real status of a plant, however, changes in any way at any moment. In an EOP operation, there are times when a specific parameter for a condition in a step already satisfies a set point before the step entry but then rapidly goes in the opposite direction. In this situation, BOs do not catch the real plant status and check only the parameter value at the point of the step entry.

Observations: Step 13.0 of E-0 requires checking if main steamlines should be isolated based on the containment vessel (CV) pressure or SG pressure. When an MSLB has occurred, the CV pressure rapidly increases to a set point for a main steam isolation signal (MSIS) and containment spray actuation signal (CSAS) and then decreases due to the CS pump operation. Therefore, under simulated emergency operations, the CV pressure generally met the set point before the step entry and decreased rapidly. Of the nine teams, two ROs reported that the parameter had already satisfied the set point for the MSIS actuation and the current CV pressure then decreased, while three ROs checked the CV pressure only at that time and reported that it did not meet the condition and thus the SRO instructed the RNO to be performed.

Step 19.0 of E-0 is to check the RCS temperature. Checking the RCS temperature and whether it is stable at a set point or trending toward the set point are required for this step. To check the trend, ROs sometimes focus on a specific trend during a very limited time in the vicinity of the step entry rather than during the whole trend. Four ROs reported that the RCS temperature was decreasing. The deceasing period, however, was very short and the decreasing trend was negligible relative to the whole trend. On the other hand, the overall trend was stable.

3.4 Decision by Information Previously Obtained

Once BOs check a parameter and report its value to SSs, SSs sometimes assume that it will not be changed at the following steps, which require checking the same parameter so that they tend to skip the repetitive action. However the parameter may increase or decrease rapidly after the initial check.

Observations: Some steps suggest two kinds of set points for a parameter separately according to the CV status, which is normal or abnormal. For those steps, an SS should check the CV status first and then compare the parameter to one between the two kinds of set points, which is suitable for the CV condition. However, the SSs exhibited a tendency to skip checking the CV status based on the information previously obtained since they already checked the CV status.

Step 16.2 of ECA 3.1, for example, is for RCS depressurization to refill a pressurizer (PZR) until when the PZR level is greater than 23% for normal containment or until when the PZR level is greater than 43% for adverse containment. Some SSs ordered the PZR to be refilled until when the PZR level was greater than 23% notwithstanding an adverse containment. They previously checked the CV status during step 11.0, which is to check intact SG levels and to control feed flow to maintain a narrow range level within a specific period when the containment is normal (or within another period different from the previous one when the containment is adverse). In this step, they were informed that the containment was not adverse. For step 16.2, they skipped checking the containment condition and instructed ROs to refill the PZR until the PZR level was greater than 23%, which is the set point for a normal containment. The containment condition, however, was changed before step 16.2.

3.5 Execution Complexity

When a step consists of too many substeps or too much complicated syntax, operators including both of SSs and BOs are likely to omit several substeps.

Observations: Step 4.0 of E-2 for the isolation of faulted SGs requires eight manipulations and four monitoring actions. Since most of the SSs simply ordered a step heading without any detailed substeps, or they skipped a portion of the related substeps, some of the sub steps were omitted for some teams. SSs, however, are trained to conduct all of the instructions in the related EOPs sequentially using the check-off box after completing each substep. The role of the check-off box is to check whether each substep is completed or not.

Step 9.0 of the ECA-3.1 to initiate an evaluation of the plant status consists of three kinds of auxiliary building radiation checks, six kinds of sample analyses, eight kinds of plant equipment evaluations, and two kinds of component manipulation actions. In this situation, some BOs omitted several actions included in this step although their SSs instructed them to perform all the substeps.

3.6 Operation by Operator's Knowledge

SSs conventionally conduct an action that is not specified in an EOP to satisfy the goal of a step.

Observations: Step 15.0 of the ECA-3.1 requires checking whether the safety injection (SI) is in service. In this regard, BOs have to perform one of the following: (1) check if any charging (CHG)/SI pump is running and if the boron injection tank (BIT) is not isolated, or (2) check if a residual heat removal (RHR) pump is running in the SI mode. In spite of the instructions, three SSs verified only the SI flow that is whether the SI was in service, even though SI flow confirmation is not described in this step.

3.7 Notes and Cautions

Notes contain information to support operator actions, and cautions contain information about potential hazards to equipment and/or operating personnel. Despite their importance, SSs seem to overlook these notes and conditions.

Observations: Cautions just before step 4.0 of E-3 and step 7.1 of the ECA-3.1 inform operators that if any ruptured SG is faulted, feed flow to the faulted SG should remain isolated during the subsequent recovery action unless it is needed for RCS cooldown. Each of the teams, however, seldom read the cautions and conducted feeding to the affected SG in conducting E-3. Only one team read the caution before conducting step 7.1 of the ECA-3.1 to isolate the faulted SG.

3.8 Foldout Page

A foldout page that is on the back page of the EOP includes several application times for actions that are applicable at any step in the EOP to prevent an accident. Therefore the foldout page should be read and kept open to check a series of symptoms when starting an EOP. In spite of that, operators usually do not use the foldout page.

Observation: Except for two SSs, most SSs did not read the foldout page when starting an EOP.

4. DISCUSSION AND CONCLUSIONS

In this paper, we analyzed the operational behaviors in following EOPs under a simulated emergency to share the evidence of a mismatch between a static model (i.e., prescribed tasks in EOPs) and a dynamic process (i.e., what actually occurs in an ongoing situation) that may result in an excessive cognitive burden in conducting EOPs. In spite of the small amount of data, some common operational behaviors were observed during the EOP operations. The observations in this study showed features similar to the results of an existing study. Massaiu involved in the OECD Halden project performed a similar research. He analyzed four scenarios, one of which is same as the scenario in this study except for the location of the MSLB. He identified eight procedure features that challenge following rule-based step-by-step procedures.

Table 3 compares the findings of this research with those of the existing study. As can be seen from Table 3, some issues were not observed in this research. They are 'the steps literal meaning vs. intentions' and 'the verbatim following'. According to the definition of the existing study, the former means 'steps might be true but their intentions are not fulfilled' and the latter denotes 'literal following is observed even when it counters operators' understanding, such as waiting for the situation to worsen to meet a condition in the procedure'. However, in the EOPs used in this study, a step intention was well fulfilled and the time to evaluate a condition was specified in each step.

In contrast, the issue of control actions of the existing study and the improper description identified in this study

Table 3. Comparison of Results in this Study and Those of the Existing Study

Issues identified from the existing study	Description	Issues in This Study
1. Control actions	Simple control manipulations do not indicate the expected responses	– Improper description
2. Trend assessment	Trends are not taken at face value but interpreted by the operators	– Parameter check at a fixed time – Decision by operator’s knowledge
3. Steps literal meaning vs. intentions	Steps might be true but their intent is not fulfilled	Not applicable
4. Foldout use	Foldout not read through before starting a procedure	– Foldout page – Continuous step
5. Execution and following complexity	Steps with mixed CR and local actions	– Execution complexity
6. Mode errors	EOPs order an operation different from normal	– Conventional operation
7. Verbatim following	Literal following is observed even when it counters operators’ understanding	Not applicable
8. Notes and cautions	Not always read	– Notes and cautions

can be classified into the same category in the sense that some steps assumed to be simple for the operators do not indicate an expected response and/or RNO in detail. The parameter check at a fixed time and the decision according to the operator’s knowledge in this study are consistent with the trend assessment issue since trends sometimes are not taken at face value but interpreted by the BOs. The conventional operation can be categorized into the issue of mode errors since SSs occasionally complete the goal of a step through their habitual operation rather than EOP description. The continuous step identified in this paper is classified by the foldout page of the existing study, because a foldout page includes continuous steps that might not be monitored or enacted when relevant. For the other issues in this study such as the foldout page, the execution complexity, and the notes and cautions, operators show similar features identified from the results of the existing study.

In conclusion, some operation behaviors were observed in conducting EOPs under a simulated emergency. Since the observations in this paper are comparable to the results of the existing study, it is strongly expected that the operational behaviors observed in domestic nuclear power plants are not country and/or organization specific but are generic behaviors of operators who have to cope with a dynamic situation using a static procedure. Therefore, even though the existing EOPs are modified through several times of revisions, it is necessary that EOPs be improved to reduce the observed mismatches by reflecting the nature of real situations.

ACKNOWLEDGEMENT

This work was partly supported by Nuclear Research & Development Program of the National Research Foundation of Korea (NRF) grant funded by the Korean Government (MEST). (Grant Code: 2012-011506).

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