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The Operators' Non-compliance Behavior to Conduct Emergency Operating Procedures - Comparing with the Complexity of the Procedural Steps

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Abstract

According to the results of related studies, one of the typical factors related to procedure related human errors is the complexity of procedures. This means that comparing the change of the operators' behavior with respect to the complexity of procedures may be meaningful in clarifying the reasons for the operators' non-compliance behavior.

In this study, to obtain data related to the operators' non-compliance behavior, emergency training records were collected using a full scope simulator. And three types of the operators' behavior (such as strict adherence, skipping redundant actions and modifying action sequences) observed from the collected emergency training records were compared with the complexity of the procedural steps.

As the results, two remarkable relationships are obtained. They are: 1) the operators seem to frequently adopt non-compliance behavior to conduct the procedural steps that have an intermediate procedural complexity, 2) the operators seems to accommodate their non-compliance behavior to the complexity of the procedural steps. Therefore, it is expected that these relationships can be used as meaningful clues not only to scrutinize the reason for non-compliance behavior but also to suggest appropriate remedies for the reduction of non-compliance behavior that can result in procedure related human error.

Key Words : Emergency operating procedures, Non-compliance behavior, The complexity of procedural steps.

1. Introduction

With industries becoming more complicated, various activities (such as process automation or computerization) have been used to reduce the operators' workload [1-3]. As one of them, the provision of appropriate procedures has been emphasized in many industries such as the nuclear, aviation and chemical industry [1, 2, 4-10]. In case of the nuclear industry, procedures have been given a higher priority than in other industries, since not only one of the important legacies from the Three Mile Island (TMI) accident is the reformation of emergency operating procedures (EOPs) [1,11-15], but also it has been reported that most accidents that actually occurred could have been effectively coped with through EOPs [16-18].

It is remarkable, however, that a significant portion of accidents (including incidents) was caused by procedure related human errors (such as omitting important actions) due to the non-compliance of procedures (i.e., did not carry out procedures in accordance with written instructions). For example, in the aviation industry, the pilots' error due to the non-compliance of procedures was reported as one of the principal causes resulting in the accidents [6, 19-21]. Similar statistics, indicating that the operators' non-compliance behavior is one of the leading causes of accidents, can also be found in the nuclear industry [22-28]. Thus, to maximize safety, it may be requisite to understand the reason why the operators do not follow procedures as written.

According to results from related studies, many useful insights that can be used to identify plausible factors leading to non-compliance behavior have been stated. One of the typical factors is the complexity of the procedures. This means that comparing the change of the operators' behavior with respect to the complexity of the procedures could be a reasonable starting point to scrutinize the operators' non-compliance behavior.

In this study, thus, to obtain data related to the operators' non-compliance behavior, emergency training records were collected using a full scope simulator installed in the training center of the reference nuclear power plant (NPP). The record collection period was from September 1999 to July 2001, and in total, 112 emergency training records performed by 24 different operating crews were collected. After that, three types of the senior reactor operators'(SROs') behavior, such as strict adherence, skipping redundant actions and modifying action sequences, were compared with the step completion(SC) scores that can represent the complexity of the procedures [29-31].

This paper is organized as follows. At first, in order to manifest the direction and the objective of this study, important factors related to non-compliance behavior are investigated based on several rationales deduced from literature. As the next, types of the SROs' non-compliance behavior observed from the emergency training records are briefly described with the reason why the SROs' behavior has to be stressed for scrutinizing non-compliance of EOPs. And then, as the results of this study, two kinds of relationships obtained from comparing the SROs' non-compliance behavior with the complexity of the procedural steps are provided. Finally, discussions related to these results are given in order to support the conclusion of this study.

2. Considerable Factors that Can Result in Non-compliance Behavior

There are several rationales that give useful insights for explaining the reason why the operators frequently do not follow procedures as written [6, 9, 10, 15, 25, 32]. From these rationales, important factors that make it difficult for the operators to obtain what they want from procedures can be identified from two different viewpoints [5, 10, 15, 23, 26, 32-35].

- The deficiencies of procedures (i.e., inaccurate or incomplete procedures): It can be regarded that non-compliance behavior could arise when the operators use deficient procedures that cannot sufficiently designate the operators' activities to accomplish the required tasks.
- The complexity of the procedures: It can be thought that non-compliance behavior could also

Table 1. The Operators' Generic Tasks to Conduct Procedures

	Generic tasks	Reference
The nuclear industry[1]	1. Understanding and assess the situation. 2. Planning a response to the emergency. 3. Adapting or revising procedures. 4. Following or applying procedures. 5. Executing task steps. 6. Monitoring progress to task goals. 7. Monitoring event changes.	[39]

1. Similar task classifications for the use of procedures can be also found in Ref. [3] and [10].

arise from a lack of understanding. In other words, it seems that the possibility of non-compliance behavior will increase if the procedures are so complicated that the operators cannot clearly understand the context of the required tasks or actions specified in the procedures.

Between these viewpoints, however, the complexity of procedures seems to be more important for understanding non-compliance behavior due to two reasons. The first one is that a relatively huge amount of effort has been made to prevent problems associated with deficient procedures. For example, in the case of nuclear industry, many guidelines or checklists have been used to investigate the suitableness of EOPs [23, 36-38]. In addition, although much more time-consuming activities may be needed, it is mandatory that "the validity of developed EOPs should be ensured through a mock-up test and walk-through." Thus, it can be assumed that problems related to deficient procedures could be properly identified through these activities.

As for the second reason, it should be recognized that, to cope with on-going emergency situations, the operators have to seek required actions through understanding the procedures before conducting them. As an example, let us consider Table 1 that shows several generic tasks to illustrate 'how the operators conduct procedures' obtained from a high-level task analysis of the aviation and the nuclear industry, respectively.

From Table 1, it is expected that the operators are likely to attempt non-compliance behavior, even accurate procedural steps that include complete sets of information and the required actions are provided with them, if the procedures are so complicated that they fail to understand what is to be done.

To understand this aspect more clearly, let us consider Fig. 1 which shows two procedural steps (the fourth and the fifth procedural step) included in the LOCA (loss of coolant accident) procedure of the reference NPP.

When the operators entered the fourth

Instructions	Contingency Actions
4. IF pressurizer pressure is less than 123.9kg/cm², THEN verify SIAS (safety injection actuation signal) and CIAS (containment isolation actuation signal) are actuated.	4. IF pressurizer pressure is less than 123.9kg/cm² and SIAS and CIAS have NOT been initiated automatically, THEN manually initiate SIAS and CIAS. a. SIAS: EF-HS-102A/102B/102C/102D. b. CIAS: EF-HS-104A/104B/104C/104D.
5. IF SIAS is actuated, THEN perform the following: a. Ensure SI (safety injection) flow is within SI flow delivery curves (Refer to Figure 2 and 3). b. Start idle HPSI (high pressure safety injection) pumps and LPSI (low pressure safety injection) pumps. c. Start idle charging pumps.	a. IF SI flow is NOT within SI flow delivery curves THEN perform ANY of the following to restore SI flow: • Ensure electrical power to SI pumps and valves. • Ensure correct SI valve lineup. • Ensure operation of necessary auxiliary systems for SI pumps. • Start additional SI pumps as needed until SI flow is within SI flow delivery curves (Refer to Figure 2 and 3).

Fig. 1. Two Procedural Steps Included in the LOCA Procedure

procedural step, if the pressurizer pressure, at that time, is larger than the set point (i.e., 123.9kg/cm^2), the operators have to move to the fifth procedural step because they do not need to perform this procedural step. In contrast, if the pressurizer pressure is under the set point, the operators have to carry out several required actions such as 'Verify SIAS actuation' and 'Verify CIAS signal,' based on the predefined action sequence. It is noted that detailed meaning of 'predefined action sequence' to conduct procedural steps included in EOPs is well summarized in Ref. [29, 40, 41].

Therefore, the operators should understand the context of the procedural steps so that they can select appropriate actions from the prescribed (i.e., static) procedural steps, in order to cope with dynamically and sometimes unpredictably changing situations [3, 6, 10, 15, 30, 33, 30]. This strongly supports the possibility that non-compliance behavior will rely on the complexity of the procedures.

From the above explanations, it may be meaningful to scrutinize the reason for procedural deviations through the comparison of the operators' behavior (i.e., how the operators conduct procedures?) with the complexity of the procedures. It is noted that, hereafter, the complexity of procedures will be referred to as the complexity of the procedural steps, since it was shown that the complexity of the procedural steps can be regarded as a 'basic' unit for evaluating the complexity of procedures and that the SC measure can properly quantify the complexity of the procedural steps due to task demands implied by the procedural steps [29-31].

3. Types of the Operators' Behavior Observed from Emergency Training Records

As stated at the end of the previous section, to scrutinize the operators' non-compliance behavior, two kinds of information may be indispensable, such as: 1) types of the operators' behavior to conduct the procedures, and 2) the complexity of the procedures. More precisely, since the SROs play a decisive role in conducting EOPs, these kinds of requisite information to scrutinize non-compliance behavior related to EOPs can be refined as follows.

- The types of the SROs' behavior;
- The complexity of the procedural steps included in EOPs.

To understand this aspect more clearly, it may be helpful to review what is the mandatory process to conduct EOPs.

3.1. How EOPs are Conducted?

When emergency situations occurred, most of the emergency operations in NPPs are performed by operating crews working in MCR (main control room), and several types of crew organizations have been usually adopted for the emergency operations [42]. In case of the reference NPP, all required actions specified in the procedural steps are performed based on the SRO' s commands.

As an example, let us consider the required actions to accomplish the fourth procedural step included in the LOCA procedure, shown in Fig. 1. To start this procedural step, the SRO has to know 'pressurizer pressure' information. At this moment, the SRO commands the reactor operator(RO) to read 'pressurizer pressure' because pressurizer is one of the main components included in the primary side. Then the RO informs the SRO of pressurizer pressure after reading an appropriate indicator, and based on this information, the SRO decides the next action. That is, if pressurizer pressure is smaller than 123.9kg/cm2 then the next action is "Verifying SIAS status." Whereas, if pressurizer

Table 2. Summaries for the Collection of Emergency Training Records

Record collection period	Emergency training scenario	The number of collected records
Sep. 1999 ~	SGTR (steam generator tube rupture)	5
Dec. 1999	LOAF (loss of all feedwater)	5
Jan. 2000 ~	LOCA (loss of coolant accident)	18
Jul. 2000	ESDE (excess steam demand event)	18
Aug. 2000 ~	SGTR	18
Dec. 2000	LOAF	18
Jan. 2001 ~	LOOP (loss of offsite power)	10
Apr. 2001	SBO (station black out)	10
	LOCA	10

pressure is over 123.9kg/cm^2 then the next action to be conducted by the SRO is "Move to next procedural step." In this way, all actions included in the rest of the procedural steps can be conducted.

Under this operation scheme, it is clear that non-compliance of EOPs would be closely related to the SROs' behavior, since EOPs are principally conducted under the SROs' direction. In addition, it is expected that most of the burden which may arise during conducting EOPs may be put on them [42]. To scrutinize non-compliance behavior related to EOPs, thus, it is worth comparing the types of the SROs' behavior with the complexity of the procedural steps.

3.2. Data Source to Identify the Operators' Behavior Types and Experience Level

To classify the SROs' behavior types, a full scope simulator installed in the training center of the reference NPP was used. This full scope simulator is designed based on a 1000MWe pressurized water reactor(PWR) type NPP with conventional control panels and alarm tiles.

In the training center of the reference NPP, a set of video recording equipment was installed in order not only to monitor what activities were taken by the operators but also to review and discuss the operators' activities with instructors after each training session is finished. Thus, all kinds of operators' activities occurring in MCR, such as valve/pump operations or communications among the crewmembers, can be recorded on a videotape.

The record collection period was from September 1999 to July 2001. During this period, the total number of training scenarios was six, and they covered all design basis accidents (DBAs) of the reference NPP. Table 2 shows summarized information for the collected emergency training records.

3.3. Identifying the Types of the SROs' Behavior to Conduct Procedural Steps

From the collected emergency training records, three types of behavior based on the SROs' activities to conduct the procedural steps were identified through protocol analyses, and they can be listed as follows.

- Type A (strict adherence): The SROs strictly

Table 3. Observed SROs' Behavior Types for Conducting Procedural Steps

	Type A	Type B	Type C	Total
Number of observations	787	62	213	1062
Percentage of occurrence	74.11	5.84	20.25	100.0

followed a procedural step as written.

- Type B (skipping redundant actions): When the SROs entered a procedural step, they either skipped identical actions that were already conducted in the previous procedural step or conducted identical actions based on information what they already knew.
- Type C (modifying action sequences): the SROs performed a procedural step using a modified action sequence that is different from a predefined one.

From the above classifications, 'Type A' means that the SROs conducted all required actions included a procedural step along with a predefined action sequence (i.e., compliance behavior). In contrast, both 'Type B' and 'Type C' imply non-compliance behavior because the SROs either skipped several actions or did not follow a predefined action sequence.

Based on these classifications, the SROs' behavior to conduct, in total, 1062 procedural steps can be identified from the collected emergency training records, and Table 3 shows summarized results for their behavior types.

4. Comparison Results

4.1. Comparison Between Behavior Types and the Complexity of Procedural Steps

To clarify the effect of the complexity of the procedural steps on the SROs' behavior, SC scores were compared with the types of the SROs' behavior. This is because the results of several studies indicated that the complexity of the procedural steps due to task demands could be properly quantified by the SC measure [29-31]. Table 4 shows the distribution profile of SC scores over the procedural steps of interest. It is noted that the meaning of the SC measure is summarized in the Appendix.

To compare SC scores and the types of the SROs' behavior, observed data were grouped with respect to several arbitrary ranges of SC scores, and then the χ^2 test was performed. These comparison results are given in Table 5 with the result of the χ^2 test, and the sum of occurrence percentages for non-compliance behavior is plotted in Fig. 2 with respect to the ranges of SC scores.

Table 4. Distribution Profile of the SC Scores

SC score[1]	Representative value	Number[2]
Under 1.124	1.025	85
1.125 ~ 1.324	1.225	104
1.325 ~ 1.524	1.425	322
1.525 ~ 1.724	1.625	261
1.725 ~ 1.924	1.825	141
1.925 ~ 2.124	2.025	77
2.125 ~ 2.324	2.225	39
2.325 ~ 2.524	2.425	20
2.525 ~ 2.724	2.625	6
Over 2.725	2.825	7
Total	-	1062

1. The minimum and maximum SC score is 0.965 and 3.028, respectively.
2. 'Number' means the number of procedural steps that belong to each interval of the SC score.

From the result of the χ^2 test in Table 5, it

Table 5. Comparison Results Between Behavior Types and the SC Scores

SC scores	The number of operators[1]	Number of observations		
		Type A	Type B	Type C
Under 1.325	24	152 (140.1)[2]	20 (11.0)	17 (37.9)
1.326 ~ 1.725	24	403 (432.0)	33 (34.0)	147 (116.9)
1.726 ~ 2.125	23	173 (161.6)	7 (12.7)	38 (43.7)
Over 2.126	20	59 (53.4)	2 (4.2)	11 (14.4)
Total		787	62	213

1. For example, the value of 24 means in total 24 operators were performed procedural steps of which SC scores are less than 1.325.
2. Scores in parentheses mean expected cell frequencies (estimated values) to perform χ^2 test. The result is: χ^2=36.26; df=6; p<0.01; rejection criteria=$\chi^2_{0.01}(6)$=22.46.

seems that the SROs' behavior could be affected by the SC scores, since the χ^2 value is greater that the rejection criterion for the null hypothesis (i.e., $\chi^2=36.26>\chi^2_{0.01}(6)=22.46$). If the SROs' behavior is affected by the SC scores (i.e., the complexity of the procedural steps), two noticeable relationships between non-compliance behavior and SC scores can be extracted.

The first one is that many SROs seem to adopt non-compliance behavior more frequently when

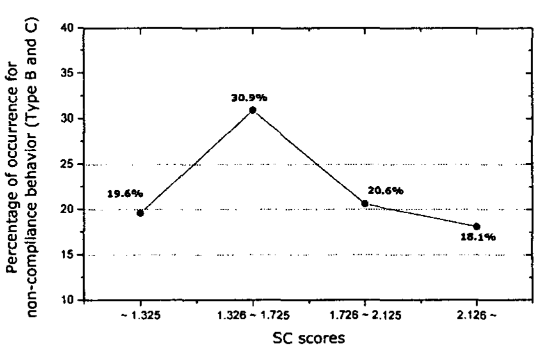

Fig. 2. The Percentage of Non-compliance Behavior with Respect to SC Scores

they entered a procedural step which has an intermediate procedural complexity, since the percentage of occurrence for non-compliance behavior shown in Fig. 2 is maximized in the SC scores ranging from 1.326 to 1.725. In contrast, when the SROs entered a procedural step that has either relatively low (i.e., SC scores under 1.325) or relatively high procedural complexity (i.e., SC scores over 1.726), most of them appear to follow a procedural step as written.

This relationship can be understood by three assumptions based on the viewpoint of the complexity of the procedural steps. Firstly, when the SROs are confronted with the procedural steps that consist of few actions with a simple action sequence, it is assumed that they will carry out the procedural steps as written because the steps are so easy that they don' t need to consider non-compliance behavior to shorten these steps. Secondly, in case of complicated procedural steps, the SROs might feel a burden adopting non-compliance behavior because the procedural steps are so complicated that shortening these steps though non-compliance behavior may not be so easy. Thirdly, in case of a procedural step that has an intermediate procedural complexity, it is reasonable to assume that the SROs will adopt non-compliance behavior to simplify it, since not only they can easily understand its context but also the outcome of adopting non-compliance behavior is quite obvious (i.e., the number of actions included in a procedural step can be easily reduced).

As for the second relationship, it can be observed that the SROs seem to accommodate their non-compliance behavior to the complexity of the procedural steps. To clarify this relationship, let us consider Fig. 3 which shows the percentage of occurrence for both 'Type B' and 'Type C' behavior, which are obtained from Table 5, respectively.

From Fig. 3, two distinctive features can be observed. The first one is that the SROs who conducted procedural steps through non-compliance behavior seem to evenly adopt 'Type B' and 'Type C' behavior, if a procedural step is relatively easy. Because, when the SROs entered the procedural steps of which the SC scores are under 1.325, the percentage of occurrence for both 'skipping redundant actions' and 'modifying action sequences' are almost identical.

In contrast, most of the non-compliance behavior by the SROs are 'modifying action sequences,' when the SROs entered procedural steps that have relatively either an intermediate or high procedural complexity (say, SC scores over 1.326), since the percentage of occurrence for

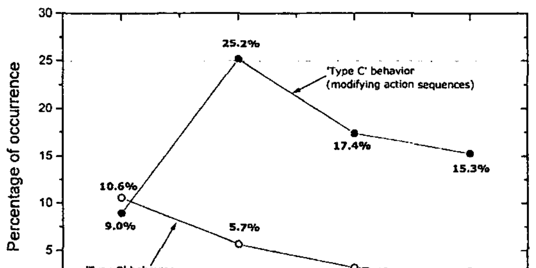

Fig. 3. Percentage for 'Type B' and 'Type C' Behavior with Respect to SC Scores

'Type C' behavior is always larger (about five times) than those of 'Type B.'

One plausible explanation for these features is that, as already mentioned, "the SROs seem to accommodate their non-compliance behavior to the complexity of the procedural steps." In other words, when the SROs entered an easy procedural step that consists of few actions with a simple action sequence, it can be sufficiently shortened through 'skipping redundant actions' behavior. While, when the SROs entered a relatively complicated procedural step that consists of many actions with a intricate action sequence, it is expected that they are likely to adopt a more 'aggressive' behavior (i.e., modifying action sequences) to shorten the procedural steps, instead of the 'meek' behavior (i.e., skipping redundant actions).

5. Discussions and Conclusion

Up to now, to scrutinize the reason of non-compliance behavior, three types of the SROs' behavior were compared with the complexity of procedural steps quantified by SC scores. As the results, two remarkable relationships are obtained. They are:

- When the SROs entered a procedural step that has an intermediate procedural complexity, they seem to frequently adopt non-compliance behavior to conduct it.
- The SROs seem to accommodate their non-compliance behavior based on the complexity of the procedural steps.

From these relationships, it is expected that useful clues for disclosing the reason for non-compliance behavior could be acquired, since the SROs' behavior seems to be affected by the complexity of the procedural steps.

However, it is noted that the question, such that "can behavior types (such as 'Type B' or 'Type

C') and two relationships observed from the emergency training records also be observed in the real field?," should be answered to ensure this expectation. In other words, if the observed behavior types or relationships are different from those in the real field, the results of this study may become less meaningful or meaningless.

Fortunately, there are several rationales indicating that behavior types observed from the emergency training records are not far from the operator's behavior that results in accidents and/or incidents. For example, in case of 'Type B' behavior, analysis results based on licensee event reports(LERs) of U.S. NPPs pointed out that a significant portion of accidents/incidents was caused by "an operator's decision upon a course of action based on what information he had [23]." In addition, as one of the performance influencing factors which can result in procedure related human errors, 'memory of recent actions' was stated by Macwan [41]. Here, this factor represents the operators' behavior such that "if the operator has recently verified that a pump is ON, when he is asked to verify the flow, he may remember that the pump was verified ON and omit verifying the flow."

Similarly, the operator's behavior called 'shortcutting' is comparable to 'Type C' behavior. Shortcutting means the operator's behavior such that several actions were categorized into one group and then checking them at once [5, 43]. In addition, when checklists were lengthy, it was pointed out that there was a tendency of shortcutting to shorten a time-consuming procedure [5]. In other words, the operators try to shorten a time-consuming procedure through finding another way to accomplish required tasks. Obviously, in this study, shortcutting corresponds to 'Type C' behavior, since 'Type C' behavior is defined as the SROs' behavior to shorten the number of required actions included in the procedural steps through modifying action sequences.

Moreover, there is a supporting rationale that these relationships obtained from this study seem to be adequate. That is, procedural deviations (i.e., non-compliance behavior) that occurred when the operators carried out required actions in the belief that they would not result in bad consequences are shaped by cost-benefit trade-offs, where the benefits are seen as outweighing the possible costs [44]. Under this concern, as can be seen in Fig. 2, it should be stressed that the percentages of occurrence for non-compliance behavior are changed along with an inverted-U shape, with respect to the SC scores. This means that the operators appear to trade-off their non-compliance behavior based on the complexity of the procedural steps.

For example, if the SROs are confronted with an easy procedural step, it was observed that most of them carried out it as written, since it can be assumed that "a procedural step is so easy that the SROs don't need to consider non-compliance behavior to shorten it." Similarly, in case of a complicated procedural step, the SROs also showed relatively high procedure compliance, since they might feel a burden shortening it. In contrast, in case of a procedural step that has an intermediate procedural complexity, it was observed that many SROs adopt non-compliance behavior to simplify it. And, this observation could be properly explained if the assumption of "not only they can easily understand its context but also the outcome of adopting non-compliance behavior is quite obvious" is introduced.

Clearly, the tendencies of the SROs' behavior coincide with the rationale of "cost-benefit trade-offs based on the complexity of the procedural steps." Therefore, based on these explanations, it is safe to say that the behavior types and relationships observed from the emergency training records are similar to those observed in the real field.

In addition, if so, it is expected that these relationships will play a significant role not only in understanding the reason for non-compliance behavior but also in suggesting appropriate remedies to decrease the frequency of procedure related human errors. In other words, as stated by Heinrich [45], if we remember that human error is not the cause of an event but a consequence of events (such as unsafe acts of persons), it is strongly expected that most of the procedure related human errors can be diminished through the reduction of non-compliance behavior (i.e., unsafe acts).

Thus, it is hoped that the relationships obtained from this study can be used as meaningful clues not only to scrutinize the reason for non-compliance behavior but also to suggest appropriate remedies for reducing procedure related human errors. For an example, one of the guidelines for checklist design, which was proposed from the aviation industry to enhance the operators' performance, is that "a long checklist should be subdivided into smaller checklists [5]." However, this guideline seems to be insufficient for real application if we cannot answer a critical question: "what is a 'long' checklist that makes the operators try to shorten it?" In this case, it is expected that the SC measure could be used to identify a checklist which the operators are likely to shorten, since the operators' behavior seems to be changed by the complexity of the procedural steps.

Although, many additional studies have to be performed to confirm the relationships between the operators' behavior and the complexity of the procedural steps, the following simple and feasible conclusion can be drawn from this study.

"Since the SROs' behavior seems to be reasonably characterized by the complexity of the procedural steps, the relationships obtained from this study can be used not only to scrutinize the reason for non-compliance behavior but also to suggest appropriate remedies for reducing non-compliance behavior that can result in procedure related human errors."

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Appendix. The Meaning of the SC Measure

As depicted in Fig. 1, each procedural step included in EOPs is written in a two-column format. Here, the left column (denoted by 'Instructions') means the expected plant responses and the right column ('Contingency Actions') presents the operators' actions that should be carried out if the conditions on the left column are not met. Thus, the operators are expected to move down and carry out actions prescribed in the left column if the expected responses are obtained. In contrast, if the expected responses are not obtained, then the operators have to carry out recommended actions given in the right column [29]. This means that the SC measure should reflect the change of the step complexity originated from two contradictory cases such as: 1) the operators only perform 'Instructions' part and 2) the operators perform both 'Instructions' and 'Contingency Actions' part [30]. Based on this concern, the SC score of each procedural step is quantified through two different ways: 1) the SC score that only covers 'Instructions' part, and 2) the SC score that covers both 'Instructions' and 'Contingency Actions' part.

For example, let us consider the fourth procedural step shown in Fig. 1. To calculate SC score for this procedural step, two kinds of graphs (the information structure and the action control graph) are needed. The information structure graph represents the amount of information that has to be processed by the operators in order to complete a given procedural step. Similarly, the action control graph includes both required actions and their logic structure (i.e., the sequence of actions to be followed by the operators) to complete a given procedural step. Based on these graphs, three kinds of complexity scores of the i^{th} procedural step can be quantified by two kinds of graph entropy measures, the first-order entropy and the second-order entropy, as summarized below [29].

- SIC_i : For the i^{th} procedural step, step information complexity (SIC) quantifies the amount of information to be processed by the operators, using the second-order entropy of the information structure graph.
- SLC_i : For the i^{th} procedural step, step logic complexity (SLC) quantifies the logical complexity using the first-order entropy of the action control graph, which is originated from the predefined sequence to conduct the required activities.
- SSC_i : For the i^{th} procedural step, step size complexity (SSC) quantifies the amount of activities to be conducted by the operators, using the second-order entropy of the action control graph.

Based on these complexity scores, the SC score of the i^{th} procedural step is determined by a weighted Euclidean norm, as shown below (please refer to Ref. [46] for more information).

$$SC_i = \sqrt{(\alpha \cdot SIC_i)^2 + (\beta \cdot SLC_i)^2 + (\gamma \cdot SSC_i)^2}$$

where, $\alpha = 0.326$, $\beta = 0.296$, $\gamma = 0.378$.

In this way, the SC scores are quantified for all procedural steps included in the EOPs of the reference NPP. In addition, three types of the operators' behavior (i.e., Type A, B and C) are separately collected based on the above classifications (i.e., for a given procedural step, the operators' behavior in conducting 'Instructions' part is distinguished from that of conducting 'Instructions' and 'Contingency Actions' part).

Reference

1. A. B. Long, Computerized operator decision aids, Nuclear Safety, 25:4, 512-524 (1984).
2. G. Guesnier and C. Hebler, Milestones in screen-based process control, Kerntechnik, 60:5-6, 225-231 (1995).
3. Y. Niwa, E. Hollnagel and M. Green, Guidelines for computerized presentation of emergency operating procedures, Nuclear Engineering and Design, 167, 113-127 (1996).
4. H. G. Stassen, G. Johannsen and N. Moray, Internal representation, internal model, human performance model and mental workload, Automatica, 26:4, 811-820 (1990).
5. A. Degani and E. L. Wiener, Cockpit checklists: concepts, design and use, Human Factors, 35:2, 345-359 (1993).
6. A. Degani, and E. L. Wiener, Procedures in complex systems: the airline cockpit, IEEE Transactions on Systems, Man and Cybernetics - Part A: Systems and Humans, 27:3, 302-312 (1997).

7. International Atomic Energy Agency, Good Practices with Respect to the Development and Use of Nuclear Power Plant Procedures, IAEA-TECDOC-1058 (1998).
8. U. S. Environmental Protection Agency, New Ways to Prevent Chemical Incidents, EPA 550-B-99-012 (1999).
9. W. Rankin, R. Hibit, J. Allen and R. Sargent, Development and evaluation of the Maintenance Error Decision Aid (MEDA) process, International Journal of Industrial Ergonomics, 26, 261-276 (2000).
10. G. Brito, Towards a model for the study of written procedure following in dynamic environments, Reliability Engineering and System Safety, 75, 233-244 (2002).
11. G. T. Klopp, Industry program needed for nuclear accident management, Power Engineering, May, 37-39 (1989).
12. G. Depond and L. Resse, Operating procedures for emergency situations in EdF PWR plants, In Proceedings of IAEA International Training Course on Accident Management in Nuclear Power Plants, Chicago, USA (1989).
13. E. M. Dougherty, Is human reliability enhanced by following procedures? In Proceedings of American Nuclear Society Winter Meeting, p. 112-113, Washington D.C (1994).
14. J. K. Vaurio, Safety-related decision making at a nuclear power plant, Nuclear Engineering and Design, 185, 335-345 (1998).
15. Y. Dien, Safety and application of procedures, or 'how do they have to use operating procedures in nuclear power plants?' Safety Science, 29, 179-87 (1998).
16. S. Kondo, Lessons learned for PSA from the SGTR incident at Mihama, unit 2, in 1991, Reliability Engineering and System Safety, 45, 57-65 (1994).
17. U.S. Nuclear Regulatory Commission, Steam Generator Tube Failures, NUREG/CR-6365. Washington D.C (1996).
18. U.S. Nuclear Regulatory Commission, Indian Point 2 Steam Generator Tube Failure Lessons-Learned Report, Final Report, TAC No. MA9163, Washington, D.C (2000).
19. U. S. Federal Aviation Administration, The Use and Design of Flightcrew Checklists and Manuals, DOT/FAA/AM-91/7, Washington, D.C (1991).
20. D. O' Hare, M. Wiggins, R. Batt and D. Morrison, Cognitive failure analysis for aircraft accident investigation, Ergonomics, 37:11, 1855-1869 (1994).
21. U.S. National Transport Safety Board, A Review of Flightcrew-involved Major Accidents of U.S. Air Carriers, 1978 Through 1990, NTSB/SS-94/01, Washington, D.C (1994).
22. D. W. Joos, Z. A. Sabri and A. A. Husseiny, Analysis of gross error rates in operating of commercial nuclear power stations, Nuclear Engineering and Design, 52, 265-300 (1979).
23. U.S. Nuclear Regulatory Commission, Development of a Checklist for Evaluating Emergency Operating Procedures Used in Nuclear Power Plants, NUREG/CR-1970. Washington D.C (1981).
24. Institute of Nuclear Power Operations, An Analysis of Root Causes in 1983 and 1984 Significant Event Reports, INPO 85-027. Atlanta GA (1985).
25. P. Marsden, Procedures in the nuclear industry, Human Factors in Nuclear Safety (N. Stanton, Editor). Taylor & Francis (1996).
26. K. Furuta, K. Sasou, R. Kubota, H. Ujita., Y. Shuto and E. Yagi, Human factor analysis of JCO criticality accident, Cognition, Technology and Work, 2, 182-203 (2000).

27. Y. Hirotsu, K. Suzuki, M. Kojima and K. Takano, Multivariate analysis of human error incidents occurring at nuclear power plants: Several occurrence patterns of observed human errors, Cognition, Technology and Work, 3, 82-91 (2001).
28. U.S. Nuclear Regulatory Commission, The Human Performance Evaluation Process: A Resources for Reviewing the Identification and Resolution of Human Performance Problem, NUREG/CR-6753, Washington D.C (2002).
29. J. Park, W. Jung and J. Ha, Development of the step complexity measure for emergency operating procedures using entropy concepts, Reliability Engineering and System Safety, 71:2, 115-130 (2001).
30. Jinkyun Park, Wondea Jung, Jaewhan Kim, Jaejoo Ha and Yunghwa Shin, The step complexity measure for emergency operating procedures - comparing with simulation data, Reliability Engineering and System Safety, 74:1, 63-74 (2001).
31. Jinkyun Park, Wondea Jung, Jaejoo Ha and Changkue Park, The step complexity measure for emergency operating procedures - measure verification, Reliability Engineering and System Safety, 77:1, 45-59 (2002).
32. R. R. Fullwood and R. E. Hall, Probabilistic Risk Assessment in the Nuclear Power Industry: Fundamentals and Applications, Pergamon Press (1988).
33. Y. Dien and R. Montmayeul, Contribution of the Ergonomic Analysis to the Improvement of the Design of Operating Procedures in Nuclear Power Plants, Electricite de France, EdF-93NB00043 (1992).
34. P. Marsden and M. Green, Optimizing procedures in manufacturing systems, International Journal of Industrial Ergonomics, 17, 43-51 (1996).
35. U.S. Nuclear Regulatory Commission, Review of Findings for Human Performance Contribution to Risk in Operating Events, NUREG/CR-6753, Washington D.C (2002).
36. U.S. Nuclear Regulatory Commission, Evaluation of Emergency Operating Procedures for Nuclear Power Plants, NUREG/CR-1875, Washington D.C (1981).
37. U.S. Nuclear Regulatory Commission, Guidelines for the Preparation of Emergency Operating Procedures, NUREG/CR-0899, Washington D.C (1982).
38. U.S. Nuclear Regulatory Commission, Checklist for Evaluating Emergency Operating Procedure Used in Nuclear Power Plants, NUREG/CR-2005, Washington D.C (1983).
39. T. Kontogiannis, Applying information technology to the presentation of emergency operating procedures: implications for usability criteria, Behaviour and Information Technology, 18:4, 261-276 (1999).
40. A. A. Husseiny, Z. A. Sabri, D. Packer, J. W. Holmes, S. K. Adams and R. J. Rodriguez, Operating procedure automation to enhance safety of nuclear power plants, Nuclear Engineering and Design, 110, 277-297 (1989).
41. A. Macwan and A. Mosleh, A methodology for modeling operator errors of commission in probabilistic risk assessment, Reliability Engineering and System, 45, 139-157 (1994).
42. N. Morray. Advanced displays, cultural stereotypes and organizational characteristics of a control room. Nuclear Safety: A Human Factors Perspective (J. Misumi, B. Wilpert and R. Miller, Editor). Taylor & Francis (1999).
43. U.S. Nuclear Regulatory Commission. Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant

Applications. NUREG/CR-1278. Washington D.C (1982).

44. D. E. Maurino, J. Reason, N. Johnston and R. B. Lee, Beyond Aviation Human Factors - Safety in High Technology Systems, Ashgate Publishing Company (1995).
45. H. W. Heinrich, D. Petersen and N. Roos, Industrial Accident Prevention: A Safety Management Approach, 5th Edition, McGraw-Hill (1980).
46. Jinkyun Park, Wondea Jung, Jaewhan Kim and Jaejoo Ha, The step complexity measure - its meaning and applications, Journal of the Korean Nuclear Society, 35:1, 80-90 (2003).