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A Feasibility Study on the Utility of SPADES+ in Accident Diagnosis

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1. Introduction

The Safety Parameter Display and Evaluation System+ (SPADES+) [1,2], used to assist emergency operating procedures (EOP) in nuclear power plants (NPPs), displays the status of safety parameters specified in the EOP and indicates whether safety functions are violated. SPADES+ includes 11 operating modes and 9 safety functions. It is a supplementary information provider rather than being directly linked to the EOP.

Recently, during the second integrated system verification at NPP site, operators expressed that they do not utilize the information provided by SPADES+ and that its usability and utility are low. Furthermore, when comparing the SPADES+ importance index [3] with other systems, it is relatively low.

In this study, the reasons for the low usability and utility of SPADES+ are analyzed, experiments are conducted to improve its utilization, and the results are evaluated.

2. Background

2.1 SPADES+ functions

SPADES+ comprises 11 operating modes, including normal operation, post-reactor trip action, optimal recovery procedures, and function recovery procedures in EOP. Operators manually select the SPADES+ operating mode according to the current state of EOP implementation.

SPADES+ generates visible and audible alarms when safety functions are compromised, assisting operators in recognizing issues.

2.2 Accident diagnosis in NPP

During accident diagnosis, operators follow the diagnostic procedure according to EOP. The diagnostic procedure is performed by following the flowchart provided in the EOP, with operators verifying key plant status information required by the flowchart.

The Operator determines accident type according to the accident diagnosis procedure or, if an accident-type diagnosis is not possible, performs function recovery procedures.

2.3 Accident diagnosis with SPADES+

During accident diagnosis, the SPADES+ program provides information on safety variables for nine safety functions after operators enter the SPADES+ accident diagnosis mode. Using the information from SPADES+, operators can verify whether safety function status check criteria are met.

2.4 Review on SPADES+ in Second Integrated System Verification at NPP site

The following review results regarding SPADES+ were derived from the site.

1) Operators do not utilize SPADES+.
2) SPADES+ is not helpful in Accident Diagnosis.
3) There is a lack of understanding and training regarding SPADES+.
4) During EOP, automatic accident-type diagnosis in SPADES+ is not performed, resulting in extremely low utilization for accident diagnosis.

3. Methods to enhance SPADES+ utility

3.1 Conducting training to improve understanding of SPADES+

In this measure, user training on the SPADES+ program itself is implemented and users are educated on its operation methods to enhance utility. This measure is applied in conjunction with that described in Section 3.2 to increase the utilization of SPADES+ during accident diagnosis.

3.2 Utilizing SPADES+ in conjunction with EOP for accident diagnosis

During an accident diagnosis with EOP, operators find it difficult to use SPADES+ for diagnosing the accident type. To address this issue, we inserted a guideline for SPADES+ into the accident diagnosis procedure of the EOP, as shown in Figure 1. It allows operators to easily diagnose the accident type by referring to the inserted SPADES+ guideline.

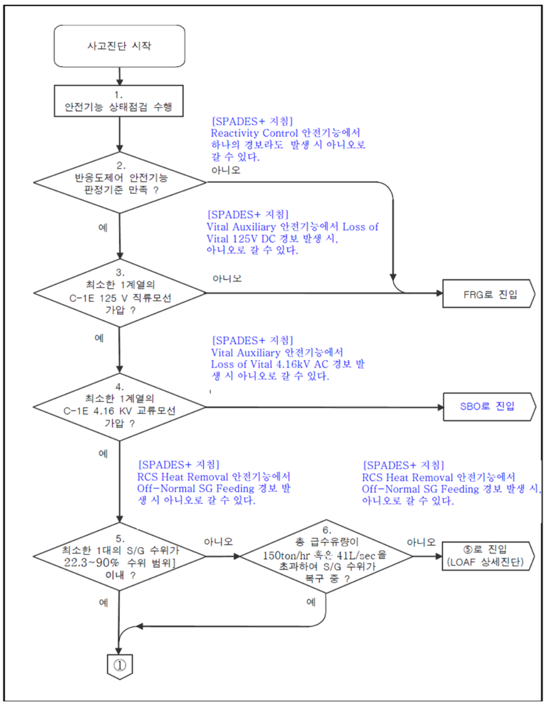

Fig. 1. Guideline for SPADES+ in the EOP

4. Experiment for SPADES+ utility

4.1 Experimental plan to enhance SPADES+ utility

To verify the effectiveness of the measures described in Section 3 to enhance SPADES+ utility, an experiment with the following plan was simulated:

1) Provide comprehensive training on SPADES+ and Information Processing System (IPS) to the participants.
2) Simulate accident scenarios.
3) Have participants perform accident diagnosis according to the accident cases in Table 1.
4) Analyze data and verify their validity.

Table 1: NPP accident scenarios

Cases	NPP Accident	Guidance for SPADES+ in EOP	SPADES+ Usable
Case 1	SBO*1	O	O
Case 2	LOCA*2	O	O
Case 3	ESDE*3	X	O
Case 4	LOCA	X	X

* 1: Station Blackout
* 2: Loss of Coolant Accident
* 3: Excess Steam Demand Event

A notable aspect of the experiment is setting different levels of utilization for SPADES+ for each case and including a case where SPADES+ is not used. Cases with and without SPADES+ are compared to check whether SPADES+ influences accident diagnosis.

4.2 Experiment design

4.2.1 Participant selection and training

A total of 14 participants were engineers experienced in NPP design. Before participating in the experiment, they received training on SPADES+ and the IPS system overview, screen operation, display components, and basic aspects of the accident diagnosis procedure.

After training, to verify the participants' proficiency with IPS/SPADES+, an experiment was conducted to measure the time taken to identify specific variables on each IPS and SPADES+ screen. The results are presented in Table 2.

Table 2: Average time consumed for IPS/SPADES+ variable identification

Consumed time for IPS Variable	Consumed time for SPADES+ Variable
13.75 s	10.84 s

4.2.2 Simulation of NPP accidents

Four accident cases were simulated (Table 1). In Case 1, SBO, which is the easiest among the cases to diagnose, was applied first to help participants become familiar with accident diagnosis. In Cases 2 and 4, LOCA accidents were applied second and fourth to serve as comparison and control groups for data analysis.

To evaluate SPADES+ utility, the method of utilizing SPADES+ was varied for each accident case. In the earlier cases, a guideline for SPADES+ to easily diagnose the accident was inserted into the EOP to facilitate extensive utilization. As the accident cases progressed, the usage of SPADES+ in EOP and the program itself was reduced and finally removed to verify whether SPADES+ influenced accident diagnosis.

4.2.3 Data collection after accident diagnosis

Following each simulated accident, data were derived by evaluating the accident diagnosis time, the number of SPADES+ references at each diagnostic branch, and any unusual qualitative behavioral patterns.

4.3 Experiment results

4.3.1 Evaluation of accident diagnosis time by case

The accident diagnosis results from Cases 1 to 4 are presented in Figure 2. Case 3 had the shortest average accident diagnosis time, while Case 2 took the longest.

On average, participants performed accident diagnosis faster in Case 4, where SPADES+ was not allowed, compared to Case 2, where SPADES+ reference methods were explicitly stated in EOP for high usability.

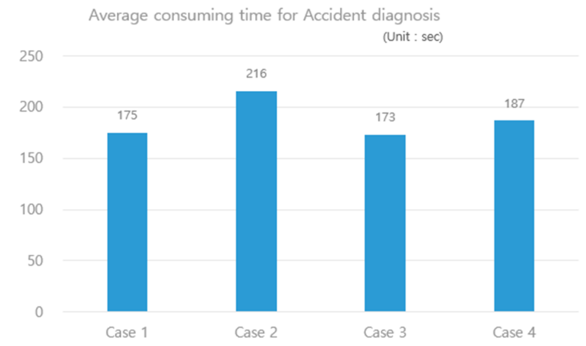

Fig. 2. Average time consumed for accident diagnosis.

4.3.2 Correlation between IPS/SPADES+ proficiency and accident diagnosis time

The correlation coefficient using Pearson's correlation coefficient between the all participants' SPADES+ or IPS proficiencies (Consumed time to find variables of IPS/SPADES+ described in 4.2.1) and the accident diagnosis time can be calculated using the following equation:

$$\gamma = \frac{\sum(x_t - \bar{x})(y_t - \bar{y})}{\sqrt{\sum(x_t - \bar{x})^2 \sum(y_t - \bar{y})^2}}$$

x_t = SPADES(IPS) Proficiency (Consumed time for finding variable)
$\bar{x}$ = Average of x_t
y_t = Average Consumed time for accident diagnosis
$\bar{y}$ = Average of y_t

The Pearson's correlation coefficient ranges between -1 and 1 where 1 indicates a perfect positive linear relationship and -1 indicates a perfect negative linear relationship. In general, a correlation coefficient greater than 0.7 is considered to indicate a strong positive relationship, while a coefficient less than 0.4 is typically interpreted as indicating a weak positive relationship.

The results for each case are given in Table 4.

Table 4: SPADES/IPS proficiency and correlation coefficients

Cases	Correlation coefficients	
	IPS Proficiency	SPADES+ Proficiency
Case 1	−0.19	0.005
Case 2	0.24	0.05
Case 3	0.68	−0.001
Case 4	0.41	−0.135

Compared to SPADES+, IPS showed a slightly stronger correlation with accident diagnosis time in most cases. However, overall there was no significant correlation between proficiency and accident diagnosis time.

4.3.3 Correlation between number of SPADES+ references and accident diagnosis time

The number of SPADES+ references in Cases 1–3 ranged between 4 and 5 times, except for Case 1. Case 1 had fewer SPADES+ references due to its quick diagnosis.

The correlation coefficients between the number of SPADES+ references and the accident diagnosis time for each case are listed in Table 5.

Table 5: Average number of SPADES+ references and correlation coefficients

Cases	Average number of SPADES+ references	Correlation coefficient
Case 1	2.2	−0.11
Case 2	4.9	0.64
Case 3	4.8	0.30

All cases showed correlation coefficients below 0.8, indicating no significant correlation between the number of SPADES+ references and accident diagnosis time.

4.3.4 SPADES+ participant feedback

After the completion of the experiment, all the participants were asked to rate the effectiveness of SPADES+ across various categories. Participants rate the utility of the program on a scale of 0 to 10, and circle any of the items(question) that ask about aspects they find beneficial. The results are presented in Table 6.

Table 6. Evaluation and ratings of SPADES+

Performer	Score* (0 to 10)	Q1	Q2	Q3	Q4
1	9	O	O		
2	8				O
3	9	O			O
4	10		O		
5	5	O			
6	5		O		
7	5	O			
8	0				
9	10	O	O		
10	5	O	O		
11	7	O			
12	9	O			
13	5				O

* Score : Rate of utility of SPADES+ Program
Q1: Does SPADES+ provide intuitive cognitive information?
Q2: Is the quantity of displayed information appropriate?
Q3: Is the displayed information highly reliable?
Q4: Is the integration of EOP and SPADES+ beneficial?

4.4 Analysis of experimental results

From the experimental data, the following results can be drawn:

(1) Improving proficiency in SPADES+ by training does not significantly reduce time required for accident diagnosis. This is evidenced by the low correlation between SPADES+ proficiency and accident diagnosis time as described in Section 4.3.2 as well as the weak relationship between the number of SPADES+ references and diagnosis time across different accident scenarios presented in Section 4.3.3.

(2) The reference guideline of SPADES+ in EOP does not appear to provide substantial assistance in accident diagnosis. This is supported by the fact that only a minority of participants selected item 4, i.e., "The integration of EOP and SPADES+ is beneficial," in Table 6. Additionally, in identical accident scenarios (LOCA, Cases 2 and 4), the average accident diagnosis time was shorter in Case 4, where SPADES+ could not be used, compared to Case 2, which featured enhanced SPADES+ integration with EOP. However, it would be premature to conclude that the integration of SPADES+ and EOP is entirely unhelpful. This is because the reduction in diagnosis time could be attributed to participants becoming more familiar with the experiment as it progressed, leading to faster diagnosis times across all cases.

5. Conclusion

In this study, experiments based on two potential solutions to enhance the utility of SPADES+ in supporting EOP in NPP were conducted. The first solution involved comprehensive training on SPADES+, while the second focused on integrating SPADES+ with EOP to increase its practicality. The experimental results suggest that neither solution provides significant benefits. Consequently, the proposed solutions for improving the utility of the existing SPADES+ system appear to have limited effectiveness. Therefore, additional strategies to enhance the practical application of the system with helpful features should be considered in future work.

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