# Application of Positive Lesson Learning Method to Mihama-2 SGTR Accident

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**Abstract:** Nuclear operators have considered past troubles as failures and have taken measures to prevent recurrence by eliminating the causes of such failures. Although these measures have contributed to improving nuclear safety, it is insufficient to strengthen them to improve safety further; a new perspective on safety is needed. Based on the Safety-II concept, many troubles that did not result in significant harm can be regarded as instances where human actions have successfully contributed to avoiding undesirable harm. Safety can be further enhanced by focusing on human actions during such troubles and utilizing them as learning opportunities to encourage positive actions. This study structuralized resilience potentials and human actions against off-normal events in nuclear power plant operations. The five types of human actions against off-normal events in nuclear power plant operations were structuralized. The five types were re-structuralized into 11 categories based on resilience potentials. A lesson learning method utilizing 11 categories derived from resilience engineering was proposed. The analysis flow of this method is (1) extracting human actions against off-normal events from trouble reports, (2) classifying the extracted human actions into 11 categories and (3) analyzing the human actions in each category and deriving measures to further improve safety. Using the proposed method, the steam generator tube rupture accident at the Mihama Nuclear Power Station Unit 2 was analyzed. The analysis results indicate that new versatile lessons not revealed in the existing trouble report can be derived through the proposed method while considering humans as a positive element. It is expected that nuclear operators will be able to enhance safety by using the obtained countermeasures as a collection of reference cases for plant operation personnel.

**Keywords:** Lesson Learning, Human Factors, Safety-II, Resilience Engineering

## 1. INTRODUCTION

Nuclear power plants are required to have a high level of safety due to the enormous impact of an accident. New regulatory standards were enacted in Japan based on the lessons learned from the 2011 accident at TEPCO's Fukushima Daiichi Nuclear Power Station (1F accident) [1]. Although existing nuclear power plants have achieved a certain level of safety improvement due to the Nuclear Regulation Authority of Japan’s additional requirements for both hardware and software measures, further safety improvements are continuously required.

Nuclear operators have considered past troubles as failures and have taken measures to prevent their recurrence by eliminating the causes of such failures. When technical factors cause the trouble, the possibility of recurrence is low if the cause is eliminated. Recurrence prevention measures such as component improvement or replacement have effectively addressed these troubles [2]. In numerous instances, the same methodology has been employed for human and technical factors. In other words, recurrence prevention measures may be implemented by revising procedure manuals to eliminate human errors identified by cause analysis and ensure compliance with the revised manuals. Although this approach offers a comprehensive explanation of the causes of the trouble and how to prevent its recurrence, this revision of procedure manuals may result in the recurrence of errors in situations where higher work efficiency is required or new workers are assigned, as typically noted by Miyazaki [3]. Furthermore, it is too demanding to establish appropriate procedures that can assume all possible situations in advance. Although these measures have contributed to improving nuclear safety, it is insufficient to strengthen them to improve safety further; a new perspective on safety is needed.

From this perspective, Safety-II and resilience engineering have attracted the attention of safety engineers recently [4]. Safety-I is the concept that "the definition of safety is a condition where the number of adverse outcomes is as low as possible," a conventional idea represented by quality management. Safety-II is a new concept that "the definition of safety is a condition where the number of intended and acceptable outcomes is as high as possible." Resilience engineering is a methodology to pursue Safety-II. Based on the Safety-II concept, many troubles that did not result in significant harm can be regarded as instances where human actions have successfully contributed to avoiding undesirable harm. For example, the steam generator tube rupture (SGTR) accident at the Mihama Nuclear Power Station Unit 2 in Japan in 1991 resulted in a small release of radioactive materials but core damage had been avoided. Safety can be further enhanced by focusing on human actions during such troubles and utilizing them as learning opportunities to encourage positive actions.

About Safety-II and resilience engineering, not only has basic research been conducted from the perspective of unexpected situations within the scope of cognitive experiments [5,6], but also applied research specific to this field has been conducted in the field of aviation [7]. In the nuclear field, it is necessary to enhance the resilience of plant operation personnel because the probability of the occurrence of events that exceed the countermeasures that have been prepared in advance cannot be reduced to zero [8]. Currently, however, the nuclear industry still needs to establish a systematic and practical method for learning positive lessons to enhance resilience. As one of the few examples of the application of the Safety-II concept in the nuclear field, Yoshizawa et al. analyzed the case of water injection recovery at Unit 3 in the 1F accident, focusing on the aspects that prevented further accident progression based on the Safety-II concept [9]. The 1F accident has detailed investigation results, but for many other troubles, detailed trouble reports rarely exist from the viewpoint of resources and necessity. Consequently, there are challenges in applying this approach to many troubles. Although the Functional Resonance Analysis Method (FRAM) [4] is a well-known method of Safety-II analysis, the longer the event chronology, the more complex and time-consuming it may be to perform a FRAM analysis. In a previous study, Horiuchi et al. examined an analysis method based on the Safety-II concept and analyzed some reactor manual shutdown events experienced by one Japanese nuclear operator. However, the accumulation of applicable cases and their application to cases other than reactor manual shutdown cases are future issues [10].

## 2. OBJECTIVE

The nuclear power industry is required to improve safety further, and effective methods are needed to learn from failures and successful cases. This study aims to develop a systematic and practical analysis method based on the Safety-II concept for human actions against off-normal events in experienced events.

The activities of nuclear power plants include operation, maintenance and waste disposal. The accidents that impact these activities most are core damage and containment failure during operation. In order to enable the analysis of troubles in which human actions avoided core damage or containment failure, this method focuses on the operation of nuclear power plants.

## 3. METHOD

### 3.1. Structuralization of Resilience Potentials and Human Actions

As resilience engineering is not a methodology for a specific system but a general one, resilience engineering should be tailored to cover nuclear power plant operations in the proposed method. As a means of tailoring, this study structuralized resilience potentials and human actions and then proposed the method by using this result. The following shows how to structuralize the resilience potentials.

First, the relationship between the plant and human resilience potentials in nuclear power plant operations was structuralized. The plant and human relationship has been considered a human-machine system. THERP (Technique for human error-rate prediction) [11], one of the human reliability analysis methods with extensive experience in probabilistic risk assessment in nuclear power plants, and Phoenix [12], a new human reliability analysis method, consider humans as one of the components of the system and model humans as those who cognize the plant status, make decisions, and operate the plant. From this perspective, this study structuralized plant and human inputs and outputs by considering cognition as an input from the plant to the human and operation as an output from the human to the plant. Cognition is monitoring parameters in the main control room using control panels and large displays or gathering information about component anomalies outside the control room. This is related to the potential of monitoring. If the operation is for changing the state of the plant, the potential of responding is related. On the other hand, the potential of monitoring is related if the operation is for cognition, for instance, operations associated with sampling for water quality testing. Additionally, there are operations on humans that do not appear directly in the human reliability analysis, such as wearing protective equipment to reduce work risks. From the above, it can be structuralized as inputs from the plant to the potential of monitoring (and outputs simultaneously if it is an operation for cognition) and outputs from the potential of responding to both the plant and humans.

Second, the causal relationships between each resilience potential were structuralized. For instance, the event development can be predicted or components can be operated based on monitored parameters. Thus, inputs are made from the potential of monitoring to the potential of anticipating and the potential of responding. Alternatively, based on predictions of the event development, parameters can be monitored, or components can be operated. Thus, inputs are made from the potential of anticipating to the potential of monitoring and the potential of responding. Unidirectional causal relationships exist between the potential of learning and the other three potentials. Plant operation personnel can monitor, anticipate and respond based on the results they have learned in daily operations and training.

The above is shown in Figure 1. It should be noted that the arrows emanating from the potential of learning are dotted lines, as they represent paths that have been implemented before any human actions against off-normal events.

Third, the types of human actions against off-normal events in nuclear power plant operations were structuralized.
In order to respond to off-normal events, it is necessary to notice the occurrence of some events. This is referred to as (1) “actions against event occurrence”.
After noticing the occurrence of the event, it is necessary to identify and eliminate the factors that caused the event and follow the plant’s constantly changing conditions. These are referred to as (2) “actions against causal factors” and (3) “actions against event development,” respectively.
If actions (2) and (3) cannot be clearly implemented, (4) “actions against work risks” are required.
If it is determined that plant operations cannot be continued in actions (2), (3), and (4), then (5) “actions for plant shutdown” are required. (5) are defined as distinct actions from (2), (3), and (4) because they are not actions to continue necessary operations.
For example, in the event of a gradual decrease in tank pressure, the action of noticing the decrease in the pressure parameter corresponds to (1) actions against event occurrence, the action of closing the hole in the tank corresponds to (2) actions against causal factors, the action of repressurizing the tank corresponds to (3) actions against event development, and the action of measuring the hazardous gas concentration corresponds to (4) actions against work risks.

Fourth, the types of human actions against off-normal events were re-structuralized based on the three resilience potentials, with the potential of learning excluded. (2) Actions against causal factors, (3) actions against event development and (4) actions against work risks can be re-structuralized about the three resilience potentials.

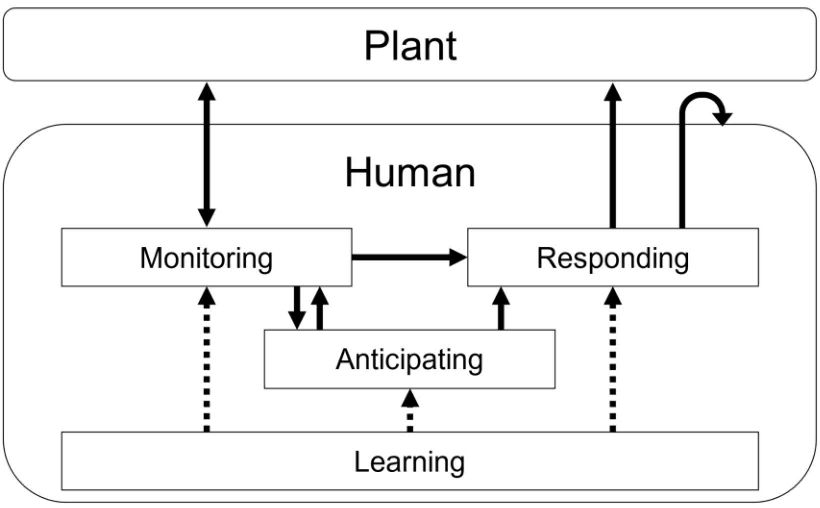


Figure 1. Structuralization of resilience potentials and human actions

(2) Actions against causal factors can be re-structuralized into collection of information on causal factors (monitoring), estimation of causal factors (anticipating), and elimination of causal factors (responding).
(3) Actions against event development can be re-structuralized into observation of event development (monitoring), prediction of event development (anticipating), and mitigation of event development (responding).
(4) Actions against work risks can be re-structuralized into confirmation of work risks (monitoring), assumption of work risks (anticipating), and reduction of work risks (responding).
(1) Actions against event occurrence can be associated with the potential of monitoring (perception of event occurrence), as these actions correspond to cognition among cognition, decision making and operation.
(5) Actions for plant shutdown can be associated with the potential of responding (plant shutdown operation), as these actions correspond to an operation to change the state of the plant.
In summary, the results of the above structuralization can be divided into 11 categories, as shown in Table 1.

### 3.2. Proposed Method

A lesson learning method utilizing 11 categories derived from resilience engineering was proposed. This method has the distinctive feature that the analysis focuses on promoting positive actions, as advocated by the Safety-II concept. The analysis flow of this method is as follows:

(1) Extracting human actions against off-normal events from trouble reports
The initial step is to extract human actions against off-normal events systematically from the human actions described in trouble reports. At this stage, organizing the extracted human actions according to chronological order and causal relationships is preferable.

(2) Classifying the extracted human actions into 11 categories
The second step is to classify the extracted human actions into 11 categories, which were derived based on resilience engineering. If human actions span multiple categories, it is preferable to subdivide them so that they can be classified into 11 categories.

(3) Analyzing the human actions in each category and deriving measures to improve safety
The third step is to analyze what was positive and what could be more positive in each human action, according to chronological order and causal relationships, and to derive measures to improve safety. Once all the extracted human actions have been analyzed, they are summarized by category.

## 4. RESULTS AND DISCUSSION

### 4.1. Summary of the Analyzed Trouble

The SGTR accident at the Mihama Nuclear Power Station Unit 2 in Japan in 1991 was selected as the target of analysis for the proposed method. This selection was made because the accident can be regarded as a successful case in which a severe accident was avoided by taking flexible human actions rather than simply complying with procedure manuals.

Table 1. 11 categories of human actions against off-normal events

| Actions | Monitoring | Anticipating | Responding |
|---|---|---|---|
| event occurrence | Perception of event occurrence | | |
| causal factors | Collection of information on causal factors | Estimation of causal factors | Elimination of causal factors |
| event development | Observation of event development | Prediction of event development | Mitigation of event development |
| work risks | Confirmation of work risks | Assumption of work risks | Reduction of work risks |
| plant shutdown | | | Plant shutdown operation |

An SGTR is one of the design basis accidents that can be expected in pressurized water reactors (PWRs). In this accident, a single heat transfer tube of a steam generator, which exchanges heat between a PWR's primary and secondary cooling systems, fails. In order to stop the outflow immediately, it is necessary to equalize the pressure of the primary cooling system and the secondary cooling system on the side of the damaged steam generator.
The SGTR is subject to a safety evaluation during the licensing process for installation in Japan. While the reactor trip and emergency core cooling systems are automatically activated, a number of operator actions are required, even in design basis accidents. In general, the following operator actions are required for safety evaluation. Failure of these operator actions and failure to take alternative measures can lead to a severe accident [13].
(1) Cognition of an event occurrence due to a reactor trip.
(2) Closing the steam admission valve of the turbine-driven auxiliary feedwater pump on the damaged steam generator side.
(3) Shutting down the auxiliary feedwater to the damaged steam generator.
(4) Closing the main steam isolation valve (MSIV) on the damaged steam generator side.
(5) Opening the main steam relief valve on the sound steam generator side.
(6) Opening the power operated relief valve (PORV) on the pressurizer.
(7) Closing the PORV.
(8) Shutting down the emergency core cooling system.

The Mihama Nuclear Power Station Unit 2 is a two-loop PWR with two steam generators. On February 9, 1991, an SGTR occurred in the steam generator of the A loop. The notable human actions that differed from the sequence of safety evaluation were as follows: (1) to notice the event's occurrence by parameter variation before the reactor trip. In (4), the MSIV was attempted to be closed in the main control room to isolate the damaged steam generator. However, confirming that the valve was completely closed was impossible, so it was retightened on site. In (6), the PORV was attempted to be opened to depressurize the primary cooling system. However, it did not function as intended, so a pressurizer auxiliary spray was used as an alternative. The measures mentioned above, which are flexible human actions, prevented a severe accident.

### 4.2. Analysis Results

The proposed method was applied to analyze the SGTR at the Mihama Nuclear Power Station Unit 2.

(1) Extracting human actions against off-normal events from trouble reports
The report published by Kansai Electric Power Co., Inc. [14] was used. This report provides an overview of the event, the development of the event, evaluations of the integrity of the reactor core and reactor vessel, investigations of the cause of the steam generator heat transfer tube damage, and measures to prevent recurrence. Ninety-eight human actions against off-normal events were systematically extracted from the human actions described in this report. Figure 2 shows the result of organizing the MSIV closing operation process according to chronological order and causal relationships as a representative example. The number of actions performed during the MSIV closing operation process was five, as listed in the Monitoring, Anticipating, and Responding columns of Figure 2.

(2) Classifying the extracted human actions into 11 categories
During the MSIV closing operation process, the action "the A-MSIV closing operation for A-SG isolation (in the main control room)" was classified as the category "plant shutdown operation." The action "confirmation that both the A-MSIV open indicator and the A-MSIV closed indicator were lit" was classified as the category "perception of event occurrence." The action "assumption that the A-MSIV was not completely closed" was classified as the category "estimation of causal factors." The action "the A-MSIV closing operation with a chain block (on site)" was classified as the category "elimination of causal factors." The action "confirmation that A-SG secondary pressure and B-SG secondary pressure began to diverge and the damaged SG was isolated" was classified as the category "observation of event development."

The results of the classification of the 98 human actions against off-normal events are shown in Table 2. It was confirmed that all human actions were classified into one of the predefined categories. No actions were classified as confirmation of work risks, assumption of work risks or reduction of work risks. In this accident, there was no development of events that directly and significantly affected the working environment, such as

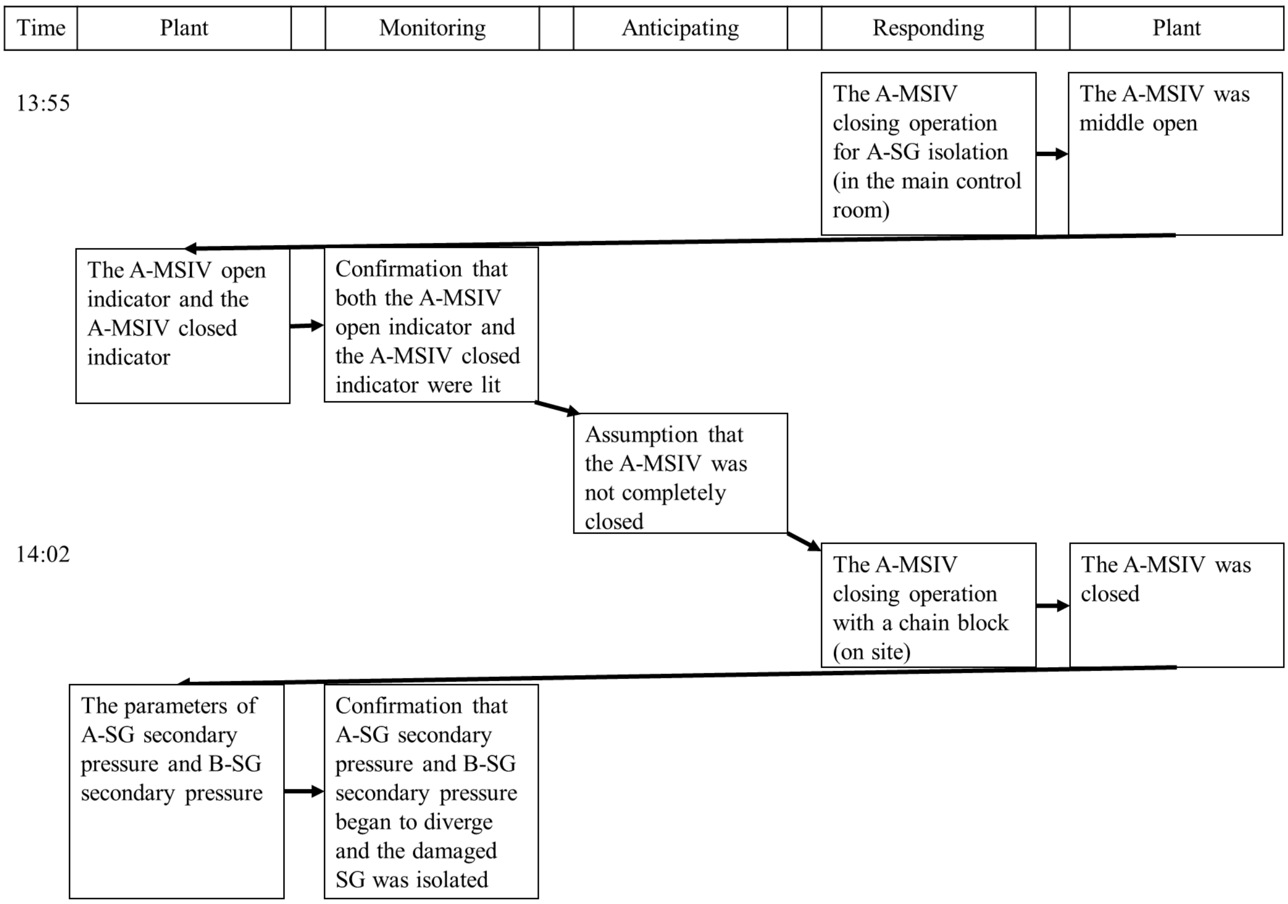


Figure 2. Organizing the human actions during the MSIV closing operation process

Table 2. Classification of human actions in the SGTR at Mihama

| **Monitoring** | | **Anticipating** | | **Responding** | |
|---|---|---|---|---|---|
| Perception of event occurrence | 3 | | | | |
| Collection of information on causal factors | 11 | Estimation of causal factors | 10 | Elimination of causal factors | 3 |
| Observation of event development | 21 | Prediction of event development | 5 | Mitigation of event development | 4 |
| Confirmation of work risks | 0 | Assumption of work risks | 0 | Reduction of work risks | 0 |
| | | | | Plant shutdown operation | 41 |

the leakage of water containing radioactive materials or the emission of high-temperature and high-pressure steam. It is assumed that the accident could have been managed with general equipment that did not require a description in the trouble report. Consequently, it is considered appropriate that these categories were zero in the analysis of this accident.

(3) Analyzing the human actions in each category and deriving measures to improve safety
Each human action’s positive or more positive points were analyzed according to chronological order and causal relationships. The results of the analysis of the MSIV closing operation process are shown in Table 3. In this process, positive or more positive points were analyzed in four out of five actions. Derived measures to improve safety were “Confirmation of the effectiveness of the previous operation,” “Enhancing the ability to estimate based on limited information,” “Preparing alternative measures in advance,” and “Preselection of alternative parameters.”

Table 3. Results of the analysis of the MSIV closing operation process

| Human Action | Category | Positive or More Positive Points | Measure |
|---|---|---|---|
| The A-MSIV closing operation for A-SG isolation (in the main control room) | Plant shutdown operation | -<br>(The operation on SGTR safety evaluation and as per procedure manual.) | |
| Confirmation that both the A-MSIV open indicator and the A-MSIV closed indicator were lit | Perception of event occurrence | The relevant plant status was checked after the operation and the failure to achieve the operation objective was confirmed. | Confirmation of the effectiveness of the previous operation |
| Assumption that the A-MSIV was not completely closed | Estimation of causal factors | It was appropriate that the indicator lights were not determined to be mislit, but rather that the A-MSIV was determined to be in an intermediate open state. | Enhancing the ability to estimate based on limited information |
| The A-MSIV closing operation with a chain block (on site) | Elimination of causal factors | As an alternative measure, an increased tightening of the A-MSIV was performed on site. | Preparing alternative measures in advance |
| Confirmation that A-SG secondary pressure and B-SG secondary pressure began to diverge and the damaged SG was isolated | Observation of event development | The appropriate parameters were selected to confirm the complete closure of the A-MSIV. | Preselection of alternative parameters |

Table 4 shows 29 measures to improve safety derived from each of the 98 human actions, with the results organized by category. The parentheses in Table 4 indicate the number of actions from which the measures were derived.

Table 4. Measures derived from the SGTR at Mihama using the proposed method

| Category | Measures |
|---|---|
| Perception of event occurrence | Confirmation of the effectiveness of the previous operation (2)<br>Utilization of plant computers (1) |
| Collection of information on causal factors | Continuous monitoring of parameters related to the event (5)<br>Preliminary organization of the parameters collected of information in response to specific alarms (2)<br>Utilization of plant computers (1)<br>Checking the plant status regardless of the specified frequency (1)<br>Checking whether there is any mutual influence when information is collected by multiple means at the same time (1) |
| Estimation of causal factors | Applying the decision criteria conservatively (2)<br>Identification of events based on multiple pieces of information (2)<br>Estimation of causal factors in an order that is readily confirmable (2)<br>Preliminary organization of the relationship between alarms and actual plant conditions (1)<br>Enhancing the ability to estimate based on limited information (1)<br>Assumption of the most unfavorable circumstances when the causal factors are unknown (1)<br>Clarification of the procedures to be followed when estimation is limited to a few patterns (1) |
| Elimination of causal factors | Preparing alternative measures in advance (1) |
| Observation of event development | Confirmation of the effectiveness of the previous operation (3)<br>Continuous observation of event development across the entire plant (1)<br>Appropriate observation of event development in situations that are different from the procedure manual (1)<br>Preselection of alternative parameters (1) |
| Prediction of event development | Preliminary consideration of the optimal timing for system restoration (1)<br>Prediction of potential future alarms (1)<br>Re-checking the contents of the procedure manual to the extent that it does not interfere with the operation (1)<br>Anticipation of situations that deviate from the established procedure manual and consideration of the appropriate monitoring and responding of such situations (1) |
| Mitigation of event development | Preliminary examination of the mitigation strategies to be employed in the event of a failure of measures (1)<br>Accurate comprehension of the priority of each procedure and the order in which they are to be followed (1)<br>Pre-understanding of the contents of the procedure manuals in order to operate prior to the event development (1) |
| Confirmation of work risks | - |
| Assumption of work risks | - |
| Reduction of work risks | - |
| Plant shutdown operation | Organization of the procedures to be prioritized in the event of a deviation from the assumed procedures (2)<br>Shutting down the plant more rapidly in the case of a higher level of urgency (1)<br>Accurate comprehension of the priority of each procedure and the order in which they are to be followed (1) |

### 4.3. Discussion

The proposed method, which is based on the Safety-II concept, does not negate the cause analysis and recurrence prevention measures based on the Safety-I concept. Further safety improvement can be achieved by using both the Safety-I and Safety-II concepts in the analysis of accidents. The effectiveness of the proposed method was examined from the perspective of whether the proposed method derives new lessons learned that were not previously revealed in existing trouble reports, which summarize the analysis and measures from the perspective of Safety-I.

The existing trouble report by Kansai Electric Power Co., Inc. listed the following as measures to prevent recurrence: strengthening quality assurance activities, improving the integrity of steam generator heat transfer tubes, improving maintenance management methods, reviewing and enhancing periodic inspection items, enhancing procedure manuals, and improving monitoring systems and measurement control systems. Among these, the recurrence prevention measure concerning actions to be taken by operators was enhancing procedure manuals. In particular, the revised manuals included descriptions of the actions to be taken in the event of malfunction of the PORV or the MSIV during SGTR, descriptions of the actions to be taken in the event of malfunction of components with safety-critical functions, clarification of the relation between the procedure manuals and clarification of the timing, sequence, and conditions of operations of components.

Although a description of the response operation is essential to enable smooth responses during the next SGTR if it is described in the procedure manuals in advance, the accident was not analyzed in the existing trouble report with a focus on the positive aspect of why humans were able to respond successfully even though the response operation was not described in the procedure manuals. The clarification of the procedure manuals' relationship, timing, sequence, and conditions of operations of components are mere corrections of the inadequacies of the procedure manuals. About the recognition of an event, a radiation monitor focusing on nitrogen-16 was developed and installed as a hardware measure to facilitate faster and more reliable recognition. However, it should be emphasized that the existing trouble report did not focus on the positive points of why humans could detect the leak from a minute heat transfer tube before it reached the SGTR early in this accident and contribute significantly to reducing radioactive material leakage.

Most of the 29 measures listed in Table 4 are not previously documented in existing trouble reports. In addition, the measure of "Examination in advance of mitigation measures to be taken when certain measures fail" is related to the measures to prevent recurrence in existing trouble reports, such as "Description of response operation in case of non-operation of the PORV or incomplete closing of the MSIV during SGTR." However, it is a new lesson learned without specifying the accident. From the preceding analysis, it can be concluded that the measures for safety improvement obtained by the proposed method are considered new lessons learned.

The existing trouble report extract focuses on those parts of the event process that are considered problematic. In contrast, the proposed method targets all off-normal response actions for analysis, thereby providing new lessons learned. In safety evaluations, the initial response to the SGTR is recognized at a reactor trip due to primary coolant leakage after the SGTR, and isolation operations are initiated 10 minutes later. In the present accident, the initial response was identified early when a minor leakage from a heat transfer tube occurred before the SGTR, and the isolation operation was initiated before the reactor trip. This represents an exemplary human response. As a result of analyzing this process with the proposed method, the following safety improvement measures were obtained: “Utilization of plant computers,” “Preliminary organization of the relationship between alarms and actual plant conditions,” “Preliminary organization of the parameters collected of information in response to specific alarms,” “Applying the decision criteria more conservatively,” “Continuous monitoring of parameters related to the event,” “Checking the plant status regardless of the specified frequency,” and “Identification of events based on multiple pieces of information.” The findings of this study indicate that the proposed method can treat humans as a beneficial element within the system, rather than solely as a source of human error and a negative influence on the system.

The analysis results indicate that new versatile lessons that were not revealed in the existing trouble report can be derived through the proposed method while considering humans as a positive element.

## 5. CONCLUSION

This study structuralized resilience potential and off-normal response actions for nuclear power plant operations and proposed a systematic and practical analysis method based on the Safety-II concept. The analysis of actual accidents using the proposed method revealed the potential for deriving highly versatile new lessons learned that are not revealed by analysis and measures from the Safety-I perspective while considering humans as a positive element.

It is expected that nuclear operators will be able to enhance safety by using the obtained countermeasures as a collection of reference cases for plant operation personnel. The plan is to accumulate a more significant number of examples of analyses conducted using the proposed method, to develop some templates for the process of deriving measures from human actions, and to study methods for other areas than plant operations, such as the maintenance of nuclear power plants.

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