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Analysis of Decision-making Models for Mitigating Accidents in Extreme Conditions

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1. Introduction

The primary goal of all nuclear power plants (NPPs) around the world is safe operation [1]. To make NPPs safe, many studies have been conducted over several decades. Nevertheless, events and accidents have occurred continuously since NPPs have started generating electricity. Moreover, severe accidents have occurred even though NPPs have been constructed safely and operated securely. Human error is one of the main causes of the NPPs' events and accidents. As reported by the Institute of Nuclear Power Operations (INPO), about 48% of all events in NPPs during 2010–2011 were human error. In addition, the Korean database, Operation Performance Information System (OPIS), reported that >20% of all events in Korean NPPs over the past decade (2002–2011) had been human error [2]. In addition, humans are imperfect, particularly under stressful conditions [2]. The main cause of one of the representative severe accidents, the Chernobyl disaster, was human error [3]. Many studies that have sought to reduce human error have been conducted over several decades so that operators do not have to allocate too much of their mental capacity to operating NPPs. In spite of these efforts, humans sometimes make mistakes, so human-related events and accidents have continued at NPPs.

Accident domains can be divided into accident prevention and accident mitigation [4]. Most human-related studies including human reliability analysis (HRA)-related studies have focused on accident prevention rather than mitigation. While preventing accidents is certainly significant, mitigation is as important as prevention. In the accident prevention domain, the environment is less serious and hazardous for humans, and therefore less stressful. Therefore, the humans who are responsible for controlling the plant can easily communicate and discuss with accurate and useful information.

Meanwhile, in the accident mitigation domain, the possibility of the instrument & control (I&C) systems of the NPP breaking due to extreme conditions are higher, so I&C systems may be unable to give correct information on what operators need to diagnose. These extreme situations can lead operators to take on a very high workload and stress. In addition, both I&C systems and communication systems can become useless, thus making communication to create strategies for plant mitigation impossible. Furthermore, if a severe accident occurs, the organization responsible for plant control will change from the small organization in the main control room to a large complex organization in a technical support center (TSC).

Nobody can assume that all information from I&C systems is accurate, so information uncertainty in the accident mitigation domain will increase compared to the accident prevention domain. In particular, if plant operators face extreme situations, they will feel anxiety, fear, and panic. Therefore, analyzing what decision-making model can be applied in the accident mitigation domain under extreme conditions is essential.

2. Importance of decision making for accident mitigation

2.1. Decision-making-related issues revealed by the Fukushima accident

Humans are imperfect, so operators make more errors than digital and analog systems. Therefore, many studies into minimizing human involvement have been conducted, such as developing automation systems and developing rational procedures. However, some parts of NPPs cannot be automated, so operators must still be involved in the system. Mitigating damage during severe accidents is one such part. Several procedures have been developed to support human operators from general operating procedure (GOP) to emergency operating procedure (EOP). However, no procedures for mitigating critical and severe accidents have yet been developed because of the characteristics of accident circumstances, such as high uncertainty and countless potential scenarios. Therefore, if a severe accident occurs, there is no choice in mitigation but to rely upon human judgment. The decision-making process is crucial for mitigating accidents with proper strategies. The Fukushima accident revealed several issues about difficulties in decision making.

First, communication between people who were far apart was impossible. Hardware systems that are connected to sensors gather necessary information from sensors that then work with control systems. The human decision-making process has similar characteristics to hardware systems. Communication is needed in all steps of the human decision-making process from the perception of the situation to its anticipation. In the Fukushima accident, both power lines and communication lines were destroyed, so the main control room (MCR) operators could not communicate with local operators who could have given them critical information. In addition, communication between the plant and government was hardly possible.

Second, operators were exposed to hazardous environments. Their mental state became affected by panic and anxiety because of the hazardous environment, such as the site blackout, seawater flooding, and radiation release. In this situation, rational decision-making is scarcely possible even if operators are very well trained. In severe accidents, the possibility of releasing radioactive material increases because the core melts. Some places could be polluted by radioactive material and some such places may play a key role in relaying critical information to support operators' decision making.

Third, plant responsibility shifts from MCR operators to a large organization. Figure 1 shows how the organization of plant control changes to a large group [5].

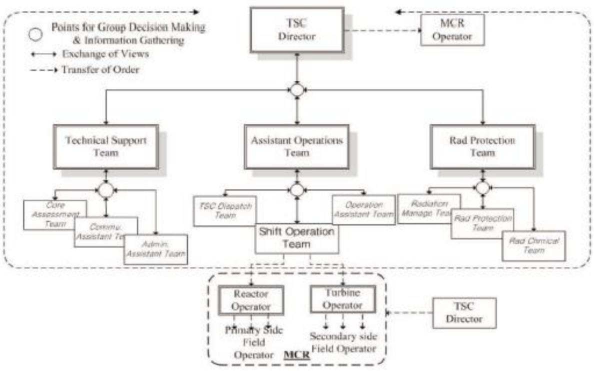

Figure 1. Technical support center organization

We can determine that a TSC has more decision-making and information-gathering processes than MCR. The structure of the TSC is not a hierarchy. Each team and TSC director exchanges their own views and confirms the advantages and disadvantages of their strategies. Then, the TSC director orders some decided on strategies from the MCR operator.

Fourth, the degree of inherent uncertainty of diagnosing the plant state and mitigating accidents was very high. Nobody can affirm that people can predict all possible accident scenarios. For this reason, a huge tsunami was not considered when designing the power plant, so the safety systems were directly damaged by the tsunami in the Fukushima accident. In addition, the operators had been poorly trained. Training for all possible scenarios is impossible because of high uncertainty, so the decision-making process was highly significant for mitigating the Fukushima accident.

Fifth, a precise procedure for mitigating the accident did not exist. Generally, NPPs are operated by rule-based procedures, such as GOP and EOP, to prevent core damage. These procedures forestall human errors by reducing the possibility of human involvement. However, none of the procedures existed for targeting severe accidents. Therefore, mitigating the Fukushima accident was completely dependent on the human decision-making process, which is slightly supported by the severe accident management guideline (SAMG).

2.2. Key considerations in decision making for mitigating accidents

We deducted the following key considerations of decision making for mitigating accidents in extreme conditions through the revealed issues from the Fukushima accident: team decision making, a time-pressured environment, the inaccessibility of information, large uncertainty for establishing strategies, unexpected accidents, and the intricate psychological state.

In the mitigation domain, team decision making is a dominant process because TSC is a large organization composed of numerous experts who have different areas of expertise. Time pressure could be a dominant factor as well because people cannot work with enough time in a hazardous radioactive-released environment. They should diagnose the plant state very quickly and make precise decisions under time pressure. In addition, each step of mitigating an accident has its own proper fixed time range. Operators should diagnose the plant state and excuse mitigating actions in the time range. In terms of gaining critical information, some I&C systems could be broken by an external event, so operators cannot obtain the necessary information to mitigate the accident. This means precise diagnosis may be near impossible, which leads operators to ineffective decision making. SAMG suggests a general guideline to operators, and it cannot be absolutely clarified because of large uncertainty surrounding the circumstances in the accident mitigation domain. Therefore, establishing strategies should be highly relied on in human decision making. There is not only one solution for mitigating an accident. Several mitigating strategies exist, and choosing one strategy should be conducted based on human decision making. Thus, human decision making in the accident mitigation domain is highly significant, so enhancing operators' performance in extreme situations is important. However, training operators for targeting on unexpected accident is almost impossible. If an accident is considered, then the accident will not be an unexpected accident. Lastly, intricate psychological problems, such as panic and anxiety, can make people irrational and illogical. If we develop a decision-making model for mitigating accidents in extreme conditions, we should consider these key factors.

3. Decision-making models

Decision making is the process of identifying and choosing alternatives based on the values, preferences, and beliefs of the decision maker. Many decision-making models have been developed for understanding the human decision-making process and enhancing the process to be more accurate and efficient. A famous decision-making model is the Observe-Orient-Decide-Act (OODA) loop suggested by Boyd [6]. It was conceptualized from observing jet fighter pilots in combat. Figure 2 depicts the OODA model. "Observe" is the process of acquiring information about the environment by interacting with it, sensing it, or receiving messages about it. "Orientation" is an interactive process of many-sided implicit cross-referencing projections, empathies, correlations, and rejections. "Decide" is the process of making a choice among hypotheses about the environmental situation and possible responses to it. Lastly, "act" is the process of testing the chosen hypothesis by interacting with the environment.

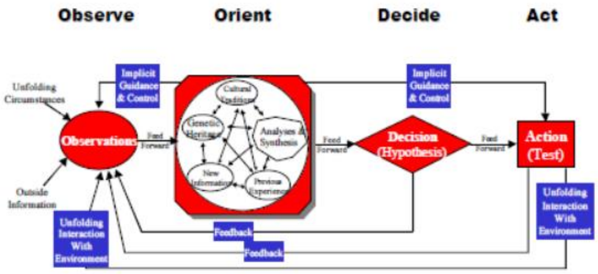

Figure 2. Depiction of OODA model

This model emphasizes the "decision time." This characteristic will be a strength if this model is applied to the decision-making process in the NPPs' accident mitigation domain. However, it also has a critical limitation. It was developed from observations of flight fights, so it was developed for targeting individual decision making. Therefore, this model is not directly applicable to collaborative decision-making by teams. In addition, according to Dehn, the OODA model lacks psychological validity [7].

As well as the OODA model, the Stimulus-Hypothesis-Option-Response (SHOR) model [8], Rasmussen's model [9], Recognition-Primed Decision-Making (RPDM) [10], etc. were developed. Each model has its own characteristics because they were developed by focusing on applying different targets. If we examine decision-making models with a wide perspective, each model can be categorized based on common features. If we categorize models based on the number of decision makers, the categories become individual and group decision making. Likewise, decision-making models can be categorized into rational decision-making and naturalistic decision-making models.

3.1. Individual & group decision-making model

Individual decision making involves only one person and has pros and cons [11]. One of its strengths is that it is quick and cost-effective. Because it is not necessary to garner other peoples' opinions, meeting with others is not required in this type of decision making. Another strength is that individuals have a tendency to take responsibility. They are accountable for their acts and performance. It is not easy to hold one person in a group accountable for a wrong decision. In addition, individual decisions are more focused and rational than group decisions. On the other hand, group decision making has ascendancy over individual decision making in some characteristics. A group has the potential to collect more and fuller information than an individual while making decisions. In addition, group decision making can forestall individuals' own intuition and psychological bias if a group has many decision makers. Moreover, hidden strategies and plans can be discovered during group decision making. However, group decision making has several weaknesses, such as group polarization and pressuring individuals to conform to the group's dominant view.

Group decision-making models include the Delphi method, consensus-oriented decision-making (CODM) model, and Hoy–Tarter model, whereas individual decision-making models include the OODA model, SHOR model, and RPDM model.

3.2. Rational & naturalistic decision-making model

The rational decision-making model is a model where individuals use facts and information, analysis, and a step-by-step procedure to come to a decision. It involves several different subordinate models, but they have similar steps [12].

1. Identifying a problem that requires a solution
2. Identifying the solution scenario
3. Carrying out a gap analysis
4. Gathering facts, options, and alternatives
5. Analyzing option outcomes
6. Selecting the best possible options
7. Implementing a solution decision and evaluating the outcome.

The rational decision-making model can provide optimal results and formal evaluation of the results. Many training programs and decision support systems have been developed using the rational decision-making model. It seems like a quite precise model, but critics of the model argue that it makes unrealistic assumptions. It assumes the decision maker is rational, the problem is clear and unambiguous, the information is complete, and there are no time and cost constraints. The OODA model, kill chain model, and triage models are types of rational decision-making models.

The naturalistic decision-making model emerged in the 1980s to study how people make decisions in real-world settings. This model emphasizes the role of experience in enabling people to categorize situations rapidly to make effective decisions. Therefore, it focuses on how people are able to make tough decisions under difficult conditions, such as limited time, uncertainty, vague goals, and unstable conditions [13]. Hammond's cognitive continuum theory, Rasmussen's model, and RPDM are included in the naturalistic decision-making model.

4. Results & analysis

Four major decision-making models were scrutinized to determine their pros and cons. Each model has different pros and cons, and we analyzed which model is the most suitable for applying decision making in an extreme situation. We matched the surveyed decision-making model with the features of decision making in an extreme situation in Table 1.

Table I: Analyzing decision-making models in accordance with features of decision making in an extreme situation

Features of decision making in extreme situation	Individual decision making	Group decision making	Rational decision making	Naturalistic decision making
Nonexistence of precise procedure	o	o	x	o
Difficulty of communication	o	x	o	o
Unstable mental state (panic, embarrassment)	x	o	o	x
Shifting responsibility to the large organization	x	o	o	o
Ambiguous information	o	o	x	o
High time pressure	o	x	x	o
Unsureness of the result of establishing strategies	x	o	x	o

We scrutinized the decision-making issues revealed by the Fukushima accident and key considerations of decision making in the accident mitigation domain in Chapter 2. Then, four major decision-making models were examined to acquire the pros and cons of the models. According to Table 1, the naturalistic decision-making model is more suitable than the rational decision-making model for applying decision making in a situation in the accident mitigation domain. Likewise, group decision making is more appropriate than individual decision making. There are many subordinate models in the group decision-making models and naturalistic decision-making models, and these subordinate models may have different characteristics and pros and cons. In the future, analysis of the subordinate models of group and naturalistic decision-making models should be conducted in detail. Furthermore, new decision-making models focusing on NPPs' accident mitigation domain should be developed in the future.

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