RESILIENCE ASSESSMENT GRID (RAG) FOR FACILITATING SAFETY CONSCIOUSNESS OF NUCLEAR POWER PLANT PERSONNEL

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Abstract
Our experience of applying the Resilience Assessment Grid (RAG) method to nuclear power plant personnel is described. Various countermeasures have been introduced in every Japanese nuclear power plant (NPP) in order to meet regulatory requirements issued after the severe accident at Fukushima-Daiichi NPP. These requirements cover diverse hardware installation, human resource enhancement, and managerial improvement. However, although these countermeasures will improve the safety of NPPs in principle, they may also have negative impacts. The most likely negative impact of such strict regulations is loss of operational flexibility, i.e. degradation of resilience potential.

The RAG method has been introduced to avoid degradation of resilience potential. However, in a preliminary stage of applying the method, the plant personnel were reluctant to accept the idea of improving operational resilience. They believed that any anomaly could be handled by following predefined operational procedures, and were reluctant to rely on resilient behavior to handle unexpected situations.

Therefore, the RAG questionnaire was modified to overcome their reluctance. The first modification was to ask interviewees to answer a set of questions related to a class of anomalies that may lead to a severe accident. This version of the modified RAG is called the *restrictive RAG.* In the second modification, the NPP operators were asked to answer mainly questions about the potential to respond and the potential to monitor, while the plant personnel in the safety division, who are responsible for developing procedures, were asked to mainly answer questions concerning the potential to learn and the potential to anticipate. This modified version of RAG was called the *cross-divisional RAG*. Finally, in the third modification, the set of questions focused on envisioning potential difficulties in conducting tasks that the interviewee is assigned to. This version of RAG was called the *brittleness- oriented RAG*. Through attempts over several years, the *brittleness-oriented RAG* was found to be useful as an introductory practice for other RAG surveys. In addition, the *brittleness- oriented RAG* itself was found to be a useful tool for facilitating consciousness concerning possible weak points of the NPP even after implementing various countermeasures. Enhancing safety consciousness seems to be indispensable for developing resilience potential in the organization.

Keywords: resilience assessment grid (RAG), safety consciousness, nuclear power plant

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1. INTRODUCTION

A wide variety of countermeasures have been introduced in every Japanese nuclear power plant (NPP) in order to meet regulatory requirements issued after the severe accident at Fukushima-Daiichi NPP. These regulations have required the installation of tremendous amounts of hardware, such as multilayered protection measures against tsunami (e.g. a seawall and watertight doors to prevent flooding of buildings), on-site AC power sources (e.g. two pre-existing permanently installed diesel generators, plus another permanently installed generator and two more mobile units), on-site DC power sources (e.g. one permanently installed battery system with capacity for 24 hours of operation, plus one mobile system and one permanently installed system both with the same operational duration). Furthermore, in addition to the significant improvements in power supply capability, the regulations require measures to prevent reactor core damage that could be induced by multiple power supply failures. Typical examples of such measures include mobile power sources for opening a safety-relief valve to reduce the pressure inside the reactor pressure vessel (RPV), and mobile water injection systems such as fire engines.

Such countermeasures might seem to improve the safety of NPPs at first glance. However, we must also consider the negative impacts of installing such large amounts of countermeasures. One negative impact is the extra time for training on operating the newly installed mobile countermeasures. Without intensive and recurrent training, it is unlikely that plant personnel can obtain and maintain sufficient capabilities to properly and efficiently handle the new mobile systems. Meanwhile, this extra time inevitably reduces the time available for operator training for normal and near-normal operations. This trade-off should be managed in a more intelligent way than the current practice.

Another negative impact of such wide-ranging regulations is operational inflexibility, i.e. degradation of resilience potential [1]. Since so many countermeasures have been installed, plant personnel are disciplined and trained to rely on them whenever a serious anomaly is envisioned. Provided the characteristics of the anomaly are within a presumed event envelope, the disturbance induced by the anomaly can be overridden by following one of the predefined operational procedures. However, if the characteristics go beyond the envelope, then the plant personnel will have difficulty if they are too heavily trained and over-adapted to the predefined operational procedures. In such difficult situations, it is highly desirable that the plant personnel can behave in a resilient manner.

In order to avoid the degradation of resilience potential, the authors have used the Resilience Assessment Grid (RAG) method [1][2]. Extensive studies of the Fukushima Dai-ichi nuclear accident conducted by one of the authors based on the principles of resilience engineering [3-7] clearly showed that enhancing resilience potential is an issue of primary importance for every NPP. Although sample questions for assessing resilience were given in preceding publications [1][2], they must be revised to reflect the importance for a specific organization [2]. This paper describes our approach toward an effective revision and the resultant outcome. We believe that the maintaining or preferably enhancing resilience potential will eventually lead to higher safety of NPPs.

2. METHOD

2.1. Initial Approach

The first phase of our project was launched in FY2016. The eventual goal is to assess the resilience potential of all divisions responsible for the safety of NPPs. In the first phase, a preliminary study was conducted within the research institute (INSS) where two researchers with extensive experience as NPP operators were available. During this phase, however, we experienced a serious difficulty: both researchers were reluctant to consider possible resilient behaviors needed to override unexpected situations. Their typical reaction was that they can respond to any disturbances since they have well-established and properly-organized operation procedures. They claimed that such procedures cover three classes of accident, namely, design-based events, severe accidents without core damage, and severe accidents with core damage. Since they can depend on the operation procedures even for the second and third class of accidents, they did not feel that they need to prepare for unexpected situations, nor to improve their resilience potential.

Based on this observation, we made one important modification: we redefined the scope of our problem. Even if NPP personnel can respond to any accidents, it is highly undesirable for the NPP to suffer a serious event scenario which could lead to a severe accident. One such serious event would be enough to convince the Japanese people to abandon nuclear power generation. Therefore, any anomalous event which could be a precursor to a severe accident must be strictly avoided. The RAG questions have been modified to reflect this condition.

2.2. Focusing on Precursors of Severe Accidents

As mentioned above, we attempted to revise the RAG questions to focus on serious event scenarios, each of which could be a precursor to a severe accident. Usually, NPP personnel in operation and safety divisions are familiar with the licensing review of the NPP. The event scenarios including various failures and/or anomalies are studied in advance of the safety review so that the safety of the NPP is ensured. Typical examples include multiple failure events such as leakage of coolant plus a failure of the high-pressure water injection system, or a loss of feedwater plus a failure of the reactor trip system. Although the probability of simultaneous occurrence of such multiple anomalies is considered to be very low, the scenarios are selected to examine the safety of the NPP. The safety study is conducted by using a validated numerical simulation code. Each of the event scenarios usually converges to a stable state, thus leading to a judgement that the NPP is safe. But this convergence is attained as a result of assuming the normal functioning of automated equipment and/or proper actions by operators. Otherwise, convergence is not always attained.

Although NPP operators are usually capable of dealing with these abnormal event scenarios by referring to the predefined operation procedures, their understanding of the deep knowledge behind the procedures indicates their resilience potential. The RAG questions are modified to reflect this consideration. Since the scope of the questions is restricted to certain categories of possible events, the RAG questions are called the *restrictive RAG*.

2.3. Division-specific Modification

As mentioned earlier, NPP operators tend to believe they can handle various event scenarios based on the operation procedures. Since we introduced the *restrictive RAG*, operators have become less reluctant to answer those questions to assess the potential to respond and the potential to monitor. However, they are still reluctant to answer the questions to assess the potential to learn and the potential to anticipate.

A second modification was introduced in FY2017 in response to this reluctance. In this second version, the operators were asked to mainly answer the questions to assess the potential to respond and the potential to monitor. The plant personnel in the safety division, which is responsible for developing the procedures, were asked to mainly answer the questions to assess the potential to learn and the potential to anticipate. Though the questions corresponding to the four potentials are intended to provide an overview of all the questions, it is not mandatory to answer questions of unassigned categories. The divided assignment of questions has been effective in reducing the psychological reluctance of plant personnel. This version of the modified RAG is called the *cross-divisional RAG*.

2.4. Focusing on Potential Brittleness

We have tried to improve the acceptance of the RAG and resilience engineering within the NPP. To do this, we modified the questions to clarify and characterize the events and/or situations in which the NPP personnel feel serious difficulties in responding and monitoring in spite of the existence of well-established procedures. This attempt is basically consistent with the proposal of a workshop concerning brittleness envisioned in workplaces [8]. This version of the revised RAG questions developed in FY2018 is called the *brittleness-oriented RAG*. Note that questions concerning learning and anticipating are not modified in this version. In a preliminary test phase, the plant personnel who volunteered to contribute to RAG development showed strong support for a prototype of the *brittleness-oriented RAG* questions. This unexpectedly favorable response has driven the development of the current *brittleness-oriented RAG* questions.

The RAG development project has been conducted for three years in a phased manner as described above. Though the response of plant personnel has not been always positive, several key persons were interested in this project. Furthermore, the Kansai Electric Power Company had already released an important position statement [9] that expresses a strong commitment to higher safety:

In the light of the nuclear accident at the Fukushima-Daiichi Nuclear Power Station, we reviewed our own practices and attitudes toward nuclear power operations and felt profound remorse that:

- our efforts on countermeasures against Severe Accidents, which are considered to be extremely infrequent, might have been inadequate;
- our awareness of voluntarily enhancing nuclear safety beyond legal and regulatory requirements might not have been enough; and
- our efforts to learn from abroad, such as collecting information on activities for enhancing safety and improving our nuclear power stations, might have been insufficient.

We have been making company-wide efforts to further enhance nuclear safety accordingly. Every one of us shall remember the lessons learned from the accident and ceaselessly strive to enhance nuclear safety to protect the people not only in the plant- hosting communities but also the whole country, and to preserve the environment.

The introduction of RAG for improving the resilience potential of the NPP closely matches the spirit behind the position statement. The authors believe that the project could make steady, though not rapid, progress under the influence of the position statement.

3. REVISED RAG

Examples of the revised RAG questions are described in this section.

3.1. *Restrictive RAG* Questions

The restrictive RAG questions to be used to assess the potential to respond and the potential to monitor are given below. There are fewer questions than the number of sample questions mentioned in the pioneering document [1]. It is also clear that some of the questions are closedended rather than open-ended, which is expected to reduce the psychological difficulty in answering the questions.

Table 1. Restricted RAG questions to assess the potential to respond

Question No. and category	Contents
1. Representative event	Mention an event scenario which, if not properly managed, could evolve to a severe accident.
2. Criteria for starting response	Are the conditions to start response activities clear? Select (Yes or No).
3. Selection of activities	Explain the reason why the predetermined response activities are effective enough to manage the event.
4. Response time	How do you assess the speed of the response? Select one. (It is fast enough. It depends. It is slow.)
5. Duration of response	How do you assess the duration of the response? Select one. (Long enough. It depends. It is insufficient.)
6. Criteria for stopping response	Are the conditions to stop responding clear? Select (Yes or No).

Table 2. Restricted RAG questions to assess the potential to monitor

Question No. and category	Contents
1. List of indicators	Are there leading indicators that can be used to raise the alert level of your organization before the occurrence of the event mentioned as the answer to question 1 in Table 1?
2. Leading indicators	How are the leading indicators validated?
3. Lagging indicators	Are there lagging indicators that can be used to recognize that the event mentioned as the answer to question 1 in Table 1 has already occurred?
4. Sufficiency	Are the indicators sufficiently useful?

It is not always possible to give clear answers to the questions to assess the potential to monitor; some events can take place almost instantaneously without symptoms. Nevertheless, the questions are meaningful in the sense that the interviewer may inquire about the possible improvement of sensor systems to support detection of the “sudden” anomalous event at an early stage.

3.2. *Cross-divisional RAG* Questions

The *restrictive RAG* questions are mainly used to obtain answers from NPP operators. On the other hand, the questions to assess the potential to learn and the potential to anticipate are used to obtain answers from personnel in the safety division of the NPP. In this regard, the current version of RAG is called *cross-divisional RAG*. Particular attention has been paid to reducing the number of questions here too. The *cross-divisional RAG* questions to assess the potential to learn is given in Table 3. The number of *cross-divisional RAG* questions to assess the potential to anticipate is also reduced compared to the sample questions in preceding documents [1][2]. The questions are listed in Table 4.

Table 3. Cross-divisional RAG questions to assess the potential to learn

Question No. and category	Contents
1. Data source	What data sources are to be surveyed for deriving lessons?
2. Criteria for selection of events	How are the events to be used for deriving lessons selected? Are there voluntary learning activities in addition to the regulatory requirement?
3. Method for lesson extraction	Are there established methods for lesson extraction?
4. Implementation	How are the derived lessons implemented?

Table 4. Cross-divisional RAG questions to assess the potential to anticipate

Question No. and category	Contents
1. Information source	What information sources do you use to anticipate future threats and opportunities?
2. Information sharing	Is there a reliable procedure to share the anticipated threats and opportunities within the organization?
3. Time span	What are the time spans of the anticipation? Are the time spans different among divisions in the organization?
4. Organizational culture	Does your organization actively anticipate the future?

The number of questions is smaller in Tables 3, 4, and 5 compared to those in preceding documents [1][2]. The number was reduced to improve acceptability to interviewees, but the answers are still expected to yield meaningful information.

3.3. *Brittleness-oriented* RAG questions

As described in section 2.4, positive responses were obtained when a preliminary version of the brittleness-oriented questions was tested. Therefore, another set of questions has been drawn up focusing on possible situations in which serious difficulties are envisioned. The sample questions related to the potential to respond are given in Table 5.

In principle, the questions related to the other three potentials can be derived to make the contents of the questions consistent with those given in Table 5. In practice, however, the questions related to the potential to respond as described in Table 5 seemed to be the most influential in raising the awareness of plant personnel concerning the necessity of developing operational resilience.

Therefore, the *brittleness-oriented RAG* questions for the four potentials are organized as follows:

- The questions described in Table 5 are employed for assessing the potential to respond.
- The questions described in Table 2 are used for assessing the potential to monitor after replacing the phrase "the answer to question 1 in Table 1" by "the answer to question 1 in Table 5".
- The questions described in Tables 3 and 4 are used as they are for assessing the potential to learn and the potential to anticipate, respectively.

Table 5. Brittleness-oriented RAG questions related to the potential to respond

Question No. and category	Contents
1. Example of situation	Mention an event and relevant situation in which you recognize serious difficulty in carrying out an assigned task. Even though the occurrence of the event and the situation may be rare, suppose that they can take place.
2. Main factors causing the difficulty	What are the main factors contributing to the serious difficulty? (e.g. insufficient hardware, lack of human resources, insufficient technical skills, etc.)
3. Reasons for existence of the factors	Mention the reasons why one of the undesirable factors is left as it is. (e.g. ignorance of managers, lack of budget, poor training program, etc.)
4. Assess the possibility of eliminating each of the reasons	What is the possibility of eliminating each of the reasons? Select one. (absolutely impossible, difficult but possible, possible)
5. Elimination of the reasons	Define practical procedures to eliminate the reason if it is possible. Also, define the method of authorizing the procedure within your division.
6. Return to step 3 and repeat.	

4. RESULTS

Although several modifications of the RAG questions were made, further development is needed in order to make more extensive use of the methodology. However, even at this stage, we obtained some tentative, important empirical observations. Owing to several experienced engineers of the Takahama NPP of Kansai Electric Power Company who served as interviewees to answer the modified versions of RAG questions, we obtained valuable suggestions for the development of more dependable RAG questions.

At present, the interviewees were mainly asked the *brittleness-oriented RAG* questions described in section 3.3. After the interview, they were first asked to rate the semantic clarity of the questions, and were then requested to give their impression of the usefulness of the RAG-based approach for improving the safety of the NPP.

The *brittleness-oriented RAG* questions were well accepted, and were found to be useful for raising consciousness concerning possible weak points (i.e. safety consciousness) of the NPP which has undergone large-scale renovations since the Fukushima Dai-ichi accident. We believe that this enhanced consciousness will eventually lead to enhanced resilience potential within the organization.

5. CONCLUDING REMARKS

Although we have not yet implemented the RAG method company-wide or plant-wide, we have obtained significantly higher acceptance from some divisions of the NPP. In particular, the plant personnel seemed to appreciate the brittleness-oriented RAG questions as highly informative and instructive. Based on this experience, the authors conclude that introducing the brittleness-oriented RAG questions would be an effective first step prior to implementing more comprehensive RAG applications.

As suggested by Hollnagel [10], the road to resilience can start from an organization with the potential to respond and the potential to monitor, and then progress can be made by developing the potential to learn. After this stage, development of the potential to anticipate can be attempted. Our attempt described in this paper is consistent with the suggestion of stepwise development of resilience potential.

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