Risk Assessment Strategy for Decommissioning of Fukushima Daiichi Nuclear Power Station

Akira Yamaguchi[1], Kazuki Hida[2], Yasunori Yamanaka[3], Yoshiyuki Narumiya[4]

[1]The University of Tokyo:7-3-1Hongo, Bunkyo-ku, Tokyo 113-8656, yamaguchi@n.t.u-tokyo.ac.jp
[2]Nuclear Damage Compensation and Decommissioning Facilitation Corporation: 2-2-5 Toranomon, Minato-ku, Tokyo 105-0001, hida-kazuki@ndf.go.jp
[3]Tokyo Electric Power Company Holdings: 1-1-3 Uchisaiwai-cho Chiyoda-ku, Tokyo 100-8560 JAPAN, yasunori@criepi.denken.or.jp
[4]The Kansai Electric Power Co., Inc.: 3-6-16, Nakanoshima, Kita-ku, Osaka,530-8270, narumiya.yoshiyuki@d5.kepco.co.jp

Risk management of the Fukushima Daiichi Nuclear Power Station decommissioning is a great challenge. In the present study, a risk management framework has been developed for the decommissioning work. It is applied to fuel assembly retrieval from Unit 3 spent fuel pool. Whole retrieval work is divided into three phases: preparation, retrieval, and transportation and storage. First of all, the endpoint has been established and the success path has been developed. Then, possible threats that are internal/external, technical/societal/management, are identified and selected. "What can go wrong?" is a question about the failure scenario. The likelihoods and consequences for each scenario are roughly estimated. Whole decommissioning project will continue for several decades; i.e. long term perspective is important. What should be emphasized is that we do not always have enough knowledge and experience of this kind. It is expected the decommissioning can make steady and good progress in support of the proposed risk management framework. Thus the risk assessment and management are required and the process needs to be updated in accordance with the most recent information and knowledge on the decommissioning works.

I. INTRODUCTION

Decommissioning of the Fukushima Daiichi Nuclear Power Station (FD-NPS) is not a straightforward task. One needs to deal with fuel debris in containment vessels, fuel assemblies in the spent fuel pools (SFPs), the contaminated water and so on. Risk characteristics of the hazardous objects are significantly different from those in an operating nuclear power plant. Thus, understanding of the risk characteristics and assigning priorities on individual tasks are important in the decommissioning of the nuclear power plants at the FD-NPS.

It is reminded that the accident at the FD-NPS is a multi-unit event. The seismic-induced tsunami evenT on March 11, 2011 resulted in the reactor core melt in three units (Ref. 1). In addition, a few thousands of fuel assemblies were left in the SFPs of four units which reactor buildings were seriously damaged and contaminated by release of radioactive materials *plan* and/or hydrogen explosion.

The risk management goal of the decommissioning project is to control and reduce the risk of the FD-NPS so that the public and workers are not exposed to significant radiation and radioactive materials are adequately confined. It is achieved by removal of the radioactive materials, in other words, by reducing the hazard potential on the site. It is noted that activities of removing or reducing the hazard potential may bring another risk of failure in the operation resulting in undesirable event. Therefore, appropriate decision making is required for every activity in the decommissioning project taking the advantage of postponing activities into consideration according to circumstances. For achieving the goal, one needs to perform activities with comprehensive and overall viewpoints. We can optimize the decision making by balancing pros and cons such as the reduced risk and added risk, advantage and disadvantage, and cost and benefit.

The purpose of this study is to propose the risk management framework for the decommissioning of the FD-NPS. The risk management framework is needed to be established for adequate and appropriate risk control and decision making as well as communication with the public and other stakeholders. All the activities and possible threats including societal and management aspects have to be identified and evaluated. Accordingly, it is expected that the decommissioning process is optimized without any irrational delay, excessive cost and undue risk. An acceptable level of overall risks of the FD-NPS is to be established through appropriate communication and dialog for all those activities with the society and public.

Retrieval of the fuel assemblies in the SFP storage in Unit 3 is selected as the issue to be discussed here in the present study. General risk management process is presented in section 2. The explanation of risk characteristics of the FD-NPS follows in section 3 as well as the description on the current status of the Unit 3 SFP. The authors discuss in section 4 the risk analysis process of FD-NPS. The risk analysis approach and tentative results are presented.

II. RISK MANAGEMENT FRAMEWORK

According to the International Risk Governance Council (IRGC), a risk governance framework is a comprehensive approach to help understand, analyze and manage important risk issues for which there are deficits in risk governance structures and processes[2]. The framework, as shown in Figure 1, comprises five linked phases: (1) pre-assessment of the risk; (2) risk appraisal; (3) risk characterization and evaluation for tolerability and acceptability judgement; (4) risk management; and (5) risk communication. Risk is an uncertain (generally adverse) consequence of an event or activity with respect to something that we value. Plural values can be assigned according to the objective and strategy.

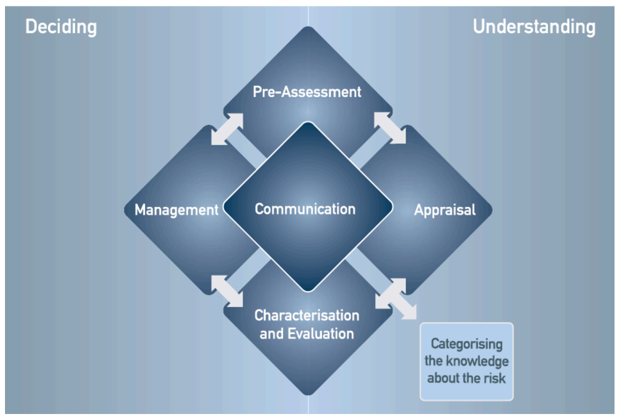

Fig. 1. IRGC's risk governance framework (Ref.2).

Kaplan and Garrick[3] suggested the idea of risk triplets. Risk is characterized and explained by answering three essential questions: 1) what can go wrong? 2) How likely is it? and 3) What are the consequences if it happens? The three questions may correspond to the pre-assessment, risk appraisal and tolerability and acceptability judgement, respectively. The risk triplets are constituents of the risk governance framework.

In a decision making process, several principles are to be established such as transparency, effectiveness and efficiency, accountability, sustainability, equity and fairness, respect for the law, practicability, and acceptability. Not only direct risks but also secondary or accompanying risks are often important. Consideration of the direct and secondary risks will result in different decision from that based on the direct risk alone. Although a regulation is essential to control the risk, inadequate and inefficient regulation sometimes increases the risk as a result. Loss of public trust is caused by misunderstanding of public perception and inappropriate stakeholder involvement, which results in significant failures of risk management. Decision makers are often required to take actions under considerable time pressure, with incomplete information and often faced by conflicting advice and public pressure. Even in situations of knowledge deficit and high uncertainty, decisions must be made and action is often needed. Therefore, risk management goals, principles and framework need to be clearly described for consistent and reliable risk management.

First of all, the success path for the endpoint is defined and constituent elements are identified. A success path is made up of several operations (i.e., constituent elements) such as planning, negotiation, funding, works and so on. Operations are subject to internal and external threats such as equipment failures, earthquakes, human errors, lack of finance, social criticism, etc. Thus all possible threats are exhaustively extracted. Every combination of operations and threats defines a scenario that is to be quantitatively analyzed. Also proposed are risk magnitude metrics used in the decision making step that follows.

Garrick[3] has suggested that every quantitative risk assessment follows the following six steps although the scope, depth and applications vary widely:

(1) Step 1: to define the system being analyzed in terms of what constitutes normal operation to serve as a baseline reference point, that is a success path,
(2) Step 2: to identify and characterize the sources of danger, that is, the hazards or threats,
(3) Step 3: to develop "what can go wrong" scenarios to establish levels of damage and consequences while identifying points of vulnerability,

(4) Step 4: to quantify the likelihoods of the different scenarios and their attendant levels of damage based on the totality of relevant evidence available,
(5) Step 5: to assemble the scenarios according to damage levels, and cast the results into the appropriate risk curves and risk priorities,
(6) Step 6: to interpret the results to guide the risk management process.

These steps provide answers to the three fundamental questions of the triplet definition of risks. Comparing the steps with the five linked phases shown in Fig. 1, it is seen that the steps 1 and 2 correspond to the pre-assessment; the steps 3 and 4 are the risk appraisal; the step 5 is the risk characterization and evaluation; and the step 6 is the risk management.

The radiological risk of the FD-NPS can be measured by two factors: one is the hazard potential such as the inventory of radioactivity and the mobility of the radioactive materials; and the other is the control and management performance such as confinement capability and monitoring capability. If we do not initiate the decommissioning works, radiological hazard potentials seem to be kept unchanged as is at present. It is noted that the radiological inventory decreases as time because of the natural decay. On the other hand, the confinement capability will be deteriorated by aging effects. The significance of individual risk source can be measured by the adequate combination of the two factors and consideration of time factor.

In the present study, the authors follow the six steps mentioned by Garrick to evaluate the risk of the activities. At the same time, emphasis is placed on the risk communication because the understanding and support from the community and society are of great value to achieve the goal of the decommissioning. It is reminded that the loss of public trust is a fatal part of the whole risk management process. These are the framework of the risk management in the decommissioning project.

III. RISK ANALYSIS OF FUKUSHIMA DAIICHI NUCLEAR POWER STATION (FD-NPS)

Different types of potential risk sources exist in the site of the FD-NPS. One is the molten core debris in the reactor Units 1, 2 and 3. It is estimated the debris are distributed in the reactor system, i.e., reactor core in the Reactor Pressure Vessel (PRV), bottom of the RPV, and bottom of the Primary Containment Vessel (PCV). The radioactivity is extremely high and available information for establishment of an optimal decommissioning approach is not enough at present. The technical strategic plan 2015 (Ref. 4) by Nuclear Damage Compensation and Decommissioning Facilitation Corporation (NDF) reports that the total debris mass are 160-180 tons, 230-240 tons and 220-230 tons for Units 1, 2, and 3, respectively. These include cladding, reactor internal structure, control rod materials and concrete and the total mass is estimated to be more than double of the initially loaded fuel mass. The report estimates most of the debris in the Unit 1 is in the bottom of the drywell of the PCV. In the Unit 2 and Unit 3, the debris are distributed in the reactor core region, lower plenum and the bottom of the RPV and the bottom of the PCV dry well. Several researches explained the reason as the early degradation of the reactor core was in dry condition for a long period and containment venting via the PCV wet well was successful in the Unit 1. As for the Units 2 and 3 reactor core cooling was achieved by the continuous operations of the Reactor Core Isolation Cooling system or High Pressure Coolant Injection system for a couple of days. As the estimate involves large uncertainty, however, further investigations are needed to establish the best approach to the retrieval of the core debris. According to the most recent plan[4], an access path to the core debris will be selected among alternatives in 2017. In FD-NPS plants, Units 1-3 suffered from the reactor core melt and the fuel debris retrieval is planned to start in 2021. The fuel debris are stably cooled at present and confined inside the building with low mobility.

In the SFP of Units 1-4, a few thousands of fuel assemblies (392, 615, 566 and 1,535 in Unit 1 to 4, respectively) were under storage. The total radioactivity of the spent fuel is the highest among the other hazard sources at FD-NPS. The effective dose is twice as high as that of the core debris. As one of the first major decommissioning works, all the 1,535 fuel assemblies in Unit 4 have been successfully carried out of the pool by December 2014. The other fuel assemblies are currently stored and cooled in the SFP and are well controlled. However, rubbles and heavy structure fell down in the pool and the structures are deteriorated more or less by the hydrogen explosion. Therefore, the retrieval of the fuel assemblies from the SFP is highly prioritized.

Contaminated water exists in the reactor and turbine buildings, trenches and storage tanks. The highly contaminated water in the trench has been already removed and the trench has been filled up. The reactor decay heat level is currently approximately 0.1% of the initial value and water supply rates are no more than 4.4 m^3/hour, 4.3 m^3/hour and 4.4 m^3/hour for Units 1, 2 and 3, respectively[5]. Hence the risk is gradually decreasing. However, some underground water flows into the buildings and the mobility of the contaminated water is a point of concern. Thus the contaminated water need to be treated with higher priorities.

Figure 2 shows the conceptual strategy of overall risk reduction at FD-NPS. The risk is defined here as an appropriate combination of the hazard potential and the likelihood of loss of confinement. The top-right region corresponds to risk with high-priority region while low priority risk source lies in the bottom-left region. Two approaches are possible to control and manage the decommissioning risk. One is to reduce the hazard potential or remove the risk sources. It is shown by the downward arrow in Fig. 2. The other is to strengthen the confinement capability and/or the surveillance and control of the hazard potential. Even if the total inventory of the risk source is the same, the likelihood of loss of confinement can be reduced by this approach. Let us consider the risk of the molten core debris, for example. The first approach is to retrieve the core debris out of the PRV and the PCV. If it is with large uncertainty and difficulty, an alternative approach to enforce the oversight and to postpone the debris retrieval until enough information becomes available may be more practical and effective than starting the retrieval activity immediately. The alternative approach will provide more confidence on the activity in the future as we ensure the risk is under control at present. This is an example on the trade-off of the risk of initiating activities and postponing activities for a period necessary to resolve the difficulty and to diminish the uncertainty.

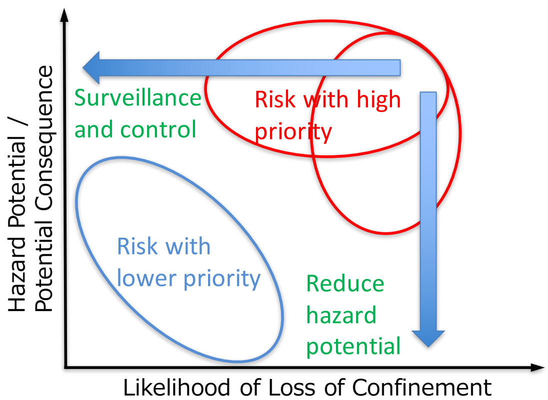

Fig. 2. Characterization of the risk sources.

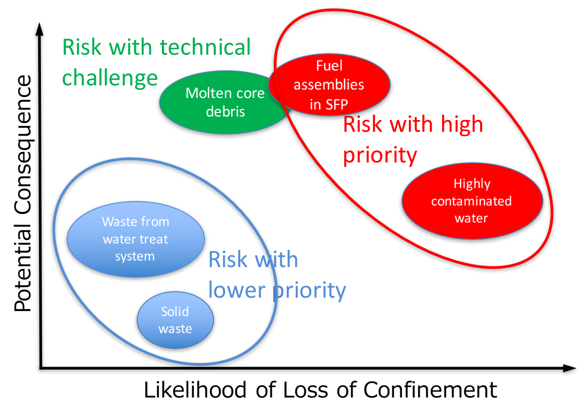

Fig. 3. Relative significance of FD-NPS risk.

Figure 3 shows the evaluation of relative significance of the hazard source in FD-NPS evaluated by reference to (Ref. 3). The potential consequences are estimated by the total inventory of radioactivity. The likelihood of the loss of confinement is estimated by the physical form of the radioactive materials, that is solid, granular, liquid, or gas, for example. The highly contaminated water is in liquid form and the mobility is high. As in Fig. 3, risks with high priority are fuel assemblies in the SFP and the highly contaminated water circulated for the core debris cooling.

From the viewpoint of the safety objective, the significance of a risk is not determined by the absolute amount of a hazardous object alone. Severity of a risk, in other words priority in risk management, is determined based on five factors: inventory of a hazard, mobility of a hazardous material, physical confinement performance, oversight and controllability, and mitigation capability. It is noted that the risk can be encapsulated and controlled by either or combination of the prevention of hazard exposure by diminishing absolute amount of hazard and confining the hazard, and mitigation of exposed hazard by improving abilities of anomaly detection and qualifying response to anomalies. Using measurable metrics of the risk magnitude, priorities and resources are allocated to each of decommissioning activities in a rational and consistent way.

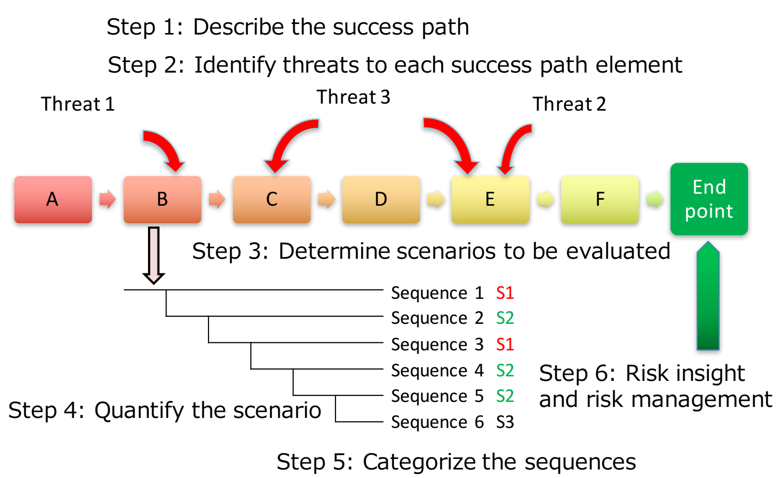

Fig. 4. Risk analysis and management process.

Safe retrieval of fuel assemblies in Unit 3 is selected as the task with the highest priority as discussed above. It is expected the retrieval of fuel assemblies is starting in 2018. The risk management procedures are described in Fig. 4. Six risk management steps (see section 2) proposed by Garrick[3] is presented in Fig. 4. Before going into the steps, we determine the endpoint or goal of the decommissioning. The goal is to store the retrieved fuel assemblies in dry casks safely. Here the success path to come to the endpoint is explicitly described as boxes and arrows in Fig. 4. Possible threats to each of the success path elements are identified. Some threats may influence on multiple elements at the same time. A combination of a threat and affected element(s) produces one scenario. Mathematical or numerical method is applied to quantify the scenario. An example of such is event tree/fault tree approach. The quantification results then are categorized in terms of the consequence and is used for the risk management. In this way the risk characteristics and profile is depicted and risk insights are in hand. The risk insights are delivered to the decision makers of the decommissioning and reflected on rational prioritization and adequate risk management process.

IV. RISK ANALYSIS OF FUKUSHIMA DAIICHI NUCLEAR POWER STATION

The decommissioning is a difficult project on which we have little experience ever and various tasks are necessary for successful achievement. Therefore, it is important to define the project goals explicitly and identify risk sources and threats that may influence the progress in the project.

The decommissioning is a long-term project and various subtasks are necessary. Individual subtask has its own characteristics and its risk contributors are different. Likewise, the fuel subassembly retrieval from the Unit 3 SFP involves several tasks with different characteristics. Therefore, it may be practical and effective to divide the course to the endpoint into three phases according to the characteristics as shown in Figure 5. The first phase is the preparation for the spent fuel retrieval; the second phase is the spent fuel retrieval operation; and the third phase is the transport and storage of the retrieved fuels. The three phases are identified in the spent fuel retrieval plan from Unit 3 spent fuel pool (Ref. 6) published by the Tokyo Electric Power Company Holdings. The end point and risk analysis and management process as in Figure 4 are defined for each of the three phases.

Fig. 5. Process for the fuel assembly retrieval from the Unit 3 spent fuel pool.

The first phase, the preparation for fuel retrieval starts from the planning for fuel retrieval. The flow diagram is shown in Fig. 6. The preparation of the fuel retrieval process is currently underway toward initiation of the fuel retrieval task. There are two kinds of tasks: removal of obstacles and cleanup of the working space, and construction and equipment installation. The endpoint is initiation of fuel retrieval from the SFP on schedule with public acceptance.

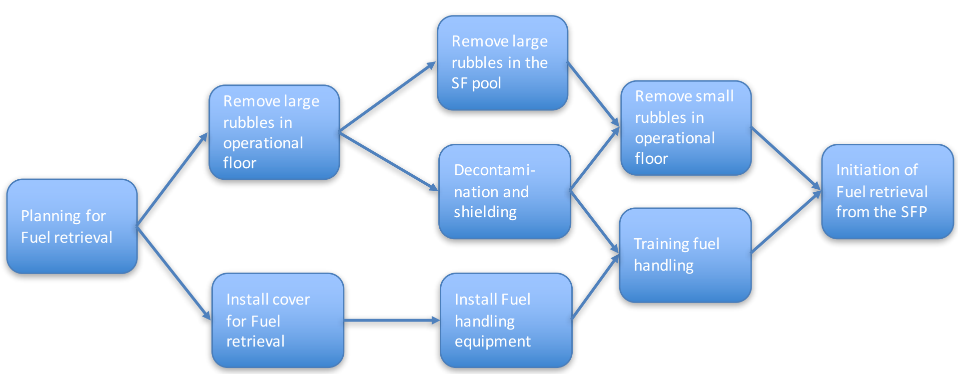

Fig. 6. Process for the 1st Phase: Preparation of Fuel Retrieval.

On the operational floor of the Unit 3, many rubbles are scattered mostly generated during the hydrogen explosion on March 13, 2011. They are the cause of the high radioactivity level. The first task is the removal of large rubbles scattered on the operational floor. Then large obstacles removal from the SFP follows. The fuel handling machine fell down and sank on the SFP. It is the largest obstacle in the pool which has been successfully removed in the last year. In the SFP, an underwater camera and three dimensional simulations were used to establish the rubble removal plan. After the major obstacles are firstly removed carefully, the next task is the decontamination of the operational floor where the most activities are performed. Shielding is placed in the working area if necessary. As the radioactivity level on the operational floor is high, remote operation is necessary for the decontamination work. In parallel to the decontamination work, small rubbles on the operational floor are to be removed. Another major task is installation of a building cover. To maintain comfort working area, the operational floor will be covered with a roof structure. Inside the cover, a fuel handling equipment will be placed. Training will be performed for every operation. Currently the building cover construction work is under exercise off-site. Through the exercise, worker's radiation protection and safety are ensured as well as problems in the construction procedures will be identified and resolved. After completing the tasks, fuel handling equipment will be installed. The last task is, needless to say, the fuel retrieval. The fuel retrieval is performed by remote operations. There are 566 fuel assemblies in the SFP. It is required to remove small to medium size rubbles sank in the pool in advance. The fuel retrieval operation will be initiated by the end of 2018 March.

TABLE I. Combination of success path element and threat for preparation for fuel retrieval.

Element of success path \ Threat		System and equipment failure			Societal factor		Management factor
		Random failure	Natural hazard	Human factor	Public trust	Maliciousness	Project management
Planning	Organization/ Budgeting	NA	NA	NA	Poor dialogue	Sabotage Anti-activity	Lack of funds
Remove large obstacles	Operational floor	Hanger failure	Crane overturn	Crane miss operation	Poor dialogue	Sabotage Anti-activity	Poor process management
	Spent Fuel Pool	Fuel failure by corrosion	Damage fuel	Fail in remote operation	Poor dialogue	Sabotage Anti-activity	Lack of workers
Establish working environment	Decontamination	Equipment failure	Fire event	Insufficient training	Exposure incident	Sabotage Anti-activity	Lack of workers
	Radiation shielding	Loss of power supply	Structural failure	Miss-evaluation	Exposure incident	Sabotage Anti-activity	Fail to monitor
Cover installation	Installation Training	Equipment failure	Typhoon /Storm	Miss operation	Poor dialogue	Sabotage Anti-activity	Schedule delay
Small rubble removal	Cutting/ Suction/removal	Manipulator failure	Seismic failure	Miss cutting operation	Report minor incident	Sabotage Anti-activity	Lack of workers

NA: Not Applicable

TABLE I. is an example illustration of success path elements and threats. The success path elements are defined in Fig. 6. There are three types of threats, i.e., system and equipment failure, societal factor and management factor. The system and equipment failure are caused by a random failure, natural hazard, and human factor. It is important to list up all possibilities of the threats regardless to the frequency and severity of the threats. Each of the cell in this table defines a combination of a success path element and threat to the element. Therefore, the cells constitute a series of initiating events regarding the fuel retrieval preparation phase. The initiating event develops plural sequences according to the corrective and mitigating countermeasure as shown in Fig. 4. All those scenarios are to be evaluated quantitatively or qualitatively. A screening process follows to identify dominant or important scenarios to be quantified.

The flow diagrams for the second phase is given in Fig. 7. The procedures are to place fuel assemblies in a transport cask, transport fuel assemblies in the cask and to carry the cask out safely. In this phase, societal factor and management factor, that is, public trust, nuclear security and project management are added to all the success path elements in common. In this phase, as the nuclear fuel are dealt with, the tasks here should be very careful. Adequate project management and good risk communication with public and other stakeholders are very important. If one fails to cope with the societal factors, the works at the FD-NPS site would not supported by public and society.

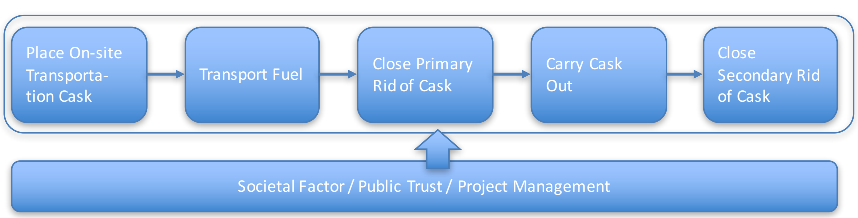

Fig. 7. Process for the second phase: Fuel Retrieval Process.

Likewise, Figure 8 presents the risk analysis and management process for the fuel transport and storage process. The retrieved fuel is firstly stored in the fuel storage pool and ultimately maintained in a dry cask. The societal and management factors are important and common in this phase as in the second phase. If the fuel transportation is in fail or unexpected incidents occur, loss of public trust could become a critical issue.

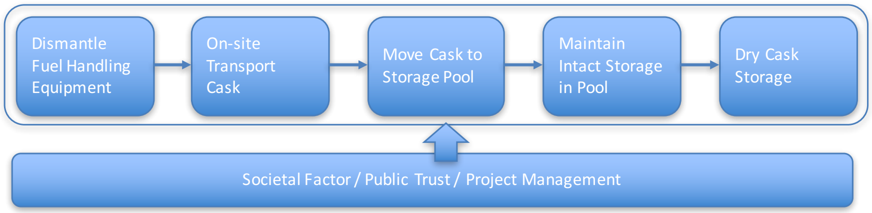

Fig. 8. Process for the third phase: Fuel transport and storage process.

The overall picture of the quantification of the risk profile for fuel assembly transport in the phase 2 is shown in TABLE II as an example. Scenarios are identified and well defined in terms of success path element and threat combination. The rest of risk management procedures is the quantification of the risk profile, i.e. likelihood, consequence and risk metrics. Current estimates on the likelihood (step 4) and consequence (step 5) are tentative and are not based on evidences. They will be evaluated based on the most recent available information and engineering judgement. The estimate may be more dependent on expert elicitation process. It is expected that expert would be able to make the best judgement because whole process is explicitly described as a result of the present risk management framework. We need to note that the FD-NPS decommissioning involves unknowns in various steps of the risk management. Technical information and operational experience becomes more available as the project goes forward and progress is made.

According to the tentative estimate as in Table II, it is considered that external events such as seismic event has larger consequence than others even if the frequency is low. On the other hand, loss of public trust shows higher likelihood because the current negative view on the nuclear power generation and remembrance of Fukushima Daiichi accident. It can result in irrational delay and reflexive oppositions to the decommissioning project. Those pullbacks in the decommissioning will ultimately increase the total risk of the FD-NPS. The situations are not preferable from the viewpoint of public safety and benefits. The authors hope the risk management process proposed in the present study will provide rational and reasonable explanation for the safe and steady progress of the decommissioning.

As we discussed that the FD-NPS decommissioning involves unknowns and uncertainties, one cannot decide some approaches are definitely the best while others are unworthy of consideration. We conclude the risk assessment and management are required and the process needs to be updated in accordance with the most recent progress and information on the decommissioning works.

TABLE II. Example of risk profile for fuel assembly transport

Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
Success Path	Threat	Failure Scenario	Likelihood	Consequence	Risk metrics
Phase: Fuel Retrieval End point: Close Secondary Rid of Cask Task: Fuel Transportation	Seismic Event	Fuel fall during transport	Low low	High	TBQ
		Radiation exposure/injury of workers	Med	Low	TBQ
	Cask failure	Radiation exposure/injury of workers	Low	Low	TBQ
		Delay in fuel removal	Med	Med	TBQ
	Long-Term Loss of Power Supply	Cooling deterioration of fuel	Low low	Med	TBQ
		Regulatory tightening	Low	Med	TBQ
		Release radioactive materials	Low low	Med	TBQ
	Public Communication	Loss of public trust	High	Med	TBQ
		Prolongation and cost increase	Med	Low	TBQ

TBQ: To Be Quantified

V. CONCLUSIONS AND FUTURE PERSPECTIVE

The Tokyo Electric Power Company Holdings is responsible for the planning and fulfilment of the decommissioning project. However, the collaboration with the Atomic Energy Society of Japan (AESJ) in the decommissioning project is very important. As the FD-NPS decommissioning is a national project, the AESJ has established the Fukushima Daiichi Decommissioning Risk Assessment and Management Working Group.

Risk management of the FD-NPS decommissioning is a great challenge. In the present study, the risk management framework has been developed. It is applied to fuel assembly retrieval from the Unit 3 SFP. First of all, the endpoint has been established and the success path has been developed. The fuel assembly retrieval work is separated into three phases of different characteristics. Then, possible threats that are internal/external, technical/societal/management, are identified and selected for each phase. The first triplet question, "what can go wrong?" asks for failure scenarios. The likelihoods and consequences for each scenario are roughly estimated.

Specific features of the FD-NPS decommissioning are the lack of sufficient knowledge on the current situations first of all. Various types of hazard potential exist and accordingly various types of works are required. It will continue for several decades; i.e. long term perspective is important. What should be emphasized is that we do not always have enough knowledge and experience of this kind. It is expected the FD-NPS decommissioning can make steady and good progress in support of the proposed risk management framework. We conclude the risk assessment and management are required and the process needs to be updated in accordance with the most recent information and knowledge on the decommissioning works.

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