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Development of Risk Informed Aging Management Program in Decommissioning

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This paper proposes to solve the issues related to aging management program (AMP) during the decommissioning phase by using risk information. The AMP for the decommissioning plants has not been established while the number of permanently shut down and decommissioned nuclear power plants are increasing in the world. The first issue is the change of the functional importance of the safety systems at the beginning of decommissioning. We propose to evaluate the importance using the probabilistic risk assessment (PRA) model with the change of specification in the decommissioning plant and to determine new importance grade. The second issue is to make the maintenance based on the appropriate risk information. This risk information should be based on the progress of decommissioning, reflected and evaluated in the PRA model, as well as information obtained from maintenance inspections, including the ROP process, and failure experience during routine operation. To address these issues, the maintenance program in decommissioning that uses the evaluation of risk information according to the decommissioning phase is proposed in this paper. [DOI: 10.1115/1.4065139]

Keywords: decommissioning, aging management, fire protection, maintenance, ROP, PRA

1 Introduction

Nuclear power plants must be managed safely according to the conditions of each life stage throughout their plant life, including construction, operation, and decommissioning. Ageing management in a rational and safety-enhancing method during the decommissioning phase is a new challenge. 212 nuclear power plants have been permanently shut down worldwide as of the end of April 2023, and the number has increased by 5 since the beginning of 2023. Among those, 193 are already in the process of decommissioning. The number of plants to be decommissioned is expected to increase further, as many countries have set the operating period of nuclear power plants at 30–40 years. The major decommissioning activities include decontamination, dismantling, removal, and fuel extraction. Since these activities do not generate revenue for the operating companies, the costs are covered by the advance reserves [1,2]. Therefore, it is necessary to develop a reasonable decommissioning plan in advance. Some systems, structures, and components (SSCs) are required to function during the decommissioning phase; some SSCs may remain in use without being replaced for as long as 80 years or more after their construction. Therefore, plant AMPs are important to improve safety during the decommissioning phase as well.

So far, AMPs for the decommissioning phase have been developed similar to those for the operation phase. Based on the results of the author's on-site surveys and interviews at four nuclear sites in three countries, it was confirmed that none of the sites has an AMP focused on decommissioning. The results of the field survey are discussed in detail in Chapter 5. No nuclear sites were identified from the other literature review as having AMPs focused on decommissioning. The International atomic energy agency (IAEA) has also defined recommended AMPs for each deterioration event, based on examples from the U.S. Nuclear Regulatory Commission (USNRC). These are called International general aging lesson learned (IGALL). In Japan, maintenance programs are drafted based on the maintenance management regulations of the Japan Electric Association. The two key elements that determine the level of importance in this maintenance program are the SSC's Design Criticality Classification and the aging modes to be considered, which are identified based on the Atomic Energy Society of Japan's "Code on Implementation and Review of Nuclear Power Plant Ageing Management Program" (AESJ-SC-P005:2022) (Plant Life Management (PLM) standard) [3]. The PLM standard is a set of standards for the implementation of decommissioning measures for nuclear power plants. No AMP focused on decommissioning is defined in these standards, and this paper presents the importance of such an AMP and the findings that contribute to the standard setting.

Aging management in the decommissioning phase differs from that in the operation phase in the following ways.

First, the required safety functions are different. In an operating plant, reactor reactivity control, core cooling, and containment are important safety functions by design. The SSCs to ensure these are called engineering safety facilities.

In a decommissioning plant, the cooling function of the fuel storage facility, e.g., spent fuel pool, is important for the safety of the nuclear fuel material, and the containment function of this facility and Radioactive Waste (RW) treatment facilities during the decommissioning period are also important.

Second, the redundancy of safety function is reduced. During the operation phase, the risk of the plant is relatively high because of the need to control fission reactions and heat removal. For this reason, the engineering safety facilities are designed to have sufficient multiplicity and diversity. On the other hand, during the decommissioning phase, some of the SSCs that comprise the engineering safety facilities are taken out of service. This means that the contribution of one of the engineering safety SSCs to the top event used in the probability evaluation to be considered in the decommissioning phase (e.g., a loss of cooling event in a fuel storage facility) is relatively larger than in the operation phase.

Finally, it is necessary to harmonize safety improvements in operating plants. The plants in operation are improving their safety

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through periodic assessments and back fitting. These may not be directly applicable to decommissioning, but the findings obtained should be reasonably reflected. In the case of Japan, many plants were moved to decommissioning after the Fukushima Daiichi Nuclear Power Plant accident. Even though new regulatory standards have not been applied to these, it is necessary to take appropriate actions such as reviewing external hazards based on lessons learned from the accident to reasonably enhance safety.

Given the differences from operating plants mentioned above, it is necessary to redefine the maintenance severity based on plant characteristics and decommissioning plans in order to manage deterioration to reasonably enhance safety in decommissioning plants. Therefore, this study proposes a method to define that importance level using risk-informed decision making, which combines engineering judgment and probabilistic considerations. First, we present a method for scoping and considering the importance of SSCs in general terms. Next, the results of applying it to the decommissioning of BWR5 are presented and the advantages of the method are discussed.

2 Methods

2.1 Redefinition of Facility Configuration. The design criticality of the SSC is based on the safety functions required for the operating condition. To define an AMP for decommissioning, it is first necessary to define the equipment configuration required for safety functions in the decommissioning plant, based on the safety functions required during decommissioning. The concept of facilities to be covered is shown in Fig. 1. According to this concept, SSCs used for core reactivity management, core cooling, and in-operation monitoring are basically un-necessary for ensuring safety in decommissioning plants. Under the Japanese inspection system, plants in the decommissioning stage are also subject to nuclear regulatory inspections, and inspection items based on the Seven Cornerstones are also applicable to decommissioned plants. By defining the facility modification process in advance and evaluating the plant's operational margins, it is possible to reasonably reduce facility margins under the supervision of the regulatory agency.

Although some of the redefinitions of necessary facilities will change according to the progress of decommissioning, special attention should be paid to the following items among the SSCs to be extracted according to the approach shown in Fig. 1.

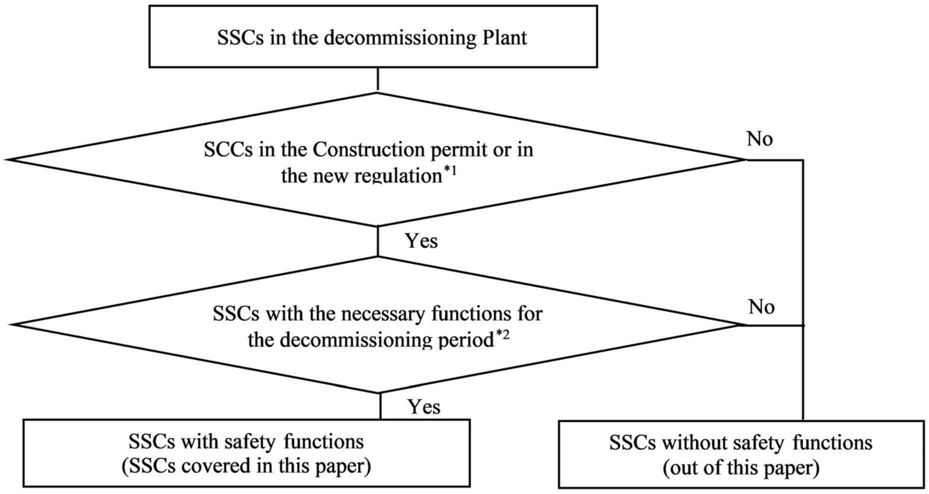
(A) Safe spent fuel storage: All fuel in the reactor core is transferred to a fuel storage facility. Even though the importance of the cooling function of the spent fuel pool is relatively higher than that of the operation, the importance of the boundary function also changes because the spent fuel pool is located outside the primary containment vessel in BWRs, which increases the safety margin to accident with time. In addition, the position of this facility will change significantly once the spent fuel has been removed from the plant. In the case of dry cask storage on site, as in the domestic case, this facility will be newly subject to redefinition.

(B) Containment of radioactive materials: Decommissioning plants also contain radioactive materials such as spent fuel and RW, and it is necessary to maintain the containment function of radioactive materials to prevent exposure of nearby residents and workers.

(C) Waste treatment facilities: Decontamination, liquid waste management, solid waste management, etc. will be required for waste treatment facilities during the decommissioning period. Depending on the decommissioning process, treatment capacity equivalent to or greater than that of the operating plant may be required.

(D) Facilities for fire protection: During the decommissioning phase, the frequency of fires may be higher than during operation, considering the aging of facilities compared to the operating plant and the characteristics of construction work and temporary change management that occur when plant facilities are removed.

(E) Resources for emergence response: Accident evolution in decommissioned plants is slower and emergency mission times are longer than in operating plants. A reasonable amount of effort has so far been devoted to managing the



*1: New regulation after Fukushima accident in Japan
*2: Necessary functions for the decommissioning period
- Containment of radioactive materials
- Cooling, storage, and handling of nuclear fuel materials
- Disposal and treatment of RW
- RW treatment facilities
- Emergency response
- Other facilities necessary to ensure safety
(related auxiliary equipment, fire protection, etc.)

Fig. 1 Flow to determine SSCs with safety functions in decommissioning

deterioration of resources for emergencies, e.g., communication equipment, radiation protective equipment, and radiation measuring equipment. In developing these AMPs, it is desirable to consider that the events to be considered will change with the progress of decommissioning and to define the strategy.

2.2 Engineering Judgment. The internal hazard of a decommissioning plant is smaller than that of operation. Therefore, it is relatively rare for the decommissioning plants to be required to identify safety margins through rigorous safety analysis, but equipment requirements for decommissioning plants are defined based on quantitative engineering judgment. In addition, in previous decommissioning studies [4] and IAEA decommissioning-related safety standards [5], safety assurance in the decommissioning phase is concentrated on the safety of waste management and radiation protection. Taking these factors into consideration, trigger events that may impair the safety functions defined in Fig. 1 are identified, and necessary equipment requirements are determined by engineering judges based on past operating experience, taking into consideration the circumstances of nonconformities that are likely to occur. By comparing the regulatory requirements for operating plants with the current status of their own plants, weaknesses against external hazards such as earthquakes, tsunamis, and weather can be identified and their effects can be examined.

Among the external events in decommissioning plants, fire is of particular note. Fire scenarios are evaluated by categorizing the occurrence of fire sources and the characteristics of fire scenarios. For the ignition source, the dominant factors are the size of the fire load of the existing structure and the presence or absence of an ignition source, given that the entry of combustible materials from outside is strictly limited. In terms of fire characteristics, from the fuel pool cooling perspective, it is necessary to consider the possibility of fire spreading to the performance maintenance equipment area and to the related equipment and cable route installation area. Therefore, the robustness of the firewall design and the strictness of the management of the area are directly affected.

In addition, based on the experience of the accident at the Fukushima Daiichi nuclear power station (NPS), the plant has general-purpose facilities that can respond flexibly in the event of an emergency due to a large-scale disaster that exceeds expectations, but these facilities are not included in the facilities subject to the application for the installation permit for the decommissioning plant. However, as long as SSCs containing spent fuel and RW exist, it is necessary to maintain and manage them. Since the SSCs are general-purpose facilities and can be replaced relatively easily, it is important to consider and confirm the maintenance method that takes this into account, considering any changes from the operating plant to ensure that the content is reasonable.

2.3 Probabilistic Consideration. In general, decommissioned plants are operated by reducing the number of facilities that maintain their functions from the operation phase in order to reduce the required functions and risks involved, and the multiplicity of engineering safety SSCs is reduced. Based on the characteristics of the decommissioned plant, probabilistic considerations are made for internal events, which are referred to when prioritizing the SSCs. In the decommissioning phase, the operational status of the plant will change step by step, and it is not realistic to construct a site-specific model for each change. Rather, it is more realistic and safety-oriented to use the model developed for the plant in operation and implement SSC selection, which allocates maintenance resources based on the estimated degree of risk change within the scope of a model that can be compared with the operating plant while reflecting the operational status of the equipment in the decommissioning phase.

Here, the damage criteria (time margin, etc.) for spent fuel can be evaluated conservatively enough by using the same evaluation method as the damage criteria in the operation phase. Based on these ideas, the spent fuel storage function of the decommissioning plant should be considered from a probabilistic point of view in order to compare it with that of the operating plant.

For internal events, it is effective to reflect the inoperable SSCs in the decommissioning phase and to compare the risk achievement worth (RAW) between the operation phase and the decommissioning phase. RAW is the risk importance that loss of functionality during operation poses to the fuel damage frequency (FDF) and is defined by the following equation:

$$\mathrm{RAW} = \frac{\text{FDF when one facility loses functionality}}{\text{FDF without loss of the function}} \tag{1}$$

In this paper, risk is quantified using "Safety Watcher," a software application that enables simple evaluation of risk. Specifically, the software quantitatively calculates the contribution of the loss of function of each system and component to the FDF.

This program is used for the quantitative risk assessment of operating plants, but it also has a function to assess the FDF of spent fuel stored in fuel pools, and can construct a model showing the plant status after the transition to decommissioning by setting the SSC, which is not subject to management in decommissioned plants, to a nonoperational state. This method enables the construction of a model that shows the plant status after the transition to decommissioning. This method enables quantitative risk assessment that reflects the state of the decommissioned plant using a common model with the operating plant.

2.4 Comprehensive Judgment. Based on the equipment requirements for the functionality of the SSCs, the SSCs to be set at a high level of importance in the decommissioning phase are selected, and the appropriate maintenance method for each SSC is comprehensively determined in consideration of IAEA's IGALL and the PLM standard in Japan.

In addition, it is necessary to consider the consistency with the existing importance classifications, and to distinguish between the existing importance classifications and the SSCs so that the response in the decommissioning plant will be clear.

3 Results

3.1 Rearrangement of Facility Configuration. In accordance with the method described in Chapter 2, a plant with spent fuel in the early decommissioning stage of BWR5 was used as an example to select SSCs to be subject to the importance setting in the decommissioning stage and to set the importance of maintenance.

In order to examine the maintenance method for rational SSC aging management, the points where the basic design of the plant is changed in the decommissioning phase are first summarized, and the points where the basic performance requirements are changed are summarized using the SSC of a BWR5 plant as an example. These are summarized in Table 1 and contribute to the study of the policy for reviewing the design specifications of each system and facility by reviewing the basic design.

3.2 Engineering Judgment. This section discusses the functions and SSCs listed in Table 1 as the aging management of decommissioning plants described in Sec. 2.2, in which aging management policies are determined by engineering judgment, taking into consideration the equipment requirements necessary for decommissioning plants and triggering events that may impair safety functions.

3.2.1 Radioactive Containment Functions. In a decommissioning plant, all spent fuel is stored in a fuel pool, and the reactor building serves as the containment facility for basic containment of radioactive materials. In addition, it is necessary to prevent the diffusion of radioactive materials when dismantling and dismantling equipment. Considering these factors, it is necessary to maintain and

Table 1 Basic design arrangement of the plant to be considered in decommissioning (example of a BWR5)

Design phenomena	Required functions	Requirements in operating plants (existing)	Requirements in decommissioning plant (proposal)
Assumed accident (loss of fuel pool water)	Fuel pool cooling	Heat removal immediately after shutdown	Heat removal according to time after shutdown Example: 1/100 of the operating time per fuel [4] (reached in about 4 months after shutdown)
	Emergency core cooling system	–Heat removal at criticality of all fuels -Multiple and diverse	–Same amount of heat removal as fuel pool cooling –No need for multiplicity and diversity (because of fuel pool cooling backup only) Example: One of the residual heat removal systems (heat removal is about the same as fuel pool cooling)
	External power source Emergency diesel generator	Normal situation 3 units	Same as on the left. 1 unit (determination that multiplicity is not required)
Radioactive release	Containment facility Ventilation facility	Building functions as a secondary containment facility and negative pressure management to prevent leakage	Containment facilities for inventory-oriented confinement and proper air supply and exhaust systems (no requirement to maintain negative pressure)
External events (fire)	Fire protection features	Compliance with technical standards of the building standard law	Individual fire protection design considering the following – Fire impact assessment – Fire PRA
Waste disposal	Liquid waste disposal Solid waste disposal	Water, resins, etc. discharged during operation	In addition to the above, plant decontamination waste liquids, resins, plant equipment waste (metals, concrete, etc.)
Declaration of emergency	Emergency response equipment and systems	Equipment and systems for restoration, radiation containment, measurement, and shielding in case of an accident at an operating reactor	Equipment and systems for radiation restoration, shielding, and measurement in case of fuel pool water loss

control the bulkhead functions of the reactor building walls, floors, compartments, and penetrations, and to maintain ventilation facilities that can properly control radioactive materials in the air.

For the reactor building walls, etc., it is considered that there will be no excesses or deficiencies in the current building verification due to the robustness of the components. On the other hand, information on defects in dynamic equipment such as supply and exhaust fans, building isolation valves, and ducts, which are system components, has been confirmed through experience in operating plants, and is thought to be the result of age-related aging due to facility management during operation. Under these circumstances, all equipment in the operating plant, except for the isolation valves in the building, are classified as class 3 critical equipment.

Therefore, it is desirable that the air supply and exhaust system be positioned as a high priority maintenance system in decommissioning plants, and that dynamic equipment be subjected to time-controlled overhaul and functional checks, and ducts be subjected to systematic visual and functional inspections of both the interior and exterior surfaces. For ducts, considering the large amount of material, a reasonable method may be to extract representative areas and check important points for aging management in a representative method, based on the fact that there are many cases where aging was confirmed in the vicinity of outdoor air intakes.

3.2.2 Radioactive Waste Treatment Functions. In a decommissioning plant, a large amount of liquid waste and waste resin from the decontamination of facilities and solid waste from the disposal of facilities are treated and managed. In addition, as in operation, liquid and solid wastes are generated on a daily basis through plant operation and normal maintenance work and must be treated.

On the other hand, in operating plants, the importance of waste treatment facilities is set low because they are for treatment at a later stage of operation and their inventory is small compared to that of nuclear fuels. The IAEA's IGALL [5] and USNRC's GALL[6] do not specifically address the aging management of waste treatment facilities, but only partially in the aggregate table of the IGALL, as they are categorized as general dynamic equipment. In addition, the PLM standard in Japan for waste treatment facilities is equivalent to that of IGALL and does not specify maintenance details for individual facilities.

The maintenance of waste treatment facilities after the transition to decommissioning has been conducted as described above, and many of them have deteriorated over time because they were positioned as less important than the systems directly related to the operation of nuclear reactors. Many of them have deteriorated over time.

Among waste treatment facilities, liquid waste treatment systems and related facilities (including distillation boilers, and solidification and drying facilities) in particular require tank storage when liquid waste accumulates and tanks have capacity limitations. If these facilities are not properly managed for deterioration, and if treatment is delayed due to breakdowns caused by equipment deterioration, daily liquid waste treatment capacity will be lost, which will interfere with plant operation, and in the worst case, may have an impact on discharge management. Considering this situation, it is important to systematically address the long-term use of these facilities by considering their deterioration during plant operation and conducting both overhaul inspections and functional checks through time-controlled maintenance, as well as considering equipment replacement by evaluating critical parts of the facilities from the viewpoint of more accurate aging management. In addition, it is important to plan for long-term use by considering equipment replacement, etc. by evaluating critical parts of equipment from the viewpoint of more accurate aging management.

3.2.3 External Event (Fire) Prevention Functions. In Japan, earthquakes, tsunamis, weather, and other external events are assumed to be the main external events, and in operating plants, protective equipment, etc., are also installed and managed as of high importance.

Among the external events in decommissioning plants, fire is the particular concern. In the case of decommissioning plants, however, the fire protection requirements have not been changed from those in the past, and therefore, the latest fire protection design may not be sufficiently considered. However, fire protection requirements have not changed in decommissioning plants, and therefore, the latest fire protection design may not be fully considered. Fire is an event that tends to occur frequently at a predictive level and has a large ripple effect when it does occur. In addition, the conventional aging management of fire protection equipment in operating plants is based on the standards stipulated in general laws and regulations such as the Fire Defense Law and the Building Standards Law, and may not adequately address the characteristics of nuclear power plant equipment.

The following discussion is conducted to identify the equipment that should be focused on among the fire protection equipment. The concept of importance of fire protection equipment is organized in the Atomic Energy Society of Japan standard. "The implementation standard concerning the internal fire Probabilistic Risk Assessment of Nuclear Power Plants" (AESJ-SC-RK007:2014) [7], and basically, the higher the value of the following Eq. (2), the higher the fire risk:

$$\Lambda = \lambda \times X \tag{2}$$

Λ: Frequency of fire scenario occurrence
λ: Fire frequency of fire source
X: Characteristic coefficient of fire scenario

The occurrence of fire scenarios is evaluated by classifying the occurrence of fire sources and the characteristics of fire scenarios. Eq. (2) indicates that the magnitude of the fire load of the existing structure and the presence or absence of ignition sources are dominant factors. As for the ignition source, it is assumed that the fire frequency (λ) can be reduced, given the strict restrictions on the entry of combustible materials from outside the structure. The characteristics of the fire scenario (X), in terms of fuel pool cooling, require consideration of the possibility of fire spreading to the performance maintenance equipment area and to the installation area of related equipment and cable routes. Therefore, the robustness of the firewall design and the strictness of the management of the area are directly affected.

Considering the above, it is desirable to set a high maintenance priority for performance maintenance equipment, these indirectly related equipment, floor and wall penetrations of the boundary wall of the fire protection compartment in the cable route, and fire dampers, and to conduct overhaul inspections when possible in addition to functional tests by time-controlled maintenance considering the design life of these critical deteriorated parts. It is desirable to conduct overhaul inspections when possible, in addition to functional tests.

In addition, information on nonconformities related to aging management of penetrations has been confirmed in many nuclear power plants in Japan, and a high rate of occurrence has been confirmed in classifying the published nonconformity information. This indicates that strengthening the aging management of penetrations is an important matter to ensure the robustness of fire protection bulkheads.

3.2.4 Equipment Management for Transition Conditions to Emergency Situations According to Accident Scenarios. Since the accident at the Fukushima Daiichi Nuclear Power Plant, emergency response to nuclear disasters has been strengthened in Japanese regulations, and systems, materials, and equipment have been maintained and managed for this purpose.

Under the current laws and regulations, even after a plant is decommissioned, it is subject to the same regulations as an operating plant (except for plants subject to the new regulatory standards), and the basic systems, materials, and equipment are maintained and managed in the same method.

On the other hand, there is a movement to make the emergency response reasonable for plants that have been decommissioned, the fuel has been cooled, and the risk is not great even in the event of loss of fuel pool cooling water. In line with this trend, it is reasonable and realistic to reduce the maintenance and management of systems and equipment from operating plants, considering the plant's risk and safety margin.

From the perspective of facility aging management, even if the number of objects to be managed is reduced from the operating plant according to the situation, there is no need to change the level of importance and aging management method. However, since emergency response equipment is general-purpose equipment and can be replaced relatively easily, it is important to consider and confirm that the maintenance method that takes this into account is reasonable, considering any changes from the operating plant. Considering this, for the time being, it is recommended that general visual inspections be conducted as time-controlled maintenance in accordance with the time of use, or by other reasonable methods.

3.3 Results of the Probabilistic Consideration. In considering the importance of the fuel pool cooling function, a probabilistic evaluation should be considered in the consideration of the maintenance importance, since the loss of this function is a direct cause of fuel damage.

The operation of the fuel pool cooling system has two pumps, which is common to both the operating plant and the decommissioning plant, but the difference is that the operation of the emergency core cooling system, which serves as a backup, is deleted in the decommissioning plant. This is because spent fuel in decommissioning plants is cooled for a sufficiently long period of time and will be reduced to 1/100 or less in about 4 months after the transition to decommissioning [8]. In fact, all current plants in Japan have been out of operation for more than 10 years, which means that the fuel has been sufficiently cooled. Therefore, the emergency core cooling system can be reduced in any of the decommissioned plants, and the model here is constructed after the reduction.

The model was developed to reflect the performance maintenance facilities in the decommissioning plant and to be consistent with the operation of the Safety Watcher, which had been used to evaluate the probability in the operating plant. Using this model, the contribution of the loss of function of each system and equipment to the FDF was quantitatively calculated in Table 2 as the degree of increase in FDF, RAW, defined in section 2.3 Eq. (1) as follows. The results in Table 2 confirm that the following situations are common to both operating and decommissioned plants.

The RAW is large for both operating and decommissioning plants in common when external power is lost. This is because the fuel pool cooling system and the fuel pool water injection system are normally operated by an external power supply, and the loss of this power supply directly affects the cooling and replenishment of the fuel pool. In addition, the emergency diesel power generation system in the operating plant is 3.37, because the emergency power supply in the operating plant is the emergency power source to the emergency core cooling system (ECCS), and the ECCS is responsible for part of the fuel pool cooling function. On the other hand, in decommissioning plants, the ECCS is an unmanaged facility, so the increase in the RAW of the emergency diesel power generation is small compared to the external power supply. However, since the ECCS also supplies power to the fuel pool cooling system as a backup for the external power supply, the RAW will be a certain value even in the event of a single loss of function.

The RAW of the condensate storage water tank, supply water system, DC power supply, and residual heat removal system of the operating plant are all indicated as "1.00," but the exact values are several digits lower, and RAW varies slightly.

In addition, the number of facilities with performance maintenance requirements in the decommissioned plant has decreased compared to the operating plant, and the following situations have been confirmed.

- The impact of the loss of function of a single system or component on the RAW is larger than that of the operating plant.
- The RAW of the fuel pool cooling system, its water source, and power supply increased significantly from the operating plant.
- The impact of the loss of function of these components is considered to be similar to the Table 2, and to a certain extent smaller than the value in the Table 2, since each of the auxiliaries of these components maintains its multiplicity.

Based on these results, it is desirable to place the maintenance importance of the systems directly related to the fuel pool cooling at a high level, and these auxiliaries at the next level as indirectly interconnected systems, and to consider these other systems from a different angle as a criterion for the equipment importance based on engineering judgment. In terms of maintenance methods, directly related systems with high maintenance importance should be positioned in the same method as operating plants, and reliability should be ensured through overhaul inspections and functional checks using time-controlled maintenance.

For indirectly related systems such as auxiliaries, it is desirable to quantitatively determine the selection criteria for time-controlled maintenance and condition monitoring maintenance, taking into consideration the multiplicity of the systems and the time margin for fuel cooling in the event of loss of function. The maintenance method should basically be the same overhaul and functional verification as for the direct systems.

3.4 Comprehensive Judgment. The critical equipment in decommissioning proposed in this paper is defined as equipment of importance class 3 or lower according to the definition in the Electric Association of Japan's technical guideline "Guideline for Importance Classification of Electrical and Mechanical Equipment with Functions to Deal with Safety Functions, Major Accidents, etc." (JEAG4612:2021) based on existing importance classification guidelines. By defining the positioning of critical equipment for maintenance management in the decommissioning plant proposed here as follows, it will be consistent with the existing importance classification and enable recognition of the importance level after the transition to decommissioning.

The maintenance method according to the importance level is also defined as follows:

- Critical equipment proposed in this paper shall be classified as equivalent to Class 3 shown in JEAG4612, and A and B grades shall be assigned again to classify critical equipment after the transition to decommissioning.
  (Example: MS-3-A)
- The maintenance method shall be basically time-controlled maintenance, but for grade-B equipment with multiplicity, condition monitoring maintenance may also be selected.

Table 2 Comparison of RAW in operating and decommissioning plants (example of a BWR5)

Functional loss system/ equipment	RAW	
	Operating plant	Decommissioning plant
Total loss of external power supply	14.57	2.52×10^9
Condensate storage tank	1.00	310
Fuel pool cooling system	2.94	68.3
Supply water system	1.00	68.3
DC power supply	1.00	64.2
Residual heat removal system (emergency core cooling system)	1.00	1.00
Emergency diesel generator	3.37	18.5

In the program in Table 3, time-controlled maintenance is adopted for SSCs of high importance as the maintenance method. This recommendation is based on the results of the analysis of nonconformities at nuclear power plants in relation to the matters described in the following sentences shown below Table 3, considering the situations described below.

Systems, structures, and components that have shifted to condition monitoring maintenance have been able to perform effective maintenance on items whose deterioration becomes apparent due to dynamic changes or data, but when other equipment is subjected to condition monitoring maintenance, it is often in a state other than the maintenance assumed in the PLM standard. This indicates that parts that have received relatively little attention in the past, such as consumables, may deteriorate as critical parts, resulting in loss of functionality due to maintenance conditions that were not anticipated in the PLM standard.

However, time-controlled maintenance is not necessarily the best method for detecting deterioration, especially for waste treatment facilities that are composed of various types of equipment, considering that deterioration characteristics often show unique trends depending on the configuration and structure of the SSCs. Therefore, it is necessary to consider the best method by combining the characteristics of SSCs and maintenance methods.

4 Considerations

4.1 Validity of the Model for Probabilistic Evaluation. The "Safety Watcher" used for probabilistic evaluation in Sec. 3.3 is software developed for probabilistic safety evaluation of the operating conditions of nuclear power plants. The appropriateness of using it for decommissioning plants is shown below.

The basic probabilistic safety evaluation method is a combination of an event tree and a fault tree to evaluate each event. This is common to both decommissioning and operating plants.

The quantification of the event tree includes the model configuration and the failure rate data used to analyze the failures. The model configuration is basically based on the operational status of the plant in question, and also incorporates portable facilities for dealing with external events, etc., to comply with the new regulatory standards in Japan. The model is able to properly simulate the facilities that will be out of operation during decommissioning, which are treated as nonoperational.

The failure rate data are selected from U.S. data (WASH-1400, NUREG, etc.), which has abundant operating experience, to ensure that the results are similar to other probabilistic evaluation codes and that the reliability is ensured by comparing with domestic failure rate data (CRIEPI).

The same U.S. data as the failure rate data are used for the evaluation of common cause failures, since no domestic data are available for this purpose. The coefficients used here are the same as those used in other evaluation codes.

The decay heat data is set to a constant value without decreasing after 2000 days after shutdown to be more conservative than the actual data.

4.2 Future Issues. The following is a discussion of possible issues to be addressed in the future.

This study summarizes the results of a study on the case where spent fuel exists in a plant as the initial stage of decommissioning. After spent fuel is removed from the plant, or whenever SSC occurs,

Table 3 Decommissioning plant aging management criteria program overview

Equipment (SSCs)	Importance of aging management	Maintenance methods	Remarks
Directly related systems of fuel pool cooling (especially dynamic equipment)	High PS-3-A: Additional definition of JEAG4612-2021	- Time-based maintenance - Overhaul and functional check	
Radioactive Waste disposal equipment	Middle MS-3-B: Additional definition of JEAG4612-2021	- Selection of time-based or condition-based maintenance (considering multiplicity, etc.) - Condition monitoring (condition monitoring maintenance equipment) - Overhaul (time-based maintenance equipment) - Functional check (all equipment)	
Wall and floor penetrations and fire dampers for firewall	High MS-3-A: Additional definition of JEAG4612-2021	-Time-based maintenance -Visual inspection (all equipment) -Disassembly and inspection (disassembled dampers) -Functional check (all equipment)	Visual inspection of penetrations is important to confirm deterioration of sealing materials (critical areas of deterioration)
Response materials and equipment in case of emergency	High MS-3-A: Additional definition of JEAG4612-2021	-Time-based maintenance -Visual inspection	Including daily inspections tailored to the object

which is when the operation of facilities in the plant is suspended, the facility conditions that will serve as input for this study will change. It is important to consider what risks are possible at each stage and to establish an aging management policy that takes these risks into account.

From the situation of the site survey, one of the important missions of decommissioning is to reduce costs as well as to ensure safety, and the current aging management has reduced costs by introducing maintenance by condition-based maintenance in each case. In contrast, reevaluating the current implementation and changing the aging management method requires resources, and it is expected to be difficult to change the method. In order to promote changes, a certain level of motivation and pressure from outside is necessary. One way to deal with this issue is to incorporate the change into standards and criteria. We are coordinating with the subcommittee of the PLM standard, which is a domestic standard, to incorporate the proposal into the standard, and are coordinating the inclusion of the proposal in the next revision. The necessity of reflecting the proposal in other standards, such as the Atomic Energy Society of Japan standard "Implementation of Decommissioning of Nuclear Facilities" (AESJ-SC-A3:2011) [9], which is a Japanese decommissioning standard, is also being considered.

4.3 Impact on Regulatory Inspections When Rational Equipment Configuration is Applied. In a decommissioning plant, the required performance for each system in the plant will change significantly, and it is assumed that the required specifications of equipment functions may change.

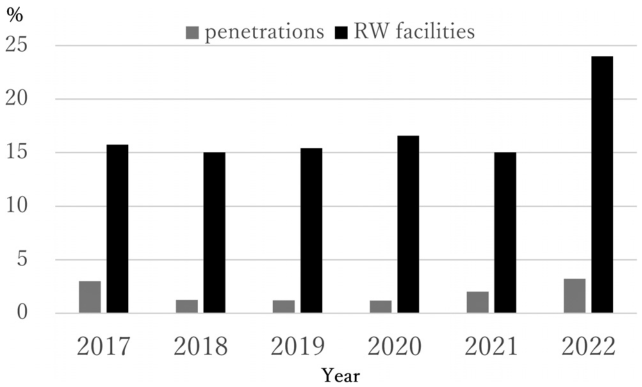


Fig. 2 Ratio of nonconformance of penetrations and radiation waste treatment facilities in a representative plant

As a typical example, in the residual heat removal system of a boiling water reactor, the specifications for an operating plant require a heat removal capability equivalent to the amount of heat generated when the reactor is shut down from rated operation, but in a decommissioning plant, only the backup function of the fuel pool cooling system is required, which is much smaller than that of an operating plant. The performance requirements for decommissioning plants are much smaller than those for operating plants.

In nuclear regulatory inspections, inspection items are summarized in a guide issued by the government based on seven cornerstones, and at the present stage, the performance of the operator to define and implement work processes is mainly monitored from the perspective of cornerstones.

Considering future operations, it is possible to reduce the design margin for the performance of each system to ensure plant performance, and establishing a design change process that does not raise questions about nuclear regulatory inspections as a standard will help ensure the margin for plant operations themselves in the future, and will be a key factor in ensuring the plant safety margin as decommissioning progresses. It is also considered useful from the viewpoint of conformance to the regulatory inspection guide "Facility Configuration Management" to show improvement in plant safety margin and to ensure change management.

4.4 On-Site Survey of Nuclear Power Plant Situation. Author visited the following decommissioning plants and inspected to confirm the status of on-site facility aging management.

(1) Dounreay NPS (United Kingdom)
(2) Ringhals NPS (Sweden)
(3) Fukushima Daini NPS (Japan)
(4) Tsuruga NPS (Japan)

None of the sites had established a risk-specific aging management policy or program for equipment deterioration in decommissioned plants, making a distinction between decommissioned and operating plants. This may be due to the following factors.

- There are no guidelines or standards that organize a common approach to facility aging management, as is the case for operating plants.
- Decommissioning of a plant involves a lower level of risk than that of an operating plant, and thus can be handled by

Table 4 PLM standard Appendix D: sealing material deterioration (excerpt) [3]

First stage screening						Second stage screening				
	Ageing phenomena expected to occur in industrial material			Phenomena to be considered for light water reactors		Ageing phenomena expected to occur for each material employed				Classification of ageing phenomena
	Ageing phenomena									
Failure mode	Category	Detailed phenomena	Definition	To be considered	Reason for not to be considered	Main material	Area and cause of occurrence	Review of necessity of expectation	Expected to occur	
Change in material	Deterioration	Deterioration	For rubber and resin, their performance decreases due to the effect of heat, radio activity, water content, etc.	Yes.		Rubber Resin	For rubber and resin which are not regularly replaced, their performance may decrease due to the effect of heat, radio activity, water content, etc.	Expectation of occurrence is required for rubber and resin.	Yes.	Deterioration

continuing the aging management of the operating plant and adjusting according to the status of individual equipment.

- The resources for decommissioning should be minimized from the viewpoint of productivity compared to the operating plant.

Considering these factors and the current status of decommissioning of nuclear power plants as shown below, it is considered that identifying the specific risks of decommissioning plants and conducting focused aging management as proposed in this paper will contribute to further improvement of safety.

4.5 Examples of Equipment Deterioration Confirmed by Nonconformance in Nuclear Power Station. From the results of the information collected on the failure information at the nuclear power plants in Japan, it was observed that the percentage of failures related to the deterioration of waste treatment facilities (including storage facilities) and seals at penetrations are increasing among the SSCs reviewed and extracted in Chapter 3.

Figure 2 shows the percentage of failures related to the deterioration of waste treatment facilities (including storage facilities) and penetration seals among the nonconformity information collected from representative plants.

The reason for this trend is that the maintenance to properly detect and counter the deterioration is not enough due to the lack of equipment deterioration based on the characteristics of the decommissioned plant.

This is considered to be caused by the following two factors in addition to the factors described in Sec. 4.3.

In decommissioned plants, deterioration tends to become more apparent as the period since installation increases, and appropriate maintenance based on such deterioration has not yet been implemented.

The importance of maintenance of these facilities is low according to the importance classification based on the JEAC technical regulations “Maintenance Management Regulations for Nuclear Power Plants” (JEAC4209:2021), and no clear maintenance policy has been established in the maintenance method based on the PLM standard.

In the PLM standard, the description for deterioration of sealing materials is “required” to assume deterioration events for performance deterioration as shown in Table 4, but in the AMP prepared by each plant, deterioration of penetration sealing materials is treated as consumables, and in principle, consumables should always be replaced at each inspection. However, the AMPs prepared by individual plants treat the deterioration of penetration sealing materials as consumables, and in principle, consumables should be replaced at every inspection, and long-term use is not assumed.

The reason for this trend is that equipment deterioration based on the characteristics of decommissioned plants has not been performed, resulting in insufficient maintenance to properly detect and counteract deterioration.

4.5.1 Verification of the Proposal by On-Site Benchmarking and the Desired Equipment Deterioration. From the situations confirmed in the some on-site benchmarking and the discussion up to this point, it has been confirmed that there have been cases where nonconformities of facilities that should be positioned as important in the decommissioning phase have become apparent due to the lack of AMPs as shown in this proposal, and that there is a tendency for nonconformities to increase. It is considered necessary from the viewpoint of not only safety but also economy to appropriately define the facility management that can minimize the release of radioactive materials to the surrounding environment and the exposure of residents while minimizing resources at the decommissioning site, as well as the facility management necessary to safely proceed with the decommissioning. Compared to the current AMP at nuclear sites, where AMP is applied in accordance with the operation phase of nuclear power plants, we believe that safety and rationality will be enhanced by applying this proposal as a response to nonconformity situations that have been confirmed to be manifested in data.

5 Conclusion

This paper has shown a deterioration management program for decommissioning plants as described in Sec. 3.4, which can contribute to the planning of decommissioning plans that are rational and still have improved safety.

The decommissioning process lasts for more than 40 years, and the risks and the importance of SSCs to be focused on change at some turning points, such as the timing of fuel discharge. This paper discusses the initial phase of decommissioning when the fuel is in the plant, but this concept and the process for AMP determination can be further typified for later phases. In addition to this, the risks inherent in each phase are discussed and a program is defined, which will contribute to improving the safety of the entire decommissioning phase by defining the plant's AMP.

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Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

Nomenclature

Acronyms and Abbreviations

AMP = aging management program
CBM = condition based maintenance
FDF = fuel damage frequency
IAEA = International Atomic Energy Agency
IGALL = International General Aging Lessons Learned
NPS = nuclear power station
PLM = plant life management
PRA = probabilistic risk assessment
RAW = risk achievement worth
RW = radioactive waste
SSCs = systems, structures, and components
USNRC = United States nuclear regulatory commission

Greek Symbols

X = characteristic coefficient of fire scenario
Λ = frequency of fire scenario occurrence
λ = fire frequency of fire source

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