Risk Informed Aging Management Program For Decommissioning Nuclear Power Plants

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Abstract: In this study, risk information is used to solve issues related to the aging management program (AMP) during the decommissioning phase. Although the number of permanently shut down and decommissioning nuclear power plants continue to increase globally, an AMP for decommissioning plants remains lacking. The development on an AMP suffers from two issues: (1) Identifying the change in the functional importance of safety systems at the beginning of the decommissioning phase, and (2) performing maintenance based on appropriate risk information. To this end, we evaluate the functional importance using a PRA model based on the change in the specification of the plant to be decommissioned and determine a new importance grade. Further, risk information is determined according to the progress of the decommissioning phase, which is reflected and evaluated in the PRA model; information is also obtained from maintenance inspections, which includes the ROP process and failures observed during routine operation. We developed a maintenance program that evaluates risk information according to the decommissioning phase to resolve these issues.

Keywords: PRA, Aging Management, Decommissioning, Reactor Oversight Process

1. INTRODUCTION

Nuclear power plants must be safely managed according to the conditions of the construction, operation, and decommissioning stages. Ensuring rational and safety enhancing ageing management during the decommissioning phase is a new challenge. A total of 212 nuclear power plants have been permanently shut down globally as of April 2023; this number has increased by 5 since the beginning of 2023. Among these, 193 nuclear power plants (NPPs) were already undergoing the decommissioning process. Several countries have set the operating period of an NPP at 30–40 years, and therefore, the number of plants that will have to be decommissioned is expected to increase further. Major decommissioning activities include decontamination, dismantling, removal, and fuel extraction. These activities do not generate revenue for the operating companies, and therefore, the incurred costs are covered by advance reserves [2][3]. Therefore, a reasonable decommissioning strategy must be developed. Some systems, structures, and components (SSCs) must remain functional during the decommissioning phase, while others may remain in use without being replaced for as long as 80 years or more after construction. Therefore, plant aging management programs (AMPs) are essential for improving safety during the decommissioning phase.

Thus far, AMPs for the decommissioning phase have been developed in a manner similar to those for the operation phase. The results of the authors' onsite surveys and interviews at four nuclear sites in three countries confirmed that none of the sites had an AMP that focused on decommissioning. Further, to the best of the author's knowledge, there are no reports on nuclear sites that employ AMPs focused on the decommissioning phase. The International Atomic Energy Agency (IAEA) has defined recommended AMPs for each deterioration event based on examples from the U.S. Nuclear Regulatory Commission (USNRC). These AMPs are referred to as the international general aging lessons learned (IGALL). In Japan, maintenance programs are designed based on the maintenance management regulations of the Japan Electric Association (JEA). The two key elements that determine the level of importance in this maintenance program include 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) (PLM standard) [7]. The PLM is a set of standards for implementing NPP decommissioning measures. These standards do not define an AMP focused on decommissioning, and therefore, this paper presents the importance of such an AMP and the findings that contribute to standard settings.

Aging management during the decommissioning phase differs from that during the operational phase in several ways, as explained below.

1) The safety functions required are different for each phase. For example, reactor reactivity control, core cooling, and containment confinement are important safety functions in an operating plant. The SSCs used to ensure these functions are called engineering safety facilities. In a decommissioned plant, the cooling function of the fuel storage facility (e.g., spent fuel pool) is important for ensuring the safety of the nuclear fuel material. The confinement function of this facility and the waste treatment facilities employed during the decommissioning period are also important factors.

2) The redundancy of the safety function is reduced. During the operation phase, risks associated with the plant are relatively high because of the need to control fission reactions and heat removal. Therefore, engineering safety facilities should be designed with sufficient multiplicity and diversity. However, during the decommissioning phase, some SSCs that comprise engineering safety facilities are removed from service. This suggests that the contribution of one engineering safety SSC 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 that in the operation phase.

3) It is necessary to harmonize safety improvements for plants in operation. The NPPs in operation continue to improve their safety through periodic assessments and backfitting.

These results may not be directly applicable to decommissioning; however, these findings need to be reflected in a reasonable manner. In Japan, many plants were decommissioned following the Fukushima Daiichi nuclear power plant accident. Although new regulatory standards have not been applied, it is necessary to take appropriate actions such as reviewing external hazards based on lessons learned from the accident to reasonably enhance safety.

Thus, it is necessary to redefine maintenance severity based on plant characteristics and decommissioning plans for managing deterioration and reasonably enhancing safety in decommissioned plants. To this end, this study proposes a method to define the importance level using risk-informed decision making, which combines engineering judgment and probabilistic considerations. We present a scoping method and consider the importance of SSC in general terms. Subsequently, the results of applying this method to the decommissioning of BWR5 are presented, and the advantages of this method are discussed.

2. METHODS

2.1. Redefinition of Facility Configurations

The design criticality of an SSC is based on the safety functions required for its operating conditions. To define an AMP for decommissioning a plant, it is necessary to first define the equipment configuration based on the safety functions required during decommissioning. The functions covered under the AMP are shown in Fig. 1. The SSCs used for core reactivity management, core cooling, and in-operation monitoring are unnecessary for ensuring safety in decommissioning plants. Under the Japanese inspection system, plants in the decommissioning stage are subject to nuclear regulatory inspections, and inspection items based on the seven cornerstones are applicable to decommissioned plants. It is possible to reasonably reduce the facility margins under the supervision of the regulatory agency by defining the facility modification process in advance and evaluating the plant's operational margins.

Although some redefinitions of the necessary facilities change according to the progress of decommissioning, the following items among the SSCs need to be focused on based on the approach shown in Fig. 1.

A) Safe spent fuel storage: The fuel in the reactor core is transferred to a fuel storage facility. Although the cooling function of the spent fuel pool is more important than 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 for accidents over time. Further, the position of the facility changes significantly once spent fuel is removed from the plant. In onsite dry cask storage as in the domestic case, the facility is subject to redefinition.

B) Confinement of radioactive materials: Plants to be decommissioned contain radioactive materials such as spent fuel and radioactive waste, and it is necessary to maintain the confinement function of radioactive materials for preventing exposure of the nearby residents and workers.

C) Waste treatment facilities: Decontamination, liquid waste management, and solid waste management are required for waste treatment facilities during the decommissioning period. Based on the decommissioning process, a 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 that 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 emergency response: Accident evolution in decommissioned plants is slower, and the emergency mission times are longer than those in operating plants. A reasonable amount of effort has been devoted to managing the deterioration of resources for emergencies such as communication, radiation bar, and radiation-measuring equipment. When developing these AMPs, it is desirable to consider events that will change with the progress of decommissioning and define the strategy.

2.2. Engineering Judgment

The internal hazards of a plant to be decommissioned are lower than those of an operational plant. Therefore, it is relatively rare for plants to be decommissioned to identify safety margins through rigorous safety analysis; however, equipment requirements for plants to be decommissioned are defined based on quantitative engineering judgment. In addition, in previous decommissioning studies [1] and IAEA decommissioning-related safety standards [5], safety assurance in the decommissioning phase concentrated on waste management safety and radiation protection. Given these factors, trigger events that can impair the safety functions defined in the previous section were identified, and the necessary equipment requirements were determined by engineering judges based on past operating experience, considering the circumstances of non-conformities that are likely to occur. Weaknesses against external hazards such as earthquakes, tsunamis, and weather can be identified by comparing the regulatory requirements for operating plants with the current status of their own plants, and their effects can be examined.

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

The accident at the Fukushima Daiichi NPP indicated that the plant has general-purpose facilities, which could respond flexibly in the event of an emergency caused by a large-scale disaster that exceeds expectations; however, these facilities are not included in the facilities subject to the application for the installation permit for the plant to be decommissioned. However, if SSCs contain spent fuel and radioactive waste, they must be maintained and managed. SSCs are general-purpose facilities and can be replaced relatively easily, and therefore, it is important to consider and confirm the maintenance method that considers any changes from the operating plant to ensure that the content is reasonable.

2.3. Probabilistic Consideration

Decommissioned plants are operated by reducing the number of facilities that maintain their functions from the operation phase for reducing the required functions and risks involved, which minimizes the multiplicity of engineering safety SSCs. Based on the characteristics of the decommissioned plant, probabilistic considerations are made for internal events referred to when prioritizing the SSCs. In the decommissioning phase, the operational status of the plant changes stepwise, and it is not realistic for constructing a site-specific model for each change. Instead, 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.

The damage criterion (time margin) for the spent fuel can be conservatively evaluated using the same evaluation method as the damage criterion in the operation phase. Based on these ideas, the spent fuel storage function of the plant to be decommissioned should be considered from a probabilistic perspective for comparison with that of the operating plant.

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

$$\text{RAW} = (\text{FDF when one facility loses functionality}) / (\text{FDF without loss of function}) \tag{1}$$

Risk is quantified using "safety watcher," a software application that enables a simple evaluation of risk. The software quantitatively calculated the contribution of the loss of function of each system and the component to the FDF. This program is used for the quantitative risk assessment of operating plants; however, it has a function for assessing the FDF of spent fuel stored in fuel pools. It can construct a model that shows the plant status after transition to decommissioning by setting the SSC, which is not subject to management in decommissioned plants, to a non-operational state. This method allows the construction of a model that indicates the status of the plant after the transition to decommissioning. This method enables a quantitative risk assessment that reflects the state of a decommissioned plant using a common model with an operating plant.

2.4. Comprehensive judgment

Based on the equipment requirements for the functionality of SSCs, those set at a high level of importance in the decommissioning phase were selected. The appropriate maintenance method for each SSC was comprehensively determined based on the IAEA's IGALL and PLM standards in Japan. In addition, it is necessary to consider consistency with the existing importance classifications and distinguish them between the existing importance classifications and SSCs so that the response in the plant to be decommissioned will be clear.

3. RESULTS

3.1. Rearrangement of Facility Configuration

In accordance with the approach described in the Methods section, a plant with spent fuel in the early decommissioning stage of BWR5 was used as an example for selecting SSCs to be subject to the importance setting in the decommissioning stage and for setting the importance of maintenance.
The points where the basic design of the plant changes in the decommissioning phase are first summarized, and the points where the basic performance requirements change are summarized using the SSC of a BWR5 plant as an example are used to examine the maintenance method for rational SSC aging management. These are summarized in Table 1, and they contribute to the study of policies for reviewing the design specifications of each system and facility by reviewing the basic design.

Table1. 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	Normal situation	Same as on the left.
	Emergency diesel generator	3 units	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

3.2. Engineering Judgment

This section discusses the functions and SSCs listed in Table 1 as the aging management of plants being decommissioned. The aging management policies are determined by engineering judgment considering equipment requirements necessary for plants being decommissioned and triggering events that may impair safety functions.

- Radioactive Confinement Function

In a plant being decommissioned, all spent fuel is stored in a fuel pool and the reactor building serves as a containment facility for the basic confinement of radioactive materials. In addition, it is necessary to prevent the diffusion of radioactive materials during equipment dismantling. Considering these factors, it is necessary to maintain and 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 reactor building walls, there will be no excesses or deficiencies in the current building verification because of the robustness of the components. 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 it is believed to be the result of age-related aging caused by 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, the air supply and exhaust system need to be positioned as a high-priority maintenance system in plants being decommissioned; dynamic equipment, subjected to time-controlled overhaul and functional checks; and ducts, subjected to systematic visual and functional inspections of both the interior and exterior surfaces. For ducts, a reasonable method considering the large amount of material may be to extract representative areas and check important points for aging management using a representative method because there are many cases where aging was confirmed in the vicinity of the outdoor air intake.

- Radioactive Waste Treatment Functions

In a plant being decommissioned, large amounts of liquid waste and waste resin from the decontamination of facilities and solid waste from the disposal of facilities are treated and managed. Further, as in operation, liquid and solid wastes are generated on a daily basis through plant operation and normal maintenance work and must be treated.

However, in operating plants, the importance of waste treatment facilities is low because they are considered for treatment at a later stage of operation, and their inventory is small compared with that of nuclear fuels. The IAEA's IGALL [5] and the 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 because they are categorized as general dynamic equipment. Further, the PLM standard for waste treatment facilities in Japan 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 are considered less important than systems directly related to the operation of nuclear reactors. Many have deteriorated over time.

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

- External Event (Fire) Prevention Functions

In Japan, earthquakes, tsunamis, weather, and other external events are considered the main external events, and operating plants, protective equipment, etc., are installed and managed as of high importance.

Among external events occurring in plants being decommissioned, fires need to be focused on, and fire protection requirements have not changed from those in the past. Therefore, the latest fire protection design may not be considered sufficiently. However, fire protection requirements have not changed in plants being decommissioned, and therefore, the latest fire protection designs may not be fully considered. Fire tends to occur frequently at a predictive level and has a large ripple effect when it occurs. In addition, the conventional aging management of fire protection equipment in operating plants is based on standards stipulated in general laws and regulations, such as the Fire Defense Law and the Building Standards Law, and it 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 for fire protection: The concept of the 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) [8]; the higher the value of equation (2), the higher is the fire risk.

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

where Λ, λ, and X represent the frequency of fire scenario occurrence, fire frequency of fire source, and characteristic coefficient of fire scenario, respectively.

The occurrence of fire scenarios is evaluated by classifying the occurrence of fire sources and their characteristics. Equation (2) indicates that the magnitude of the fire load on the existing structure and the presence or absence of ignition sources are the dominant factors. For the ignition source, 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 affected directly.

It is desirable to set a high maintenance priority for performance maintenance equipment such as 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 conducted under time-controlled maintenance considering the design life of these critically deteriorated parts. In addition to the functional tests, it is desirable to conduct overhaul inspections.

In addition, information on nonconformities related to the aging management of penetration has been confirmed in many nuclear power plants in Japan, and a high rate of occurrence has been confirmed when classifying published nonconformity information. This implies that strengthening the aging management of the penetration is important for ensuring the robustness of fire protection bulkheads.

- Equipment Management for Transition Conditions to Emergency Situations Based on Accident Scenarios

Owing to the Fukushima Daiichi Nuclear Power Plant accident, the emergency response to nuclear disasters has been strengthened by Japanese regulations, and systems, materials, and equipment have been maintained and managed for this purpose.

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

However, there is a need to make the emergency response reasonable for plants that have been decommissioned, the fuel has been cooled, and the risk is not significant, even in the event of the loss of fuel pool cooling water. In line with this trend, it is reasonable and realistic for reducing the maintenance and management of systems and equipment in operating plants by considering the plant's risk and safety margins.

From the perspective of facility aging management, there is no need to change the level of importance or aging management methods even if the number of objects to be managed is reduced in the operating plant according to the scenario. The emergency response equipment is a general-purpose equipment and can be replaced relatively easily, and therefore, it is important to consider and confirm that the maintenance method that considers this is reasonable, which considers any changes from the operating plant. For the time being, it is recommended that general visual inspections need to be conducted as time-controlled maintenance in accordance with the time of use or by using other reasonable methods.

3.3. Results of Probabilistic Consideration

Considering the importance of the fuel pool cooling function, a probabilistic evaluation should consider the maintenance importance because 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 plant being decommissioned; however, the difference is that the operation of the emergency core cooling system, which serves as backup, is deleted in the plant being decommissioned. This is because the spent fuel in plants being decommissioned is cooled for a sufficiently long period and is reduced to 1/100 or less in approximately four months after the transition to decommissioning [4]. All current plants in Japan have been out of operation for more than ten years, which means that the fuel has been cooled sufficiently. Therefore, the emergency core cooling system can be reduced in any decommissioned plant, and the model can be constructed after reduction. The model was developed to reflect the performance of maintenance facilities in the plant being decommissioned and be consistent with the operation of the Safety Watcher 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 calculated quantitatively in Table 2 as the degree of increase in FDF and RAW, as defined equation (1). The results in Table 2 confirm that the following situations are common to both operating and decommissioned plants:

Table2. 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

RAW is large for both operating and plants being decommissioned when external power is lost because the fuel pool cooling system and fuel pool water injection system are normally operated by an external power supply. The loss of this power supply directly affects the cooling and replenishment of the fuel pool. Further, the emergency diesel power generation system in the operating plant is 3.37 because the emergency power supply in the operating plant is an emergency power source for the emergency core cooling system (ECCS) responsible for a part of the fuel pool cooling function. However, in plants being decommissioned, the ECCS is an unmanaged facility, and therefore, the increase in the RAW of emergency diesel power generation is small compared to the external power supply. However, RAW has a certain value even in the event of a single loss of function because the ECCS also supplies power to the fuel pool cooling system as a backup for the external power supply.

The RAW of the condensate storage water tank, supply water system, DC power supply, and residual heat removal system of the operating plant are 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.

1) The impact of the loss of function of a single system or component on RAW is greater than that of the operating plant.

2) The RAW of the fuel-pool cooling system, its water source, and power supply increased significantly from those of the operating plant.

3) The impact of the loss of function of these components is considered similar to that in Table 2, and it is smaller than the value in Table 2 because 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 related directly to fuel-pool cooling at a high level, and auxiliaries at the next level as indirectly interconnected systems to consider these other systems from a different angle as a criterion for equipment importance based on engineering judgment. In terms of maintenance methods, directly related systems with high maintenance importance should be positioned in the same manner 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 determine the selection criteria quantitatively for time-controlled maintenance and condition-monitoring maintenance, considering the multiplicity of the systems and the time margin for fuel cooling in the event of a loss of function. The maintenance method should have the same overhaul and functional verification as direct systems.

3.4. Comprehensive Judgment

The critical equipment in plants being decommissioned 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 the existing importance classification guidelines. The positioning of critical equipment for maintenance management in the plant being decommissioned proposed here is 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 defined as follows:
1) The critical equipment proposed in this study should be classified as equivalent to Class 3 as shown in JEAG4612, and grades A and B should be assigned to classify critical equipment after the transition to decommissioning (e.g., MS-3-A).
2) The maintenance method should be time-controlled; however, for grade B equipment with multiplicity, condition monitoring maintenance may also be selected.
In the program shown in Table 3, time-controlled maintenance was adopted as the maintenance method for the highly important SSCs. This recommendation is based on the results of the analysis of nonconformities at nuclear power plants considering the situations described below.

Table3. 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	High	-Time-based maintenance -Visual inspection	Including daily inspections tailored to the object

equipment in case of emergency	MS-3-A: Additional definition of JEAG4612-2021		

SSCs shifted to condition monitoring maintenance perform effective maintenance on items whose deterioration becomes apparent because of dynamic changes or data; however, it is often in a state other than the maintenance assumed in the PLM standard when other equipment is subjected to condition monitoring maintenance. This indicates that parts that have received relatively little attention in the past such as consumables may deteriorate into critical parts, which results in the loss of functionality caused by maintenance conditions not anticipated in the PLM standard.

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

4. CONSIDERATIONS

4.1. Validity of the Model for Probabilistic Evaluation

The “Safety Watcher” used for probabilistic evaluation in Section 3.3 is software developed for the probabilistic safety evaluation of the operating conditions of nuclear power plants. Its appropriateness for plants being decommissioned is as follows:

The basic probabilistic safety evaluation method combines an event tree and a fault tree to evaluate each event, which is common in both decommissioned and operating plants. The quantification of the event tree includes the model configuration and failure rate data used to analyze the failures. The model configuration was based on the operational status of the plant in question and it incorporated portable facilities for dealing with external events for complying with the new regulatory standards in Japan. The model can properly simulate facilities that will be out-of-operation during decommissioning and are treated as non-operational. The failure rate data were selected from US data (WASH-1400, NUREG, etc.), which have abundant operating experience to ensure that the results are similar to other probabilistic evaluation codes, and reliability is ensured by comparison with domestic failure rate data (CRIEPI).

The same US data as the failure rate data were used for evaluating common-cause failures because no domestic data were available for this purpose. The coefficients used here were the same as those used in the other evaluation codes. The decay heat data were set to a constant value without decreasing 2000 days after shutdown to be more conservative than the actual data.

4.2. Future Issues

This paper summarizes the results of a study on the case in which spent fuel exists in a plant at the initial stage of decommissioning. After the spent fuel is removed from the plant or whenever SSC occurs, the facility conditions that serve as inputs for this study also change. The possible risks at each stage need to be considered and an aging management policy that considers these risks should be established.

Based on the site survey, an important mission of decommissioning is to reduce costs and ensure safety, and the current aging management has reduced costs by introducing maintenance using CBM in each case. Further, re-evaluating the current implementation and changing the aging management method require resources, which makes it difficult to change the method. To promote change, a certain level of external motivation and pressure is required. One way to address this issue is to incorporate the change into standards and criteria. We coordinate with the subcommittee of the domestic PLM standard to incorporate the proposal into the standard and coordinate its inclusion 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-A3:2022) [9], which is a Japanese decommissioning standard, is also being considered.

5. CONCLUSION

This paper presented a deterioration management program for plants being decommissioned that contributes to the planning of plants being decommissioned that are rational and still have improved safety. The decommissioning process lasts for more than 40 years, and the risks and importance of SSCs should be focused on changes at turning points such as at the time of fuel discharge. This study discussed the initial phase of decommissioning when the fuel is in the plant; however, this concept and the process for AMP determination can be further developed in the later phases. In addition, the risks inherent in each phase were discussed, and a program that will contribute to improving the safety of the entire decommissioning phase was defined by defining the AMP of the plant.

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