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Outline of Guidelines for Maintenance and Management of Structures in Nuclear Facilities

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Technical report

Outline of Guidelines for Maintenance and Management of Structures in Nuclear Facilities

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Abstract

“Guidelines for Maintenance and Management of Structures in Nuclear Facilities” was published by the Architectural Institute of Japan in 2008 and revised in 2015. This is the first standard that covers the maintenance and management of structures in Japanese Nuclear Facilities. This has been contributing to the broad activities related to the life-time management of Nuclear Facilities. This paper outlines these guidelines.

1. Introduction

In order to formulate a standard for maintenance and management of structures in nuclear facilities, “Guidelines for Maintenance and Management of Structures in Nuclear Facilities” (hereafter called “Guidelines”) was published by the Architectural Institute of Japan in 2008 and revised in 2015 (AIJ 2015).

This paper outlines these Guidelines, which include nine chapters as shown in **Fig. 1**.

2. Objective of guidelines

To maintain the functions required of structures in nuclear facilities throughout their in-service period, it is important that the functions to be maintained should be identified to ensure reliable maintenance based on periodical inspections. These maintenance activities are expected to prevent trouble likely to occur in long-term operation. Maintenance of structures at nuclear facilities has been based on this idea. The approach to maintenance has relied on use of, or on application by analogy of, related knowledge and standards on degradation due to aging of general structures and civil engineering structures. No systematic maintenance guidelines have been established that are commonly applicable to structures at nuclear facilities. Thus, the AIJ decided to prepare a set of Guidelines for Maintenance and Manage-

ment of Structures at Nuclear Facilities for use in maintaining the functions required of these structures throughout their in-service period.

3. Principle of guidelines

This section outlines “Chapter 2: Basis for maintenance”, “Chapter 3: Required functions and related performance characteristics” and “Chapter 5: Preparation of maintenance plans”, which describe the principles of the Guidelines.

3.1 Basis for maintenance and management

Maintenance and management of structures at nuclear facilities shall be performed to maintain their required functions throughout their in-service periods. The soundness of these structures shall be evaluated by

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Fig. 1 Contents of guidelines.

verifying satisfaction of the required performance level of the structural components and members necessary to fulfill the required structure functions, and shall be secured by taking appropriate countermeasures and verifying their effectiveness.

Information on the relation between required functions, related performance characteristics, and soundness evaluations is based on the Nordic Five Level System (Fig. 2).

When maintenance of structures at nuclear facilities is applied to this hierarchy, the purpose is to “ensure public safety through the maintenance of structures at nuclear facilities.” Specific requirements to achieve this purpose are functional requirements, which correspond to, e.g., functions to support important equipment (supporting function) and to prevent radioactive material leakage to outside the structure (leak-proof function). Performance requirements are specific requirements necessary to satisfy functional requirements. Hence, performance requirements refer to, for example, liquid-tightness performance required of the leak-proof function. A performance verification method is for determining the attainment of a required performance level through comparison of inspection results, appropriate analysis, and experimental results with evaluation criteria. A deemed-to-satisfy provision is a means of securing performance without the need of performance verification and is established to specify specific structural dimensions, materials, construction methods, etc., deemed to satisfy the required performance level.

The principle of maintenance and management shown in the present Guidelines is to conduct the following activities in accordance with the above concept. The interrelationship between the activities is shown in Fig. 3.

(1) It is necessary to identify the functions required of

structures at nuclear facilities and the performance characteristics required for the maintenance of these functions.

- (2) While taking account of the degradation mechanisms in concrete and steel-framed structures under the conditions specific to structures at nuclear facilities, such as environmental, siting, structural, and material, the degradation phenomena and degradation factors to be monitored shall be defined.
- (3) Prior to maintenance, a maintenance plan shall be established. This plan shall describe the basic approach to inspections, soundness evaluations, countermeasures and their effectiveness verification, and records.
- (4) An inspection plan shall be established based on the maintenance plan to specify the inspection method, the parts to be inspected, the timing of inspection, the inspection implementation scheme, etc. Inspections shall be performed according to this inspection plan.

Fig. 2 Concept of hierarchical performance design of buildings.

Fig. 3 Overview of maintenance and management.

- (5) An evaluation item shall be set for each degradation phenomenon and degradation factor to be monitored, so that the structure can be evaluated for soundness at the time of inspection and during its in-service period.
- (6) In accordance with the results of soundness evaluation, a countermeasure shall be taken, such as continuing or improving the current inspection practices and executing repair work. If any repair work is executed, the repaired portion shall be checked by periodical inspection as well as by additional inspection as necessary to ensure that the repaired portion is restored to the performance level expected at the time of repair planning.
- (7) The results of inspection, soundness evaluation, countermeasure implementation and effectiveness verification shall be recorded accurately and in detail and stored with easy access for future maintenance references.
- (8) The cycle from maintenance planning to countermeasure implementation and effectiveness verification shall be repeated for continuous improvement of maintenance practices to ensure more effective maintenance.

3.2 Structure performance changes

The structure's performance affected by degradation due to aging tends to show a gradual change over time throughout its in-service period. The degree of this change depends on the degree of initial performance, environmental conditions, and maintenance practices. Meanwhile, the structure's performance affected by degradation due to sudden event tends to change within a short time. Structures at nuclear facilities should be designed to satisfy their required performance level throughout their in-service period. Even if the required performance level is changed according to a revision of relevant codes and standards, structures must satisfy

newly prescribed level. The maintenance covered in the Guidelines must ensure that the structure's performance varied by degradation due to aging or degradation due to sudden event meets the required level from the present into the future. In case the required performance level is changed and some of the inspection results fail to meet the evaluation criteria, it is reasonably acceptable if the structure's soundness as a whole is maintained.

Figure 4 shows a schematic of changes in performance of a structure affected by degradation due to aging considered in the Guidelines. The performance of a hard-to-replace concrete may show different changes depending on the evaluation item (e.g. The compressive strength increases in the early stage and stops increasing in the long term. The carbonation depth proceeds fast in the early stage and slowly in the long term), but basically show gradual changes with maintaining the required performance level. Meanwhile, inherently replaceable materials like a coating are specified prescriptive requirements (a deemed-to-satisfy provision) such as the material specifications and the construction methods. Their performance is maintained by replacing at periodic intervals throughout its in-service period. The maintenance covered in the Guidelines primarily focuses on ensuring the non-occurrence of rapid performance degradation in hard-to-replace structures, and is not intended to restore or improve the structure's performance, with the exception of replaceable materials such as coatings. In other words, in principle, structures shall always be kept in a sound condition through inspection, soundness evaluation, and repairs or other countermeasures.

In the seismic diagnosis of a general structure, seismic performance of the structure is evaluated with consideration of the degradation due to aging. The seismic performance of a structure is estimated by multiplying a coefficient according to aging level to its initial performance. Since structures at nuclear facilities are constantly maintained, severe deterioration sometimes ob-

*: The level of performance, which reflects the latest knowledge, required at the point of soundness evaluation (The level of performance required at the time of design is not necessarily used throughout the in-service period of the building.)

Fig. 4 Conceptual graph of changes in performance characteristics of a building prone to degradation due to aging assumed in the maintenance in accordance with the present Guidelines.

served in general structures is not expected. However, it is reported that natural frequency of structures decreases by earthquake effects or by degradation due to aging. In case the dynamic characteristics of structures at nuclear facilities show noticeable changes caused by earthquake effects or degradation due to aging, their structural soundness should be evaluated with taking account of such changes. Since the principal cause of these decreases in natural frequency due to earthquake effects has not been clarified, how to specify the dynamic characteristics of structures remains a challenge for analytical evaluation. It will be necessary in future to promote studies on soundness evaluation of structures affected by earthquake and to accumulate scientific knowledge.

3.3 Minimization of damage to a structure during maintenance

In an inspection for current soundness evaluation, the whole structure should be inspected. Accordingly, in principle, damage to concrete shall be checked by visual method. For visually unobservable changes in concrete strength, their tendencies are grasped using non-destructive methods. There may be cases where strength is assessed by core sampling for verification and accuracy enhancement of a non-destructive method. Core sampling not only causes damage to structures but also does not necessarily provide more information than visual methods. Hence, it is assumed that soundness evaluation will remain valid even if the use of core sampling is limited.

Meanwhile, inspection for long-term soundness evaluation is required to measure the degree of effect of each degradation factor in order to predict the progression of degradation phenomena. Accordingly, there may be cases that require use of a local destructive method, such as core sampling or drilling.

From the above, even in the case of core sampling and other inspection methods classified as local destructive methods, inspections for current soundness evaluation

and for long-term soundness evaluation will differ in specific procedure and/or significance. In any case, the use of local destructive methods shall be kept to the very minimum to avoid damage to structures as much as possible.

3.4 Required functions and related performance characteristics for nuclear facilities

It is necessary to identify the functions required of structures at nuclear facilities and the performance characteristics required for the maintenance of such functions in accordance with the basic concept described above in Section 3.1. The required functions of structures at nuclear facilities are shown in Fig. 5. These are classified into two functions, one for ordinary structures and the other specially required for structures at nuclear facilities.

The functions required of a structure generally include supporting function for its own dead weight and live and seismic loads; comfort use-related functions such as vibration isolation and sound proofing; functions to withstand secular changes and to resist fire and other high-temperature phenomena. These functions are similarly required of nuclear facilities. In the Guidelines, these general functions shall be collectively called the usage function.

The following additional functions are specially required for structures at nuclear facilities.

- Supporting function

A function with which to support major installations and equipment during normal operation or an earthquake.

- Pressure-proof function

A function with which to withstand pressures. In the case of a concrete containment vessel, a function required of its concrete portion.

- Shielding function

A function with which to reduce the radiation dose to a predetermined level to prevent radiation exposure

Fig. 5 Functions required of buildings at nuclear facilities.

Table 1 Required functions and related performance characteristics.

Required function Performance characteristics	Usage function	Supporting function	Pressure-proof function	Shielding function	Leak-proof function	Negative-pressure holding function	Secondary-accident prevention function
Structural safety	✓	✓	✓	-	-	-	✓
Usability	✓ ^{*1}	-	-	-	✓ (liquid-tightness)	✓ (airtightness)	-
Shielding performance	-	-	-	✓	-	-	-
Durability	(✓) ^{*2}	(✓) ^{*2}	(✓) ^{*2}	(✓) ^{*2}	(✓) ^{*2}	(✓) ^{*2}	(✓) ^{*2}
Fire resistance	(✓) ^{*3}	(✓) ^{*3}	-	-	-	-	(✓) ^{*3}

*1: Aesthetic appearance shall be considered as necessary.

*2: In the present Guidelines, durability shall be considered as a performance characteristic included in structural safety, usability, and shielding performance.

*3: In the present Guidelines, fire resistance shall be considered as part of structural safety and usability.

impact on the general public and occupationally exposed personnel.

- Leak-proof function

A function with which to prevent leakage of liquid radioactive materials from a specified area to outside.

- Negative-pressure holding function

A function in which some areas in a nuclear facility are kept under negative pressure by ventilation air-conditioning equipment to reduce external discharge of radioactive materials.

- Secondary-accident prevention function

A function with which to prevent any damage, falling, or overturning of a structure from compromising the functions of installations and equipment.

While the supporting and secondary-accident prevention functions can be regarded here as part of the usage function required also of general structures, these functions are intentionally defined as those specifically required of nuclear facilities, emphasizing that nuclear facilities are required to have a higher level of safety against seismic and similar loads than general structures.

Whether a structure's required functions can be maintained depends on the performance of its structural components and members. Therefore, the required functions must be related to the required performance characteristics to define the levels of performance necessary to keep the structure functional.

Table 1 shows the relation of the required functions covered in the Guidelines to the performance characteristics of structural components and members. Supporting, pressure-proofing, shielding, leak-proofing, negative-pressure holding, and secondary-accident prevention functions are defined as those required of structures at nuclear facilities.

Structural safety characteristics shall include load-bearing capacity for general loads (structure's dead weight, live loads, seismic loads, wind loads, and snow loads) taken into consideration in the design of a struc-

ture and shall also include load-bearing capacity for temperature loads, fatigue capacity against cyclic loads, and impact resistance capacity against impact loads.

Usability is a generic term for performance characteristics required for comfortable use of structures and refers to, among other things, resistance capacity against increase in deflection under permanent load due to creep, vibration isolation performance against harmful vibration, thermal insulation performance against heat, waterproof performance against ordinary rainfall and water usage, liquid- and air-tightness of concrete skeletons constructed by conventional methods, and surface protection of coatings and surface finishes. In some cases, aesthetic appearance not directly related to performance characteristics of structural components and members may have to be taken into consideration and hence shall be included in usability.

Shielding performance is specifically required of some areas of each structure in nuclear facilities and refers mainly to neutron and gamma ray shielding performance.

Durability shall be regarded as a generic term for resistance to degradation due to aging in various performance characteristics and shall be included in performance characteristics related to structural safety, usability, and shielding performance rather than as an independent performance category.

For fire resistance, performance characteristics, such as damage resistance, heat shielding performance, and flame shielding performance, and the specification code for their satisfaction are stipulated in, e.g., the Structure Standards Act and the Order for Enforcement of the same, the provisions of which shall be complied with for nuclear facilities. In the Guidelines, fire damage resistance shall be considered as part of structural safety (load-bearing capacity for special loads) while heat and flame shielding performance shall be considered as part of usability (protection of the internal environment against heat).

Table 2 Comparison of two maintenance categories.

Category of maintenance	Maintenance for ensuring current soundness		Maintenance for ensuring long-term soundness
Item to be monitored	Degradation phenomenon		Degradation factor ^{*1}
Type of degradation	Degradation due to aging	Degradation due to sudden event	Degradation due to aging
Type of inspection	Periodical inspection for current soundness evaluation	Extra inspection	Periodical inspection for long-term soundness evaluation
Part to be inspected	Buildings in their entirety		Representative part
Inspection method	Mainly visual method		Mainly local destructive method
Item to be evaluated for soundness	Presence/absence or degree of degradation phenomenon		Degree of effect of degradation factor
Soundness evaluation method	Comparison between inspection results and evaluation criteria		Comparison between progression prediction and evaluation criteria based on inspection results
Timing for inspection and soundness evaluation	Every 5 years or less ^{*2}	As a situation such as an earthquake occurs	Allowed to be less frequent than the maintenance for ensuring the current soundness

*1: Degradation factor leading to a degradation phenomenon that may mainly affect the structural safety and shielding performance of a building

*2: In the case of a visual method

Thus, the functions required of structures at nuclear facilities shall be related to structural safety, usability, and shielding performance in the Guidelines.

3.5 Two maintenance methods

The maintenance in the Guidelines assumes that structures shall be checked for performance by inspection and soundness evaluation and that they shall be kept in sound condition without letting any noticeable decrease in

performance manifest itself, and that this shall be achieved by repairs and other countermeasures. Accordingly, the Guidelines assume the following two categories of maintenance:

- Maintenance for ensuring current soundness

In order to check structures for current soundness, their current condition shall be assessed by grasping the presence/absence or degree of any degradation phenomenon, and an appropriate countermeasure(s) shall be taken.

- Maintenance for ensuring long-term soundness

In order to ensure that structures' functions will be maintained into the future, the degrees of effect of degradation factors shall be grasped before the occurrence of any degradation phenomenon. At the same time, the long-term effect shall be evaluated by a method such as progression prediction to take an appropriate countermeasure(s).

Maintenance for ensuring current soundness shall be practiced as the basic mode of maintenance and shall be supplemented by maintenance for ensuring long-term soundness to make it possible to demonstrate that current structural soundness is maintained and to ensure that no noticeable decrease in performance will occur during the rest of the in-service period. **Table 2** compares the two maintenance categories.

(1) Maintenance for ensuring the current soundness

The purpose of this maintenance is to ensure that current structural soundness is maintained. Hence, this maintenance shall be performed relatively frequently and the specific activities involved shall include investigating the presence/absence of degradation likely to lead to reduced structural performance and taking an appropriate countermeasure(s) in response to the evaluation results.

Figure 6 shows the flow of the specific maintenance activities to be implemented.

Fig. 6 Implementation flow for the maintenance for ensuring the current soundness.

In the Guidelines, the causes of a direct decrease in structural performance are regarded as degradation phenomena.

Degradation due to aging that occurs over time shall be investigated by periodical inspection for current soundness evaluation. Meanwhile, degradation due to earthquakes, typhoons, fires, and other sudden events shall be investigated by extra inspection. These degradation phenomena often occur in the form of damage such as cracking in concrete surfaces and coated surfaces, except for some phenomena, such as reduced concrete strength, and can therefore be grasped by visual methods. This is performed to determine the presence/absence of any current structural damage and hence in principle shall be performed for structures in their entirety.

Inspection results shall be checked against evaluation criteria to perform structure soundness evaluation and consider countermeasures. If it is necessary to investigate degradation factors contributory to any degradation phenomenon in order to consider repair methods and other countermeasures, non-destructive, local destructive, and other methods shall be used to collect detailed data. After any repair, its effectiveness shall be verified. At the same time, the results of inspection, soundness evaluation, and countermeasure implementation and effectiveness verification shall be recorded and stored to review the maintenance plan as necessary.

(2) Maintenance for ensuring long-term soundness

The purpose of this maintenance is to check structures for soundness now and into the future. Even if no likely degradation phenomenon manifests itself now, the degrees of effect of degradation factors contributory to degradation phenomena shall be grasped and specific activities shall include predicting whether structural performance would be maintained above the required level during the assumed period. **Figure 7** shows the flow of the specific maintenance activities to be implemented.

Since this maintenance is intended for degradation that proceeds over time, its scope does not include degradation due to sudden event. Hence, necessary data shall be collected by periodical inspection for long-term soundness evaluation. This data collection shall precede the manifestation of any degradation phenomenon. Accordingly, a local destructive method may become necessary rather than a visual method or a non-destructive method. The parts to be inspected must be specified in advance and must be representative of each structure. Moreover, from the perspective of the importance of structures at nuclear facilities, precautions must be taken to avoid damaging the skeleton due to sampling of specimens. It is desirable to minimize the number of inspection points.

This maintenance uses techniques, such as local destructive methods that cause damage to skeletons. Therefore, this maintenance should not be performed for all degradation factors. Instead, the degradation factors to be monitored should be extracted with focus on those

contributory to any degradation phenomenon that may affect the structural safety and shielding performance that are critical for the safety of structures. Degradation phenomena are expected to proceed at points likely to be significantly affected by degradation factors. Therefore, by selecting such points as representative parts, the number of inspection points can be reduced. It should be noted that degradation factors that affect the usability of structures should be deemed as having already been assessed because the related degradation phenomena are checked in the maintenance for ensuring current soundness.

The degrees of effect of degradation factors shall be grasped based on data collected through inspection. At the same time, a progression prediction shall be made by checking the predicted values against the evaluation criteria to perform soundness evaluation and consider countermeasures. After any repair is performed, its effectiveness shall be verified. At the same time, the results of inspection, soundness evaluation, and countermeasure implementation and effectiveness verification shall be recorded and stored to review the maintenance plan as necessary. Since this maintenance is intended for degradation that does not proceed rapidly, the required inspection and soundness evaluation may be performed at intervals longer than in maintenance for ensuring current soundness. Note that use of longer intervals is effective in minimizing damage to skeletons due to the local destructive method.

Fig. 7 Implementation flow for maintenance for ensuring long-term soundness.

4. Degradation phenomena and degradation factors

(1) Approach to selection of degradation phenomena and degradation factors to be monitored

In the Guidelines, the terms, degradation, degradation phenomenon, and degradation factors are defined as follows:

- Degradation:
A decrease in the performance of a structure.
- Degradation phenomenon
A phenomenon that leads to decreased performance of structural components or members in a structure.
- Degradation factor
A major factor leading to a degradation phenomenon.

Figure 8 shows the flow for selecting degradation phenomena affecting the performance of structures at nuclear facilities and the responsible degradation factors.

First, based on domestic and overseas maintenance-related guidelines, data are collected and collated on the degradation phenomenon, degradation factors, and degradation mechanisms that affect the performance characteristics of structures as summarized in Chapter 3 “Required functions and related performance” of the Guidelines. Then, selection is made of the degradation phenomena and degradation factors to be monitored for maintenance, taking into consideration the characteristics of structures at nuclear facilities, such as environmental conditions, site conditions, structural conditions, and material conditions.

Degradation phenomena and degradation factors for each of the concrete and steel-framed structures are selected according to the following three steps:

- a) Collection and collation of existing knowledge on degradation phenomena and degradation factors

- b) Selection of degradation factors based on the characteristics of nuclear facilities
- c) Summary of degradation phenomena and degradation factors to be monitored

The steps are outlined as follows:

(2) Collection and collation of existing knowledge on degradation phenomena and degradation factors

Based on domestic and overseas guidelines currently available, existing knowledge of degradation phenomena and degradation factors in general structures and structures at nuclear facilities is collected and collated for concrete structures and steel-framed structures. There may be cases where what is regarded in certain guidelines as a degradation phenomenon is regarded in others as a degradation factor. In the Guidelines, what causes a direct decrease in performance is regarded as a degradation phenomenon, while what causes a degradation phenomenon is classified as a degradation factor. For example, some guidelines regard concrete carbonation as a degradation phenomenon. Concrete carbonation, however, does not compromise structural safety. It is not until rebar corrosion occurs due to the progression of concrete carbonation that structural safety is compromised. Therefore, carbonation is regarded herein as a degradation factor. Similarly, chloride penetration itself does not cause a direct decrease in performance but causes rebar corrosion, which leads to a decrease in structural safety. Hence, chloride penetration is also regarded as a degradation factor. Some guidelines regard cracking as a degradation factor because water and oxygen penetration via cracks results in rebar corrosion. Cracking, however, may cause a direct decrease in structural safety or usability and hence is regarded in the

Fig. 8 Selection flow for degradation phenomena and degradation factors.

Table 3 Degradation phenomena and degradation factors specified by existing guidelines to be monitored (for concrete structures).

Degradation phenomenon	Degradation factor											
	Heat (elevated temperatures)	Radiation exposure	Carbonation	Chloride penetration	Alkali-aggregate reaction	Machine vibration	Freeze-thaw	Chemical attack	Drying shrinkage	Creep	Insolation	Weathering
Reduced concrete strength	✓	✓										✓
Cracking	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
Spalling and falling			✓	✓	✓	✓	✓	✓				✓
Rebar corrosion			✓	✓	✓		✓	✓				✓
Deflection										✓		
Vibration						✓						
Abrasion												✓
Explosive spalling									✓			
Water leakage												
Moisture diffusion	✓	✓										✓

Table 4 Degradation phenomena and degradation factors specified by existing guidelines to be monitored (for steel framed structures).

Degradation phenomenon	Degradation factor				
	Coating degradation	Plating degradation (loss of galvanized plating)	Cyclic loads due to winds, etc. (fatigue)	Loads due to earthquakes, typhoons, etc.	Heat due to fire
Steel corrosion	✓	✓			
Reduced strength due to heat					✓
Yielding, buckling, crack, fracture, and excessive deformation of steel				✓	✓
Slipping, crack, and fracture of joint			✓	✓	✓
Looseness and fracture of bolt					
Reduced strength due to fatigue			✓		

Guidelines as a degradation phenomenon.

Relations between degradation phenomena and degradation factors specified by existing guidelines are summarized for concrete and steel-framed structures as shown in **Tables 3** and **4**.

Degradation factors leading to degradation phenomena of reduced concrete strength are heat (elevated temperatures), radiation exposure, weathering, and heat due to fire. Concrete cracking is regarded, as mentioned above, as a degradation phenomenon. It has several degradation factors including heat (elevated temperature), radiation exposure, carbonation, chloride penetration, and machine vibration.

For steel-framed structures, the degradation factors leading to the degradation phenomenon of steel corrosion

are coating degradation and plating degradation (loss of galvanized plating). Cyclic loads due to wind, etc. (fatigue) cause reduced strength due to fatigue, a degradation phenomenon.

The selected degradation phenomena may decrease the performance characteristics of structures at nuclear facilities. **Tables 5** and **6** show the degradation phenomena that may decrease performance characteristic values (structural safety, usability, and shielding performance) for concrete and steel-framed structure, respectively. Degradation phenomena related to each of the performance characteristics are classified into degradation due to aging and degradation due to sudden event, to be consistent with the maintenance plan, where earthquake, typhoon, fire, etc. are assumed to cause degrada-

Table 5 Relation of performance characteristics of concrete structures at nuclear facilities to degradation phenomena.

Performance characteristic	Degradation phenomenon	
	Degradation due to aging	Degradation due to sudden event (earthquake, typhoon, fire, etc.)
Structural safety	Reduced concrete strength Cracking Rebar corrosion Spalling and falling	Reduced concrete strength Cracking Spalling and falling Explosive spalling
Usability	Cracking Spalling and falling Deflection Vibration Abrasion Water leakage	Cracking Spalling and falling Explosive spalling
Shielding performance	Moisture diffusion Cracking Spalling and falling	Moisture diffusion Cracking Spalling and falling Explosive spalling

Table 6 Relation between performance characteristics and degradation phenomena in steel framed structures at nuclear facilities.

Performance characteristic	Degradation phenomenon	
	Degradation due to aging	Degradation due to sudden event (earthquake, typhoon, fire, etc.)
Structural safety	Steel corrosion Slipping, crack, and fracture of joint Looseness and fracture of bolt Reduced strength due to fatigue	Reduced strength due to heat Yielding, buckling, crack, fracture, and excessive deformation of steel Slipping, crack, and fracture of joint Looseness and fracture of bolt
Usability	Steel corrosion Slipping, crack, and fracture of joint Looseness and fracture of bolt	Yielding, buckling, crack, fracture, and excessive deformation of steel Slipping, crack, and fracture of joint Looseness and fracture of bolt

tion due to sudden event.

The relations between performance characteristics and degradation phenomena are as follows:

- The structural safety of a concrete structure may be reduced due to cross-sectional area reductions and cracks resulting from reduced concrete strength, rebar corrosion, explosive spalling, or spalling and dropping.
- Usability is a generic term for performance characteristics required for comfortable use of structures and refers to, among other things, liquid-tightness, air-tightness, resistance capacity to increases in deflection, and vibration isolation performance against harmful vibration. Liquid-tightness and air-tightness may be reduced due to cracking, while resistance capacity against increases in deflection may be reduced due to creep and overloads.
- Shielding performance relates to concrete density and member thickness. Density reductions due to moisture diffusion, member thickness reductions due to explosive spalling or spalling and dropping, and excessive cracking may result in decreases in shielding performance.
- Structural safety of a steel-framed structure may decrease due to steel corrosion, reduced strength due to heat, yielding, buckling, cracking, fracturing or excessive deformation of any steel member, slipping, cracking or fracturing of any joint, looseness or fracturing of any bolt, or any reduced strength due to fatigue.

cessive deformation of any steel member, slipping, cracking or fracturing of any joint, looseness or fracturing of any bolt, or any reduced strength due to fatigue.

- The usability of a steel-framed structure relates to, among other things, vibration isolation performance against harmful vibration or resistance capacity against increases in deflection. These performance characteristics may be affected by steel corrosion, yielding, buckling, cracking, fracturing, or excessive deformation of any steel member; slipping, cracking or fracturing of any joint; or looseness or fracture of any bolt.

It is important for selection of degradation phenomena and degradation factors, evaluation, and progression prediction, to understand degradation mechanisms for each degradation factor. Degradation mechanisms are summarized for each degradation factor specified by existing guidelines to be monitored. The degradation factors are shown in **Tables 3** and **4** for concrete and steel-framed structures, respectively.

(3) Selection of degradation factors based on characteristics of nuclear facilities

Structures at nuclear facilities exist in a unique environment. Degradation mechanics need to be considered

when degradation factors are selected according to conditions such as environmental conditions and site conditions. Moreover, degradation mechanics are also important for evaluation of degradation progression processes and prediction of progression.

Degradation factors to be monitored are selected through summarization of characteristics of nuclear facilities. The following conditions of nuclear facilities are used as selection criteria: a) Environmental conditions, b) Site conditions, c) Structural conditions, d) Material conditions and e) Concrete surface protection conditions.

a) Environmental conditions

- Parts of structures in nuclear facilities are exposed to elevated temperatures.
- Nuclear power plants use the nuclear fission reaction of radioactive materials, and parts of their structures are exposed to radiation.
- Many machines are installed in structures at nuclear facilities, and many parts of structures are exposed to vibration.
- Structures in nuclear facilities include bulk-receiving docks with floors, etc., exposed to loads due to inbound and outbound vehicular traffic and equipment deliveries.
- With fewer people inside than in general structures, structures at nuclear facilities tend to be low in carbon dioxide gas concentration.

b) Site conditions

- Nuclear power plants in Japan are located in coastal areas, and their facilities may be exposed to airborne sea salt particles.
- Existing nuclear facilities are located in either semi-frost damage prone areas or general frost damage prone areas with a minor or higher frost damage risk.
- No existing nuclear facilities are located in vicinities of hot-spring areas or acidic river basins.
- Nuclear facilities are not different from general structures regarding factors (ultraviolet rays, heat, moisture, blown sand, mechanical stress, etc.) leading to carbonation (outdoors), insolation, weathering, drying, or coating degradation.

c) Structural conditions

- Many parts of steel reinforced concrete structures at nuclear facilities have larger cross-sections and covering thicknesses than those in general structures.
- In principle, structures at nuclear facilities are supported directly on a rock mass or indirectly via piles.
- Structures at nuclear facilities are equipped with many pieces of heavy equipment. Therefore, larger live loads are taken into consideration than in general structures.

d) Material conditions

- When structures at nuclear facilities are built, stringent control is in place for the selection and mixing of concrete materials.

e) Concrete surface protection conditions

- Outdoor coverings in structures at newer nuclear facilities are thicker than those in general structures and are protected with a finishing material such as a coating.
- Moreover, many parts have indoor concrete surfaces coated for easier removal of radioactive materials adhering to them (decontamination).
- Furthermore, parts in contact with liquids are covered with liners or coating films.

For degradation factors selected according to maintenance-related guidelines, degradation mechanisms are summarized, and ones to be monitored are selected based on the characteristics of nuclear facilities. **Table 7** and **Table 8** show the selected degradation factors to be monitored for concrete and steel-framed structures at nuclear facilities.

Chemical attack, differential settlement, and overloads are not selected as degradation factors for degradation due to aging of concrete structures. The reasons include the facts that no existing nuclear facilities are located in vicinities of hot-spring areas or acidic river basins and that differential settlement is unlikely because the structures at nuclear facilities are supported directly on bed-rock or indirectly via piles. Freeze-thaw is selected in areas with a minor or higher frost damage risk as a degradation factor to be monitored only for usability.

All the degradation factors for steel-framed structures are selected to be monitored.

(4) Summary of degradation phenomena and degradation factors to be monitored

Based on the results mentioned above, **Tables 9** and **10** show the relations between degradation phenomena and degradation factors to be monitored for concrete and steel-framed structures, respectively, at nuclear facilities. In the tables, degradation phenomena are grouped by performance characteristics, and combinations with degradation factors are shown. Degradation due to aging and degradation due to sudden event are shown in respective tables.

5. Inspection and soundness evaluation

Inspection and Soundness evaluation follows the PDCA cycle (Plan, Do, Check and Action) and plans for improvement through the in-service period. Inspection and Soundness in the PDCA cycle includes collecting basic information on maintenance, predicting soundness and contributing to Nuclear Safety.

Inspection should use a general way and the latest way. This section describes a basic way of thinking about the choice of an inspection method. The criteria in Soundness evaluation reflects the latest knowledge and a record.

This section, in addition to the Inspection and Soundness evaluation, also describes “Countermeasures and verification of effectiveness” and “Records”.

Table 7 Selection results of degradation factors to be monitored for concrete structures at nuclear facilities (Legend: ✓: To be selected as degradation factor and –: Not to be selected as degradation factor)

Degradation factor	Selection results	Applicable part	Remarks
Heat (elevated temperatures)	✓	Reactor body foundation, internal concrete, etc.	
Radiation exposure	✓	Reactor body foundation, shell wall, and internal concrete	
Carbonation	✓	Concrete in general	• In applicable parts with coating, degradation progression is inhibited.
Chloride penetration	✓	Buildings' external wall surfaces	• In applicable parts with coating, degradation progression is inhibited.
Alkali-aggregate reaction	✓	Concrete in general	
Machine vibration	✓	Turbine generator pedestal, emergency generator foundations, pump and motor foundations, etc.	
Freeze-thaw	✓*	Local parts around openings and parapets on external walls	• In areas with a minor or higher frost damage risk, only usability shall be monitored.
Chemical attack	–	–	• No existing nuclear facilities are located in vicinities of hot-spring areas or acidic river basins. • Indoor parts are unlikely to undergo chemical attack.
Drying shrinkage	✓	Walls, columns, beams, floors, etc.	• Structural safety and shielding performance do not seem likely to be compromised. Accordingly, only usability shall be monitored.
Creep	✓	Beams and floors	• The effect of creep has been taken into design consideration. Accordingly, only usability shall be monitored.
Insolation	✓	Rooftop, etc.	• The effect of temperature rise is minor even on a rooftop, with a waterproof layer and its protective material provided on it. Accordingly, only usability shall be monitored. • The walls restraining a rooftop floor shall also be assessed.
Weathering	✓	Buildings' external wall surfaces	• Considering the large concrete covering thicknesses in nuclear facilities, weathering has a minor effect on the structural safety and shielding performance of buildings. Accordingly, only usability shall be monitored. • Applicable parts with coating are less prone to degradation.
Vehicular traffic, etc.	✓	Floors, etc.	• Degradation will be limited to the surface layers of applicable parts. Accordingly, only usability shall be monitored.
Differential settlement	–	–	• In principle, nuclear facilities are supported directly on a rock mass or indirectly via piles on it and are unlikely to undergo differential settlement.
Overloads	–	–	• Prior to installing any heavy equipment, etc., exceeding the load assumed at the design phase, an evaluation is performed by an architect(s)/engineer(s) as necessary to ensure the soundness of structural components and that of members.
Loads due to earthquakes, typhoons, etc.	✓	Walls, columns, beams, floors, etc.	
Heat due to fire	✓	Parts in rooms on fire	

*: Dependent on site conditions.

Table 8 Selection results of degradation factors to be monitored for steel-framed structures at nuclear facilities (Legend: ✓: To be selected as degradation factor).

Degradation factor	Results of selection	Typical applicable part	Remarks
Coating degradation	✓	Stacks and roof trusses	
Plating degradation (loss of galvanized plating)	✓	Stacks and roof trusses	
Cyclic loads due to winds, etc. (fatigue)	✓	Stacks	
Loads due to earthquakes, typhoons, etc.	✓	Stacks and roof trusses	
Heat due to fire	✓	Stacks and roof trusses	

Table 9(a) Summary of degradation phenomena and degradation factors in degradation due to aging of concrete structures at nuclear facilities.

Performance characteristic	Degradation phenomenon	Degradation factor											
		Heat (elevated temperatures)	Radiation exposure	Carbonation	Chloride penetration	Alkali-aggregate reaction	Machine vibration	Freeze-thaw	Drying shrinkage	Creep	Insolation	Weathering	Vehicular traffic, etc.
Structural safety	Reduced concrete strength	✓	✓										
	Cracking	✓	✓	✓	✓	✓	✓						
	Rebar corrosion			✓	✓	✓							
	Spalling and falling			✓	✓	✓	✓						
Usability	Cracking	✓	✓	✓	✓	✓	✓	✓ *	✓		✓	✓	
	Spalling and falling			✓	✓	✓	✓	✓ *					
	Deflection								✓				
	Vibration						✓						✓
	Abrasion												✓
	Water leakage								✓				
Shielding performance	Moisture diffusion	✓	✓										
	Cracking	✓	✓	✓	✓	✓	✓						
	Spalling and falling			✓	✓	✓	✓						

*: Dependent on site conditions

Table 9(b) Summary of degradation phenomena and degradation factors in degradation due to sudden event of concrete structures at nuclear facilities.

Performance characteristic	Degradation phenomenon	Degradation factor	
		Loads due to earthquakes, typhoons, etc.	Heat due to fire
Structural safety	Reduced concrete strength		✓
	Cracking	✓	✓
	Spalling and falling	✓	✓
	Explosive spalling		✓
Usability	Cracking	✓	✓
	Spalling and falling	✓	✓
	Explosive spalling		✓
Shielding performance	Moisture diffusion		✓
	Cracking	✓	✓
	Spalling and falling	✓	✓
	Explosive spalling		✓

Table 10(a) Summary of degradation phenomena and degradation factors in degradation due to aging of steel-framed structures at nuclear facilities.

Performance characteristic	Degradation phenomenon	Degradation factor		
		Coating degradation	Plating degradation (loss of galvanized plating)	Cyclic loads due to winds, etc. (fatigue)
Structural safety	Reduced strength due to fatigue			✓
	Steel corrosion	✓	✓	
	Slipping, crack, and fracture of joint			✓
	Looseness and fracture of bolt			✓
Usability	Steel corrosion	✓	✓	
	Slipping, crack, and fracture of joint			✓
	Looseness and fracture of bolt			✓

Table 10(b) Summary of degradation phenomena and degradation factors in degradation due to sudden event of steel-framed structures at nuclear facilities.

Performance characteristic	Degradation phenomenon	Degradation factor	
		Loads due to earthquakes, typhoons, etc.	Heat due to fire
Structural safety	Reduced strength due to heat		✓
	Yielding, buckling, crack, fracture, and excessive deformation of steel	✓	✓
	Slipping, crack, and fracture of joint	✓	✓
	Looseness and fracture of bolt	✓	✓
Usability	Yielding, buckling, crack, fracture, and excessive deformation of steel	✓	✓
	Slipping, crack, and fracture of joint	✓	✓
	Looseness and fracture of bolt	✓	✓

(1) Inspection

a. Categories of inspections

Inspections are divided into periodical inspections performed at periodic intervals and extra inspections performed in response to earthquake, typhoon, fire, etc. The purpose of periodical inspections is to grasp the state of degradation due to aging of structures at nuclear facilities. The purpose of extra inspections is to check for damage to all parts of structures at nuclear facilities immediately after an earthquake typhoon, or fire.

b. Periodical inspections

1) Category and method

Periodical inspections are divided largely into periodical inspections for current soundness evaluation and periodical

inspections for long-term soundness evaluation. Each is subdivided into inspections using a direct or indirect method. In any case, inspections shall be performed by a direct method represented by visual, non-destructive, and local destructive methods and alternatively by an indirect method (an environmental conditions survey-based method, a nearby inspection results-based method, or a method using simulated specimens). Periodical inspections for current soundness evaluation shall be performed on structures in their entirety, in principle using visual and non-destructive methods. Meanwhile, periodical inspections for long-term soundness evaluation may involve the use of local destructive methods for representative parts.

Figure 9 shows the categories and methods of periodical inspections.

Fig. 9 Categories and methods of periodical inspections.

Table 11 Periodical inspections for current soundness evaluation (concrete structures).

Degradation phenomenon	Related performance characteristic	Applicable part	Inspection item	Inspection method
Reduced concrete strength	Structural safety	Parts heated to high temperature	Temperature	Indirect methods (temperature analysis and radiation dose analysis)
		Parts subjected to long-term radiation exposure	Radiation dose	
		Concrete structures in general	Change in compressive strength	Non-destructive methods (rebound number method and elastic wave method) Local destructive method (core-sampling method)
Moisture diffusion	Shielding performance	Parts required to be shielded	Temperature	Indirect method (temperature analysis)
Cracking	Structural safety Usability Shielding performance	Concrete structures in general	State of cracking	Visual method (crack measurement)
Rebar corrosion	Structural safety		Rust fluid	Visual method (hammering method) Local destructive method (chipping method)
Spalling and falling	Structural safety Usability Shielding performance		Presence/absence of spalling and falling	Visual method (hammering method)
				Non-destructive method (infrared method, etc.)
Deflection	Usability	Parts supporting heavy equipment	Deformation amount	Visual method (deformation measurement)
Vibration	Usability	Parts supporting vibration generating equipment	Vibration	Non-destructive method (vibration measurement)
Abrasion	Usability	Vehicular/heavy object passage floor	Abrasion	Visual method (surface measurement)
Water leakage	Usability	Roof slabs, aboveground and underground external walls, and internal walls	Water leakage	Visual method (hammering method)

2) Periodical inspection for current soundness evaluation

a) Concrete structures

Periodical inspections for current soundness evaluation are repeated at periodic intervals focusing on degradation phenomena due to aging. Periodical inspection methods for current soundness evaluation are divided into direct and indirect methods. Periodical inspections for current soundness evaluation of a concrete structure are indicated in **Table 11**.

Degradation phenomena due to aging in concrete structures become apparent on concrete surfaces, except for reduced concrete strength and moisture diffusion.

The visual method is suitable for quick inspection for any damage that becomes apparent on a wide surface area. It shall be used, as the standard inspection method for concrete structures, to inspect any degradation phenomenon that becomes apparent on a concrete surface, such as cracking, rebar corrosion, spalling and falling, deflection, abrasion, and water leakage. When a concrete surface is protected with a coating or liner, a check shall be made for any coating quality defect (discoloration, reduced gloss, chalking, fouling, etc.) or any surface damage (swelling, cracking, peeling, wear, etc.). If there is no surface damage, the concrete surface need not be directly checked.

b) Steel-framed structures

Degradation phenomena due to aging in steel-framed structures become apparent on their surfaces. Therefore, the standard method of periodical inspections for current soundness evaluation of steel-framed structures shall be the visual method, similar to that for concrete structures.

Periodical inspections for current soundness evaluation of a steel-framed structure are indicated in **Table 12**.

At the same time, for steel-framed structures, a check shall also be made for surface rust and partial loss of cross-section in addition to coating quality defect (discoloration, reduced gloss, chalking, fouling, etc.) and surface layer damage (swelling, cracking, peeling, wear, etc.).

3) Periodical inspections for long-term soundness evaluation

a) Concrete structures

Periodical inspections for long-term soundness evaluation are intended to grasp the effect of each degradation factor. Points with a marked effect shall be selected and inspected. As with the direct methods in periodical inspections for current soundness evaluation, damage to structures must be avoided. In some cases, however, the use of a local destructive method may be necessary to grasp the effect of each degradation factor. Periodical inspections for long-term soundness evaluation of a

Table 12 Periodical inspections for current soundness evaluation (steel-framed structures).

Degradation phenomenon	Related performance characteristic	Applicable part	Inspection item	Inspection method
Reduced strength due to fatigue	Structural safety	Parts (stacks, etc.) under cyclic loads due to winds, etc.	Coating quality defect Plating quality defect Excessive deformation	Visual method
Steel corrosion	Structural safety Usability	Steel-framed structures in general Foundation joints	Coating quality defect Plating quality defect	Visual method
Slipping, crack, and fracture of joint Looseness and fracture of bolt	Structural safety Usability	Parts (stacks, etc.) under cyclic loads due to winds, etc.	Coating quality defect Plating quality defect	Visual method (Hammering method and marking check)

Table 13 Periodical inspections for long-term soundness evaluation (concrete structures).

Degradation factor	Applicable part	Inspection item	Inspection method
Heat (elevated temperature)	Parts heated to high temperature	Temperature	Indirect method (Environmental conditions survey-based method)
Radiation exposure	Parts subjected to long-term radiation exposure	Radiation dose	
Carbonation	Concrete structures in general	Carbonation depth	Local destructive method
Chloride penetration	Concrete structures' external walls, etc., exposed to airborne salt particles	Chloride content	Local destructive method
Alkali-aggregate reaction	Concrete structures in general	Cracking	Visual method
Machine vibration	Turbine generator pedestals, emergency diesel generator foundations, pump/motor foundations, etc.	Cracking	Visual method

Table 14 Periodical inspections for long-term soundness evaluation (steel-framed structures).

Degradation factor	Applicable part	Inspection item	Inspection method
Coating degradation Plating degradation (Loss of galvanized plating)	Steel-framed structures in general	Coating quality defect Plating quality defect	Visual method
Cyclic loads due to winds, etc. (fatigue)	Parts (stacks, etc.) under cyclic loads due to winds, etc.	Coating quality defect Plating quality defect Excessive deformation or deflection	Visual method Non-destructive method (Ultrasonic testing (UT), liquid penetrant testing (PT))

concrete structure are indicated in **Table 13**.

When the relevant part is difficult to access and inspect by a direct method due to the problem of high altitude or equipment layout, an indirect method shall be used.

b) Steel-framed structures

Periodical inspections for long-term soundness evaluation of a steel-framed structure are indicated in **Table 14**.

In periodical inspections for long-term soundness evaluation of steel-framed structures, points at which a relatively large stress occurs and points that may be affected by fatigue under cyclic loads due to winds, etc. shall be checked by a visual method or a non-destructive method.

4) Extra inspection

a) Concrete structures

Extra inspections of a concrete structure shall be performed to check the structure in its entirety for any degradation phenomenon for loads due to earthquake, typhoon, etc., or to check around a fire-damaged point for any degradation phenomenon. A degradation phenome-

non in a concrete structure often manifests itself as surface damage and therefore can be grasped by a visual method in extra inspections, similar to periodical inspections. If damage is detected by a visual method, a more detailed inspection shall be performed by the method shown in **Table 15** to grasp effects on related performance characteristics.

b) Steel-framed structures

Extra inspections of a steel-framed structure shall be performed to check the structure in its entirety for any degradation phenomenon for loads due to earthquake, typhoon, etc., or to check around a fire-damaged point for any degradation phenomenon. A degradation phenomenon in a steel-framed structure often manifests itself as surface damage and therefore can be grasped by a visual method in extra inspections, similar to periodical inspections. If any damage is detected by a visual method, a more detailed inspection shall be performed by the method shown in **Table 16** to grasp the effects on the related performance characteristics.

Table 15 Extra inspections (concrete structures).

Degradation factor	Applicable part	Related performance characteristic	Degradation phenomenon	Inspection item	Inspection method
Loads due to earthquakes, typhoons, etc.	Damaged point	Structural safety Usability Shielding performance	Cracking	State of cracking	Visual method (Crack measurement) (Hammering method)
			Spalling and falling	Presence/absence of spalling and falling	
Heat due to fire	Fire-damaged point	Structural safety Usability Shielding performance	Reduced concrete strength	Carbonation depth	Local destructive method (Drilled-hole method) (Core-sampling method)
				Change in compressive strength	Non-destructive method (Rebound number method) (Elastic wave method)
					Local destructive method (Core-sampling method)
			Cracking	State of cracking	Visual method (Crack measurement)
			Spalling and falling	Presence/absence of spalling and falling	Visual method (Hammering method)
			Explosive spalling	Range of explosive spalling	Visual method (Hammering method)

Table 16 Extra inspections (steel-framed structures).

Degradation factor	Applicable part	Affected performance characteristics	Degradation phenomenon	Inspection item	Inspection method
Loads due to earthquakes, typhoons, etc.	Damaged point	Structural safety Usability	Yielding, buckling, crack, fracture, and excessive deformation of steel	Peeling/cracking of coating	Visual Non-destructive
				Any peeling of mill scale	
			Slipping, crack and fracture of joint, and looseness and fracture of bolt	Any buckled, cracked, fractured, or excessively deformed steel	
				Any slipped, cracked, or fractured joint	
Heat due to fire	Fire-damaged point	Structural safety Usability	Reduced strength due to heat	Any loosened or broken bolt	Local destructive
			Yielding, buckling, crack, fracture, and excessive deformation of steel	Stress-strain curve	Visual Non-destructive
				Peeling/cracking of coating	
			Slipping, crack and fracture of joint, and looseness and fracture of bolt	Any peeling of mill scale	
				Measurement of buckling, crack, fracture, of excessive deformation of steel	
				Any slipped, cracked, or fractured joint	
				Measurement of looseness or fracture of bolt	

5) Inspection plan

An inspection plan consists of an inspection method, timing of inspection, parts to be inspected and an inspection implementation scheme.

(2) Soundness evaluation

a. Outline

A structure soundness evaluation is an act of checking the results of inspection and progression prediction against predetermined evaluation criteria to ensure that a structure's level of performance necessary to remain functional is maintained. If the results of the soundness evaluation reveal that functions are not maintained or may be compromised, an appropriate countermeasure(s) shall be taken.

b. Evaluation of current soundness

A structure's performance changes as degradation phenomena proceed. Accordingly, soundness evaluation performed with focus on a degradation phenomenon currently underway provides the basis for the structure's maintenance. Maintenance flow for current soundness evaluation is indicated in Fig. 10.

In a current soundness evaluation, the results of periodical and extra inspections for current soundness evaluation shall be checked against a predetermined set of evaluation criteria and shall be rated as A1 (Sound), A2 (Follow-up observation), or A3 (To be discussed).

The rating shall be A1 (Sound) when the inspection results meet the evaluation criteria, A2 (Follow-up observation) when degradation is apparent but the inspec-

tion results meet the evaluation criteria, and A3 (To be discussed) when the inspection results fail to meet the evaluation criteria.

The evaluation criteria shall be set based on, among other things, existing guidelines, latest knowledge, and evidential data supported by actual measurement results, from the perspective of securing the level of performance required to maintain the necessary function(s).

Evaluation ratings and evaluation criteria for current soundness evaluation are indicated in **Table 17**. Evaluation ratings and evaluation criteria for cracking are indicated in **Table 18**.

Evaluation ratings are judged by the presence of degradation phenomena. Especially, evaluation ratings and evaluation criteria for cracking are based on degradation factors.

c. Evaluation of long-term soundness

In a long-term soundness evaluation, the results of a progression prediction shall be checked against a set of predetermined evaluation criteria and rated as B1 (Sound), B2 (Follow-up required), or B3 (To be dis-

cussed). Maintenance flow for long-term soundness evaluation is indicated in **Fig. 11**.

B1 (Sound) shall be given when the results of a progression prediction meet the evaluation criteria. B2 (Follow-up observation) shall be given when the results of an inspection meet the evaluation criteria at the moment but are unlikely to meet the evaluation criteria during the in-service period. B3 (To be discussed) shall be given when the results of an inspection and the like at the moment do not already meet the evaluation criteria.

Progression predictions can be made using inspection results or existing formulae for prediction of progression. As for degradation factors for which a formula for prediction of progression is available, it is possible to predict the progression of degradation during the in-service period based on the applicable formula. It is also possible to predict the tendency of progression of degradation from the results of inspections performed in the past.

Formulae have been proposed for predicting progression for carbonation, chloride penetration, and cyclic loads due to winds, etc. (fatigue). When there are necessary data available, it is possible to make a progression

Fig. 10 Maintenance flow for current soundness evaluation.

Fig. 11 Maintenance flow for long-term soundness evaluation.

Table 17 Evaluation ratings and evaluation criteria for current soundness evaluation.

Degradation phenomena		Evaluation rating and evaluation criteria		
		A1 (Sound)	A2 (Follow-up observation)	A3 (To be discussed)
Concrete structures	Reduced concrete strength	compressive concrete strength is equal to or above the design strength	—	compressive concrete strength is below the design strength
	Moisture diffusion	a soundness evaluation		
	Cracking	Refer to Table 18		
	Rebar corrosion	No rebar corrosion (rust fluid)	—	Any rebar corrosion (rust fluid)
	Spalling and falling	No spalling and falling	—	Any spalling and falling
	Deflection	No deflection	—	Any deflection
		deflection span ratio is less than 1/300	—	deflection span ratio is 1/300 or more
	Vibration	No vibration	—	Any vibration
	Abrasion	No exposed coarse aggregate	—	Any exposed coarse aggregate
	Water leakage	No water leakage or water leak mark	—	Any water leakage or water leak mark
	Degradation phenomena due to fire	No effect of the fire	—	Any effect of the fire
Steel-framed structures	Reduced strength due to fatigue	No damage on coating or plating	—	Any damage on coating or plating
	Steel corrosion	little rust or few coating plating quality defects	Any damage (tiny rust spots on all over the surface, large rust spots) on coating or plating	Any steel member is corroded and reduced in cross-sectional area
	Yielding, buckling, crack, fracture, or excessive deformation of steel members	No damage on the coating or plating	—	Any damage on the coating or plating
	Yielding, buckling, crack, fracture, or excessive deformation of steel members			
	Degradation phenomena due to fire	No effect of the fire	—	Any effect of the fire

Table 18 Evaluation ratings and evaluation criteria for cracking.

Affected performance characteristic		Evaluation rating and evaluation criteria		
		A1 (Sound)	A2 (Follow-up observation)	A3 (To be discussed)
Structural safety		No cracking likely to affect structural safety	—	Cracking likely to affect structural safety
Usability		Crack width: Below 0.3 mm (outdoor) Below 0.4 mm (indoor)	Crack width: 0.3 mm or more but less than 0.8 mm (outdoor) 0.4 mm or more but less than 1.0 mm (indoor)	Crack width: 0.8 mm or more (outdoor) 1.0 mm or more (indoor)
		Crack-free coating ^{*1}	—	Cracked coating ^{*1}
Liquid-tightness		Crack width: 0.05 mm or less ^{*2}	Crack width: More than 0.05 mm but less than 0.2 mm ^{*2}	Crack width: 0.2 mm or more ^{*2}
Shielding performance		The evaluation ratings for usability shall apply with necessary modifications.		

*1: When the usability (liquid-tightness) is evaluated based on the condition of coating

*2: When the usability (liquid-tightness) is evaluated based on the condition of concrete

Table 19 Evaluation criterion for Degradation factors.

Degradation factor	Evaluation item	Evaluation criterion
Heat (structural safety)	Concrete temperature	In general parts, within 65°C. In local parts (piping penetration, etc.), within 90°C.
Heat (shielding performance)	Highest internal temperature	Within 88°C when the heat is due to neutrons. Within 177°C when the heat is due to gamma rays.
	Ambient environmental temperature	Within 71°C when the heat is due to neutrons. Within 149°C when the heat is due to gamma rays.
Radiation exposure (structural safety)	Radiation exposure dose	1×10^{20} n/cm ² or less for neutron exposure dose during in-service period. 2×10^8 Gy (2×10^{10} rad) or less for gamma ray exposure dose.
Carbonation	Carbonation depth	During the in-service period, the carbonation depth has not increased so much as to cause rebar corrosion.
Chloride penetration	Corrosion amount	The rebar corrosion amount has not reached the level for cracking to occur.
	Amount of chloride ions	The amount of chloride ions at rebars has not reached the level for rebar corrosion to occur.

prediction. Note, however, that coefficients or the like used in an existing formula for prediction of progression are often formulated based on the results of accelerated degradation of specimens. Hence, the results of a prediction on an actual structure may differ from those of its inspection. Therefore, a formula for predicting progression must be checked in advance for its applicability.

With a collation of inspection results accumulated over years, even in the absence of a formula for prediction of progression, it is possible to predict the tendency of the effect due to the degradation factor. Generally, degradation due to aging does not proceed rapidly. Therefore, if the results of inspections performed in the past reveal that no degradation phenomenon affecting performance has occurred, the risk of rapid performance degradation in future shall be estimated as low. Even if there is a paucity of accumulated inspection results, this prediction method will be effective if the future period to be covered is relatively short.

Evaluation criteria for degradation factors are indicated in **Table 19**. It is difficult to make a direct prediction of the progression of any effect due to machine vibration and alkali aggregate reaction. Therefore, such a prediction shall be based on the crack occurrence situation. Accordingly, in a soundness evaluation for machine vibration and alkali aggregate reaction, A1 (Sound) and A3 (To be discussed), the evaluation ratings for cracks affecting structural safety, shall be read as B1 (Sound) and B3 (To be discussed), respectively.

In steel-framed structures, the condition of coating or plating is checked by periodical inspections for current soundness evaluation and mainly by the visual method. The evaluation ratings for coating degradation and plating degradation (loss of galvanized plating) in the present Guidelines shall be B1 (Sound) for damage-free coating or plating and B3 (To be discussed) for any coating/plating quality defect. To ensure long-term prevention of steel member corrosion, it is important to maintain the soundness of the coating or plating. The need for periodic recoating shall be determined based on useful life evaluation.

It is difficult to make a direct prediction of the progression of any effect due to cyclic loads due to winds,

etc. fatigue. Therefore, such a prediction shall be based on the results of an inspection by the visual method on the condition of the coating or plating and the presence/absence of excessive deformation. The evaluation ratings shall be in line with current soundness evaluation. The rating shall be B1 (Sound) for damage-free coating or plating and shall be B3 (To be discussed) when any coating/plating quality defect or any excessive deformation is detected by the visual method.

(3) Countermeasures and verification of effectiveness

To maintain the functions required of nuclear facilities, it is necessary to implement countermeasures based on the results of current or long-term soundness evaluations so that the current performance of the structures during the in-service period will exceed the required level. **Figure 12** shows the flow of maintenance countermeasure implementation and effectiveness verifications.

Methods of implementing countermeasures shall include continuation of the current inspection, enhancement of inspections, and repairs. Repairs shall include countermeasures implemented alternatively, such as consideration for members or structural components, when repairs are unavailable, or when the required performance level cannot be achieved by repairs. Any alternative countermeasure implemented shall be checked for its effectiveness.

(4) Records

For continuous implementation of maintenance, the following items shall be recorded:

- Maintenance plan
- Contents and results of inspections
- Methods and results of soundness evaluations
- Contents and results of countermeasures and methods and results of effectiveness verifications

To enhance the reliability and effectiveness of maintenance, it is necessary to record and store information on maintenance while analyzing records and continuously making improvements.

The results of inspections, soundness evaluations, and countermeasures and effectiveness verifications shall be

(A1 to A3 show the evaluation ratings for current soundness evaluation, while B1 to B3 show those for long-term soundness evaluation.)

Fig. 12 Flow of maintenance countermeasure implementation and effectiveness verification.

recorded accurately and in detail, using predetermined forms, to allow easy understanding of maintenance activities. Even if the methods of recording and storage are changed due to improvements in the maintenance method and technological advancements, arrangements shall be made to allow continued use of past records. When records are electronically stored, data leakage or loss shall be borne in mind. As for data handling, it is recommended to specify an appropriate control method and implement measures for ensuring information security.

6. Conclusion

Safe long-term use of nuclear facilities depends heavily on proper design, construction, and maintenance.

There are an increasing number of nuclear power plants in service for more than 30 years since the start of operation. Accordingly, the importance of maintenance of nuclear facilities is increasing, in addition to the traditionally recognized importance of their design and construction. So far, however, the maintenance of

buildings at nuclear facilities has been left to the individual operators in the absence of standardized criteria and guidelines.

Under such circumstances, the previous version of the present Guidelines was established in 2008 as a set of guiding principles that set standards for maintenance work to be performed to maintain the functions required of buildings in nuclear power plants over a long period. In addition, the Guidelines were revised to reflect the latest knowledge in 2015. Since then, the present Guidelines have been useful in a wide range of maintenance activities from daily inspection to building soundness evaluation with focus on aging.

This paper has outlined the Guidelines applied to nuclear facilities in Japan. An English version of the Guidelines will be released by the Architectural Institute of Japan.

Reference

AII, (2015). "Guidelines for maintenance and management of structures in nuclear facilities." Architectural Institute of Japan, Tokyo. (in Japanese)