Development of Maintenance Technology
- Measures against Aging Deterioration / New Inspection System / Advanced Operation -

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After the Fukushima Daiichi Accident, more than half of the Japan's nuclear power plants have now been operating for more than 30 years. Some have applied for extensions so that they could keep operating for more than 40 years. Higher reliability and reliability operation are required for these aging plants. On top of that, new requirements such as the new regulations in light of the lessons learned from the Fukushima Daiichi Accident, as well as a new inspection system that aims to achieve continuous improvement in safety, have also been imposed on the aging plants. Furthermore, due to the deregulation of electric utilities, nuclear power generation is also expected to make some efforts toward enhanced competitiveness against other energy sources. In order to address these changes in the business environment, it is necessary to conduct a review from a new perspective in addition to maintenance technologies so far. Mitsubishi Heavy Industries, Ltd. (MHI) will contribute to Japan's energy security by supporting electric power companies with further improvement in our maintenance technologies.

1. Introduction

For the aging plants, Plant Life Management (PLM) is conducted before 30 years (and every 10 years thereafter), in addition to the additional "Special Inspection" carried for plants that apply for an extension of service after 40 years of operation. In addition, new requirements, such as compliance with the new inspection system that aims to continuous improvement in safety performance, have also been imposed on the aging plants. The activities, which contribute to improve plant operation rate and reduce fuel cycle cost and operation cost, have also been advanced in order to strengthen the competitiveness against other power sources (hereinafter referred to as advanced operation). In order to address these changes, it is necessary to review things from a new perspective in addition to the maintenance technologies so far. MHI has been working on the further improvement of maintenance technologies focusing on aging management, and the details of our individual activities will be introduced below.

2. Aging Management

In order to secure the operation of long-serving nuclear power plants, it is necessary to properly carry out maintenance management for maintaining and recovering original functions and performance, by conducting additional maintenance work on top of the ordinary inspection efforts, after understanding the deterioration of facilities caused by aging based on the latest scientific knowledges. These aging management would sufficiently secure the integrity of the plants for long-term operation.

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2.1 Plant Life Management (PLM)

According to the provision of "Ministerial Ordinance for Commercial Nuclear Power Reactors concerning the Installation, Operation, etc." (Article 82-1) (Technical Assessment of Age-related Deterioration of Commercial Nuclear Installations), electric power companies are obligated to conduct "Plant Life Management (PLM)" on the equipment and structures crucial to safety before t 30 years (and every 10 years thereafter), assuming their long-term operation in the future. It is mandatory for them to create a long-term maintenance and management policy based on PLM and to include the policy in the operational safety programs, the details of which need to be examined and approved by the Nuclear Regulation Authority.

Since PLM was conducted for the first time in Japan in 1999, MHI has worked on improving the assessment procedure while incorporating operational experience in nuclear power plants and the latest knowledges from research and development both at Japan and overseas. **Figure 1** illustrates the process of PLM, an outline of which is also described below.

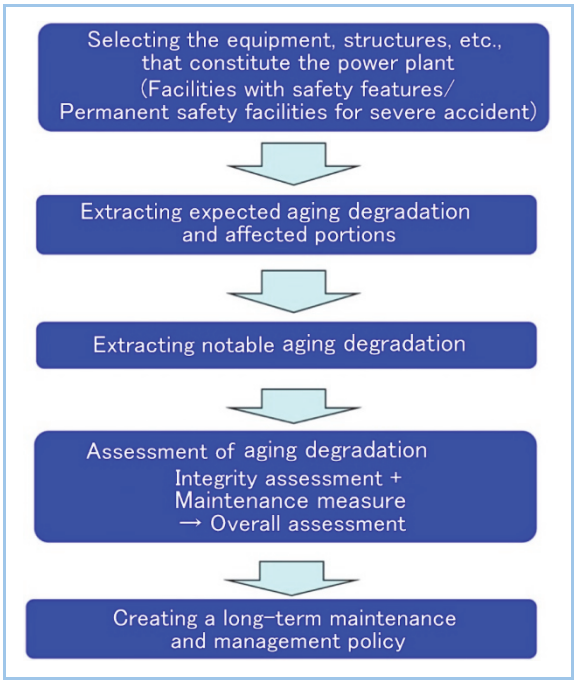

Figure 1 Process of Plant Life Management (PLM)

PLM covers all equipment and structures which have safety features in nuclear power plants. It extracts and categorizes aging degradation expected in individual parts of the subject equipment and structures, taking into account their materials, service conditions, etc., based on the newest codes and standards, the latest knowledges and operational experience, including actual problems that have occurred both at Japan and overseas. With respect to notable aging degradation, they examine the structure of the equipment and structures and whether the integrity of features is secured, assuming a certain level of the occurrence and progress of aging degradation during long-term operation. It also evaluates the adequacy of the current maintenance work in terms of addressing the expected aging degradation, and consequently provides a comprehensive assessment of the validity of the long-term operation of the facilities being evaluated.

According to the knowledges accumulated through various research and development work so far, the 6 typical notable aging degradation events extracted by PLM are: low-cycle fatigue, neutron irradiation embrittlement, irradiation-assisted stress corrosion cracking, thermal aging of stainless steel, insulation deterioration in electric and instrumentation facilities, and decreased strength and shielding ability of concrete structures. They take into consideration the conditions for a severe accident and temperature environment. For instance, in the pressurized thermal shock assessment of the neutron irradiation embrittlement of the nuclear reactor vessel, the integrity is evaluated in light of the transient changes at the time of a sever accident. Furthermore, in terms of the insulation deterioration in the electric and instrumentation facilities, a integrity evaluation is conducted, taking

into account the temperature, radiation dose, etc., at the time of a sever accident, in addition to the design basis accident.

On top of these, PLM extracts the events deemed necessary to be taken into account in terms of the seismic and tsunami resistance as notable aging degradation for safety reasons as well. Consequently, it evaluates the safety of the equipment and structures against earthquakes and tsunamis, based on the occurrence and advancement of aging degradation due to long-term operation, in order to confirm that it satisfies the acceptable value. As for the latest knowledges both at Japan and overseas, we will continue to examine whether they should be incorporated into PLM through various research efforts.

2.2 Approval system for the extension of operational period

The Amendment to the Reactor Regulation Act enacted in July 2013 requires compliance with the new regulations. It has introduced permission for extension which also defines the operational period for nuclear power plants. This approval system stipulates that the operational period of a nuclear power plant is 40 years from the commencement of operation and can be extended once for a maximum of 20 years, provided that it has obtained approval from the Nuclear Regulation Authority prior to the expiry of the initial term. In order to apply for approval, it is necessary to conduct a special inspection of the nuclear reactor vessel and other equipment and to create an assessment report on the extent of age-related deterioration of individual equipment and a long-term maintenance and management policy, assuming the operational period of 60 years, in light of the results of the special inspection. To obtain permission, the results of the age-related deterioration assessment and other required elements need to satisfy the technical standards even after taking into account the 60 years' worth of deterioration.

For Pressurized Water Reactors (PWR) under the approval system, a Special Inspection is conducted on the reactor vessel, containment vessel and concrete structures as shown in **Figure 2** and **Table 1**, for the purpose of understanding in detail the extent of their aging degradation deterioration after being in operation for nearly 40 years. This Special Inspection has been conducted in 3 PWR plants so far.

The Special Inspection of the reactor vessel is performed in terms of neutron irradiation embrittlement as an aging degradation. For the core area of the reactor vessel, an inspection with an ultrasonic testing is required. For the nozzle corners, which are the joints connecting the reactor vessel assumed to have fatigue and primary coolant nozzles where the structure is discontinuous, an eddy-current testing is also required. As for the Bottom-Mounted Instrumentation (BMI) where stress corrosion cracking is anticipated, the inner and exterior surfaces require an eddy-current testing and visual test, respectively[(1)]. The equipment utilized for the inspection of the core area of the reactor vessel and nozzle corners are illustrated in **Figure 3**. The reactor vessel cannot be accessed due to its high radiation dose. Therefore, the inspection needs to be conducted using machines by remote control. MHI has developed the required equipment and systems that can perform tasks remotely even in portions with a complex shape such as nozzle corners and the BMI, such as the Advanced UT Machine (A-UT Machine) which utilizes an autonomous under-water navigation robot that is small, light and easy to assemble or pack up, and thereby allows the inspection to be completed in a short time, in order to make the inspection possible.

Consequently, safe and stable operation can be achieved for a longer period than before by managing the deterioration of the equipment at nuclear power plants in accordance with PLM based on the operational period, as well as by taking necessary maintenance measures.

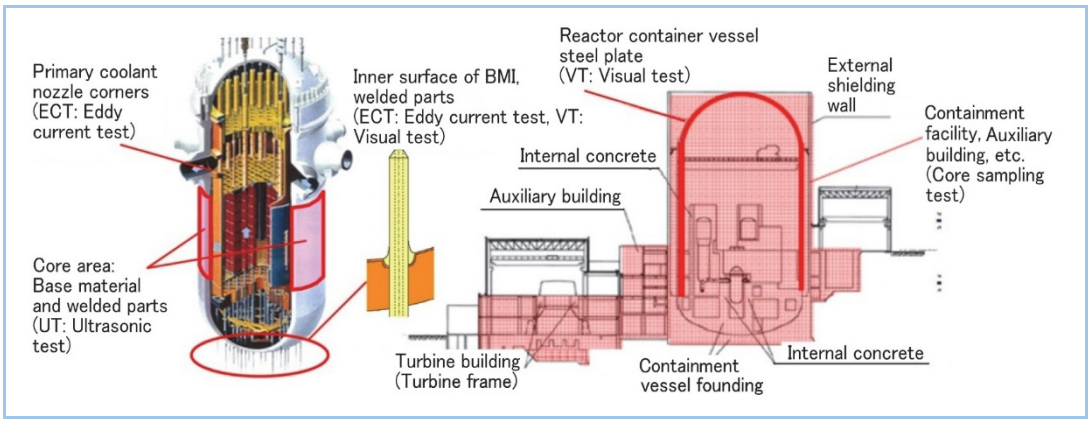

Figure 2 Special Inspection overview

Table 1 Special inspection overview

Subject equipment	Subject part	Subject deterioration event	Inspection procedure
Reactor vessel	・Base material and welded parts (100% of the core area)	Irradiation embrittlement	・Determining whether any flaw is present with Ultrasonic Testing (UT)
	・Primary coolant nozzle corners (Cladding surface)	Fatigue	・Determining whether any cracks are present with the surface inspection or Eddy current testing
	・Bottom-Mounted Instrumentation (BMI) (All)	Stress corrosion cracking	・Determining whether there are any cracks in the welded part with the visual test (MVT-1) and whether there are any defects on the inner surface of BMI with the surface inspection or Eddy current testing
Containment vessel	・Containment vessel steel plate (Any and all accessible areas)	Corrosion	・Examining the coating condition with the visual test (VT-4)
		Decrease in strength/shielding ability	・Examining with core sampling the strength, shielding ability, neutralization, salt and alkali-aggregate reaction
Concrete structures	・Concrete structures, systems and equipment with safety features, as well as concrete structures holding them ・Concrete constructions and equipment designated as the permanent installations for severe accident response, as well as concrete structures holding them	Decrease in strength/shielding ability	・Examining with core sampling the strength, shielding ability, neutralization, salt penetration and alkali-aggregate reaction

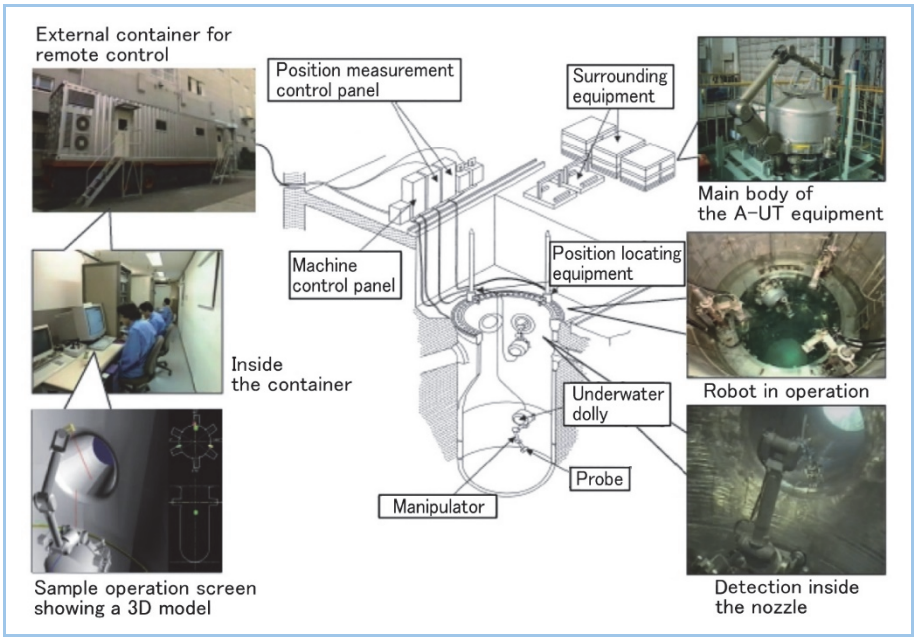

Figure 3 Ultrasonic testing equipment for reactor vessel

3. Correspondence to new inspection system

Under the new inspection system that came into full force on April 1, 2020, compliance with standards and permissions is now examined primarily by electric power companies instead of the regulatory authorities, i.e., the Nuclear Regulation Authority. Therefore, the electric power companies are required to be able to explain compliance with standards and permissions more than before. Furthermore, for existing nuclear power plants it is also necessary to organize the information and data in a systematic manner in accordance with configuration management.

As risk information is utilized as a standard for supervision and assessment in the new inspection system, it is necessary to establish the Probabilistic Risk Assessment (PRA) ※1 model for the assessment. On top of that, it is expected to promote maintenance activities utilizing risk information.

In order to meet the new needs associated with this new inspection system, MHI has been working on various studies and research efforts in cooperation with electric power companies. This report will explain what we are working on.

※1 A methodology to express the degree of safety based on the possibility of the risk of leading to a severe accident, by quantitatively assessing the frequency of an accident and the impact thereof at the time of its occurrence, in terms of any and all possible accidents which could occur in nuclear facilities and related facilities.

3.1 Outline of the new inspection system

The new inspection system was implemented on April 1, 2020 and has come into full force since. Upon its implementation, the examination of compliance with standards and permissions, which used to be carried out by the regulatory authorities, has now been fully taken over by electric power companies who conduct it in the same manner as a pre-operation inspection by the operator.

The Nuclear Regulation Authority is now in charge of overall surveillance and assessment in terms of the progress in all maintenance activities carried out by electric power companies from the design phase, and has been given free access to the nuclear power plants, design documents and other related information. Furthermore, they are authorized to impose additional regulatory measures on the electric power companies when the margin in terms of safety features/performance is reduced or falls outside of the designated range.

As described above, the Nuclear Regulation Authority would promote the continuous enhancement of safety on the electric power company's own accord by conducting a comprehensive inspection of their activities, in order to secure an even higher level of safety. **Figure 4** illustrates the process of surveillance and assessment in the nuclear regulatory inspection [(2)]. The inspection results are classified into 5 rankings from the perspective of safety significance, and additional regulatory measures are determined for each ranking. Among these 5 rankings, risk information (PRA) is utilized as the assessment standard for the top 3[(3)]. **Figure 5** demonstrates the rankings of safety significance in the nuclear regulatory inspection.

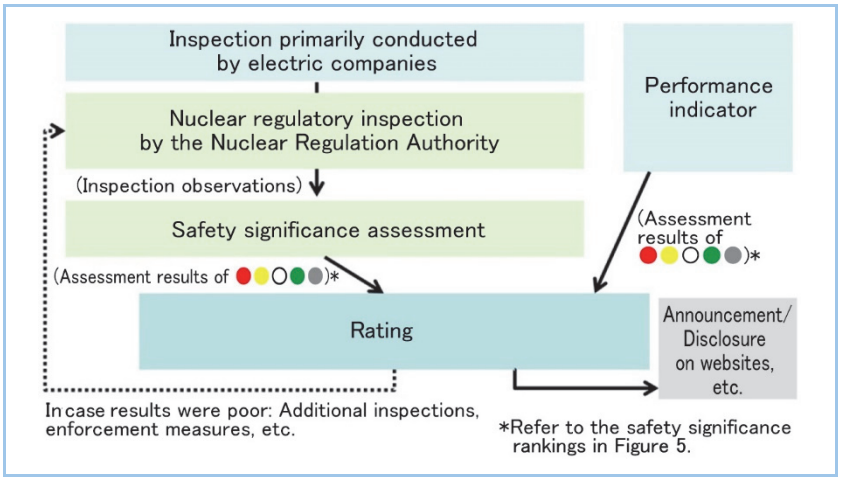

Figure 4 Process of surveillance and assessment in the nuclear regulatory inspection

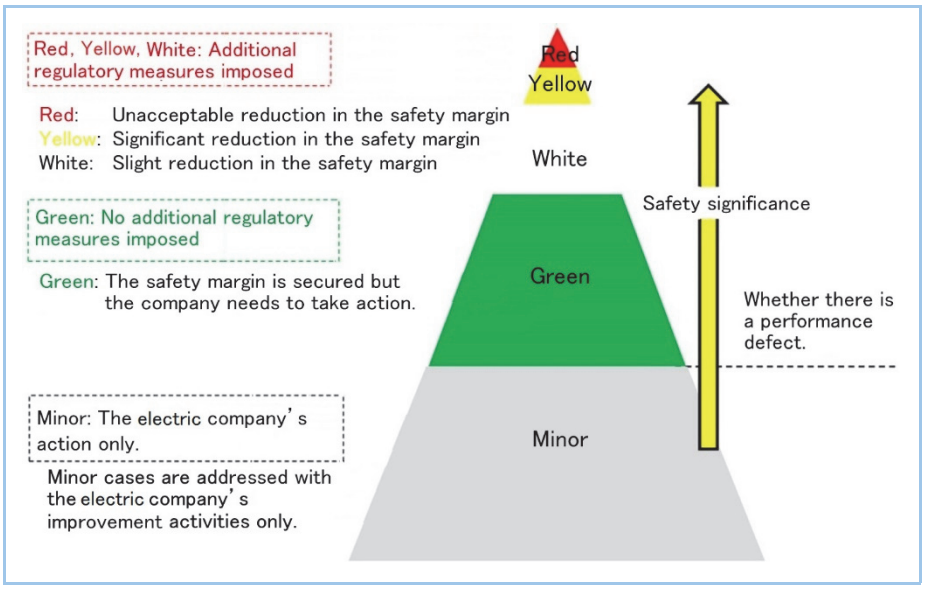

Figure 5 Safety significance rankings in the nuclear regulatory inspection

As described above, any maintenance activity by electric power companies is subject to surveillance and assessment in the new inspection system, and because the Nuclear Regulation Authority would conduct such surveillance and assessment as necessary utilizing the free access, the electric power companies are required to manage the facility information in a more systematic manner than before. In order to address this issue, it is important to manage the facility information based on the concept of configuration management, which is a framework for identifying the "Design Requirements," "Facility Configuration Information" and "Physical Configuration," where their consistency is maintained and managed systematically, to update the information promptly when any alteration or remodeling is carried out to the facility and to cross-check the consistency with existing information. **Figure 6** shows the relationship between the 3 elements of configuration management.

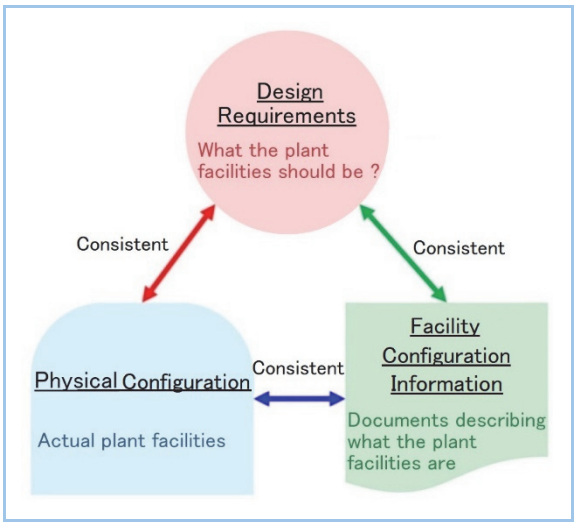

Figure 6 Relationship between 3 elements of configuration management

3.2 MHI's efforts

3.2.1 Organizing Design Basis Documents

The facility information needs to be maintained and managed in a systematic manner based on configuration management. Therefore, organizing and linking relevant information beforehand helps to reduce the workload, lessening tasks such as checking and looking up when any facility alteration or remodeling occurs.

In the preparatory stages before the launch of the new inspection system, there was an increasing need amongst electric power companies to organize the facility information. Since MHI, as a plant manufacturer, possesses information about the design basis leading to the "Design Requirements", we have contributed to the efforts made by electric power companies

in organizing various information, such as the ”Design Requirements” and facility features necessary for securing safety, as well as the method for examining whether the functions required for plant equipment are properly maintained, as Design Basis Documents.

Although our contribution focused on the organization of the Design Basis Documents for individual plants so far, we will endeavor to expand the coverage of our support to the updating of and modifications to the Design Basis Documents in light of facility alterations, remodeling, etc.

3.2.2 3D As-Built Management System

The configuration management is, as described above, a framework for maintaining and managing the consistency between the 3 elements, “Design Requirements,” “Facility Configuration Information” and “Physical Configuration,” in a systematic manner. In this respect, we believe that it is possible to utilize “3D As-Built Management System” where the current facility conditions can be reviewed in image data.

The 3D As-Built Management System has been developed as a tool for planning engineering work, which performs coupling of the actual plant equipment data obtained with a 3D laser scanner, in order to create a panoramic photograph from all directions, which would allow a desktop review of the latest on-site conditions of the plant. Some facilities in nuclear power plants cannot be reviewed/examined during operation. Therefore, we believe that being able to look at the images of the actual conditions would be useful in terms of the review of the “Physical Configuration” in configuration management. Furthermore, as the data from the 3D As-Built Management System can be linked to the attribute information and other related data, linking it to various information relating to the ”Design Requirements” and ”Facility Configuration Information”, as shown **Figure 7**, could be very useful for configuration management.

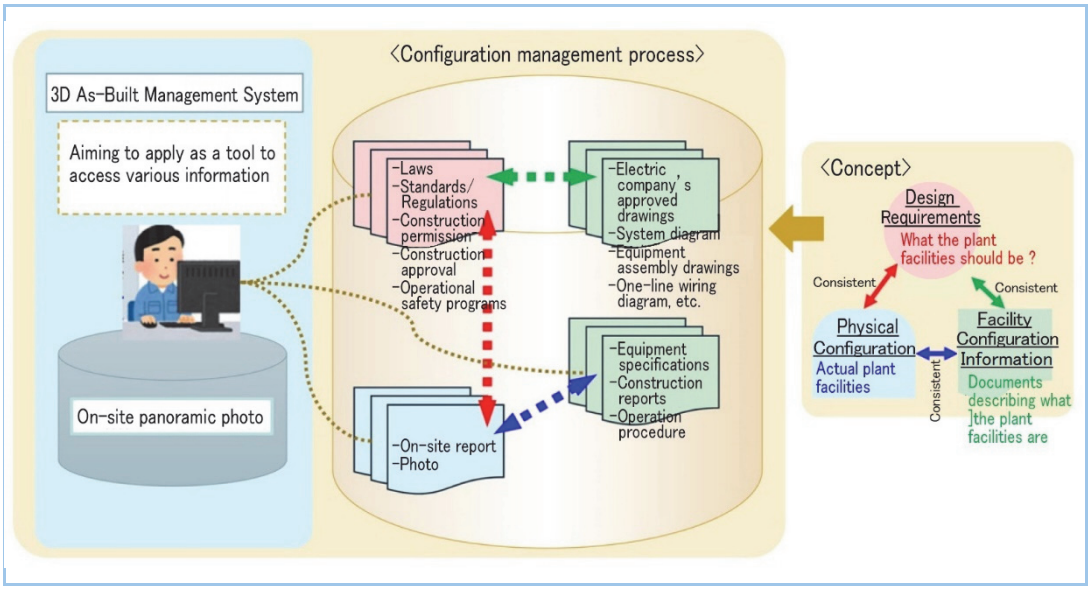

Figure 7 Relationship between configuration management process and 3D As-Built Management System

3.2.3 Development of PRA model

As part of the safety significance assessment of the knowledges from the nuclear regulatory inspection, the new inspection system utilizes PRA as a tool to assess the impact that the knowledges would have on the risks. PRA is a method of quantitatively assessing the frequency of an accident and the impact thereof at the time of its occurrence based on probability theory. Since electric power companies were required to develop the PRA model upon the implementation of the new inspection system, MHI has been contributing to the development and upgrading of the model, taking advantage of our extensive knowledge and experience in the design and assessment of plant equipment.

In the U.S., various other efforts utilizing risk information, in addition to regulatory activities, have also been made and have been extended to the maintenance activities. For

instance, with respect to the safety significance classifications, which used to be defined in a deterministic way, the extent of the risk significance obtained by PRA in a quantitative manner is taken into account, leading to the investment of resources into the maintenance of equipment that is deemed more important from both perspectives. Furthermore, even the frequency of the function testing and the acceptable period while not on standby, which are conventionally prescribed in the operational safety programs from a deterministic aspect, are undergoing a review in accordance with the extent of the impact that the reliability of individual system features and the period during which they are unavailable would have on the risks. In Japan, following such a trend, it has become increasingly common to utilize risk information. Accordingly, MHI will continue to contribute to the enhancement of plant safety by establishing a method for quantitatively assessing the changes in the risks related to maintenance activities and conducting maintenance work, which would focus more on equipment with safety significance.

4. Advanced operation

Nuclear power generation needs to contribute to the stable supply of electricity as a base-load power source. Meanwhile, due to the deregulation of electric utilities, the market principle based on the abolishment of regional monopolies, open access to the market and free pricing have been introduced, also requiring competitiveness in terms of the unit price in nuclear power generation. In order to boost the unit price competitiveness, it is necessary to work on the reduction of power generation costs including the fuel cycle cost, while also improving the plant operation rate and electric output. This report refers to these efforts collectively as advanced operation, and introduces the maintenance technologies necessary to achieve them, such as a shortening of the regular inspection process, the introduction of long-term cycle operation, improved electrical output.

4.1 Shortened process for regular inspection

Electric power companies are obligated to conduct inspections on a regular basis (operator's regular inspection) on major facilities at nuclear power plants. Currently, Jpan's nuclear power plants undergo regular inspection every 13 months' of operation. On the other hand, after the introduction of the new regulations, the requirements for individual facilities have been partially changed and the conventional standard regular inspection process has been extended, which have become major factors for the lower plant operation rate. Therefore, efforts to shorten the regular inspection process have been growing in importance. The regular inspection consists of an overhaul and leak inspection, which would examine whether the functions of major facilities are properly maintained. In addition, consumables such as fuels are replaced and scheduled repair work of the facilities is conducted. MHI analyses the inspection conducted by electric power companies as described above in terms of the individual tasks deemed critical in the regular inspection process and is working to reduce the burden associated with the inspection through the introduction of rotation parts, the standardization of tasks by improving engineering tools and the enhancement of durability by using improved materials to combat age-related deterioration. For example, let us introduce the high durability polyethylene lining for seawater cooling pipes. The seawater cooling pipes have a anticorrosion polyethylene lining applied to the inside of the carbon steel pipe. The high durability polyethylene material increases the durability of the lining material and its resistance to cavitation erosion[※2]. **Figure 8** shows an observation of a test piece of high durability polyethylene after erosion testing. According to the observation, we can see that the high durability polyethylene has a significantly higher erosion resistance compared with the conventional polyethylene. Consequently, the burden associated with the inspection can be reduced by utilizing the high durability polyethylene as the lining material, as it increases the reliability of the seawater pipe and thereby extends the inspection cycle.

※2 A phenomenon in which a large number of bubbles generated in a liquid cause surface damage when they collapse near the surface of a material.

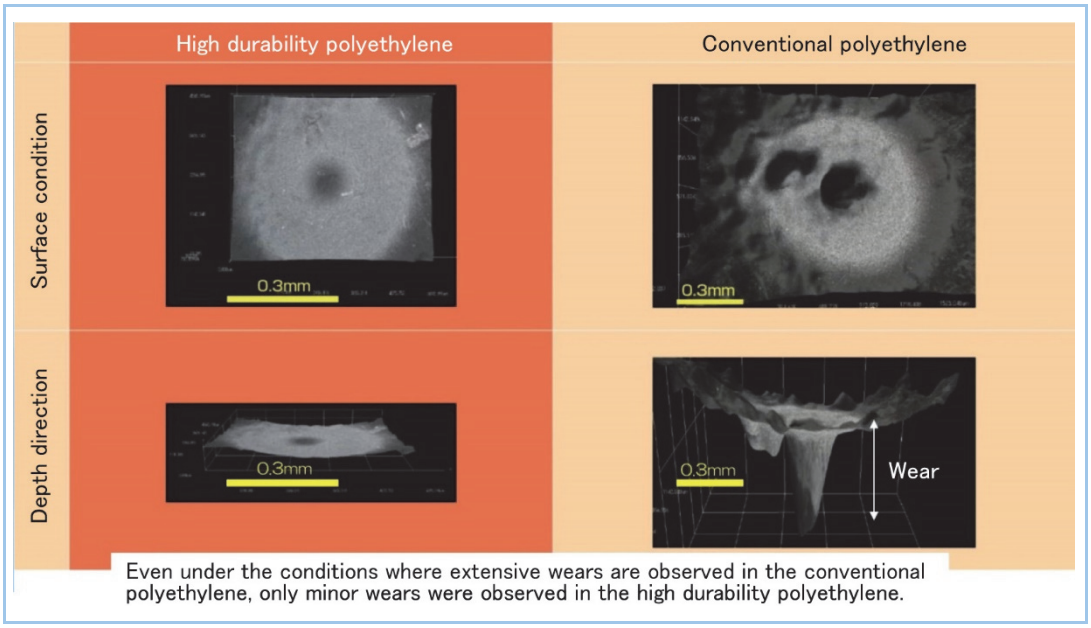

Figure 8 Observation of a test piece after applying a cavitation jet for a certain period

4.2 Extended-cycle operation

Another way of increasing the plant operation rate is the introduction of extended-cycle operation. In January 2009, the inspection system was updated to make it possible to extend the operational period of nuclear reactors from the conventional 13 months up to 24 months if the required procedure was followed in accordance with the Reactor Regulation Act. Upon the introduction of extended-cycle operation, the interval between regular inspections can be extended. Consequently, electric power companies are required to submit "Explanation regarding the nuclear reactor's operational period" as an appendix to the operational safety programs, which provides the grounds for the validity of the reactor's operation period, based on the assessment of the impact of the extended interval between inspections of individual equipment from a maintenance and management aspect. The technical validity for extending the inspection interval shall be determined based on "Reviews on past inspections and replacement work," "Assessment according to the deterioration trend," "Assessment based on research outcomes" and "Benchmark for similar equipment" in terms of the facilities subject to the assessment. Furthermore, upon the introduction extended-cycle operation, though the maximum burnup is 48 GWd/t [※3] in the present fuel use, it is possible to achieve a reduction in the fuel cycle cost by applying a high burnup fuel with a maximum burnup of 55GWd/t, which would limit the number of fuel units replaced at the time of regular inspections.

※3 A unit of burnup. The thermal energy generated by the fission reaction during the stay of the fuel loaded in the reactor is indicated per unit fuel weight.

4.3 Taking measures for improved electric output

Improved electric output would make most of the performance of existing plants. The electric output can be improved by increasing the process efficiency (plant efficiency) during the conversion of the steam energy generated in the steam generator to electric energy, as well as by increasing the amount of heat generated in the reactor (core thermal power), which would also increase the steam flow that is generated in the steam generator. One example for increased plant efficiency is an upgrade of the turbine design so that the energy production is at its maximum throughout the year at the rated thermal output due to a shift from the rated electric output to rated thermal output in the operation. Specifically, **Figure 9** illustrates an example with a high-pressure turbine. The design is intended to achieve higher efficiency by applying a fully 3-dimensional design blade, optimizing the cascade geometry at its entrance/exit portions and making the final-stage moving blade longer in a low-pressure turbine. Furthermore, it utilizes a fully integrated rotor in order to eliminate the risk of stress corrosion cracking. It also utilizes the integral shroud blade where the entire blade from the root to the tip is built in an integrated manner so that blade vibration is suppressed, which enhances the reliability and maintainability, as well as reduces the operational cost. In the future, it will be

possible to further improve the electric output by taking other measures to increase the core thermal power, some of which already have a wide range of practical applications overseas.

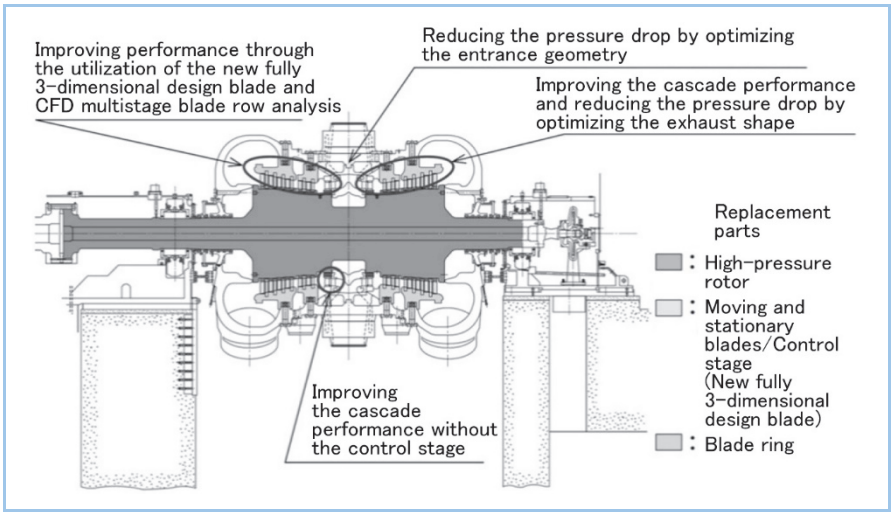

Figure 9 High-efficiency turbine (High-pressure turbine)

5. Conclusion

With respect to the efforts associated with nuclear power plants, we have described some activities from the aspect of the development of maintenance technologies. More than half of Japan's nuclear power plants have been operating for more than 30 years, but we have managed to achieve long-term operation and secure their integrity by conducting PLM every 10 years, as well as carry out Special Inspection for those plants operating for more than 40 years. Meanwhile, corresponding to the new inspection system, we can contribute to the continuous improvement of the safety of nuclear power plants through various measures taken in collaboration with electric power companies for the new system, which aims to perform inspections with higher reliability. Furthermore, prior to increased competitiveness of nuclear energy compared with other power sources, we were aiming to contribute to society through nuclear power plants as more valuable power sources by making efforts such as a shortened regular inspection process, the introduction of long-term cycle operation and improved electrical output. MHI will continue to improve the safety and economic compatibility of Japan's nuclear power plants.

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