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Study of the Optimization of Maintenance Plan for Nuclear Power Plants

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ABSTRACT

This paper proposes a quantitative evaluation method for the maintenance plan for nuclear power plants, developed by introducing the scientific approach, and also proposes a method to search for an optimum maintenance plan to be obtained by maximizing nuclear safety and economic efficiency simultaneously, then balancing them. As a result of consideration, the following results were obtained.

(1) The quantitative evaluation methodology for optimizing the maintenance plan for nuclear power plants was developed.
(2) The computer simulation of maintenance planning for a couple of BWR systems by using this methodology was carried out. It was concluded that this methodology can produce a new maintenance plan which meets the maintenance targets corresponding to optimum maintenance.

KEYWORDS

Nuclear Power Plant, Maintenance Optimization, Maintenance Law, Maintenance Equation, Maintenance Targets, Plant Safety, Plant Economic Efficiency, Maintenance Plan, Maintenance Work-team Performance

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1. Introduction

Since the 1970's, maintenance in industrial plants has become more and more important. This is because industrial plants began growing larger rapidly. Problems, failures and accidents in these large plants may have very big impact on the owner, society and the environment. Only industrial plants that are well designed, constructed, operated and maintained can assure plant safety and economic efficiency. Maintenance is very important and should be on the same footing with design, construction and operation. The US nuclear power industry since 1980 is a good example. Since 1980 the US nuclear plants have placed great emphasis on improving maintenance and, as a result, the plants are now performing at a very high level of safety and availability.

Up to now, Japan has largely emphasized design, construction and operation rather than maintenance in their nuclear plants. This is because maintenance was largely field or site oriented and experience based. There was little or no interest in developing the foundations of maintenance activities in a systematic way and as technical or academic discipline. This is in contrast to design, construction, and operation where a lot of technical knowledge and experience was assembled, then coupled with scientific techniques and methods, and organized into technical disciplines that could be widely taught, shared and applied.

However, recently the situation is shifting. A lot of technical experience and knowledge has also been accumulating in the maintenance area for Japanese nuclear power plants. So it is an appropriate time to utilize that information to develop fundamental principles applicable to maintenance. We can then lay down the foundation, couple these with scientific techniques and methods, and define a structured discipline of maintenance science or engineering.

This study, with the background described above, develops a systematic, quantitative evaluation method of maintenance for nuclear power plants by introducing the scientific approach. The study also reveals a method to obtain an optimum maintenance plan to be obtained by seeking to maximize nuclear safety and economic efficiency simultaneously and balancing them. The summary of the study is shown below.

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2. Maintenance Structure and Fundamentals

In a field that maintenance activities for an industrial plant are performed, there are a plant system which ageing degradation occurs as time in service passes, and a human system which restores the ageing degradation but sometimes makes human errors. Maintenance activities are performed between the two (Fig.1.). As a result, the plant system results in certain conditions, then is put into service and makes a product.

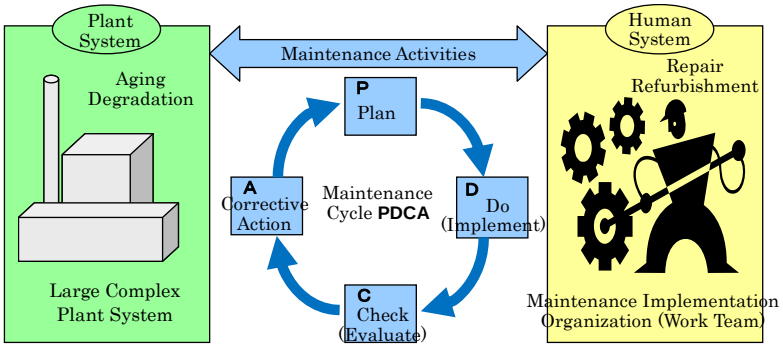

Fig.1. Maintenance phenomena in maintenance field

By regarding the relationship between the plant system and human system described above as "Maintenance Phenomena" and applying such a scientific methodology as utilized in physics to it, fundamental things are considered below, which are necessary for maintenance optimization. These include laws governing maintenance phenomena and its formulation, and methodologies to obtain an optimum solution of the maintenance plan.

2.1. Maintenance Phenomena and Laws Governing Them

For all industrial plants, a high level of safety and economic efficiency are required simultaneously, as well as it is required to meet social needs. They cannot survive without meeting these requirements. This is a basic concept in realizing an excellent maintenance, therefore it could be said that this is a final goal of maintenance activities.

In this study, these high level items are called as maintenance law, and are defined as follows [1].

- The first law of maintenance: Meeting of Social Needs
  Maintenance shall be effective in meeting social needs.
- The second law of maintenance: Maximization of Safety
  Maintenance shall demand a maximization of safety under given conditions.
- The third law of maintenance: Maximization of Economic Efficiency
  Maintenance shall demand a maximization of economic efficiency (minimization of maintenance costs) under given conditions.

2.2. Formulization of Maintenance Law

Generally speaking, providing excessive maintenance to a component to enhance its reliability and consequently enhance a safety of a whole plant system, then maintenance cost increases and economic efficiency decreases. On the contrary, by reducing maintenance activities to enhance an economic efficiency of a whole plant system, then the reliability and safety reduces. If this relationship between the safety and economic efficiency where the maintenance law governs is reduced to determining its extreme value, it could be considered to be an equation governing maintenance, i.e. maintenance equation [2].

The concept of risk (frequency $\times$ impact) to enable discussing safety and economic efficiency on an equal footing, it is considered below to describe a function S relating to safety and a function E relating to economic efficiency.

Function S (hereafter called as "safety risk function") is a function relating to the safety of the nuclear power plant system and therefore is assumed to be core damage frequency (CDF). CDF indicates the likelihood of an accident causing reactor core damage in the nuclear power plant which

consists of n components, meaning $i = 1, 2, 3 \ldots n$. When a failure rate of the i-th component is defined as λ_i, CDF is defined as follows.

$$S = CDF(\{\lambda_i | i \in \Omega\}) \tag{1}$$

When X_i is defined as maintenance plan for the i-th component, a failure rate λ_i of the i-th component can be considered to be a function of X_i, because it is a consequence of the maintenance plan X_i applied to the i-th component, and Ω is a set of the n components which the nuclear power plant consists of.

On the other hand, Function E (hereafter called as "Economic risk function") is a function relating to the economic efficiency of the nuclear power plant system and, therefore, it is proper to use a production cost for it here. It should be a maintenance related out of the total production cost because this study focuses on maintenance only.

As the production cost is a ratio of total maintenance cost (C_{total}) and power generation (Pr), it is shown as below.

$$C_{total} = \sum_{i \in \Omega} \{ \underbrace{C_P(X_i)}_{\text{Planned maintenance}} + \underbrace{\lambda_i \cdot T_{ope} \cdot C_{Ri}}_{\text{Restoration cost for component failure}} \} + \underbrace{C_{fail}}_{\text{Production loss from component failure}}$$

$$C_{fail} = \underbrace{\sum_{i \in \Omega} \{ GFF(\lambda_i) \cdot T_{ope} \cdot \alpha_i \cdot C_{Li} \}}_{\text{Production loss from component failure in the normal system}} + \underbrace{\sum_{i \in \Omega_S} (\beta_i \cdot \lambda_i \cdot T_{ope} \cdot C_{Li})}_{\text{Production loss from component failure in the safety system}}$$

$$Pr = G \cdot \{ \underbrace{Y}_{\text{One year (8760 hours)}} - \underbrace{T_0(\{X_i | i \in \Omega\})}_{\text{Plant outage time (hours/year)}} - \underbrace{T_{fail}}_{\text{Plant down time from component failure (hours/year)}} \}$$

$$T_{fail} = \underbrace{\sum_{i \in \Omega} \{ GFF(\lambda_i) \cdot T_{ope} \cdot T_{Li} \}}_{\text{Plant down time from component failure in the normal system}} + \underbrace{\sum_{i \in \Omega_S} (\beta_i \cdot \lambda_i \cdot T_{ope} \cdot T_{Li})}_{\text{Plant down time from component failure in the safety system}}$$

Where,

C_{total} : Total cost including a cost for the planned maintenance plan X_i which is provided to the i-th component, a cost required for the restoration in a failure of the i-th component which has a failure rate λ_i and a production loss from the i-th component failure.

$C_P(X_i)$: Cost for the planned maintenance plan X_i which is provided to the i-th component (Yen/year)

T_{ope} : Operating time per year

$$T_{ope} = (Y - T_0) / \left(1 + \sum_{i \in \Omega} \{ GFF(\lambda_i) \cdot T_{Li} \} + \sum_{i \in \Omega_S} (\beta_i \cdot \lambda_i \cdot T_{Li}) \right)$$

C_{Ri} : Cost for the restoration of the i-th component when it fails (Yen)

C_{fail} : Cost for power generation loss corresponding to plant down time due to the i-th component failure

$GFF(\lambda_i)$: Generation Failure Frequency as an economic assessment event in the nuclear plants which consist of the n components. The i-th component has a failure rate of λ_i.

α_i : Coefficient of plant output reduction when component i fails

C_{Li} : Power production loss cost caused by an occurrence of the above terminal condition (¥:Yen) (=Unit production loss cost (¥/hour)× T_{Li}(hours))

Pr : Total power production per year

G : Rated Power output (kW/hour)

Y : 8760 hours in a year
$T_0(X_i)$: Planned plant outage duration (hours/year)
T_{fail} : Forced plant outage duration caused by component failure
β : Ratio of the frequency of forced plant outages caused by the incompletion of repairing safety-related stand-by components within the allowed outage time to the frequency of the safety-related stand-by component failures
T_{Li} : Time required for restoring failed i-th component (in the case of safety-related stand-by components, it is the time of forced plant outage caused by the incompletion of repairing within the allowed outage time)
Ω_S : Set of safety-related stand-by components, and subset of the universal set of n components constituting a whole plant system

Based on the above, the economic risk function E is expressed by the following equation.

$$E = C_{total}/Pr \qquad (2)$$

In this study, the functions S and E respectively are regarded as a function of maintenance plan X_i and the maintenance optimization is handled as a problem of discovering a set of maintenance plans $\sum(X_i)$ for all components in a system of interest which contains all of maintenance plan X_i for each component. $\sum(X_i)$ is required to meet the maintenance goal or targets [3] for nuclear safety and economic efficiency.

The contents discussed above can be expressed as shown in Fig. 2. S_T and E_T are defined as the tentative targets on safety risk and economic risk respectively which are set for the calculation for obtaining new improved maintenance plan.

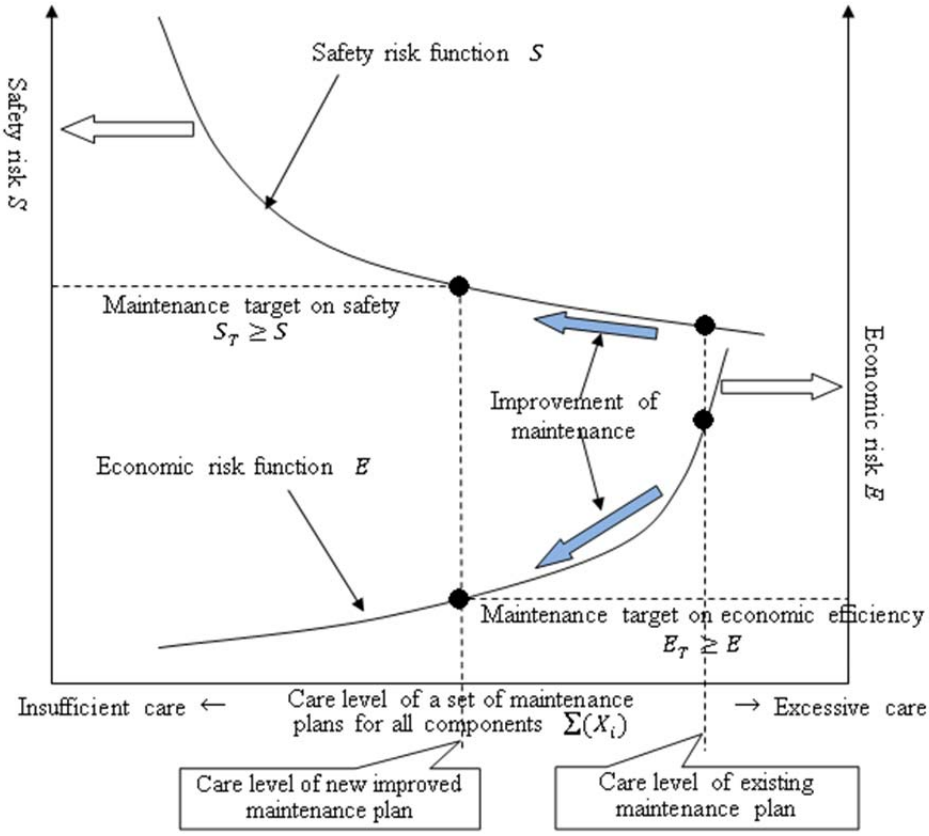

Fig.2 Relationship between plant safety and plant economic efficiency in maintenance field

2.3. Approaches on Maintenance Plan and Maintenance Work-team Performance

(1) Evaluation of an effect due to the appropriateness of maintenance plan [4]

The maintenance plan, i.e. inspection plan or corrective action plan, for components, is very important. It should be take into account the essential features of component portions that degrade, and their degradation modes. It also needs to specify appropriate maintenance plan for the component and the appropriate timing when the tasks should be implemented. If the maintenance plan is not carried out in time, then it is difficult to maintain functions of the component and of the plant system that consists of the components, even if maintenance activities based on the appropriate maintenance plan are appropriate. Therefore, quality of the maintenance plan could give an impact on component failure rates in the second and the third period in the bathtub curve shown in Fig. 3, rather than failure rate in the first period known as "initial failure period" by human error, etc. This means that the quality of maintenance plan could change component failure rates in the second and the third period in the curve.

Thus, in a simulation analysis on maintenance planning, it is necessary to make it possible to incorporate the quality of maintenance plan on the failure rate of components by taking account of the above.

(2) Evaluation of the effect of performance [4] by maintenance work-team

Maintenance work team performances (accuracy and efficiency) can be considered to be determined by the three factors of human system, that is, (i) maintenance procedure, (ii) maintenance work-team and (iii) tools including equipment and materials for maintenance. They could give an effect on component conditions after maintenance work. Therefore, the accuracy of maintenance work-team is evaluated as a factor which gives an effect on component failure rate as described above.

If a maintenance work team has higher effectiveness of maintenance work performances, then that can be considered to produce lower human error frequency in the first period in the bathtub curve shown in Fig. 3. If the team has lesser effectiveness, then that can be considered to produce higher human error frequency.

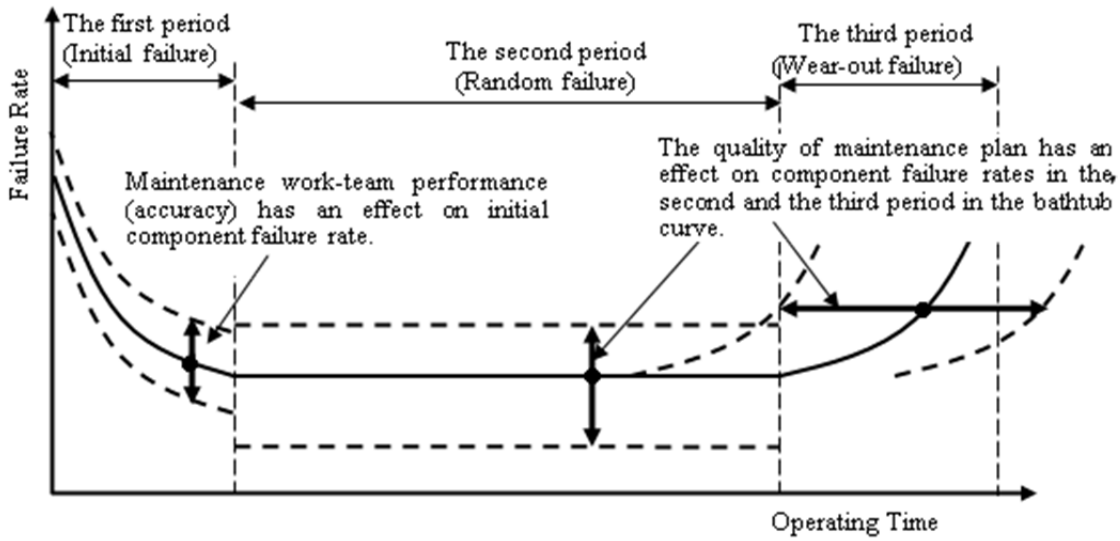

Fig.3 Relationship between appropriateness of maintenance applied to component and its failure rate

3. Simulation Analysis for Inspection Planning

3.1 Overview of Analysis

The simulation analysis was done by focusing on an inspection plan which is one of the maintenance plans. The primary goal is to obtain an optimum inspection plan for a simplified set of the overall BWR systems, i.e. RFW (Reactor Feed Water System) and HPCS (High Pressure Core Spray system) shown in Fig.4. An overview of the analysis is shown in Fig.5.

3.2 Analytical Model

(1) Governing equation used in the Analysis

The functions *S* and *E* discussed in the section 2.2 were used for evaluating the safety and economic efficiency of the plant systems described above.

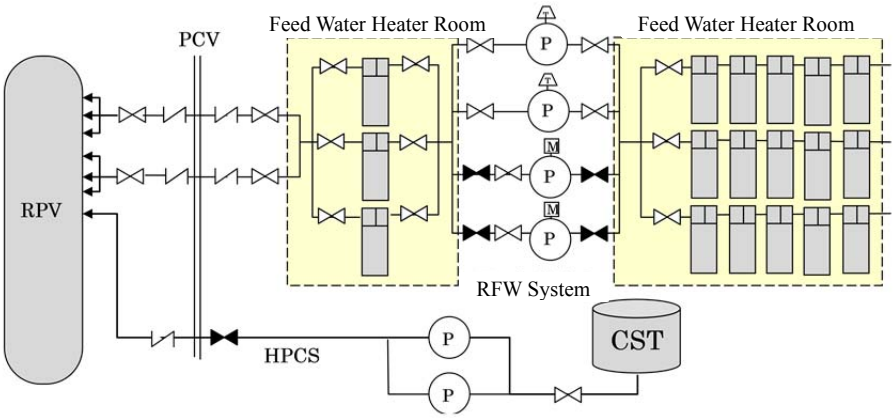

Fig.4 Plant systems for the simulation analysis

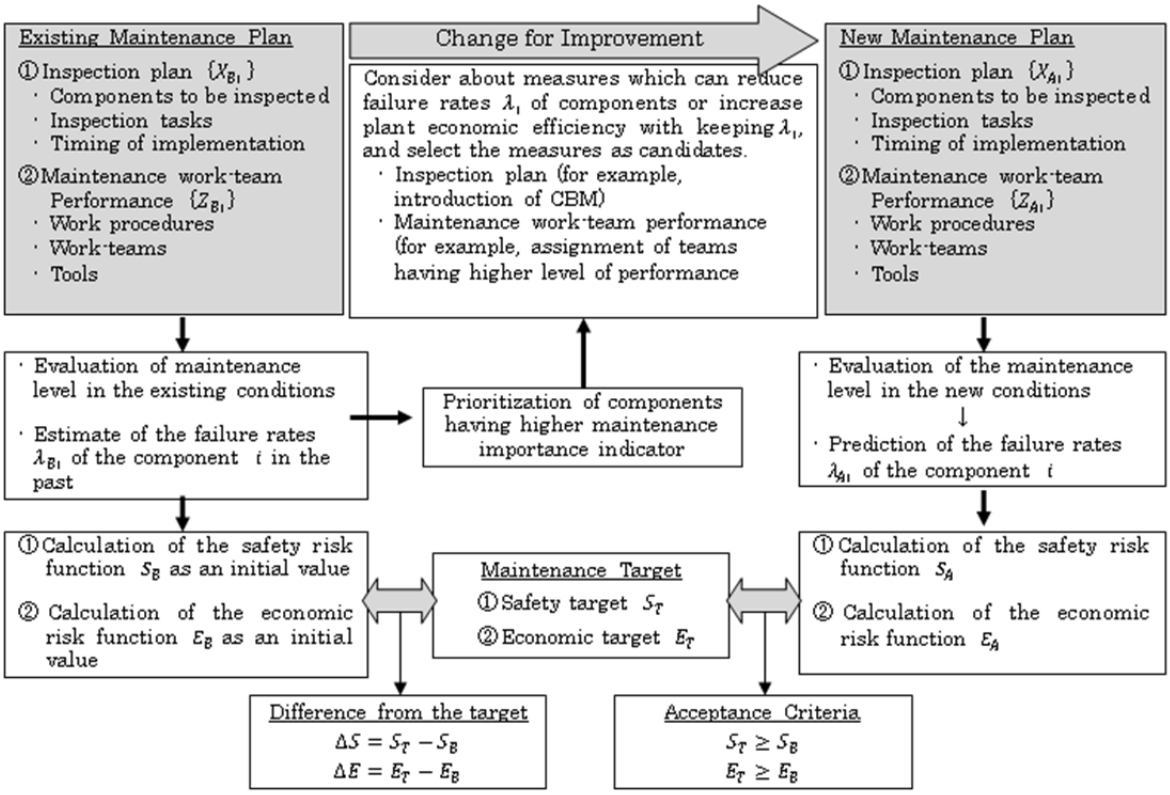

Fig.5 Production process of optimum maintenance plan

(2) Probabilistic analysis model used in this analysis

As for the function *S*, CDF was calculated by using the example calculation [5] in the condition of 1,100 MWe BWR-5 full-power operation released on the internet. Specifically, the CDF was obtained by substituting the HPCS failure frequency calculated in this study into one in the example calculation. In addition, the calculation was done only for large break LOCA, medium break LOCA and small break LOCA which are major contributors to the CDF.

As for the function E, the calculation was done by taking account of failures of the components constituting the RFW system and HPCS system.

The failure rate of the RFW was calculated by using the probabilistic risk assessment method. For this calculation, the power decreased events shown in Table 1 was taken into account and the

analytical model including fault tree analysis model shown in Fig.6 was constructed to calculate failure frequencies of the each event.

The failure rate of the HPCS was also calculated by using the probabilistic risk assessment method. The failures of HPCS as the safety related stand-by system do not lead to a forced plant outage if they can be repaired within AOT. But if they cannot, they lead to forced plant shutdown. The frequency of such forced plant shutdowns was assumed to be 10% of the failure frequency of the safety related stand-by systems in this study, taking account of the past experiences.

Table 1 Relation between function failure of reactor feed water system and plant power loss

Power Generation Loss	Failures of the Feed Water Pumps				Failures of the Feed Water Heaters	Failures of the Feed Water System Check valves
	TD- FWP A	TD-FWP B	MD-FWP A	MD-FWP B		
100%	×	×	×	×	—	—
	—	—	—	—	×	—
	—	—	—	—	—	×
75%	×	×	○	×	—	—
	×	×	×	○	—	—
50%	○	×	×	×	—	—
	×	○	×	×	—	—
	×	×	○	○	—	—
25%	○	×	○	×	—	—
	○	×	×	○	—	—
	×	○	○	×	—	—
	×	○	×	○	—	—
0%	×	○	○	○	—	—
	○	×	○	○	—	—
	○	○	○	×	—	—
	○	○	×	○	—	—
	○	○	×	×	—	—

×: Failure ○: Running —: N/A

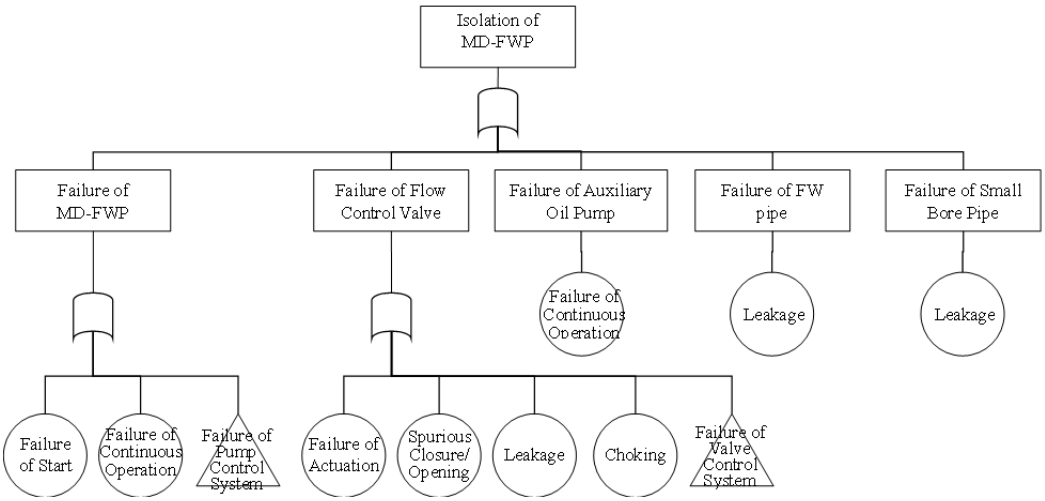

Fig.6 Fault tree for used in the simulation analyses (Example)

(3) Analytical models of inspection plan and maintenance work-team performance

① Improvement of inspection plan

When trying to improve an inspection plan consisting of three factors, i.e. an object to be inspected, inspection tasks for it and timing of the implementation, the followings are taken into account.

a) Initial failure (The first period in the bathtub curve in Fig.3.)

The initial failure rate can be considered not to be affected by the quality of inspection plan but could be by maintenance work-team performance, i.e. accuracy of maintenance work. So the inspection is assumed to have no impact from inspection plan in this simulation.

b) Random failure (The second period in the bathtub curve)

The random failure rate can be considered to be affected by the quality of inspection plan. So the simulation analysis is conducted by considering the followings.

· Case 1-1: Overhaul Interval Extension

The period between overhaul of components is extended by a factor of two. The component failure rate in the second period of bathtub curve is assumed to increase proportional to the extended period. (Ⓐ in Fig.7)

· Case 1-2: Overhaul Interval Extension with Reduced Component Failure Rate Compared to Case 1-1.)

As with the case 1-1, the overhaul interval of component is extended some years, but the failure rate is assumed to be a half of the case 1-1. (Ⓑ in Fig.7)

· Case 2: Introduction of Simplified Disassembly Inspection

The overhaul interval of component is extended some years, and the simplified disassembly inspection, which means to conduct only maintenance plan of uncoupling and centering for rotating components, is conducted at the midpoint during the overhaul interval. (Ⓒ in Fig.7) This is applied to only rotating components. As the components are not completely disassembled in this case and therefore, do not need many, complex or laborious works, it is proper to assume a low probability of causing human errors in field work or to expect no initial failures induced by human error.

· Case 3: Condition Based Maintenance (Periodic Monitoring)

The overhaul interval of component is extended some years and the periodic monitoring of component conditions is frequently conducted between overhauls in a condition-based maintenance mode. (Ⓓ in Fig.7) This is applied to only rotating components like pump or motor, MOV, and check valve. The other components are assumed to have a regular overhaul as in the past.

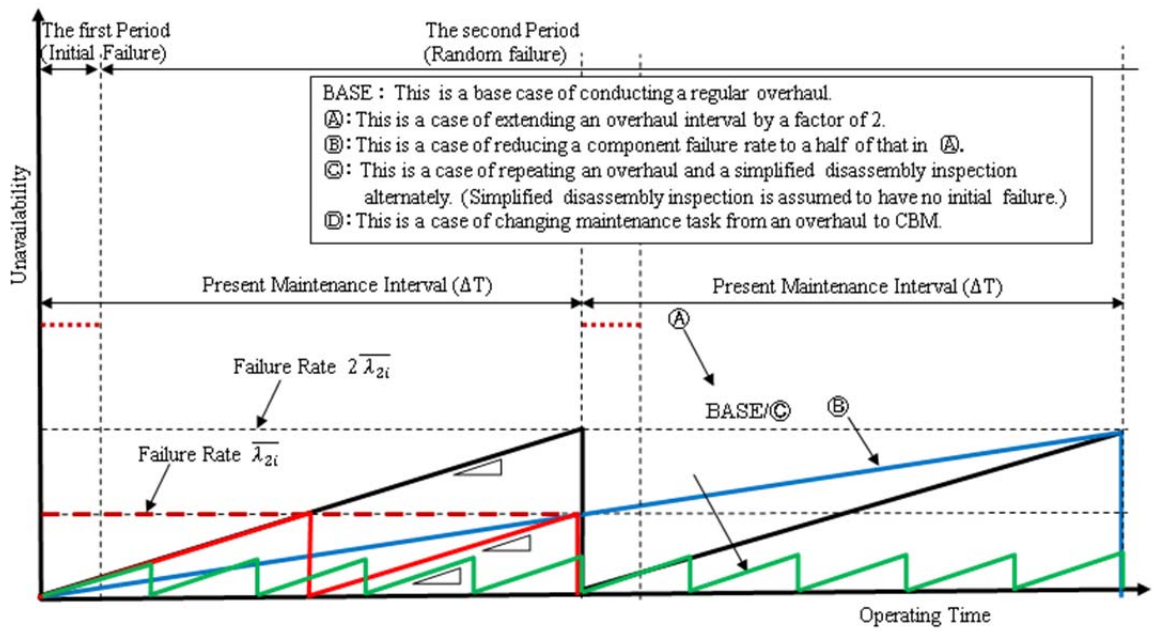

Fig.7 Relation between maintenance plan and analytical models of component failure rate

② Maintenance work-team performance

As shown in Fig.8, the component failure rate λ_i is consisted of the initial failure rate λ_{1i} and the random failure rate λ_{2i} and is expressed as follows.

$$\lambda_i \times \Delta T = \overline{\lambda_{1i}} \times \Delta t_1 + \overline{\lambda_{2i}} \times \Delta t_2 \fallingdotseq \overline{\lambda_{1i}} \times \Delta t_1 + \overline{\lambda_{2i}} \times \Delta T$$

Changing the above equation, the following equation can be obtained.

$$\lambda_i = \overline{\lambda_{1i}} \cdot \left(\frac{\Delta t_1}{\Delta T}\right) + \overline{\lambda_{2i}} \quad (3)$$

Where,

λ_i: Average failure rate of the component over the overhaul interval

Δt_1: Initial failure period, Δt_2 : Random failure period

$\overline{\lambda_{1i}}$: Average of the initial failure rate λ_{1i} over the initial failure period Δt_1

$\overline{\lambda_{2i}}$: Average of the initial failure rate λ_{2i} over the initial failure period Δt_2

ΔT : Overhaul interval of the component

As the maintenance work-team performance, i.e. accuracy of field work can be considered to affect mainly an initial failure rate, the following equation is assumed to be true by incorporating an influence factor ε into the above equation (3). If the maintenance work-team has higher effectiveness than before, it is assumed to be $\varepsilon < 1$. On the contrary, if the maintenance work-team has lesser effectiveness, it is assumed to be $\varepsilon > 1$.

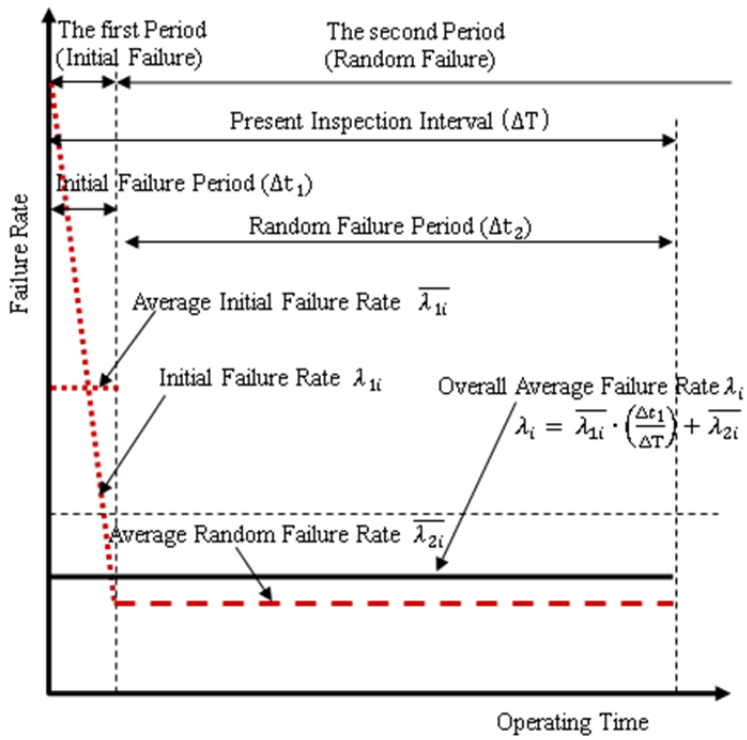

Fig.8 Component failure rate composed of initial and random failure

$$\lambda_i = \overline{\lambda_{1i}} \cdot \left(\frac{\Delta t}{\Delta T}\right) \cdot \varepsilon + \overline{\lambda_{2i}} \quad (4)$$

According to the operating experiences in Japanese nuclear plants, the human error frequency is reported to be about 15% [6], the initial failure rate and random failure rate are 15%, 85% respectively.

3.3 Method of Analysis

(1) Procedure of the simulation analysis

The simulation analysis is conducted as follows.

① The contents of the existing inspection plan for a certain target system are assumed. To improve the plan, the maintenance plans for some components in the system are selected for maintenance optimization, are gathered together as a new inspection plan, and both the old and new plans are

analyzed.

② By making use of the relation between tasks for inspection and component failure rate shown in Fig.7, the safety risk function S and the economic risk function E are calculated for both the old and new maintenance approaches. Then the difference between the existing and new inspection plan is evaluated.

③ By making use of the relation between maintenance work-team performance and component failure rate discussed above or varying ε in the equation (4) as a parameter, the safety risk function S and the economic risk function E are calculated. Then the difference between before and after the change of ε is evaluated, and the impact of the new plan can be assessed.

(2) Analytical conditions

① Assumptions

In consideration of the past performance etc., the followings are assumed in the calculation of the safety risk function S and the economic risk function E.

- Plant: 1,100MWe BWR-5
- Plant Life: 40 years
- Operating Cycle: 13 months (396 days)
- Plant Outage Duration: 3 months (91 days)
- Unit production loss cost: ¥200M/day

② Initial conditions etc.

The followings are assumed.

a) Inspection plan

The existing inspection plan $\{X_{Bi}\}$ for the components in the plant systems is shown at the pre-change column in Table 2. The new inspection plan consisting of the candidate tasks for some components in the plant systems is shown at the post-change column in Table 2.

b) Failure rate λ_{Bi} of component i in the pre change, cost for repair etc.

The data contained in the reference "Investigation on failure rate for PRA [7]" is used in this simulation analysis. The cost for repair and the duration required for repair are assumed as follows.

- Small failures: ¥100M, Two weeks
- Medium failures: ¥500M, One Month
- Major failures: These cases are excluded in this simulation analysis because they vary over a wide range with each case.

3.4 Obtained Results and Consideration

The results of the simulation analysis with the change of inspection plan and maintenance work-team performance are shown in Table 3 and table 4 respectively.

(1) Results of the cases of changing inspection plan

The objective of Case 1-1 (Overhaul Interval Extension) is to confirm how much the change of inspection plan to expand the overhaul intervals for higher economic efficiency impacts on the safety function S (CDF) and the economic function E (Production cost). The result of the analysis shows that E decreases while failure rates of the components increase. This means that the reduction of E due to the expansion of overhaul intervals is bigger than the increase of E due to the increase of component failure rates. The problem here is that for the results of the analysis to be valid, more effort is required. The effort is needed to develop probabilistic analysis models for the economic risk evaluation and to create the data base of various component failure rates etc. suitable for the economic risk evaluation. This is because the PRA methodology was developed for plant safety evaluation and the component failure rate data for it were also created for plant safety evaluation. Therefore, they may not have been developed for the purpose of economic risk evaluation as discussed in this paper. Thus, it may be necessary to review the methodology proposed in this paper and to revise a part of the methodology if necessary.

When component failures, troubles or incidents occur in nuclear power plant in Japan, larger cost and longer period for repair are needed in comparison with other advanced countries because

thorough investigation and determination of their causes and perfect countermeasures are required. For this reason, it is predicted that there is a big difference in the result of economic risk evaluation between Japanese and other advanced countries' nuclear power plants.

On the other hand, the result shows that *S* increases while failure rates of the components increase. In this way, if the overhaul intervals of the components are extended without anticipation of keeping their failure rates equal or less than before, sometimes the safety risk becomes higher while the economic risk becomes less. If the increase of the safety risk is acceptable comparing with the safety target preset before changing the inspection plan.

The objective of Case 1-2 is to confirm how much the change of the inspection plan -- extending the overhaul intervals of some components for higher economic efficiency -- gives an impact on the safety function *S* (CDF) and the economic function *E* (Production cost). This option is effective only when a planner has the firm conviction that the extension of overhaul intervals produces no major increase in the component failure rates. The result of the analysis shows that *S* remains the same as before and *E* significantly decreases. This is quite natural because the component failure rates were assumed to remain the same as before in Case 1-1. This option may be very effective in such plants as the Japanese nuclear plants where periodic overhaul of the components in relatively short intervals has been historically done.

Table 2 Analytical conditions before and after the change of maintenance plan

Reactor Feed Water System

Maintenance Objects		Unit Number	Before the Change		After the Change		Contents of the Change of the Maintenance Plan			
			Maintenance plan	Cost (¥/Component)	Maintenance plan (Candidate)	Cost (¥/Component)	Extension of the Interval (Before →After) Unit: Month	Case 1 (Extension of the overhaul Interval)	Case 2 (Introduction of Simplified Disassembly Inspection)	Case 3 (Introduction of CBM)
Area around FW Heaters	FW Heater	18	TBM（Tube ECT）	20M	Same as on the left	20M	Interval（8→12,16）	○		
	Main Pipe	390	TBM（Wall Thickness Measurement etc.）	3M	Same as on the left	3M	No change(8)			
	Small Bore Pipe	137	TBM（NDI）	1M	Same as on the left	1M	No change(8)			
Around FW Check Valves	Check Valve	4	TBM（Overhaul）	20M	Same as on the left	20M	Interval（6→9,12）	○		
					CBM (Valve Disc Monitoring)		Monitoring Frequency （Every two month）			○
	Main Pipe	36	TBM（Wall Thickness Measurement etc.）	3M	Same as on the left	3 M	No change(8)			
	Small Bore Pipe	10	TBM（NDI）	1M	Same as on the left	1 M	No change(8)			
Area around TD-FW Pumps	TD-FW Pump (including the Turbine for Pump Drive)	2	TBM（Overhaul）	130M	Same as on the left	130 M	Interval（4→6.8）	○		
					TBM (Simplified Disassembly Inspection)	15 M	Interval（4→6,.8）		○	
					CBM (Vibration Analysis, Oil Analysis)	0. M	Monitoring Frequency 【Every two month】			○
	Main Pipe	6	TBM（Wall Thickness Measurement etc.）	3M	Same as on the left	3 M	No change(8)			
	Small Bore Pipe	23	TBM（NDI）	1M	Same as on the left	1 M	No change(8)			
	Auxiliary Oil Pump	1	TBM（Overhaul）	10M	Same as on the left	10 M	Interval（8→12,16）	○		
					TBM (Simplified Disassembly Inspection)	3 M	Interval（8→12,16）		○	
					CBM (Vibration Analysis, Oil Analysis)	0. M	Monitoring Frequency(Every two month)			○
Area around MD-FW Pumps	Motor-driven Pump (including the motor)	2	TBM（Overhaul）	70M	Same as on the left	70 M	Interval（8→12,16）	○		
					TBM (Simplified Disassembly Inspection)	22 M	Interval（8→12,16）		○	
					CBM (Vibration Analysis, Oil Analysis)	0. M	Monitoring Frequency (Every two month)			○
	Control System for the Pump	1		50M	Same as on the left	50 M	No change(4)			
	FCV	2	TBM（Overhaul）	10M	Same as on the left	10 M	No change(4)			
	Control System for the FCV	3	TBM	17M	TBM	17 M	No change(4)			
	Main Pipe	6	TBM(Pipe Wall Measurement)	3M	Same as on the left	3 M	No change(8)			
	Small Bore Pipe	23	TBM（NDI）	1M	Same as on the left	1 M	No change(8)			
	Auxiliary oil pump	1	TBM（Overhaul）	10M	Same as on the left	10 M	Interval（8→12,16）	○		
					TBM (Simplified Disassembly Inspection)	3 M	Interval（8→12,16）		○	
					CBM (Vibration Analysis, Oil Analysis)	0. M	Monitoring Frequency (Every two month)			○

High Pressure Core Injection System

Outside PCV	Motor-driven Pump	1	TBM (Overhaul)	50 M	Same as on the left	50 M	Interval（8→12,16）	○		
					TBM (Simplified Disassembly Inspection)	15 M	Interval（8→12,16）		○	
					CBM (Vibration Analysis, Oil Analysis)	0. M	Monitoring Frequency (Every two month)			○
	Control System for the Pump	1	TBM	50 M	Same as on the left	50 M	No change(4)			
	Reactor Injection Valve	1	TBM（Overhaul）	10 M	Same as on the left	10 M	Interval（8→12,16）	○		
					CBM (Valve Disc Monitoring)	0. M	Monitoring Frequency (Every two month)			○
	Control System for the Valve	1	TBM	50 M	Same as on the left	50 M	No change(4)			
	Emergency DG	2	TBM（Overhaul）	125 M	Same as on the left	200 M	Interval（8→12,16）	○		
					CBM (Engine Signature Analysis)	0. M	Monitoring Frequency (Every one month)			○
	Control System for the EDG	2	TBM	25 M	Same as on the left	50 M				
	Main Pipe	60		3 M	Same as on the left	3 M	No change(8)			
	Small Bore Pipe	13		10 M	Same as on the left	10 M	No change(8)			
	Condensate Storage Tank	1	TBM（Overhaul）	30 M	Same as on the left	30 M	Interval（8→12,16）	○		
Inside PCV	Main Pipe	5	TBM(Pipe Wall Measurement)	3 M	Same as on the left	3 M	No change(8)			
	Small Bore Pipe	1	TBM（NDI）	1 M	Same as on the left	1 M	No change(8)			

The objective of Case 2 (Introduction of Simplified Disassembly Inspection) is to confirm how much the change of the inspection plan -- extending the overhaul intervals of some components and adding simplified maintenance (for example, simple maintenance works including just only uncoupling and centering for rotating components) at the midpoint of the extended interval between two overhauls -- gives an impact on *S* and *E*. This case is derived from the good practices in the US nuclear plants that the simplified maintenance (uncoupling and centering) has been successfully applied to such rotating components as pumps or motors because they have had relatively many failures due to misalignment, mismatch, center shifting etc. The result of the analysis shows that *S* does not increase and *E* decreases. This option promises a certain level of economic effect without any increase of plant safety risk. It may also provide less human error rate because of less field work by maintenance team. But it should be noted that this option is effective only when it needs less field work or cost, and a planner has the firm conviction that it produces no major increase in the component failure rates.

Table 3 Effect of the change of maintenance plan on plant safety and economic efficiency

	Evaluation Items \ Case		Base Case	Case 1-1 (Overhaul interval: twice the base case)	Case 1-2 (Failure rate: a half of Case 1-1)	Case 2 (Introduction of Simplified Disassembly Inspection)	Case 3 (Introduction of CBM)
1	Total Maintenance Cost (2) (A)	¥/Year	490,024,686	371,892,377 298,743,081	357,999,686 269,974,686	453,166,224 433,433,976	408,652,158 381,464,272
	Planned Maintenance Cost	¥/Year	448,600,000	316,575,000 228,550,000	316,575,000 228,550,000	416,425,000 393,350,000	391,600,000 365,100,000
	Unplanned Maintenance Cost	¥/Year	23,139,899	31,681,399 40,799,170	23,139,899 23,139,899	18,562,288 21,831,700	3,927,386 3,380,835
	Cost due to Generation Loss (Failure of RFW)	¥/Year	13,029,172	16,410,376 20,066,989	13,029,172 13,029,172	12,954,697 13,005,625	12,549,573 12,539,476
	Cost due to Generation Loss (Failure of HPCS)	¥/Year	5,255,615	7,225,602 9,326,922	5,255,615 5,255,615	5,224,240 5,246,650	575,199 443,961
2	Total Power Generation (B)	Kwh/Year	5,989,581,800	5,988,649,900 5,987,620,300	5,989,581,800 5,989,581,800	5,989,600,300 5,989,587,100	5,990,554,900 5,990,511,100
	Annual Ope. Hour－Plant Outage Hours	Day/Year	227	227 227	227 227	227 227	227 227
	Generation Loss (Failure of RFW)	Day/Year	0.0869	0.109 0.134	0.0869 0.0869	0.0864 0.0867	0.0837 0.0836
	Generation Loss (Failure of HPCS)	Day/Year	0.0350	0.0482 0.0622	0.0350 0.0350	0.0348 0.0350	0.0038 0.0030
3	Unit Cost for Maintenance (A/B) (Economic Risk *E*)	¥/Kwh	0.0818	0.0621 (24% Decrease) 0.0499 (39% Decrease)	0.0598 (27% Decrease) 0.0451 (45% Decrease)	0.0757 (7% Decrease) 0.0724 (11% Decrease)	0.0682 (17% Decrease) 0.0637 (22% Decrease)

(1) Upper row：Calculation results in case of 1.5 times the overhaul interval in the base case.
Lower row：Calculation results in case of 2 times the overhaul interval in the base case.
(2) This includes a maintenance cost of all the components considered in this calculation.

	Evaluation Items \ Case		Base Case	Case 1-1	Case 1-2	Case 2	Case 3
1	Core Damage Frequency CDF (1) (/Reactor Year) （Safety Risk *S*）	Case of 1.5 times the overhaul interval in the base case	2.07×10^{-8}	2.65×10^{-8} (28% Increase)	2.07×10^{-8} (±0%)	2.06×10^{-8} (0.5% Decrease)	6.98×10^{-9} (66% Decrease)
		Case of 2 times the overhaul interval in the base case		3.26×10^{-8} (57% Increase)	2.07×10^{-8} (±0%)	2.07×10^{-8} (±0%)	6.60×10^{-9} (68% Decrease)

(1) The calculation was done by focusing on Small, Intermediate and Large LOCA out of all CDF events.

Table 4 Effect of the change of maintenance work-team performance on plant safety and economic efficiency

	Evaluation Items \ Case		Maintenance Work-team Performance Improvement Factor					
			$\varepsilon = 0.1$	$\varepsilon = 0.5$	$\varepsilon = 0.8$	$\varepsilon = 1.0$	$\varepsilon = 1.2$	$\varepsilon = 1.5$
1	Total Maintenance Cost (1) (A)	¥/Year	484,410,423	486,904,806	489,400,541	490,024,686	491,273,229	493,146,678
	Planned Maintenance Cost	¥/Year	448,600,000	448,600,000	448,600,000	448,600,000	448,600,000	448,600,000
	Unplanned Maintenance Cost	¥/Year	20,013,325	21,402,810	22,792,460	23,139,899	23,834,807	24,877,246
	Cost due to Generation Loss (Failure of RFW)	¥/Year	11,250,991	12,040,552	12,831,300	13,029,172	13,425,139	14,019,646
	Cost due to Generation Loss (Failure of HPCS)	¥/Year	4,546,107	4,861,444	5,176,781	5,255,615	5,413,283	5,649,786
2	Total Power Generation (B)	Kwh/Year	5,990,200,000	5,989,824,700	5,989,632,000	5,989,581,800	5,989,484,100	5,989,336,300
	Annual Ope. Hour－Plant Outage Hours	Day/Year	227	227	227	227	227	227
	Generation Loss (Failure of RFW)	Day/Year	0.0750	0.0803	0.0855	0.0869	0.0895	0.0935
	Generation Loss (Failure of HPCS)	Day/Year	0.0303	0.0324	0.0345	0.0350	0.0361	0.0377
3	Unit Cost for Maintenance (A/B) (Economic Risk *E*)	¥/Kwh	0.0809 (1.1%)	0.0813 (0.6% Decrease)	0.0816 (0.2% Decrease)	0.0818	0.0820 (0.2% Increase)	0.0823 (0.6% Increase)

(1) This includes a maintenance cost of all the components considered in this calculation.

	Evaluation Items \ Case	Maintenance Work-team Performance Improvement Factor					
		$\varepsilon = 0.1$	$\varepsilon = 0.5$	$\varepsilon = 0.8$	$\varepsilon = 1.0$	$\varepsilon = 1.2$	$\varepsilon = 1.5$
1	Core Damage Frequency CDF (1)（/炉年） （安全リスク*S*）	1.81×10^{-8} (12.6% Decrease)	1.92×10^{-8} (7.2% Decrease)	2.01×10^{-8} (2.9% Decrease)	2.07×10^{-8} （Base Case）	2.13×10^{-8} (2.9% Increase)	2.21×10^{-8} (6.8% Increase)

(1) The calculation was done by focusing on Small, Intermediate and Large LOCA out of all CDF events.

The objective of Case 3 (Condition Based Maintenance) is to confirm how much the change of the inspection plan -- extending the overhaul intervals of some components and adding frequent condition monitoring to check the integrity of the components over the extended interval between overhauls-- gives an impact on *S* and *E*. The result of the analysis shows that both *S* and *E* decrease significantly. This option should be incorporated into the existing inspection plan for maintenance optimization. But

it is effective only when some condition monitoring technologies exist which are applicable to detect failure symptom due to degradation and a planner has the firm conviction that it is a reliable technology. Fortunately, several kinds of condition monitoring technologies, for example, vibration analysis, lubricant analysis, MOV analysis, diesel engine analysis etc., have been applied to components in US and European nuclear power plants for a long time and they are considered to be proven. So it is expected that those technologies are applied to Japanese nuclear power plants and many other new condition monitoring technologies will be developed.

(2) Results of the cases of changing maintenance work-team performance

The objective of this analysis is to confirm how much the change of maintenance work-team performance (Accuracy of field work) gives an impact on *S* and *E*. The result of the analysis shows that the maintenance work-team performance has an insignificant effect on E, but has a significant effect on *S* because an improvement of maintenance work-team performance could reduce the safety risk *S* significantly.

$\varepsilon = 0.1$ (The initial failure rate is assumed to nearly equal zero.): 12.5% down

$\varepsilon = 1.5$ (The initial failure rate is assumed to be much greater than in previous years.): 6.8% up

If the rationalization of maintenance progresses in the future, then the future random failure rates of components would be less than in previous years, and the improvement of maintenance work-team performance to reduce initial failure rates would become increasingly important. Therefore, it will become more important to make a quantitative correlation quantitatively between maintenance work-team performance and component failure rates. Additionally, the improvement of maintenance work-team performance can be achieved by improving the three factors of the human system in maintenance (maintenance work procedure, maintenance work-team and tools) through education and training, benchmark activities, workshops etc.

4. Conclusion

Recently a lot of technical experience and knowledge has been accumulating in the maintenance area for Japanese nuclear power plants. So it is an appropriate time to utilize that information to develop fundamental principles applicable to maintenance. With this background, this study developed a methodology of making a new inspection plan and new on-site work-team plan, which meet the maintenance targets considered to be optimum at that time. The method introduces the use of the scientific and quantitative approach, and also revealed that it was possible to assess new plans through computer simulation.

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