Maintenance Index for System Safety Assessment for Aging Nuclear Power Plant

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ABSTRACT
In this research, called the “the maintenance index,” was proposed to evaluate the reliability of nuclear power plant safety systems by taking into account periodic maintenance of the systems. The change in reliability as a result of changing activity is estimated by this index. The Maintenance Index offers a more comprehensive evaluation of nuclear power plant safety.

KEYWORDS
maintenance index, system safety, reliability of system function

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1. Introduction
A nuclear power plant’s complexity, with its multitude of infracting components, challenges the efforts of safety engineers. Conventional assessments are based on the reliability of safety systems designed to perform particular functions. Furthermore, the reliability of these systems are based on the corrective reliability of individual devices and structures. It is the individual safety function of these systems that can prevent and mitigate accidents characteristic of nuclear power plants. These systems are in place to account for Design Based Events (DBE). Considering the reliability of each of these systems, the overall safety on the nuclear power plant can be estimated regarding DBE.

However, the same conventional safety assessment falls short in providing an accurate estimate of a plant’s true safety capability over time because it only evaluates how each system fails without considering periodic maintenance. Devices and structures cannot avoid decreased reliability from consistent usage, a problem usually alleviated by maintenance. This ability of the system to perform the necessary safety function is likely misrepresented by conventional indices. The aim of this research is to develop a new nuclear power plant safety assessment focusing on changes in reliability over time considering both aging effects and maintenance effects. We named this assessment “the Maintenance Index” (MI), and in this paper, its basic concept will be explained.

2. Scheme of Maintenance Index
2.1 Flow chart of the maintenance index evaluation
A nuclear power plant is a large scale complex system that consists of numerous devices and structures. The devices and structures are classified into systems such as the main steam piping system

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of BWR, the primary and secondary coolant systems of PWR, and the turbine system, etc. The MI focuses on devices and structures incorporated into plant safety systems.

Fig. 1 shows a flow chart of the MI evaluation. The first step is to select a safety system from four function groups; the boundary function, the cooling function, the control function, and the common function (power supply). The former three functions are conventional and the last one is our original proposal, regarding the events that transpired during the Fukushima Daiichi NPP accident. After the system is selected, the second step is to determine the devices and structures required for the system to function appropriately.

For the third step, the failure of the equipment and structures is divided into dynamic or static causes. Each cause is classified into their failure modes, and the failure rate $\lambda_i$ of each mode is determined from existing database such as NUCIA\[^1\].

For the fourth step, the probability of each failure mode is modeled proportional to time as $t\lambda_i$ given an a priori assumed maintenance plan. The revised failure probabilities are summed up to the function loss probability of the complete system.

In the last step, the function loss probability is re-evaluated by slightly changing the initial maintenance plan. The sensitivity to changes in functional loss probability with regards to changes in the maintenance plan provides the safety estimate for MI.

2.2 Failure rate from dynamic cause

Table 1 shows an example of the failure rate of several dynamic failure modes referenced from NUCIA\[^1\]. The upper table is the demand failure rate and the lower is the time failure rate for some of the failure modes of certain devices. The failure rates were calculated using a Bayes model (MCMC models)\[^2\] from the assumed total demanding factor ($D$) and the total operating time ($h$); $1/D$ and $1/h$ was used respectively for the calculation to normalize the data. These data are used to calculate
time-series failure probability of devices and structures. Using the failure rate of each failure mode $\lambda_i$, the probability of failure was modeled proportional to time as $t\lambda_i$ without considering maintenance.

<table>
<thead>
<tr>
<th>Models</th>
<th>Fault mode</th>
<th>Number of cases observed</th>
<th>Assumed total demanding factor (D)</th>
<th>Bayes statistics (MCMC method)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergency DG</td>
<td>Start up fail</td>
<td>46</td>
<td>54,795</td>
<td>1.9E-03</td>
</tr>
<tr>
<td>Electrical pump</td>
<td>Start up fail</td>
<td>5</td>
<td>183,898</td>
<td>4.3E-05</td>
</tr>
<tr>
<td>Turbine driving pump</td>
<td>Start up fail</td>
<td>22</td>
<td>14,933</td>
<td>2.0E-03</td>
</tr>
<tr>
<td>Electrical valve</td>
<td>Opening fail</td>
<td>16</td>
<td>648,842</td>
<td>3.4E-05</td>
</tr>
<tr>
<td></td>
<td>Closing fail</td>
<td>7</td>
<td>649,357</td>
<td>7.9E-06</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model</th>
<th>Fault mode</th>
<th>Number of cases observed</th>
<th>Total operating time (h)</th>
<th>Bayes statistics (MCMC method)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergency DG</td>
<td>Start up fail</td>
<td>46</td>
<td>1.6E+07</td>
<td>6.5E-06</td>
</tr>
<tr>
<td>Turbine driving pump</td>
<td>Start up fail</td>
<td>22</td>
<td>8.7E+06</td>
<td>3.8E-06</td>
</tr>
<tr>
<td></td>
<td>Continuing operation fail</td>
<td>10</td>
<td>1.0E+07</td>
<td>2.0E-06</td>
</tr>
<tr>
<td>Electrical valve (Pure water)</td>
<td>Running fail</td>
<td>25</td>
<td>1.2E+09</td>
<td>1.5E-08</td>
</tr>
<tr>
<td></td>
<td>Opened or closed by mistake</td>
<td>0</td>
<td>1.2E+09</td>
<td>1.4E-09</td>
</tr>
<tr>
<td></td>
<td>Blockade</td>
<td>2</td>
<td>1.2E+09</td>
<td>2.7E-09</td>
</tr>
<tr>
<td></td>
<td>Exterior leakage</td>
<td>1</td>
<td>1.2E+09</td>
<td>1.9E-09</td>
</tr>
<tr>
<td></td>
<td>Interior leakage</td>
<td>2</td>
<td>1.2E+09</td>
<td>2.7E-09</td>
</tr>
<tr>
<td>Blocking equipment</td>
<td>Running fail</td>
<td>13</td>
<td>9.2E+08</td>
<td>1.6E-08</td>
</tr>
<tr>
<td></td>
<td>Opening error</td>
<td>14</td>
<td>9.2E+08</td>
<td>2.8E-08</td>
</tr>
<tr>
<td></td>
<td>Closing error</td>
<td>2</td>
<td>9.2E+08</td>
<td>3.1E-09</td>
</tr>
</tbody>
</table>

2.3 Effect of maintenance (only dynamic failure)

The following five evaluation criterions were applied to determine the effect of maintenance on each failure mode:

i) Can the failure mode be prevented by maintenance? If No, the failure probability increases monotonically proportional to time.

ii) Where does the failure probability increase to? Can the cause of the failure mode be removed by overhaul? If No, the failure probability increases until its end of life. If Yes, the failure probability decreases to zero at every exchange.
iii) After overhaul inspection, is a test operation performed under real operating conditions? If No, the decrease in failure probability is limited because the possibility of human error during reassembly cannot be eliminated. If Yes, the possibility of human error can be eliminated.

iv) Is the Condition Based Maintenance applied? If Yes, the failure rate is decreased. Here we assume it decreases to half of the original.

Figure 2 shows an example of the time-series probability of several failure modes for electrical pump. Cables cannot undergo maintenance until the end of lifetime, and, as a result, the failure probability perpetually increases linearly over time. The instrumentation and control equipment as well as the motor insulator undergo overhaul inspection. Therefore, these components’ failure probability increase linearly until exchange, then the failure probability reset to its initial value. The failure probability of the sliding part follows the overhaul inspection trend; but considering the possibility of human error during assembling, the effect of maintenance does not return the component to its initial failure probability. Nonetheless, the possibility of human factor can be considerably reduced if the test operation is in real condition, allowing for a larger recovery in failure probability.

![Fig. 2. Example of the time-series of probability of several failure mode of electrical pump](image)

2.4 System’s functional loss probability calculation

A system’s functional loss probability was calculated as the sum of the failure probabilities of devices and structures. The system’s function was assumed to be lost when the devices and structures that compose the system have failed. Fig. 3 shows a model of conditional tree diagram to evaluate the probability of function loss of “reactor cooling”. The “reactor cooling” function is lost if one of the RHR systems (low pressure flooding mode), LPCS system, HPCS system, or ADS system fails.
3. Evaluation Results by Maintenance Index

Fig. 4 shows the time-series probability of failure of each component associated with the valves and pumps, within the RHR’s A-system. However, the calculation only included dynamic failure and the static ones (damage in pipe boundary) are not considered. Instrumentation and control equipment degradation contribute the largest probability for the valve’s failure, while sliding parts adherence has the secondary dominant failure mechanism for the pump.

Fig. 4. Example of calculated time-variation of fails of valve and pump of RHR’s A-system due to each failure mode (left: valve, right: pump)

Fig. 5. Example of calculated time-variation of failure of valve and pump due to each failure mode of RHR’s A-system
Fig. 6. Example of calculated time-variation of probability of loss of “reactor cooling” function

The RHR system provided the largest failure risk for the “Reactor Cooling” function as shown in Fig. 6. In Fig. 5, the pump’s failure probability is larger than that of valve. Among the failure modes of the valve, the contribution of instrumentation and control equipment degradation was found to be dominant (Fig. 4 left). On the other hand, among the failure modes of the pump, the contribution of sliding part adherence is the second largest (Fig. 4 right). Therefore, it can be inferred that the effect of overhaul inspection interval to the increase in probability of loss of “Reactor Cooling” is lower for the valve in comparison to the pump.

Fig. 7 compares the changes in probability of loss of “Reactor Cooling” function over 50 years by changing the overhaul inspection intervals of the valve (5 years interval) and pump (10 years interval). The effect on the valve was an increase of 1% of probability of loss of “Reactor Cooling”. On the other hand, the pump experienced an increase as large as 13%. Thus, by comparing system reliability before and after changes in maintenance interval, the effect of change of maintenance condition value can be evaluated.

Fig. 7. Comparison of ratio of the probability of loss of “Reactor Cooling” function for the valve (left) and the pump (right) projected for the next 50 years by changing the overhaul inspection interval

4. Conclusion

A new index was proposed to estimate the reliability of nuclear power plant safety system over time, taking into account aging and maintenance. This index will be useful to evaluate the impact of maintenance activity and to suggest improvements of maintenance protocols in order to increase of system safety.

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References