CHEMICAL ENGINEERING TRANSACTIONS

VOL. 33, 2013

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet

Guest Editors: Enrico Zio, Piero Baraldi

ISBN 978-88-95608-24-2; **ISSN** 1974-9791 DOI: 10.3303/CET1333143

Monitoring Method Development for Safety Component on Standby State

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Although failure probabilities of several components have been dramatically reduced so far, it is still difficult to meet the required reliability in the safety-critical applications such as Nuclear Power Plant (NPP). Most of the components of which successful operation on demand is a crucial factor of safety are in standby states. Generally it is very difficult to detect the failure of standby components since their operation status cannot be observed. Periodic testing is currently the only mean to cope with this uncertainty. In this paper, a concept of a monitoring method for standby safety components is proposed in order to guarantee their integrity
The proposed method basically operates the target component for the final decision of failure. However, for this approach, we should solve some problems: the time for component operation in certain signal, the independence from the other working parts during the operation for diagnosis, and the surveillance test interval. To solve these problems, the proposed method is composed with direct and indirect inspection methods. Furthermore, to show the effectiveness of proposed monitoring method, sensitivity analysis according to the surveillance test interval was conducted.

1. Introduction

After the Fukushima nuclear accident, the importance of nuclear power plant safety has been further emphasized, internationally. Therefore, to improve the safety of nuclear power plants, diverse passive cooling systems are being proposed. However, all passive systems are not identical. It can be divided into 4 categories (IAEA-TECDOC-626, 1991). Among them, most of passive residual heat removal systems belong to category D, meaning they have active initiation and passive execution characteristics. In other words, they still have active characteristics which are signal inputs, eternal power source, and mechanical movement. Among these active characteristics, mechanical movement was identified as the crucial factor for the successful operation of the system through Probabilistic Safety Analysis (PSA).
The representing mechanical part for the passive system is Mower Operated Valve (MOV) and the check valve. Varieties of passive systems which include such valve are presented (IAEA-TECDOC-1624, 2009). These valves isolate the passive system from the operating region during the normal situation. However, when an accident occurs, it connects a new path to remove heat. For this reason, in order to build a greatly reliable passive system, normal functioning of such a valve should be guaranteed. However, the soundness of these valves can only be examined during the specific period due to interference to the operating region and limitation of accessibility. It is difficult to guarantee the performance of its functions through this inspection method. In this paper, as a solution to this problem, a concept of monitoring method for standby safety components is proposed.
In section 2, basic approaching concept of proposed monitoring method will be described. In section 3, general monitoring methods and their characteristics will be presented. Section 4 proposes an effective logic that combines the characteristics introduced in section 3. Finally, in section 5, the proposed method will be analysed in mathematical way.

Please cite this article as: Sung Min S., Bo Gyung B., Hyun Gook H., 2013, Monitoring method development for safety component on standby state, Chemical Engineering Transactions, 33, 853-858 DOI: 10.3303/CET1333143

2. Basic approaching concept

In this section, the basic approaching concept of the monitoring methods will be discussed. First, the unit of unserviceability of target component can be expressed in unavailability equation. Low unavailability means the component operates well undoubtedly. For the unavailability equation, there are some assumptions: the failure occurrence is time dependent, the component is inspected periodically, and the unavailability is 0 immediately after the inspection or repair. Under the above assumptions, mean unavailability can be given as Eq. (4). Here, Eq. (1) expresses the unavailability due to the occurrence of failure and this equation is obtained from linear ageing model (Kancev D., 2011). Eq. (2) expresses the unavailability due to the inspection procedure, and Eq. (3) expresses the unavailability due to the repair procedure.

$$\mathrm{Q_F(t)} = \rho + \frac{1}{6}T_i(3\lambda_0 + 2\theta T_i) \tag{1}$$

$$\mathrm{Q_T(t)} = T_t \times \frac{1}{T_i} \tag{2}$$

$$\mathrm{Q_R(t)} = (\rho + \lambda_0 T_i)\frac{T_r}{T_i} \tag{3}$$

$$\mathrm{Q}_{mean}(\mathrm{t}) = \mathrm{Q_F} + Q_T + \mathrm{Q_R} \tag{4}$$

Notice that ρ is failure probability per demand and it is assumed as a constant value, T_i is surveillance test interval (STI), λ_0 is standby failure rate, θ is linear aging rate, T_t is test duration, and T_r is mean time to repair. When viewed through the equations above, the shorten STI results the smaller$Q_F(t)$. However, shorter STI makes the increase in $Q_T(t)$ simultaneously. Here is the important concept to reduce the mean unavailability of component. If there is an inspection method which does not increase the QT, the mean component unavailability can be lowered effectively. In the other words, if some inspection method does not interfere to the expected function of component, it is possible to lower the STI without any limitation. This study is focused on this point.

3. General monitoring methods and their characteristics

Simply, the methods to inspect the soundness of a component on standby state can be divided into two: 1. Leaving the component in the quiescent state and acquiring some signal through a sensor, 2. operating the component and checking the status of their operation directly. For convenience, former method will be named as Online Monitoring (OM), and later as Running Test (RT). Wideness of inspecting range and reliability of inspection result can be the major criteria of the monitoring method. According to these criteria, the OM and RT can be expressed as shown in Figure. 1.

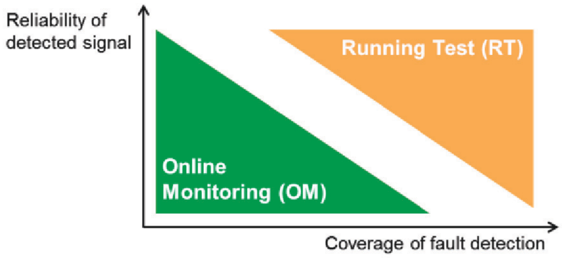

Figure 1 Characteristic of OM and RT

In Figure. 1, RT has broad fault detection coverage because all the elements in a component can be checked during the inspection. In addition, it is highly reliable because the test result is clearly identified. On the other hand, through OM, it is hard to inspect all causes of failure by one sensing method because the failure characteristics are different according to each failure. Accordingly, the inspection through OM has relatively narrow fault detection coverage. Furthermore, reliability of inspection result is relatively low because the data collected through indirect way. Based on Figure. 1, RT looks like the best option. However, there are some constraints of RT. If the RT which needs real operation of component affects the normal operation region of the system, it can lead to undesirable accidents. Therefore, an isolation procedure from the normal operation region is essential. However, OM does not interfere to the expected function of component. For more efficient and reliable monitoring method, the advantages of OM and RT should be adopted simultaneously. To this end, the constraints should be overcome, and the combination method for those two methods is needed to be developed.

4. Monitoring method development

In Figure. 2, there is a flowchart presenting a combination of OM and RT. The key features of this flowchart are described as follows. Information for the final decision is achieved through RT (d), and RT is activated by the results of OM (a) and Regular Running Test Interval (b). Fault judgment via RT is not simply decided by outward works. To inspect the target component in depth, the RT should gather overall potential information of failure and give it to the Fault judgment. If fault judgment can't find any failure, the data will be stored in the data base (e) and will be utilized to track a failure trend for each element in a component.

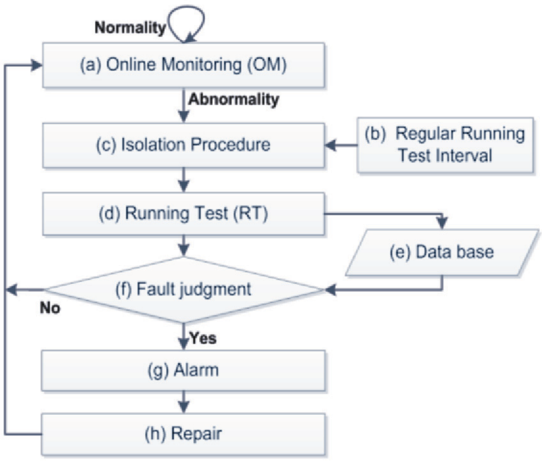

Figure 2 Flow diagram of proposed monitoring method

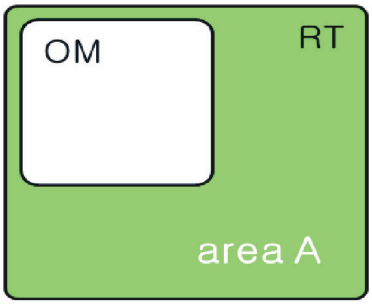

Figure 3 Fault detection coverage

Characteristics and requirements of each procedure are, in turn, described below. First, online monitoring (OM) performs a function activating RT through the isolation procedure by inspecting the abnormalities of major causes of failure. It inspects the component with very short interval without actual operation. Almost real time inspection but low reliability is the main characteristics of OM. The low reliability of OM signal can be supplemented by connecting to RT. Fault detection coverage of OM and RT are shown in Figure. 3. Figure. 3 was given under an assumption that all the faults can be detected by RT. In Table 1, possible cases for failure judgment are described. In this table, case 3 is related to the area A in Figure. 3. When OM cannot detect any abnormality and the RT is not activated by regular running test interval, the causes of failure that belong to area A are treated as normal without any basis. At this point, some uncertainties exist. The fault detection coverage of OM should be expanded in order to reduce these uncertainties. Proper techniques for OM are well organized by IAEA-TECDOC-1551, 2007. Additionally, the effect of inaccurate OM signal should be considered. There are two cases originating from this problem. One is that OM cannot detect failure although there exist some failures under detected coverage, and another case is that the OM generates RT activating signal even if there isn't any failure. Simply, the former case is same as the reduction of fault detection coverage. This is an individual defect of sensing device, so mere device performance improvement is required. However, the latter case is difference. It generates RT activation signal more frequently. As explained before, frequent inspection has pros and cons. This point is reflected to the unavailability equation later.

Table 1 Possible cases for fault judgment

Case	OM signal	RT activation	RT signal	Fault judgment
1	Abnormal	RT activation by OM	Abnormal	Fault
2	Abnormal	RT activation by OM	Normal	Normal
3	Normal	-	-	Normal
4	Normal	RT activation by set period	Normal	Normal
5	Normal	RT activation by set period	Abnormal	Fault

Second, the regular running test interval is explained. If there isn't the RT activation signal caused by OM, the component will stay in case3 in Table 1 where the uncertainty exists. Therefore, there is a need to activate the RT periodically to inspect the causes of failure which are not monitored by OM. However, too short period can cause aging of the component, again. Reasonable period is needed to be set.
Next, the isolation procedure (c) is investigated. Since the RT basically makes the component run, as described above, it can lead undesirable accidents because of interference to the normal operating region. Accordingly, an isolation procedure is essential to maintain independence from the normal operation area. This procedure can be achieved by changing the internal structure of the component or by changing the external system design. Figure 4 presents a simple example of the isolation procedure changing the system design. One MOV is replaced by serially connected two MOVs. In this example, normally closed MOV_1 is the target of this monitoring method, and normally opened MOV_2 is adopted to isolate the passive system from the normal operation region. By opening and closing MOV_1 and MOV_2 following the proposed sequence, the passive system can remain independently from the normal operating region.

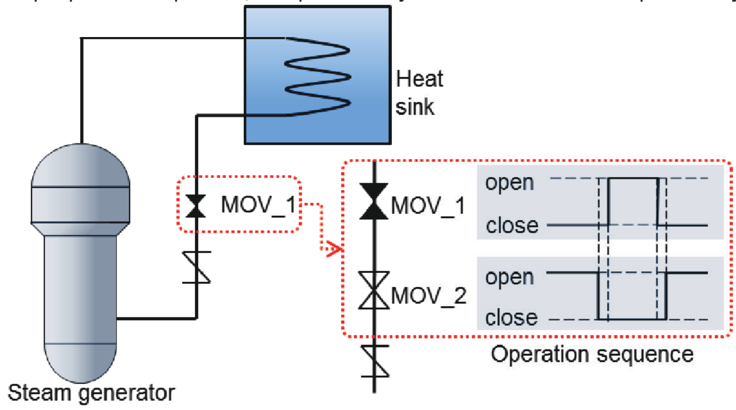

Figure 4 Example of isolation procedure

Next, running test (d), Data base (e) and Fault judgment (f) are investigated together below. The proposed monitoring method decides the failure occurrence using the information obtained through RT. To this end, all causes of failure should be detected by RT, and the detecting signal also should be reliable. Therefore, RT cannot simply achieve the data through mere outward works. It should provide potential and comprehensive information of existing failure. For this purpose, analysing the electrical signature that obtained from actual operation can be a method. As a good example of this method, there is Motor Current Signature Analysis (MCSA) for MOV inspection. MCSA gathers voltage and current information from the motor and detect existing faults in it by analysing electrical signature. This method has been advanced considerably (Okano Valve., 2009). Fault judgment (f) decides the failure occurrence by comparing the normal data in data base (e) with the information taken from RT. If fault judgment cannot find any failure, the data will be stored in the data base (e), and this data can be utilized to set a failure trend for each element in a component. If fault judgment finds any failure, it goes to the alarm state (g) and can be repaired (h). After the repair process, it goes to the OM state, again.

5. Mathematical analysis

In this section, the proposed monitoring method was analysed in mathematical way. By adopting the proposed monitoring method, Eq. (1), (2) and (3) can be modified like below.

$$Q_F(t) = \rho + \frac{1}{6}T_{i\_om}\left(3\lambda_0 + 2\theta T_{i\_om}\right)C_{om} + \frac{1}{6}T_{i\_rt}\left(3\lambda_0 + 2\theta T_{i\_rt}\right)(1 - C_{om}) \tag{5}$$

$$Q_{RT}(t) = T_{rt}\left[\frac{1}{T_{i\_rt}} + \frac{1}{e_{om}}\right] + \left(\rho + \lambda_0 T_{i\_rt}\right)C_{om}\frac{T_{rt}}{T_{i\_rt}} \tag{6}$$

$$Q_R(t) = \left(\rho + \lambda_0 T_{i\_rt}\right)\frac{T_r}{T_{i\_rt}} \tag{7}$$

Where, ρ is failure probability per demand, T_{i_om} is OM STI, λ_0 is standby failure rate, θ is linear aging rate,$C_{\mathrm{om}}$is OM fault detection coverage which is same to multiply actual coverage by signal accuracy, T_{i_rt} is Regular RT interval (RT SIT), T_{rt} is RT duration, e_{om} : unnecessary RT interval by OM mistake, and T_r is mean time to repair. Unavailability due to the failure has been modified as shown in Eq. (5). In accordance with the proposed monitoring method combining the OM and RT, the unavailability is divided in to three terms, and second and third terms have its own fault detection coverage and test period. Roughly, the unit of test period for OM and RT will be second and hour, respectively. Therefore, unavailability of the second term of Eq. (5) is much smaller than the third term. Even the second term can be ignored due to this big difference of STI. In addition to that, there is the parameter for fault detection coverage of OM (C_{OM}) in the second term. It can, intuitionally, be known that extended portion of C_{OM} should also be ignored. Therefore, enlargement of C_{OM} can be an efficient way to improve the total unavailability. In addition to that, reducing T_{i_rt} is another efficient parameter to improve total unavailability. However, the optimal T_{i_rt} should be decided because frequently activated RT raise the$Q_{RT}(t)$.

Next, unavailability due to the RT has been modified as shown in Eq. (6). This equation contains all causes of RT activation signal; RT activation signal can be occurred by regular RT interval, mistaken OM, and correct detection of OM. Finally, unavailability due to the repair procedure has same form of Eq. (3) as shown in Eq. (7).

In this study, to obtain meaningful insight, sensitivity analyses are performed using the parameters in table 2. and presented in Figure 5. Some of parameters in table 2 are obtained from technical specifications and TIRGALEX which is the ageing failure rate data base in NUREG/CR-5248, and the others are assumed. The source of each parameter is indicated in table 2.

Table 2 Assumptions for the sensitivity analysis

	Parameter	Value (Unit	source
ρ	failure probability per demand	1.82x10-3	*
T_{i_om}	OM interval	2.78x10-4 (/h)	1 second **
λ_0	standby failure rate	5.83x10-6 (/h)	*
θ	linear aging rate	1x10-5(/h/y)	***
C_{om}	OM fault detection coverage	0, 0.5, 0.75, 1	**
T_{i_rt}	Regular RT interval	24~4320 (h)	1day~6months **
T_{rt}	RT duration	0.75 (h)	*
e_{om}	unnecessary RT interval by OM mistake	∞	Accurate OM signal **
T_r	mean time to repair	8	*

(* Technical specifications, **supposition, ***TIRGALEX)

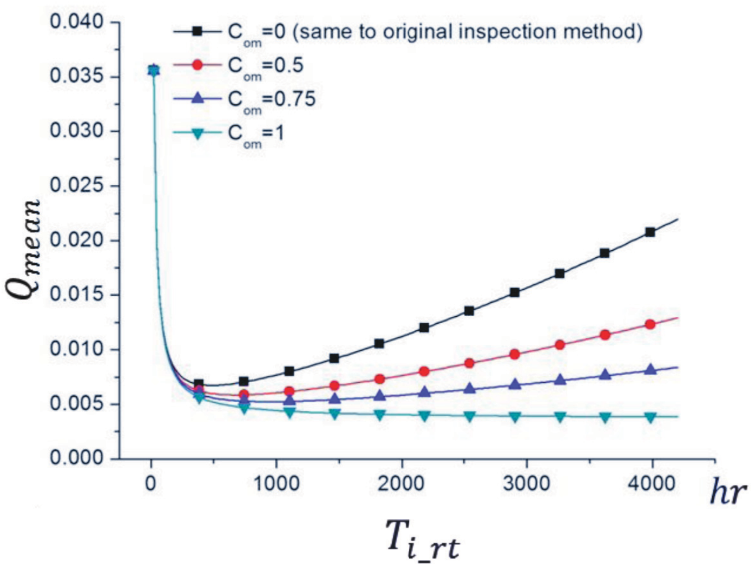

Figure 5 Mean unavailability change according to the T_{i_rt} and C_{om}

As shown in figure 5, by adopting proposed monitoring method, component unavailability can be reduced significantly. In case of a MOV which was inspected for each 3 months (2160 hr), component unavailability was 0.012. However, the unavailability of this component can be lowered to 0.008 and 0.006 when C_{om}=0.5 and 0.75, respectively. Moreover, the mean unavailability can be further reduced through shortening the T_{i_rt} up to 40 days. Whereas, in case of Com=1, mean unavailability simply increased through shortening the T_{i_rt}. Since the analysis results is obtained from the ideal assumption that the accuracy of OM signal is perfect, performing of RT just raise$Q_{RT}(t)$. From this figure followings are learned: extending C_{OM} with high accuracy is the best way, but if wide C_{OM} is not obtained, the total unavailability can be improved by optimal T_{i_rt}

6. Conclusion

In this paper, the efficient way to improve the component reliability was proposed by combining the Online Monitoring (OM) and Running Test (RT). By utilizing OM to RT, some portion of faults in a component could be detected without any interference to original function. To improve the component reliability, detecting all causes of failure by OM with high accuracy is the best way. However, when C_{OM} is low, it can be supported by optimal T_{i_rt}. To make the proposed monitoring method applicable, proper techniques which can inspect a component without movement are need to be studied further.

Acknowledgement

This work was supported by the Nuclear Research & Development program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Trade, Industry & Energy (No. 20111510100010 and 20121610100030)

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