AVAILABILITY IMPROVEMENT OF STANDBY SAFETY COMPONENT BASED ON ONLINE STATUS MMONITORING AND TEST INTERVAL ADJUSDTMENT

Sung Min Shin[1], Hyun Gook Kang[2], Wondea Jung[3]

[1] *Integrated Safety Assessment Division, KAERI, Daedeok-daero 989-111, Yuseong, Daejeon, Republic of Korea, 305-353, smshin@kaeri.re.kr*
[2] *Department of Nuclear and Quantum Engineering, KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon, Republic of Korea, 305-701 , hyungook@kaist.ac.kr*
[3] *Integrated Safety Assessment Division, KAERI, Daedeok-daero 989-111, Yuseong, Daejeon, Republic of Korea, 305-353, wdjung@kaeri.re.kr*

The safety of nuclear power plants (NPPs) has been treated as a major issue over the last few decades, and has been particularly emphasized in recent years. Most of safety systems in NPP basically control various standby mechanical components to set coolant flow path. In this context, for more reliable systems and safer NPPs, the availability of these mechanical components should be improved. In order to deduce appropriate strategies for the availability improvement, a general component unavailability model is developed, which takes into account aging effects, test duration, and repair duration. Based on this model, strategies for availability improvement of standby component are suggested. The strategies are broadly categorized as online status monitoring, which monitors failures occurring during standby or operation, and test interval adjustment, which adaptively manages the test interval for each standby turn. To analyze the effects of these strategies, their influences are formulaically reflected to the general unavailability model. The feasibility of the proposed strategies is demonstrated via a case study for a MOV. As a result of the analysis, the average unavailability of the valves for their expected lifetimes can be greatly reduced to 51.28%, when compared to the cases with no improvement strategies.

I. INTRODUCTION

In accident situations, the basic function of most safety systems in nuclear power plant (NPP) is the transference of residual heat from the core to the ultimate heat sink. Although different systems can be utilized according to the accident situation, whatever they are, they all control the flow path of coolant. For this path control, an active valve is generally used. Since each component has its own failure probability, NPPs have adopted redundancy and diversity concepts to lower the failure probability of the entire system. This approach, however, increases system complexity and entails additional costs for construction and maintenance. Whereas, the availability of the components themselves can be improved when their abnormalities are properly monitored and managed, even if the components have the same failure probability. By doing so, the reliability of the standby systems and the safety of NPPs can be directly enhanced. Therefore, suitable methodologies and practical techniques for the availability improvement of standby safety components should be developed.

Currently, to maintain the availability of standby components, periodic surveillance tests (full stroke tests is an operational test involving movements to all positions for required functioning, and actually improvement of component integrity is not expected after this test since it does not require disassembling or repair process but aging can occur) are being applied to them, and to quantify the availability of each component, unavailability measures have been introduced and are widely used. From the point of view of one standby turn, more frequent operational testing could help to reduce component unavailable time caused by failure because more frequent testing means earlier failure detection after occurrence. In consideration of the whole lifetime of the component, however, more frequent tests can lead to additional unavailable time caused by the testing itself and the additional occurrence of failures because of accumulated aging effects. Therefore, component aging, test duration, and repair duration should be comprehensively considered to improve component availability.

Standby components can age on account of two factors: (1) standby stress which accumulates over waiting time, and (2) test stress which accumulates through operations for testing. For the generic model, essentially, both factors should be considered together. Kim. et al. (Ref. 1) provided a well-organized mathematical foundation for both factors. In order to utilize this foundation, specific values for each aging factor must be obtained, but there are many difficulties to derive such detailed values from real operational experience. The U.S. nuclear regulatory commission (NRC) has conducted studies on the aging of components that are used in NPPs to analyze the effects of component aging on the core damage frequency (CDF) (Ref. 2-3). In these references, they provided linear aging rates of several important components. By utilizing these aging rates with existing failure information and the surveillance test interval, the approximate values of the aging factors for Kim's model can be derived. Accordingly, to apply the aging effects to the unavailability model, the frame of Kim's model is utilized. This model, however, still has limitations to reflect the effect of various strategies for availability improvement because it does not take into account the effects of tests and repairs. It considers only aging effects.

Some previous studies (Ref. 4-6) reflect the test effect in their unavailability model for the optimization of testing schedules. In these studies, it is assumed that the component is partially or fully unavailable during test activities. Actually, test durations can considerably affect the component unavailability when the testing is performed more frequently. Therefore, for the general model, the effect of test duration needs to be reflected to the component unavailability.

Khalaquzzaman, M. et al. (Ref. 6) properly applied the effect of repair to the unavailability model by adding expected unavailable time at the end of the test, the value of which is the multiplication of mean time to repair (MTTR) and component unavailability at the end of each standby time. The effect of repair duration on the general unavailability model can be applied in the same manner.

The purpose of this study is to suggest proper strategies to improve the availability of standby safety components. Therefore, based on the general component unavailability model considering above factors, this study suggests strategies for availability improvement of the standby component. The strategies are broadly categorized as online status monitoring and test interval adjustment. The online status monitoring can be subdivided into monitoring the integrity of important elements during standby, and monitoring on completion of intended function during operation. The test interval adjustment adaptively manages the test interval for each standby turn. To analyze the effects of these strategies, their influences are formulaically reflected to the general unavailability model, and the feasibility of the proposed strategies is demonstrated via a case study for a MOV.

The remainder of this paper is structured as follows: in section II, a general unavailability model for standby components is developed. In this model, aging effects, test duration, and repair duration are considered together. Based on the model, two strategies to improve the component availability, online status monitoring and test interval adjustment are proposed section III. In section IV, the feasibility of the proposed strategies are demonstrated via a case study for the MOV. Section V summarizes and concludes this study.

II. GENERAL UNAVAILABILTIY MODEL OF STANDBY COMPONENTS

II.A. Considerations for development of general unavailability model

II.A.1. Component failures in consideration of aging effects

The failures of a component can be divided into two depending on when they occurred. Some failures occur on demand and some occur between tests (during standby), and each failure has their own residual failure probability and rate. In addition to the residual values, aging effect need to be reflected to them for the general component unavailability model. So the aging effects are applied

The condition of a component operated only one time is obviously different from a component tested many times. At each test, the component may be worn down, so the effect of it accumulates along with the number of operations. The aging effect caused by operation for testing purpose is named "test stress". The test stress can make the both kinds of failures occur more frequently, so they should be the functions of operation number.

Waiting a long time may also deteriorate the condition of a component. The condition of recently installed component would be different from a component installed many years ago. This aging effect accumulating over time is named "standby stress", and it can make failures between tests occur more frequently. Therefore, failure rate for failures occurring between tests should be the function of elapsed time since its installation.

Kim. et al. (Ref. 1) provided a well-organized mathematical foundation for the adoption of the both stresses for aging effect. When the both stresses are considered for a specific timing, component unavailability caused by failure can be expressed like Eq. 1. The relation between the specific timing and elapsed time is shown in Fig. 1. By substituting Eqs. 3 and 4 into Eq. 1, Eq. 5 can be obtained. The equation indicates component unavailability caused by failure over time after n tests and before the next test:

$$\boldsymbol{q_f(n,t) = \rho(n) + \int_{t_n}^{t_n+t} \lambda(n,t')dt' \quad for \quad t \in [0, I_n]} \tag{1}$$

$$\boldsymbol{t_n = \sum_0^{n-1} I_i \;\; for\; n \geq 1,\, t_0 = 0} \tag{2}$$

$$\boldsymbol{\rho(n) = \rho_0 + \rho_0 p_1 n} \tag{3}$$

$$\boldsymbol{\lambda(n,t) = \lambda_0 + \lambda_0 p_2 n + \alpha(t_n + t)} \tag{4}$$

$$\boldsymbol{q_f}(\mathbf{n},\mathbf{t}) = \boldsymbol{\rho_0} + \boldsymbol{\rho_0 p_1 n} + \boldsymbol{t}\left(\boldsymbol{\lambda_0}(\mathbf{1} + \boldsymbol{p_2 n}) + \boldsymbol{\alpha}(\boldsymbol{t_n} + \tfrac{1}{2}\boldsymbol{t})\right) \quad (5)$$

where,
$q_f(n,t)$: Between tests, component unavailability caused by failure as a function of the number of tests performed and elapsed time since the last test
t_n: Elapsed time to the end of n-th test since its installation
$\rho(n)$: Failure probability for failures occurring on demand
$\lambda(n,t)$: Standby failure rate (per unit time) for failures occurring between tests
n: Number of tests performed on the component
t: Elapsed time since the end of last test
I_n: Test interval (standby time after n-th test and before next test)
ρ_0: Residual demand-failure probability
λ_0: Residual standby time-related failure rate
α: Aging factor associated with aging alone
p_1: Test degradation factor associated with demand failures
p_2: Test degradation factor for standby time-related failures

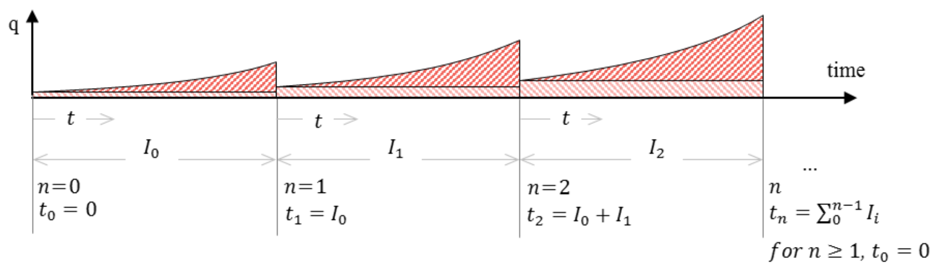

Fig. 1. Component unavailability caused by failure in consideration of aging effects

II.A.2. Test and repair duration

If there is a demand for operation, excluding the time for the overhaul period, standby safety component is expected to work immediately. However, when the component is being tested, its intended function cannot be performed promptly because of preceded isolation procedures, such as bypass from the ordinary path. These isolation procedures are essential to prevent unnecessary accidents, so the component unavailability caused by these procedures is inevitable as well. The effect of the test duration on the total component unavailability might be negligible when the duration is very short compared to the standby interval, but it will be considerable when the tests are executed more frequently. Therefore when the different test frequencies are considered to improve component availability (this approach is actually considered in the study), the test duration should be reflected in the general unavailability model. In this study, the component unavailability caused by the test duration (q_t) is simply assumed to be 1, which indicates that the component is completely inoperable for the intended purpose during the test. The component, of course, is not operable during repair process. So the component unavailability caused by repair duration (q_r) is also 1.

$$\boldsymbol{q_t} = \mathbf{1} \quad (6)$$

$$\boldsymbol{q_r} = \mathbf{1} \quad (7)$$

II.B. General unavailability model for standby components

When the aging effect, test duration, and repair duration are considered together, the general component unavailability according the time and operation history can be illustrated like Fig. 2. The notable changes from Fig. 1. to Fig. 2. are the additions of test and repair time. The unavailable time caused by the test duration (Q_t) can simply be obtained by multiplying component unavailability caused by test (q_t) and the test duration (T_t) together as expressed in Eq. 8, and the unavailable time caused by repair (Q_r) can be expressed through multiplication of component unavailability caused by repair (q_r), repair duration (T_r), and the component unavailability at each surveillance test like Eq. 9. When the effects of test and repair time are considered to the existing component unavailability model, the Eq. 2. needs to be modified like Eq. 10. Then during standby, the unavailable time caused by failure (Q_f) for each standby turn (n) can be obtained by integrating component unavailability caused by failure (q_f) over the standby time which is same to the test interval (I_n), as expressed in Eq. 11.

$$\boldsymbol{Q_t = q_t \times T_t} \tag{8}$$

$$\boldsymbol{Q_r(n, I_n), = q_r \times T_r \times q_f(n, I_n)} \tag{9}$$

$$\boldsymbol{t_n = \sum_0^{n-1}(I_i + R_i) + nT_t \quad for\ n \geq 1, t_0 = 0} \tag{10}$$

$$\boldsymbol{Q_f(n, I_n) = \int_{t_n}^{t_n+I_n} q_f(n, t)dt} \tag{11}$$

where,
T_t: Test duration
T_r: Mean Time To Repair, MTTR
R_n: Repair duration after test at n-th standby turn
Q_t: Component unavailable time caused by test
Q_r: Component unavailable time caused by repair
Q_f: Component unavailable time caused by failure

Based on the developed general unavailability model, the effectiveness of strategies for availability improvement will be examined. In order to compare the effectiveness of different conditions for each strategy, an objective index is needed. In this study, as an effectiveness measure (the index), average component unavailability (q_{ave}) for its expected life time is introduced.

A set of expected unavailable time for one standby turn will be the summation of Eqs. 8, 9, and 11. Then the q_{ave} can be calculated by dividing the sum of all unavailable times (the all areas in Fig. 2) for every standby turns by the expected lifetime (t_{total}), as in Eq. 12. By comparing the q_{ave}, the effectiveness of different conditions for each strategy can be analyzed. Here, m is the total number of tests performed for each strategy.

$$\boldsymbol{q_{ave} = \frac{\sum_{i=0}^{m}\{Q_f(i, I_i) + Q_r(i, I_i)\} + mQ_t}{t_{total}}} \tag{12}$$

where,
t_{total}: The expected lifetime of a component
m: Total number of tests performed for expected lifetime

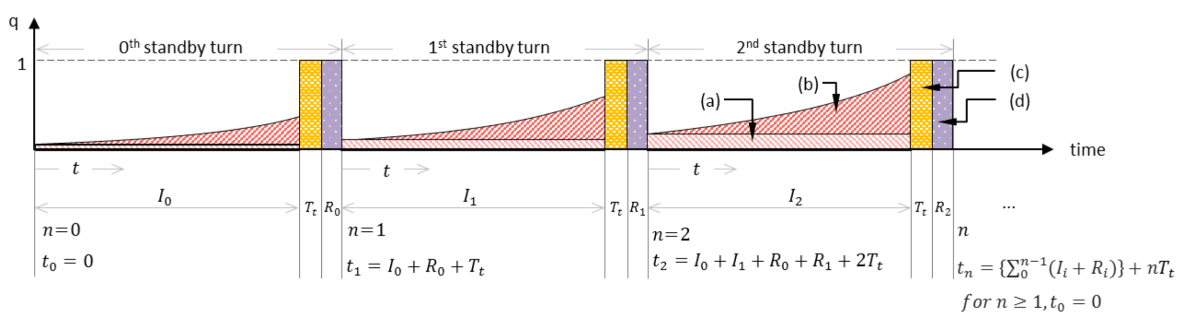

Fig. 2. General component unavailability (Each area means expected unavailable time caused by (a): failure of elements which mainly affected by test stress only, (b): failure of element which affected by both test stress and standby stress, (c) test duration, (d) and repair)

III. STRATEGIES FOR AVAILABILITY IMPROVEMENT OF STANDBY COMPONENTS

In this section, strategies for availability improvement are introduced and applied to the unavailability model. Mainly, the expression for component unavailability caused by failure is modified when the online status monitoring strategies are applied, and the standby time for each standby turn is modified when the test interval adjustment strategy is applied in consideration of operation history of a component.

III.A. Online status monitoring

III.A.1. Monitoring of important elements during standby

Standby component itself does not provide any information for the perception of its condition because it is not in operation. So, periodic full stroke testing is being performed on standby component to check abnormalities. However, frequent testing leads to additional test stress and unavailable time caused by the test duration. So, monitoring on important elements during standby should basically pursue inoperative sensing techniques. In order to decrease component unavailability caused by failure, the failure must be detected immediately and be linked with proper maintenance activities. Therefore, the monitoring technique should have very short sensing interval for the immediate failure detection.

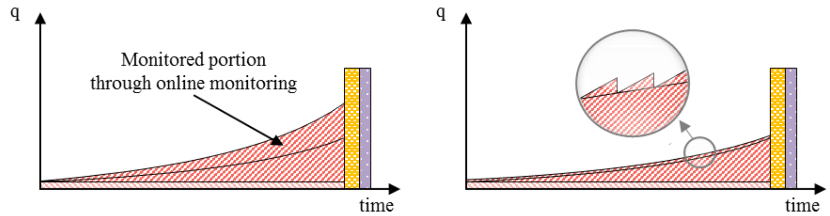

Fig. 3. Changes in unavailability by online status monitoring during standby

Fig. 3. illustrates the change in component unavailability when some proportion of failures that can occur between tests is monitored without actual operation and with very short sensing intervals. Actually, online status monitoring is also a kind of periodic test, but it does not cause aging effect. To analyze the effectiveness of this method in a quantitative manner, Eq. 5. needs to be modified in consideration of detection coverage of failures occurring between tests (C_1) as in Eq. 13.

$$\boldsymbol{q_f(n,t) = \rho_0 + \rho_0 p_1 n + t\left(\lambda_0(1+p_2 n) + \alpha\left(t_n + \tfrac{1}{2}t\right)\right)(1-C_1) + t_{on}\left(\lambda_0(1+p_2 n) + \alpha(t_{k-on} + \tfrac{1}{2}t_{on})\right)C_1} \quad (13)$$

where,
C_1 Detection coverage of failures occurring between tests
t_{on} Elapsed time since the end of the last sensing
$t_{\mathrm{k-on}}$ Elapsed time to the end of the k-th sensing since its installation

In the modified equation, the monitored proportion of failures occurring between tests is checked with sensing interval (I_{on}, $0 < t_{on} < I_{on}$) of the adopted monitoring technique, and the remaining proportion of the failures occurring between tests ($1 - C_1$) is checked with surveillance test interval (I_n, $0 < t < I_n$). Actually, there is enormous difference between sensing interval of monitoring technique (I_{on}) and periodic surveillance test interval (I_n). For example, the sensing interval will be something in the order of maximum few minutes, and the periodic test interval will be something in order of minimum few days. In this point of view, the unavailability caused by monitored proportion of failures will be a thousand times smaller than the one which is not monitored. In other words, thanks to the short sensing interval, it become small enough to be ignored, and the component unavailability can be lowered proportional to the detection coverage (C_1). Therefore, the Eq. 13. can be simplified like Eq. 14.

$$\boldsymbol{q_f(n,t) \approx \rho_0 + \rho_0 p_1 n + t\left(\lambda_0(1+p_2 n) + \alpha\left(t_n + \tfrac{1}{2}t\right)\right)(1-C_1)} \quad (14)$$

III.A.2. Monitoring of intended function during operation

If an accident occurs on the NPP, mitigation actions in system level are activated to prevent progress of the accident. If a failure occurs in the component, however, there is no mitigation concept in component level except manual recovery action within limited time (It even has limitation inaccessibility). In a sense, monitoring on completion of intended function during operation is a kind of mitigation action in component level.

When a problem occurs on an element which is not revealed by surveillance test and is not checked by online status monitoring during standby, the component may not perform its intended function on demand. In this situation, if the uncompleted functioning is detected and some supplementary procedure can be executed, the component unavailability can be decreased significantly. To investigate the effectiveness of this strategy in quantitative way, the Eq. 14. needs to be modified again. Before to make the modification, the relation between the failure detection coverage through online status monitoring during standby (C_1) and the failure detection coverage of this approach (C_2) need to be confirmed. Fig. 4. shows the relation between two coverages. As shown in (c) in this figure, this approach covers failures occurring on demand as well as failures occurring between tests. Component failure is the case that the intended function cannot be performed. However, even if there are some abnormalities, they will not cause a failure to the component when the suggested monitoring concept is applied during operation. Consequently, the Eq. 14. can be modified by taking out the proportion of C_2 from the right hand side. When the all monitoring methods are adopted, the component unavailability caused by failures can be decreased to correspond to the proportion of (d) in the Fig. 4. In this study, although the detection accuracy was assumed to be perfect, and only the fault detection coverage was considered, the fault detection coverage should be considered with its accuracy. Although the detection accuracy problem was excluded in this study, these problems need to be revisited.

$$\boldsymbol{q_f(n,t) \approx \left[\rho_0 + \rho_0 p_1 n + t\left(\lambda_0(1+p_2 n) + \alpha\left(t_n + \frac{1}{2}t\right)\right)(1-C_1)\right](1-C_2)} \tag{14}$$

where,
C_2 Detection coverage of failures occurring on demand

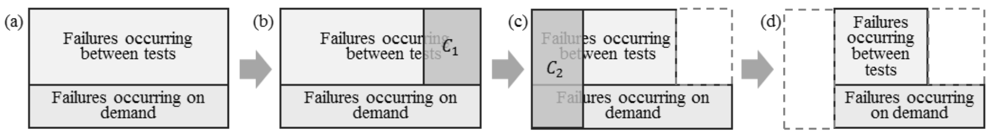

Fig. 4. Failure detection coverage of each monitoring strategy

III.B. Test interval adjustment

Fig. 5. shows the schematic unavailability of a standby component around the beginning and ending of its lifetime when it was tested using a periodic surveillance interval. Near the end of the lifetime, the area representing the unavailable time may be broadened considerably compared with that slightly after the installation because of the accumulated aging effect. In this situation, a specific portion of the unavailable time (q_{fb}) can be removed if there is an additional test (t_b) between t_a and t_c (prearranged periodic test intervals). Based on this manner, the total unavailable time can be further reduced when the component is tested more frequently at the later portion of the lifetime. However, as mentioned before, additional tests lead to additional test stress and an unavailable time caused by the test duration. To apply this concept properly, merits and demerits should be considered together.

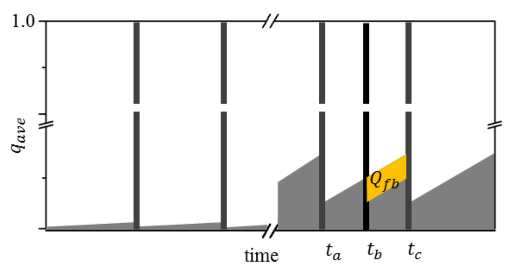

Fig. 5. Changes in unavailability by additional test execution

Two parameters, the initial test interval (I_0) and the decreasing rate (r_d) are adopted to realize the effect of this strategy. I_0 is the standby time before the first test after its installation. r_d is a proportion of the current test interval versus the previous test interval, and it can be expressed in Eq. 15. Therefore, when the test interval adjustment is adopted, the test interval (I_n) will be a variable, not a constant, which can be expressed like Eq. 16. Through the various combinations of I_0 and r_d, the changing trend of average component unavailability for its lifetime can be scrutinized. Then, by analyzing the trend, the best test plan which have lowest average component unavailability can be found. Aside from T_0 and r_d, this method can reflect all other changes to obtain the best test plan.

$$\boldsymbol{r_d = \frac{I_{n+1}}{I_n}} \tag{15}$$

$$\boldsymbol{I_n = I_o {r_d}^n} \tag{16}$$

IV. APPLICATION OF THE STRATEGIES TO A MOTOR-OPERATED VALVE

IV.A. Basis of the application to the strategies to the MOV

To realize the online status monitoring method, some techniques, which can check the integrity of target elements without actual operation and with very short sensing intervals, should be applied during standby, and some technique which can detect incomplete functioning and activate complementary procedure should be applied during operation.

For the online status monitoring method during standby, a technique that checking motor health at standstill through impedance analysis can be considered to detect some abnormalities of motor in MOV (Ref. 7), and for the monitoring method during operation, piezoelectric (PZT) sensor, which measure changes in force by converting it to an electrical charge, can be considered to directly confirm complete valve closing. The feasibility of each technique is checked through related experiment (Ref. 7) and investigation on valve closing mechanism (Ref. 8), but the detailed descriptions of them are skipped in this paper. Fig. 6. shows relations between strategies and applied techniques for each monitoring strategies. In case of test interval adjustment, there is no need for specific technique because it just numerically find the best combination of initial test interval and decreasing rate to lower the average component unavailability.

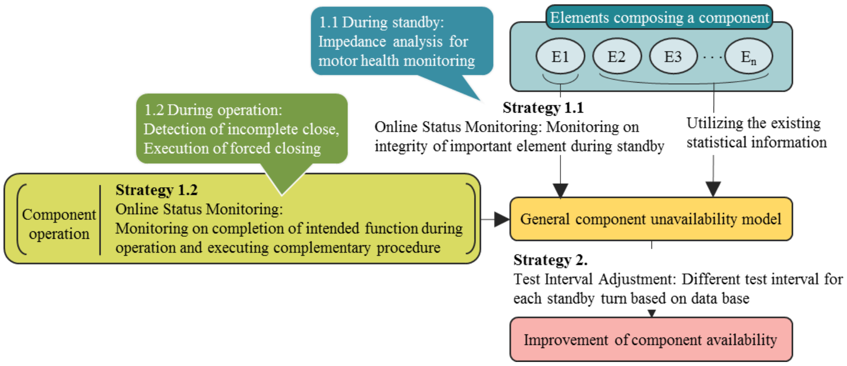

Fig. 6. Online status monitoring techniques for the MOV

Prior to performing the quantitative analysis, failure detection coverage of each monitoring strategy need to be set, and for this, actual MOV failure cases under periodic test scheme are checked. The U.S. NRC analyzed MOV failure events in U.S. NPP safety-related systems during the period from 1980 through 2000 (Ref. 9). Based on discovery method and descriptions for each failure case, the total 149 failure cases are categorized into two groups, failures occurring between surveillance test intervals (97 cases) and failures occurring on demand (52 cases). Among the failure cases occurring during standby state, 20 failure cases are expected to be detected through impedance analysis method. Therefore, the fault detection coverage of impedance analysis for failures occurring between surveillance tests (C_1) is 20.62% (20/97). Based on the classification of the failure cases depending on failure mode, there are 60 failure to close (FTC) cases. Among FTC, many cases (34 cases) are incomplete closure caused by abnormally equilibrated relationship between spring pack compression and stem trust, and these cases are not overlap with the cases for application of impedance method. As these incomplete closure cases can be mitigated by using the suggested monitoring method during operation, the failure detection coverage for the failures occurring on demand (C_2) is 26.36% (34/(149-20))

The probabilistic parameters of the MOV for quantitative analysis are shown in Table 1. Among the parameters, ρ_0 and λ_0, T_t and T_r are taken from NRC data (Ref. 10) and Harunuzzaman's study (Ref. 44), respectively, and α is obtained from the TIRGALEX-MOD1 database, which was developed by the NRC (Ref. 3). Whereas, p_1 and p_2 are difficult to obtain from the available database because the existing failure database does not typically provide this detailed information. Instead of specific values for the parameters, their maximum values can be represented in terms of the known parameters (Ref. 11). And then to get the p_1 and p_2 from the maximum values, the ratio of demand-related failures to standby time-related failures is required. So, the above categorization for failures occurring on demand and during standby state used again for this deduction.

Table 1 Probabilistic parameters of the MOV

ρ_0	λ_0	α	p_1	p_2	T_t	T_r	C_1	C_2	t_{total}
1.00E-3	3.21E-6 (/h)	1E-6 (/h/y)	9.29E-2	5.00E-2	0.75 (h)	8 (h)	20.6%	26.4%	20 (yr)

IV.B. Quantitative effectiveness analysis of the strategies to the MOV

Fig. 7. illustrates the changes in component unavailability when some proportions of failures occurring between surveillance tests and on demand are monitored. In this figure, case (a) is the case when none of the strategies is applied, and (b) is the case when only the impedance analysis method is applied for some proportion of failures occurring between surveillance tests, and (c) is the case that the failures related to incomplete closing are monitored in addition to the condition of case (b). The q_{ave} decreases with additional application of monitoring scheme. The best test plans for each monitoring condition are summarized in Table 2. As a result of the effectiveness analysis, by adopting impedance analysis method and

incomplete closing detection method, the unavailability of MOV can be decreased up to 0.0151, which is approximately 64.53% of the best value (0.0234) when there is no monitoring scheme.

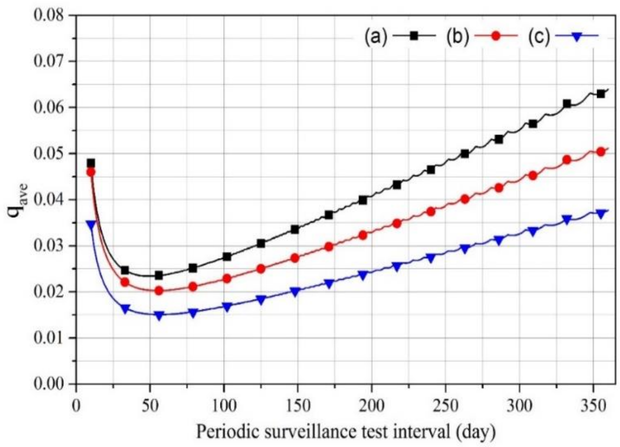

Fig. 7. Average MOV unavailability according to the fixed test interval with different online status monitoring strategies (a): no online status monitoring, (b): $\boldsymbol{C_1 = 0.206}$ and $\boldsymbol{C_2 = 0}$, (c):$\boldsymbol{C_1 = 0.206}$ and $\boldsymbol{C_2 = 0.264}$

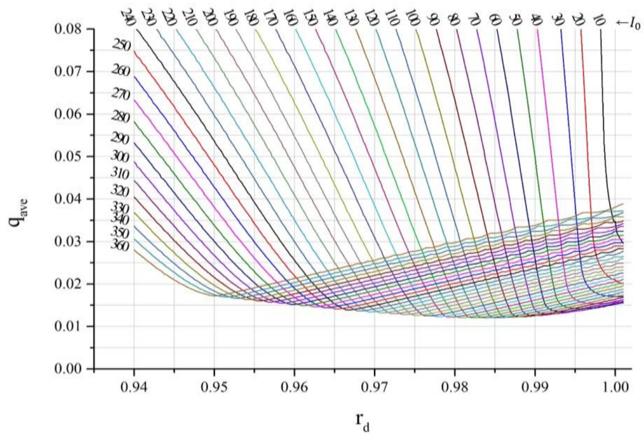

Fig. 8. Average MOV unavailability according to various combinations of initial test interval ($\boldsymbol{I_0}$) and decreasing rate ($\boldsymbol{r_d}$) with online status monitoring ($\boldsymbol{C_1}$=0.206, $\boldsymbol{C_2}$=0.264)

Table 2 Minimum MOV unavailability and test interval under each monitoring strategy

Case	(a)	(b)	(c)
Test interval	50	55	55
q_{ave}	2.34E-2	2.03E-2	1.51E-2

As mentioned in section III.B, the total unavailable time can be reduced when the component is tested mote frequently at the later portion of the lifetime. Therefore, in this section, numerical analysis is performed to check the effectiveness of this strategy through various combinations of initial test interval and decreasing rate to the (c) at the Fig. 7. of which conditions are C_1=0.206 and C_2=0.264. Fig. 8. shows the result of this calculation. When the two strategies for availability improvement are applied together, the minimum component unavailability is 0.0120 under conditions of 120 days for I_0 and 98.40% for r_d. This unavailability value is 51.28% and 79.47% of the lowest unavailability of the cases that no improvement strategy and just monitoring scheme applied strategy, respectively.

V. CONCLUDING REMARKS

To find legitimate strategies for the improvement of standby component availability, a general unavailability model needs to be derived first. For this purpose, an unavailability model for standby components accounting for aging effects, test duration, and repair duration was developed. Based on this model, two strategies for availability improvement were suggested. To quantitatively analyze the effects of these strategies on component unavailability, their influence was formulaically reflected on the generic model. Then the feasibility of the proposed strategies was demonstrated via a case study for the MOV.

As a result of the case study, it was confirmed that the suggested strategies were very effective in improving the availability of the standby components. Through the suggested strategies, the average unavailability of the MOV for its lifetime could be reduced to 51.28% of the lowest value of the case with no availability improvement strategies.

When the unavailability model considers aging effects and test/repair duration times, the calculated average unavailability values are larger than expected, compared to the commonly known values. This discrepancy comes from a lack of probabilistic data. To apply the suggested methods in practice, first, a detailed and accurate database should be established to deduce the credible parameters. The database should be capable of providing the number of operations or tests, in-service time, maintenance history, failure area and source, and detailed descriptions of failure for classification. It should be noted that although the calculated values have some uncertainty from the database, the unavailability for each standby component has been reduced. The results of this study can surely provide meaningful insight about availability improvement based on these relative comparisons.

While the proposed schemes were developed for the availability improvement of standby component, this study has potential applicability to other research areas because it can provide the most realistic availability of standby components. This is achieved by combining the actual measured information, the estimated information from probabilistic data, and the operation history. In this point of view, the suggested strategies can be connected to preventive maintenance plans for cost and risk effective management, dynamic probabilistic safety assessments for more realistic and accurate analysis, and risk-informed regulations.

ACKNOWLEDGMENTS

This work was supported by Nuclear Research & Development Program of the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (Grant Number: NRF-2015M2A8A4021648)

REFERENCES

1. I.S. KIM, S.A. MARTORELL, W.E. VESELY. and P.K. SAMANTA, "Risk Analysis of Surveillance Requirements including Their Adverse Effects," *Reliab. Eng. Syst. Saf.,* **45,** *3*, 225 (1994)
2. I.S. LEVY, J. WREATHALL, G. DEMOSS, A. WOLFORD, E.P. COLLINS and D.B. JARRELL, "Prioritization of TIRGALEX Recommended Components for Further Aging Research." *US Nucl. Regul. Comm. NUREG/CR-5248*. (1988)
3. W.E. VESELY, R.E. KURTH and S.M. SCALZO, "Evaluations of Core Melt Frequency Effects Due to Component Aging and Maintenance." *US Nucl. Regul. Comm. NUREG/CR-5510*. (1990)
4. P.J. COURTOIS, and P. DELSARTE, "On the Optimal Scheduling of Periodic Tests and Maintenance for Reliable Redundant Components." *Reliab. Eng. Syst. Saf.,* **91,** *1,* 66 (2006)
5. A. VOLKANOVSKI and L. CIZELJ, "Nuclear Power Plant Maintenance Optimization with Heuristic Algorithm." *Sci. Technol. Nucl. Install.,* **2014,** 1 (2014)
6. M. KHALAQUZZAMAN, H.G. KANG, M.C. KIM and P.H. SEONG, "Quantification of Unavailability Caused by Random Failures and Maintenance Human Errors in Nuclear Power Plants." *Nucl. Eng. Des.*, **240,** *6,* 1606 (2010)
7. S.M. SHIN, B.H. CHOI and H.G. KANG, "Motor Health Monitoring at Standstill Through Impedance Analysis," *IEEE Trans. Ind. Electron*., **63**, *7*, 4422 (2016)
8. J. HOSLER, "Nuclear Maintenance Applications Center: Application Guide for Motor-Operated Valves in Nuclear Power Plants - Revision 2," *Electr. Power Res. Inst.*, (2007)
9. T.E. WIERMAN, D.M. RASMUSON, N.B. STOCKTON, "Common-Cause Failure Event Insights Motor-Operated Valves Common-Cause Failure Event Insights Motor-Operated Valves." *US Nucl. Regul Comm. NUREG/CR-6819.* (2003)
10. S.A. EIDE, T.E. WIERMAN, C.D. GENTILLON, D.M. RASMUSON and C.L. ATWOOD, "Industry-Average Performance for Components and Initiating Events at U.S. Commercial Nuclear Power Plants." *US Nucl. Regul. Comm. NUREG/CR-6928* (2007)
11. I.S. KIM, S. MARTORELL, W.E. VESELY and P.K. SAMANTA, "Quantitative Evaluation of Surveillance Test Intervals including Test-Caused Risks." *US Nucl. Regul. Comm. NUREG/CR-5775.* (1992)