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Methodology development for availability improvement of standby equipment

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1. Introduction

There are many standby devices in a nuclear power plant (NPP). The main purpose of these devices is to mitigate accident consequences in the event of an emergency. During normal operation, there is no need to operate these devices; however, their good condition should always be maintained to ensure that the intended function will be achieved when a demand comes. However, it is difficult to guarantee their condition because non-operating equipment does not give detectable diagnostic information. Currently, periodic testing is the only method to address this problem.

In some analyses of standby systems, the reliability of the entire system tends to depend on some specific equipment that is on standby state and is supposed to mechanically move. This process is referred to as startup [1]. Although this trend is noticeable in a passive system, it is not confined to passive features, as some active systems have a similar trend. This problem can be solved to some degree by multiple-redundancy design, but this approach has limitations because of common cause failure.

The core damage frequency (CDF) of operating and constructing pressurized nuclear plants are ranging on the order of 10^{-5} and 10^{-6} per year. The target CDF of new NPP design has been set at 10^{-7}. In this context, although various systems are currently studied, availability improvement of standby equipment will be more efficient than the additional application of safety systems. It is obvious in every aspect, such as management and cost efficiency.

Here, soundness can affect equipment unavailability, and the soundness degrades because of aging. However, some studies did not consider aging when calculating the unavailability [2-7]. Standby equipment can age because of two important factors: (1) standby stress which accumulates over time, and (2) test stress which accumulates with the number of tests (or operations). Both factors should be considered together when aging is considered. However, some studies only considered standby stress [8, 9] or test stress [10, 11]. There are some previous studies which considered both factors [12, 13]. Besides equipment soundness related to aging effect, some process like bypass during test also can affect equipment unavailability because the original function of equipment cannot be performed immediately during this process. However, there are seldom studies dealing with above factors as a whole problem.

This study investigated a general approach to calculate the unavailability of standby equipment which considers aging caused by standby and test stresses and bypass process. Based on this general approach, we propose two maintenance strategies which aim to reduce standby equipment unavailability. In section 2, the general approach is presented. As one of the strategies, the changing test interval method (CIM) is introduced in section 3, and its effectiveness is also analyzed. The online monitoring method (OMM) is investigated in section 4 as another method to reduce equipment unavailability. In section 5, a combination of these two methods is analyzed.

2. General approach for unavailability of standby equipment

2.1Equipment unavailability caused by failure

In a probabilistic safety assessment (PSA), the unavailability of standby equipment, which is periodically tested (or operated), is expressed by Eq. 1 under the assumption that the failure occurrence follows an exponential distribution. However, this equation is not sufficient to reflect the actual situation for two reasons. First, there is no way to reflect the effect of aging after repeated testing and elapsed time since its installation. If there is no failure, the unavailability of the equipment is simply reset to 0, which is called reliability renewal. Second, failure is not the only reason that causes equipment unavailability; as previously mentioned, test duration also causes unavailability. The effect of testing the equipment condition is considered in this section, and the additional unavailability caused by the test duration is considered in section 2.2.

$$q_{ave} = \frac{1}{\mathrm{T}}\int_0^T q(t)dt = 1 - \frac{1}{\lambda T}\left(1 - \mathrm{e}^{-\lambda T}\right) \approx \frac{1}{2}\lambda\mathrm{T} \qquad (1)$$

In this study, the test means full-stroke operational surveillance which can cause aging. Even if there is no failure, the actual condition of the equipment may still be changed because of stresses. Equipment tested (or operated) once and equipment tested many times are in different conditions. Here, the concept which makes this difference is termed test stress. In addition, equipment that was recently installed and equipment that was installed 1 year ago are in different conditions. This difference can be caused by another concept, which is termed standby stress. Therefore, the unavailability caused by standby equipment failure should be a function of the number of tests and the elapsed time. Considering the two stresses, equipment unavailability caused by failure can be expressed by Eq. 2 [12]. Test stress affects

ρ and λ (Eq. 4 and 5), and standby stress affects λ (Eq. 5). The correlations between the test interval and specific timing are shown in Figure 1.

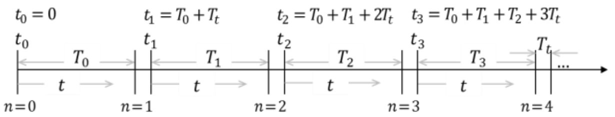

Fig. 1 Correlation between the test interval and specific timing

$$q_f(\mathrm{n,t}) = \rho(n) + \int_{t_n}^{t_n+t} \lambda(n,t')dt' \quad for \quad t \in [0, T_n] \quad (2)$$

$$t_n = \sum_0^{n-1} T_i + nT_t \quad for\, n \geq 1, (t_0 = 0\, for\, n = 0) \quad (3)$$

$$\rho(n) = \rho_0 + \rho_0 p_1 n \quad (4)$$

$$\lambda(n,t) = \lambda_0 + \lambda_0 p_2 n + \alpha(t_n + t) \quad (5)$$

where
$q_f(n,t)$ = Equipment unavailability caused by failure as a function of the number of performed tests and the elapsed time since the last test (t)
$\rho(n)$ = Failure probability associated with the failures that are affected by test stress
$\lambda(n,t)$ = Failure rate associated with the failures that are affected by test stress and standby stress
t_n = Elapsed time after the nth test
n = Number of tests that have been performed on the equipment
t = Elapsed time since the last test
T_n = Test interval (standby time after the nth test and before the next test)
ρ_0 = Residual failure probability
p_1 = Test degradation factor that is associated with test stress
λ_0 = Residual failure rate
p_2 = Test degradation factor that is associated with standby stress
α = Aging factor that is only associated with time
T_t = Test duration

By substituting Eqs. 4 and 5 into Eq. 2, the following equation is obtained for equipment unavailability over time after n tests and before the next test.

$$q_f(\mathrm{n,t}) = \rho_0 + \rho_0 p_1 n + t\left(\lambda_0(1 + p_2 n) + \alpha(2t_n + \tfrac{1}{2}t)\right) \quad (6)$$

2.2 Equipment unavailability caused by test duration

Excluding the overhaul, standby equipment is expected to work immediately. However, when the standby equipment is tested, its original function cannot be performed immediately because of some isolation procedures, such as bypass. This isolation procedure is essential to prevent interruption to the operation area because testing can otherwise lead to an unnecessary accident, but the unavailable time of the equipment that is caused by this procedure is inevitable. The effect of this time duration on the total equipment unavailability is different according to the relative scale between test duration and standby time. However, regardless of this difference, test duration should be reflected unavailability equation for generalized form. In this study, the equipment unavailability caused by the test duration (q_t) is simply assumed to be 1, which indicates that the equipment is not operable at all for the intended purpose.

$$q_t = 1 \quad (7)$$

2.3 Average equipment unavailability q_{ave}

The unavailability (y axis) and unavailable time (area) of standby equipment that is periodically tested can be expressed like Figure 2. To compare the effectiveness of different test plans, the average equipment unavailability (q_{ave}) was calculated by dividing the sum of the unavailable time (the area in Figure 2) by the total expected lifetime. Here, test plan means the number of tests (or test intervals) for lifetime.

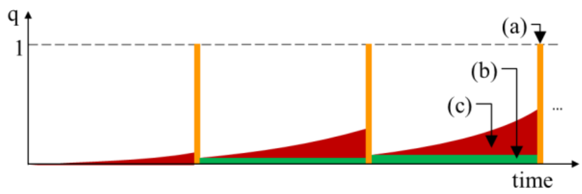

Fig. 2 Equipment unavailability change along the time. (Each area means unavailable time caused by (a): test duration, (b): failures affected by test stress, (c): failures affected by test and standby stress.)

Between performing tests, the unavailable time caused by failure (Q_f) can be calculated by integrating q_f along the time for each standby turn, as shown in Eq. 8. When the unavailable time is caused by the test duration (Q_t), it is simply calculated by multiplying 1 by the test duration (T_t), as shown in Eq. 9, because the unavailability caused by the test duration was assumed to be 1 as mentioned.

$$Q_f(n, T_n) = \int_{t_n}^{t_n+T_n} q_f(n,t)dt \quad (8)$$

$$Q_t = 1 \times T_t \quad (9)$$

In the final safety analysis report (FSAR), there is a rule regarding the pumps and valves which are in standby state. If there are no extenuating circumstances, the full-stroke operational test should be performed once every three months. Two important facts can be figured out from this regulation. First, the standby equipment has been tested at fixed intervals. Second, the standby equipment is fully operated for the test. The second point was the basis of definition of the test described in chapter 2.1. Using the developed equations, q_{ave} was investigated for different fixed test intervals. For the calculation, a motor-operated valve (MOV) was selected as an example of standby equipment, and the parameters in Table 1 were used [14-16].

Table 1. MOV unavailability parameters

Parameter	value
ρ_0	*1.82E-3*
p_1	*0.073*
λ_0	*5.83E-6(/h)*
p_2	*0.021*
α	*1E-6(/h/y)*
T_t	*0.75(h)*
t_{total}	*60(y)*

Figure 3 presents q_{ave} according to the fixed test interval (10-360 days). When the MOV was tested once every 90 days, as indicated in the FSAR, q_{ave} was 0.1049, which is not the minimum value in this calculation. The minimum q_{ave} (0.0862) was achieved when it was tested with 45 days of interval. When the MOV was tested more frequently, the q_{ave} value increased not because of the test duration (T_t) but because of test stress because the test duration of this MOV (0.75 h) was still relatively short compared to the standby time. Furthermore, when this MOV was tested more sporadically, the main cause of the high $\boldsymbol{q_{ave}}$ was standby stress.

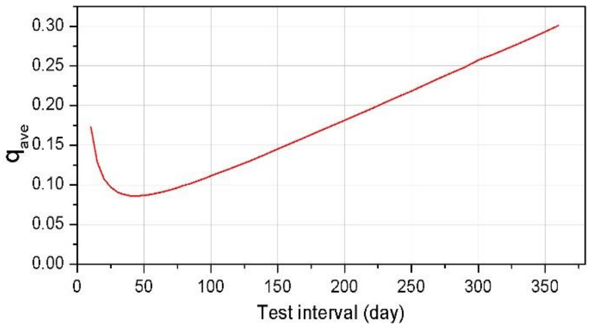

Fig. 3 $\mathbf{q_{ave}}$ changes according to the fixed test interval for 60 yrs.

3. Changing test interval method (CIM)

3.1 Concept of CIM

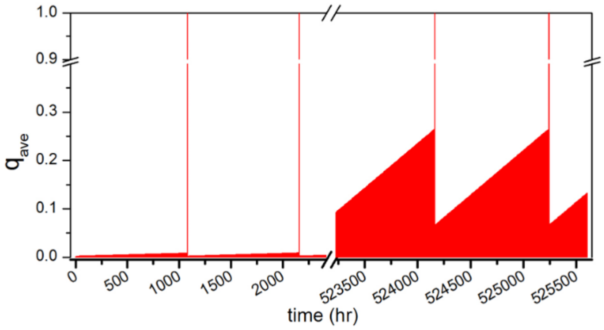

Fig. 4 Unavailable time of the MOV at the beginning and ending of an NPP life ($\boldsymbol{T_t}$= 45 days)

Figure 4 presents the unavailability of the MOV at the beginning and end of its life time during which it was tested at fixed intervals (45 days). Near the end, the area that represents the unavailable time expands considerably compared to that in the beginning because ρ and λ remain large after the test. Under the conditions near the end, the total unavailable time can be reduced when the test is performed more frequently. This is the basic concept of changing test interval method.

3.2 Effectiveness of the CIM

The total unavailable time of standby equipment can be reduced when the equipment is tested sporadically at the beginning and more frequently near the end of the life time. To evaluate the effect of this approach, two variables (initial test interval T_0 and decreasing rate r_d) are adopted. Here, various conditions, which consist of T_0 and r_d, are applied to the MOV, which has the characteristics listed in Table 1, and the q_{ave} values for each condition are calculated. T_0 was set from 10 to 360 days. r_d was set proportionally to the previous test interval, as shown in Eq. 10 (98-100.2%), but when the test interval was shorter than 12h, it was set to 12h.

$$\boldsymbol{r_d} = \frac{\boldsymbol{T_{n+1}}}{\boldsymbol{T_n}} \tag{10}$$

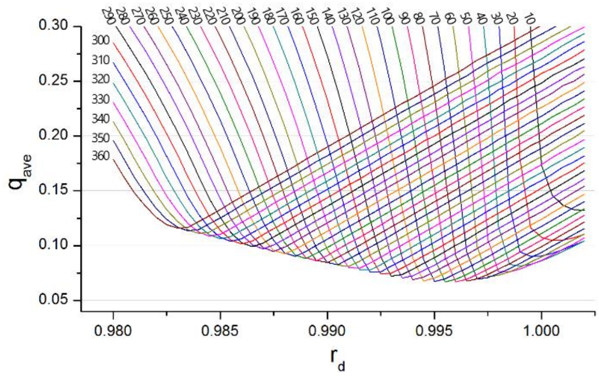

Fig. 5 Changes in $\boldsymbol{q_{ave}}$ according to the initial test interval ($\boldsymbol{T_0}$) and decreasing rate ($\boldsymbol{r_d}$)

Figure 5 presents q_{ave} for each test condition. When this MOV was tested with a fixed test interval (r_d=1), 45 days was the optimal plan with $q_{ave} = 0.0862$. However, as shown in Figure 5, q_{ave} can decrease further. The optimal had an initial test interval of 100 days and a decrease rate of 99.55%. In this condition, q_{ave} was 0.0668, which was approximately 77.5% of the previous optimal value when it tested with fixed interval. The optimal test plan can also be altered by changing the other conditions aside from T_0 and r_d. For instance, when the plant lifetime is shortened from 60 to 30 years, the optimal test plan has an initial test interval of 90 days and a decrease rate of 99.2%. In this case, the minimum q_{ave} was 0.0366. If some constants that represent the equipment characteristics are changed, the optimal test plan is also changed. This method can be applied to all the conditions and all kinds of standby equipment.

4. Online Monitoring Method (OMM)

The terminology "online monitoring" has been frequently used, but the actual meaning varies for each case. Although it is occasionally used to indicate successive surveillance for the operating equipment, in this study, it is used for surveillance of standby equipment that uses external devices, such as sensors, and does not directly operate the equipment. In this section, the OMM was analyzed as another method to reduce q_{ave} using the framework of the general approach developed in section 2.

4.1 Concept of OMM

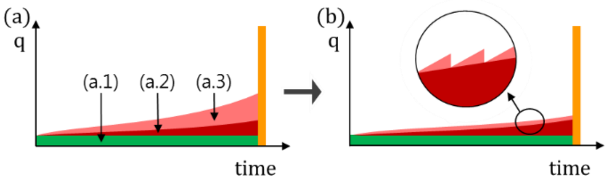

Fig. 6 Schematic diagram of the OMM concept

Failures of standby equipment can be divided into two categories (Figure 6): failures that are affected by only test stress (a1), which is related to Eq. 4, and failures that are affected by standby and test stress (a2, a3), which are related to Eq. 5. The online monitoring in this study detects some portion (a3) of failures of the latter case. The failures of the MOV have been analyzed and classified by the US NRC [17, 18]. In these reports, valve back seating is a failure that is affected by only test stress, so it does not degrade between tests when there is no test. However, motor pinion binding is a failure that is affected by both test stress and standby stress. When we consider only the time between tests, the standby equipment is degraded by standby stress, so some of these failures can be detected using the OMM. Thus, the OMM must have the following two characteristics regarding the equipt unavailability. First, it should not interfere with the original function of the equipment so that there is no aging and unavailable time caused by the OMM. Second, the test interval must be shorten to reduce the uncertainty related to the monitored failures. Figure 6 (b) presents the change in the equipment unavailability when the standby equipment adopts a monitoring method satisfied with these two characteristics.

4.2 Effectiveness of the OMM

To quantitatively investigate the effectiveness of the OMM, Eq. 6 must be modified by reflecting the OMM. The fault detection coverage and accuracy are the important factors for this modification. There is no problem when the OMM works correctly for the intended detection coverage, but there are two possible problems when it does not work correctly: there is an undetected failure, and the detecting signal appears when there is no failure. The former problem reduces the detection coverage. Therefore, the actual fault detection coverage (C_{om}) be the result of (intended coverage) × (1 - missing proportion). The latter problem causes an unnecessary test, which causes equipment aging. This problem affects the equipment differently according to the timing of its occurrence, and the frequency of the occurrence varies according to the sensitivity of the applied sensors. This effect can be applied to q_{ave} by assuming additional tests at the expected timing. However, in this section, the effects of these problems are not considered because we focus on the general effectiveness of the OMM. Thus, we assumed that the missing proportion was 0 and that there were no unnecessary tests.

As previously mentioned, the OMM detects failures that are related to standby stress. Therefore, some failures (C_{om}) are monitored using the interval of the OMM (T_{om}), and the remainder $(1-C_{om})$ is checked by the interval of the CIM. The equipment unavailability for the OMM-monitored portion (C_{om}) was approximated as the average value for the monitoring interval (T_{om}), as shown in Eq. 10. The error of this approximation is negligible because the monitoring interval is considerably shorter than that of the CIM.

$$q_f(n,t) = \rho_0 + \rho_0 p_1 n + t\left(\lambda_0(1+p_2 n) + \alpha(2t_n + \tfrac{1}{2}t)\right)(1-C_{om}) + \left(\frac{1}{T_{om}}\int_0^{T_{om}} t\left(\lambda_0(1+p_2 n)+\alpha(2t_n+\tfrac{1}{2}t)\right)dt\right)C_{om} \quad (10)$$

where
C_{om} = Fault detection coverage of the OMM $\left(intended\ coverage \times (1 - missing\ proportion)\right)$
T_{om}= Online monitoring interval

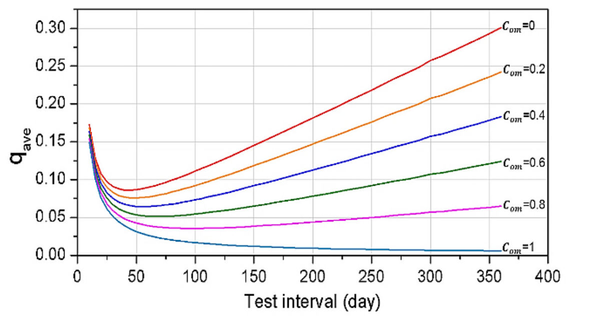

Fig. 7 $\boldsymbol{q_{ave}}$ changes according to $\boldsymbol{C_{om}}$ with a fixed test interval

Figure 7 presents the changes in q_{ave} according to C_{om} when the equipment is tested at a fixed interval. For this calculation, the information in Table 1 was used again. In addition, T_{om} was assumed to be 1s. In this figure, $C_{om} = 0$ indicates that no portion of the standby-stress-related failures is monitored. This case is identical to the result in Figure 3. C_{om}= 1 indicates that all standby-stress-related failures are detected using the OMM. The overall q_{ave} for each case decreases according to the increase in C_{om}. Furthermore, as shown in Table 2, the optimal test interval for the lowest q_{ave} increases with increases in C_{om} because a test is not necessary if test stress is allowed when we consider the benefit of the reduced uncertainty due to the OMM. When C_{om}= 1, the optimal test interval was 360 days, which was the largest calculation range. However, the ideal assumptions that there are no unnecessary tests performed by the OMM and that there are no missing portions of the detected coverage should be considered for this result.

Table 2. Optimal test plan for each C_{om} when it was tested with a fixed interval

C_{om}	*Test interval*	q_{ave}
0	*45*	*0.0862*
0.2	*50*	*0.0757*
0.4	*55*	*0.0643*
0.6	*70*	*0.0514*
0.8	*95*	*0.0355*
1	*360*	*0.0059*

5. Combination of the CIM and OMM

5.1 Combination of the CIM and OMM

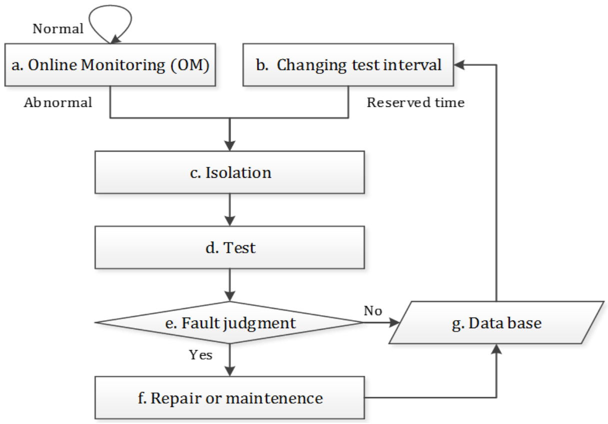

Fig. 8 Sequence of the combination of the CIM and OMM

Because the CIM and OMM are closely connected, they can be combined. The combination and their sequence are shown in Figure 8. During the standby time, standby-stress-related failures are detected by online monitoring (a), so some uncertainties caused by these failures can be removed. If an abnormality is detected, the test (d) will be performed after the isolation process (c). At the fault judgment (e), when the abnormality is judged as a failure, the repair or maintenance process (f) is performed. Through this process, the equipment conditions may change because some elements are replaced. These changes must be saved for the recalculation of the optimal test plan. More detailed descriptions will be discussed in section 5.2. The database is updated even if there is no abnormality because a certain number of tests is required to calculate the optimal test plan. In addition to the detection of abnormality using the OMM, the equipment can be tested by the reserved time of the changing test interval (b), which is essential for the detection of failures that are not monitored by the OMM.

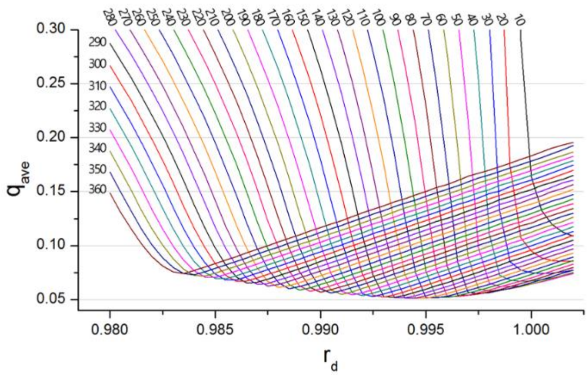

Figure 9 When $\boldsymbol{C_{om}}$=0.4, $\boldsymbol{q_{ave}}$ changes according to the initial test interval ($\boldsymbol{T_0}$) and the decreasing rate ($\boldsymbol{r_d}$)

Figure 9 shows q_{ave} when the CIM is applied to the representative case of C_{om}=0.4. In this calculation, q_{ave} was 0.0507, and the optimal test plan was T_0=125 days and r_d=99.45%. These results share some similarities with those in Figures 5 and 7. First, compared with Figure 5, both cases used the CIM, but in Figure 9, we used the additional OMM for 40% of the standby-stress-related failures. As a result, the q_{ave} value of the optimal plan was reduced to 75.9%. Second, compared with Figure 7, both cases used the OMM (C_{om}=0.4), but in Figure 9, we also used the CIM. Therefore, the optimal q_{ave} value was reduced to 78.8%. For the C_{om}=0.4 cases, the total number of tests was 397 when the equipment was tested with a fixed interval (55 days) and 568 when it was tested with a changing interval (T_0 =125, r_d=99.45%). If the test cost must be calculated, these numbers should be considered. Similarly to the CIM case when some condition was changed, the optimal test plan differed for each value of C_{om}. The optimal test plans for the other values of C_{om} and their associated q_{ave} values are summarized in Table 3. For C_{om}=1, the minimum q_{ave} was obtained when r_d was larger than 1. However, this result is identical to the result of the 360-day fixed test interval. When all standby-stress-related values are perfectly detected, the equipment test is not required. Therefore, the optimal plan includes fewer tests.

Table 3 Optimal test plan for each $\boldsymbol{C_{om}}$ when the equipment was tested at a changing

C_{om}	T_0	r_d	q_{ave}
0	100	99.55%	*0.0668*
0.2	*110*	*99.50%*	*0.0593*
0.4	*125*	*99.45%*	*0.0507*
0.6	*150*	*99.35%*	*0.0410*
0.8	*215*	*99.05%*	*0.0288*
1	*360*	*100.2%*	*0.0057*

5.2 Updating of the CIM after repair

If there is a real failure, the equipment will be repaired (e-f in Figure 8). After the repair, the parameters (ρ_0, λ_0, p_1, p_2, and α) that express the equipment conditions should be modified. However, these modifications are difficult to estimate because it is extremely rare for an identical failure to occur at the same timing. Therefore, in this section, the method to reflect the effect of the repair using the given initial parameters is introduced and an example is presented. After the repair process, which replaces some failed elements, Eqs. 4 and 5 can be revised to Eqs. 11 and 12. The aging effects of the replaced element, which have been accumulated because of test and standby stress since it installation before the failure occurs, should be removed. When the optimal test plan for the remaining lifetime after the failure occurrence is calculated, the equipment conditions for the number of tests and the elapsed time should be added from n_f and t_f, rather than resetting both values to 0.

$$\rho(n) = \rho_0 + \rho_0 p_1 n - \left(\left(\rho_0 + \rho_0 p_1 n_f\right) - \left(\rho_0 + \rho_0 p_1 n_0\right)\right)\frac{n_{T-r}}{n_T} \quad (11)$$

$$\lambda(n,t) = \lambda_0 + \lambda_0 p_2 n + \alpha(t_n + t) - \left[\left(\lambda_0 + \lambda_0 p_2 n_f + \alpha(t_f)\right) - \left(\lambda_0 + \lambda_0 p_2 n_0 + \alpha(t_0)\right)\right]\frac{n_{TS-r}}{n_{TS}} \quad (12)$$

where
n_f = Number of tests performed on the equipment before failure occurs
t_f = Elapsed time before the failure occurs since the equipment installation
n_0 = 0, Number of tests immediately after installation
t_0 = 0, Elapsed time immediately after installation
n_T = Expected total number of failures that are only related to test stress
n_{T-r} = Expected number of failures of the replaced element that are related to only test stress
n_{TS} = Expected total number of failures that are related to test stress and standby stress
n_{TS-r} = Expected number of failures of the replaced element that are related to test stress and standby stress

A simple example is presented here. Under the same conditions that are applied to the MOV in Figure 9, a failure that is only related to test stress occurs 30 years after equipment installation. The ratio ($\frac{n_{TS-r}}{n_{TS}}$) of n_{TS-r} (number of failures that are expected to occur at the replaced element) to n_{TS} (total number of failures that are only related to test stress) is 0.2. q_{ave} was recalculated for the remaining lifetime (30 years) according to T_0 and r_d and shown in Figure 10. The optimal test plan for that timing of failure occurrence has an initial test interval of 55 days and a decrease rate of 99.55%. q_{ave} was 0.0656 for this test plan. The optimal test interval was considerably short than the one immediately after installation because there is a large uncertainty caused by the high failure rate due to the accumulated standby stress. This method can be applied to the maintenance strategy. Let's assume a situation that a few decades passed since its installation but actual failure is not appeared yet. In this situation, the cost effectiveness can be quantitatively compared by dividing the q_{ave} difference when some element replaced by the element cost. It will be a help to make a decision for maintenance.

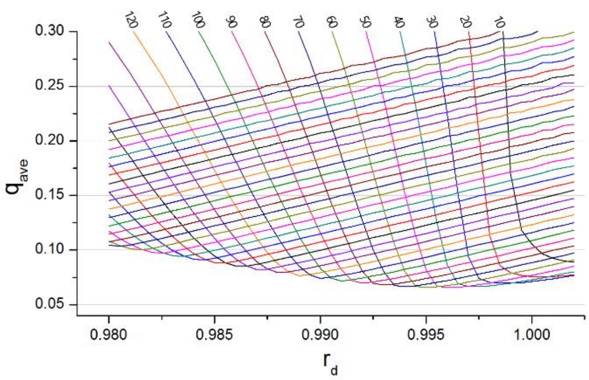

Fig. 10 Recalculated changes in $\boldsymbol{q_{ave}}$ for the remaining lifetime (30 years)

6. Concluding Remarks

A general approach to calculate the unavailability of standby equipment that is periodically tested was investigated. Using this approach, the average equipment unavailability was calculated for the entire lifetime. The CIM and OMM were presented as a method to reduce equipment unavailability. In the example case addressed in this study, when the CIM was applied, q_{ave} could be lowered to approximately 77.5% of the default value. When the OMM was applied, q_{ave} could be lowered to approximately 74.6% of the default value for C_{om}=0.4. In particular, q_{ave} could be further decreased with increases in C_{om}. These two methods can be combined to further reduce equipment unavailability. The optimal test plan for the lowest q_{ave} was changed according to each condition, which is related to the condition of equipment itself and applied methods. The proposed methods can be applied to dynamic PSA, detailed regulations, and maintenance strategies because they can provide information on the equipment according to different conditions and time.

Two requirements need to be satisfied for these applications. First, a database of detailed information, such as the number (or the timing) of tests and the failure characteristics, should be established. The obtained q_{ave} value in this study tends to be larger than the known value, although it is the average value for 60 years. To obtain accurate results, the correct parameters must be obtained from the database. However, the currently available database is limited. Second, suitable techniques that can be applied to the OMM need to be studied. For example, sensors to detect failures and a signal process method to enhance the accuracy are some of them.

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