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Development of STI/AOT Optimization Methodology and an Application to the AFWPs with Adverse Effects

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Abstract

Adverse effects caused by the surveillance test for the components of nuclear power plant involve plant transients, unnecessary wear, burden on licensee's time, and the radiation exposure to personnel along with the characteristics of each component. The optimization methodology of STI and AOT has been developed and applied to AFWPs of a reference plant. The approach proposed in this paper consists of the results in minimal mean unavailability of the two-out-of-four system with adverse effects are analytically calculated for the example system. The surveillance testing strategy are given by the sequential test, the staggered test and the train staggered test, which is a mixed test scheme. In the system level, the sensitivity analyses for the STI and AOT, are performed for the measure of the system unavailability of the top event in the fault tree developed for the example system. This methodology may contribute to establishing the basis for the risk-based regulations.

1. Introduction

The surveillance test interval(STI) and allowed outage time(AOT) of the components in the reference plant[1] were restricted by the surveillance requirements(SR) and limiting conditions for operating (LCO) of technical specification(TS). The current STI and AOT developed by the deterministic analysis and engineering operating experience. This improvement contributes to enhancing safety and operability without hardware changes for the equipments of nuclear power plants.

The safety-significant components, such as emergency diesel generators and auxiliary feedwater pumps, have been often tested on the schedule specified in TS. This frequent test has raised concern about the progressive wear-out of the equipments due to the accumulation of degradation caused by the test itself. Adverse effects caused by the surveillance test for the components involved were plant transients, unnecessary wear, burden on licensee's time and radiation exposure to personnel along with the characteristics of each component[1]. Unnecessary wear and licensee burden were identified as the dominant adverse effects for the auxiliary feedwater pumps (AFWPs). A significant cause of the unnecessary wear of the AFWPs results from component testing, which is conducted by recirculating flow through a minimum recirculation line which is not adequate size.

The approach in this paper for the optimal STI and AOT of the AFWPs of the reference plant[1] consists of the component level and system level. In the component level, the optimal STI which results in minimal system unavailability of the 2/4 system with adverse effects are analytically obtained for AFWPs. The mean unavailability is functions of the random failure, demand failure, common cause failure and human error committed when test and maintenance are performed. The basic model of the random failure and the demand failure rate, which consider the degradation mechanisms and wear caused by surveillance test, are given as following;

$$\lambda = \lambda_0\left\{(1-P_1) + P_1\left(\frac{W}{T}\right)\right\}, \tag{1}$$

$$D = D_0\left\{(1-P_2) + P_2\left(\frac{W}{T}\right)\right\}, \tag{2}$$

where the parameters used denotes the following;

λ_0 : the random failure rate,

D_0 : the demand failure rate,

P_1 : the test degradation factor for standby time-related failures,

P_2 : the degradation factor associated with demand failures,

T : the period of surveillance test interval,

W : the current surveillance test interval considering the random and demand failure data.

These models represent linearizations for the non-linear test caused model[2]. Since the previous work assumed that the demand and random failure rates have values of constants, the adverse effects associated with test and maintenance could not be incorporated as important factors. These linearized models are used to obtain the analytical system unav ailability.

The advantages on the staggered test base include the small chances of occurrences of common cause failures, which results in the reduced system unavailability. But the staggered test bears disadvantage, which requires additional licensed operators and overtime. It can also extended the time required to perform surveillance tests. The surveillance testing strategy for the 2/4 redundant system of the AFWPs used in this paper includes the sequential test, the staggered test and the train staggered test, which is sequential test performed in a train.

In system level, the sensitivity analyses for the STI and AOT are performed for the measure of the system unavailability. The fault tree of the auxiliary feedwater system(AFWS) in the reference plant are modeled and evaluated by using the IRRAS Code[6]. The data collected during the individual plant examination(IPE) are used for calculations.

2. The AFWPS of the Reference Plant

Figure 1 shows the simplified P&ID of the AFWS of the reference plant. The AFWS have two trains, while each train consists of both one motor driven pump and one diesel driven pump. The main function of each pump is to supply the auxiliary feedwater to the steam generators in order to continue to retrain water level of S/G, when the main water system is inoperable. The capability of each pump is 50% supplement of S/G water level. Therefore, the logic of the system can be assumed as the 2/4 system. The substantial safety function of AFWPs for S/G during the accidents is sufficiently assured by operation of a pump at least. The current surveillance test interval allowed in technical specifications is required monthly on a staggered test basis. This scheme may give the licensee a burden on licensee's time. In this study, analysis of system level is performed for AFW system regarding both trains.

2.1. Adverse Effects Caused by Test

Table 1 summarized the dominant adverse effects caused by the several example tests. Adverse effects caused by the test involve plant transients, unnecessary wear, burden on licensee's time and the radiation exposure to personnel along with the characteristics

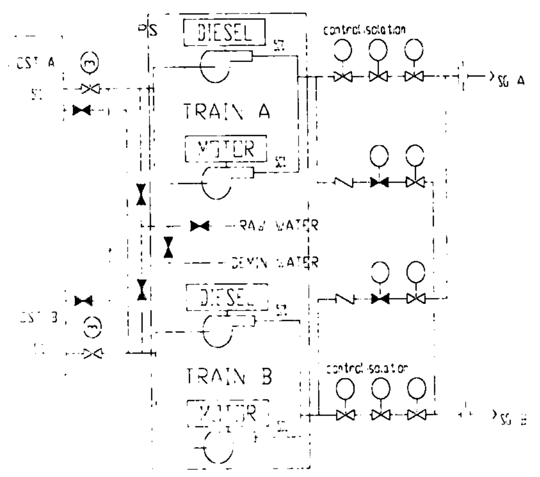

Fig. 1. Simplified P&ID of the AFWS of the Reference Plant

Table 1. Dominant Adverse Effects(AE) from the Components[2]

AE / SS*	Plant Transient	Unnecessary Wear	Licensee Burden	Radiation Exposure
MSIV	O			
DGs		O		
AFWP		O	O	
ECCS			O	O

* SS : Surveillance system

of each component[2]. Unnecessary wear and licensee burden were identified as dominant adverse effects of the AFWPs testing. A significant cause of the unnecessary wear resulting from testing the pumps by recirculating flow through a minimum recirculation line which is not adequate sized. Even if these recirculation lines are expanded, the frequent testing may cause the wear.

2.2. Analytical Unavailability

Figure 2a shows the staggered test scheme which are periodically divided into uniform intervals for each component of 2/4 system. The parameter, τ, represents the test period for each component. The parameter, τ_r(BC, DE, FG and HI), represents surveillance duration time for one component. The analytical solutions for the system unavailability are obtained by using the failure factors with the random failure, demand failure rate, common cause failure (CCF) probability and human error probability. The random failure and demand failure rate are incorporated in the following model linearized from the non-linear test-caused model. The model with the degradation mechanisms caused by test can be expressed by the following Eqn. (3)-(6) ;

$$\lambda_{r1} = \lambda_{01}\left\{ (1-P_{r1}) + P_{r1}\left(\frac{W}{T}\right)\right\}, \tag{3}$$

$$\lambda_{r2} = \lambda_{02}\left\{ (1-P_{r2}) + P_{r2}\left(\frac{W}{T}\right)\right\}, \tag{4}$$

$$D_{r1} = D_{01}\left\{ (1-P_{d1}) + P_{d1}\left(\frac{W}{T}\right)\right\}, \tag{5}$$

and

$$D_{r2} = D_{02}\left\{ (1-P_{d2}) + P_{d2}\left(\frac{W}{T}\right)\right\}, \tag{6}$$

where subscript 1 and 2 : diesel driven pumps and motor driven pumps.

λ_{01} and λ_{02} : random failure rate,

D_{01} and D_{02} : demand failure rate,

P_{r1} and P_{r2} : the test degradation factor for standby time-related failure,

P_{d1} and P_{d2} : the degradation factor associated with demand failures,

T : the period of surveillance test interval,

W : the current surveillance test interval considering the random and demand failure data.

The β model is used here for common cause failures. The start-up and the operation power are different from the typical situations. For diesel driven pumps and motor driven pumps, the characteristics associated with CCFs are modeled and expressed in the following Eqn. (7)-(10);

$$\frac{\beta_{r1}}{(1-\beta_{r1})}\lambda_{r1} = \lambda_{c1}, \tag{7}$$

$$\frac{\beta_{r2}}{(1-\beta_{r2})}\lambda_{r2} = \lambda_{c2}, \tag{8}$$

$$\frac{\beta_{d1}}{(1-\beta_{d1})} D_{d1} = D_{c1}, \qquad (9)$$

$$\frac{\beta_{d2}}{(1-\beta_{d21})} D_{d2} = D_{c2}. \qquad (10)$$

Total random failure rate is ;

$$\lambda_{r1} + \lambda_{c1} = \lambda_1, \qquad (11)$$

and

$$\lambda_{r2} + \lambda_{c2} = \lambda_2 .$$

Total demand failure rate is ;

$$D_{d1} + D_{c1} = D_1, \qquad (13)$$

and

$$D_{d2} + D_{c2} = D_2 \qquad (14)$$

r_1 and r_2 represent human error rates. The human errors may occur on test and maintenance. Any dependent human error between consecutive test actions is negligible when the staggered test is performed. It is because the surveillance duration times are uniformly separated.

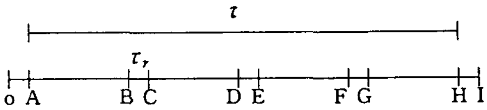

Fig. 2a. Staggered Test Scheme

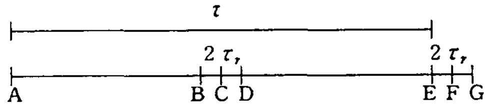

Fig. 2b. Train Staggered Test scheme

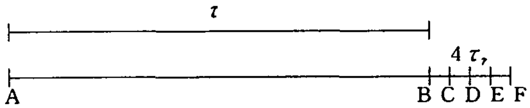

Fig. 2c. Sequential Test Scheme

Table 2a. Unavailability with Random Failure and Demand Failure

	Staggered Test	Train Staggered Test	Sequential Test
F1	$2(D_{d_2}^2 D_{d_1} + D_{d_2} D_{d_1}^2)$	$2(D_{d_2}^2 D_{d_1} + D_{d_2} D_{d_1}^2)$	$2(D_{d_2}^2 D_{d_1} + D_{d_2} D_{d_1}^2)$
F2	$2(D_{c_1} D_{d_2} + D_{c_2} D_{d_1})$	$2(D_{c_1} D_{d_2} + D_{c_2} D_{d_1})$	$2(D_{c_1} D_{d_2} + D_{c_2} D_{d_1})$
F3	$(D_{d_1}^2 \lambda_{r_2} + D_{d_2}^2 \lambda_{r_1})\tau$	$(D_{d_1}^2 \lambda_{r_2} + D_{d_2}^2 \lambda_{r_1})\tau$	$(D_{d_1}^2 \lambda_{r_2} + D_{d_2}^2 \lambda_{r_1})\tau$
F4	$2(D_{d_1} D_{d_2} \lambda_{r_1} + D_{d_2} D_{d_1} \lambda_{r_2})\tau$	$2(D_{d_1} D_{d_2} \lambda_{r_1} + D_{d_2} D_{d_1} \lambda_{r_2})\tau$	$2(D_{d_1} D_{d_2} \lambda_{r_1} + D_{d_2} D_{d_1} \lambda_{r_2})\tau$
F5	$(D_{d_1} \lambda_{r_1} \lambda_{r_2} + D_{d_2} \lambda_{r_2} \lambda_{r_1})\frac{23\tau^2}{24}$	$(D_{d_1} \lambda_{r_1} \lambda_{r_2} + D_{d_2} \lambda_{r_2} \lambda_{r_1})\frac{13\tau^2}{12}$	$(D_{d_1} \lambda_{r_1} \lambda_{r_2} + D_{d_2} \lambda_{r_2} \lambda_{r_1})\frac{4\tau^2}{3}$
F6	$(D_{d_2} \lambda_{r_1}^2 + D_{d_1} \lambda_{r_2}^2)\frac{5\tau^2}{12}$	$(D_{d_2} \lambda_{r_1}^2 + D_{d_1} \lambda_{r_2}^2)\frac{5\tau^2}{12}$	$(D_{d_2} \lambda_{r_1}^2 + D_{d_1} \lambda_{r_2}^2)\frac{2\tau^2}{3}$
F7	$(\lambda_{r_1}^2 \lambda_{r_2} + \lambda_{r_1} \lambda_{r_2}^2)\frac{25\tau^3}{384}$	$(\lambda_{r_1}^2 \lambda_{r_2} + \lambda_{r_1} \lambda_{r_2}^2)\frac{\tau^3}{4}$	$(\lambda_{r_1}^2 \lambda_{r_2} + \lambda_{r_1} \lambda_{r_2}^2)\frac{\tau^3}{2}$
F8	$(D_{c_1} \lambda_{r_2} + D_{c_2} \lambda_{r_1})\tau$	$(D_{c_1} \lambda_{r_2} + D_{c_2} \lambda_{r_1})\tau$	$(D_{c_1} \lambda_{r_2} + D_{c_2} \lambda_{r_1})\tau$
F9	$(D_{d_2} \lambda_{c_1} + D_{d_1} \lambda_{c_2})\frac{3\tau}{2}$	$(D_{d_2} \lambda_{c_1} + D_{d_1} \lambda_{c_2})\frac{3\tau}{2}$	$(D_{d_2} \lambda_{c_1} + D_{d_1} \lambda_{c_2})\tau$
F10	$(\lambda_{c_1} \lambda_{r_2} + \lambda_{c_2} \lambda_{r_1})\frac{35\tau^2}{48}$	$(\lambda_{c_1} \lambda_{r_2} + \lambda_{c_2} \lambda_{r_1})\frac{19\tau^2}{24}$	$(\lambda_{c_1} \lambda_{r_2} + \lambda_{c_2} \lambda_{r_1})\frac{2\tau^2}{3}$
F11	$2\{(D_{d_1}^2 + D_{c_1} + D_{d_2}^2 + D_{c_2} + 2(D_2 D_{d_1} + D_1 D_{d_2})\}\frac{\tau_r}{\tau}$	$2\{(D_{d_1}^2 + D_{c_1} + D_{d_2}^2 + D_{c_2} + 2(D_2 D_{d_1} + D_1 D_{d_2})\}\frac{\tau_r}{\tau}$	$2\{ D_{d_1}^2 + D_{c_1} + D_{d_2}^2 + D_{c_2} + 2(D_2 D_{d_1} + D_1 D_{d_2})\}\frac{\tau}{\tau}$
F12	$2(D_{d_2} \lambda_{r_2} + D_1 \lambda_{r_2} + D_{d_2} \lambda_1 + D_{d_1} \lambda_{r_1} + D_2 \lambda_{r_1} + D_{d_1} \lambda_2)\tau_r$	$(3D_{d_2} \lambda_{r_2} + 3D_1 \lambda_{r_2} + 2D_{d_2} \lambda_1 + D_{d_1} \lambda_{r_1} + D_2 \lambda_{r_1} + 2D_{d_1} \lambda_2)\tau_r$	$(3D_{d_2} \lambda_{r_2} + 3D_1 \lambda_{r_2} + 2D_{d_2} \lambda_1 + D_{d_1} \lambda_{r_1} + D_2 \lambda_{r_1} + 2D_{d_1} \lambda_2)\tau_r$
F13	$(\lambda_{c_1} + \lambda_{c_2})\frac{3}{2}\tau_r + (\lambda_1 \lambda_{r_2} + \lambda_2 \lambda_{r_1})\tau\tau_r$	$(\lambda_{c_1} + 2\lambda_{c_2})\tau_r + (3\lambda_1 \lambda_{r_2} + \lambda_2 \lambda_{r_1})\frac{\tau\tau_r}{2}$ $\lambda_{r_2}^2 \tau\tau_r + \lambda_{r_1}^2 \frac{\tau_r^2}{2}$	$(\lambda_{c_1} + 2\lambda_{c_2})\tau_r + (\lambda_{r_2}^2 + 2\lambda_1 \lambda_{r_2} + \lambda_2 \lambda_{r_1} + \lambda_{r_1}^2 \frac{\tau_r}{2\tau})\tau\tau_r$

Table 2b. Unavailability with Human Error

F14	$2(\gamma_1\gamma_2^2 + \gamma_1^2\gamma_2)$	$2(\gamma_1\gamma_2^2 + \gamma_1^2\gamma_2)$	$2(\gamma_1\gamma_2^2 + \gamma_1^2\gamma_2)$
F15	$4\gamma_1\gamma_2\left\{D_t + \frac{\tau}{2}(\lambda_1+\lambda_2)\right\}$	$4\gamma_1\gamma_2(D_t + \lambda_t\frac{\tau}{2})$	$4\gamma_1\gamma_2(D_t + \lambda_t\frac{\tau}{2})$
F16	$\gamma_2^2\left\{(D_1+D_{d_1}) + \frac{\tau}{2}(\lambda_{r_1}+\lambda_1)\right.$	$\gamma_2^2(D_1 + D_{d_1} + \frac{3\tau}{4}\lambda_1 + \frac{\tau}{4}\lambda$	$\gamma_2^2\left(D_1 + D_{d_1} + \frac{\tau}{2}(\lambda_1+\lambda_{r_1})\right)$
F17	$\gamma_1^2\left\{(D_2+D_{d_2}) + \frac{\tau}{2}(\lambda_2+\lambda_{r_2})\right.$	$\gamma_1^2\left(D_2 + D_{d_2} + \frac{3\tau}{4}\lambda_2 + \frac{\tau}{4}\lambda_{r_2}\right.$	$\gamma_1^2\left(D_2 + D_{d_2} + \frac{\tau}{2}(\lambda_2+\lambda_{r_2})\right)$
F18	$2\gamma_1\{(D_{d_2}^2 + D_{c_2} + 2D_1D_{d_2}) + (D_{d_2}\lambda_{r_2} + D_{d_2}\lambda_1 + D_1\lambda_{r_2})\tau + \lambda_{c_2}\frac{3\tau}{4} + \lambda_{r_2}^2\frac{5\tau^2}{24} + \lambda_1\lambda_{r_2}\frac{31\tau^2}{24}\}$	$2\gamma_1\{D_{d_2}^2 + 2D_{d_2}D_1 + D_{c_2} + (D_{d_2}\lambda_{r_2} + D_1\lambda_{r_2} + D_{d_2}\lambda_1)\tau \lambda_{r_2}^2\frac{5\tau^2}{24} + \lambda_{c_2}\frac{3\tau}{4} + \lambda_{r_2}\lambda_1\frac{13\tau^2}{24}\}$	$2\gamma_1\{D_{d_2}^2 + 2D_{d_2}D_1 + D_{c_2} + (D_{d_2}\lambda_{r_2} + D_1\lambda_{r_2} + D_{d_2}\lambda_1)\tau + \lambda_{r_2}^2\frac{\tau^2}{3} + \lambda_{c_2}\frac{\tau}{2} + \lambda_{r_2}\lambda_1\frac{2\tau^2}{3}\}$
F19	$2\gamma_2\{(D_{d_1}^2 + D_{c_1} + 2D_2D_{d_1}) + (D_{d_1}\lambda_{r_1} + D_{d_1}\lambda_2 + D_2\lambda_{r_1})\tau + \lambda_{c_1}\frac{3\tau}{4} + \lambda_{r_1}^2\frac{5\tau^2}{24} + \lambda_2\lambda_{r_1}\frac{31\tau^2}{24}\}$	$2\gamma_2\{D_{d_1}^2 + 2D_{d_1}D_2 + D_{c_1} + (D_{d_1}\lambda_{r_1} + D_2\lambda_{r_1} + D_{d_1}\lambda_2) \lambda_{r_1}^2\frac{5\tau^2}{24} + \lambda_{c_1}\frac{3\tau}{4} + \lambda_{r_1}\lambda_2\frac{13\tau^2}{24}\}$	$2\gamma_2\{D_{d_1}^2 + 2D_{d_1}D_2 + D_{c_1} + (D_{d_1}\lambda_{r_1} + D_2\lambda_{r_1} + D_{d_1}\lambda_2)\tau \lambda_{r_1}^2\frac{\tau^2}{3} + \lambda_{c_1}\frac{\tau}{2} + \lambda_{r_1}\lambda_2\frac{2\tau^2}{3}\}$
F20	$2(4\gamma_1\gamma_2 + \gamma_1^2 + \gamma_2^2)\frac{\tau_r}{\tau}$	$2(4\gamma_1\gamma_2 + \gamma_1^2 + \gamma_2^2)\frac{\tau_r}{\tau}$	$2(4\gamma_1\gamma_2 + \gamma_1^2 + \gamma_2^2)\frac{\tau_r}{\tau}$
F21	$2\gamma_1\left\{(D_2+D_{d_2})\frac{\tau_r}{\tau} + \lambda_2\frac{3}{4}\tau_r + \lambda_{r_2}\frac{1}{4}\tau_r + 2D_t\frac{\tau_r}{\tau} + \lambda_t\tau_r\right\}$	$2\gamma_1\left\{(D_2+D_{d_2})\frac{\tau_r}{\tau} + \lambda_2\frac{5}{2}\tau_r + \lambda_{r_2}\frac{1}{2}\tau_r + 2D_t\frac{\tau_r}{\tau} + \lambda_t\frac{\tau_r}{2}\right\}$	$2\gamma_1\left\{(D_2+D_{d_2})\frac{\tau_r}{\tau} + \lambda_2\frac{3}{2}\tau_r + \lambda_{r_2}\frac{1}{2}\tau_r + 2D_t\frac{\tau_r}{\tau} + \lambda_t\frac{\tau_r}{2}\right\}$
F22	$2\gamma_2\left\{(D_1+D_{d_1})\frac{\tau_r}{\tau} + \lambda_1\frac{3}{4}\tau_r + \lambda_{r_1}\frac{1}{4}\tau_r + 2D_t\frac{\tau_r}{\tau} + \lambda_t\tau_r\right\}$	$2\gamma_2\left\{(D_1+D_{d_1})\frac{\tau_r}{\tau} + \lambda_{r_1}\frac{1}{2}\frac{\tau_r^2}{\tau} + 2D_t\frac{\tau_r}{\tau} + \lambda_t\frac{3}{2}\tau_r\right\}$	$2\gamma_2\left\{(D_1+D_{d_1})\frac{\tau_r}{\tau} + 2D_t\frac{\tau_r}{\tau} + \lambda_t\frac{3}{2}\tau_r\right\}$

Figure 2b shows the train staggered test scheme, in which the sequential test in a train is performed and the staggered test is performed in terms of trains. The system unavailabilities are obtained through Eqn. (3)-(14). The conditional dependency of human action performed during maintenance is assumed medium(MD) in this study.

Figure 2c shows the conventional sequential test scheme. Or each components of all trains are tested sequentially.

Table 2 lists and itemizes the analytical results for the system unavailability. The F1 item denotes the mean system unavailability for both two diesel pumps and one motor pump and one diesel pump and two motor pumps downed. From F2 to F22, the total system unavailability is obtained in the following Eqn. (15) ;

Total unavailability ;

$$Q_t = \sum_{i=1}^{22} F_i \qquad (15)$$

2.3. Unavailability Calculations

Table 3 represents the data for calculations in this study and they are cited from the IPE study in the plant[1]. The error factor used here is a value of 10. The data on adverse effects caused by test and maintenance are given by specific failure data of the AFWPs in the LERs[8]. A review of LERs shows that 26% of the motor driven pumps had failed due to the rotation element itself and 42% of pump failure were found during surveillance test[1].

Table 3. Failure Data of AFWPs[1]

	Random Failure	Demand failure	CCF (Beta)	Human Error
Motor Pump	3.0E-3/d	1.5E-4/hr	0.0546 (demand) 0.003 (random)	3.28E-3 7.98E-4
Diesel Pump	2.0E-2/d	1.0E-4/hr	0.0546 (demand) 0.003 (random)	3.28E-3 7.98E-4

Table 4. Failure Occurrence Ratio(%) of AFWPs[8]

Lack of Lubrication or Cooling	Maintenance Error	Wear/end of life	Not stated	Etc
23%	17%	15%	19%	23%

Table 5. Mean Unavailability of AFWPs

	Staggered test	Train staggered test	Sequential test
30 days	7.62×10^{-4}	1.07×10^{-3}	1.54×10^{-3}
	7.62×10^{-4} (Wear)	1.07×10^{-3} (Wear)	1.54×10^{-3} (Wear)
60 days	2.68×10^{-3}	4.83×10^{-3}	8.1×10^{-3}
	1.91×10^{-3} (Wear)	3.35×10^{-3} (Wear)	5.50×10^{-3} (Wear)
90 days	6.38×10^{-3}	1.36×10^{-2}	2.40×10^{-2}
	3.91×10^{-3} (Wear)	7.96×10^{-3} (Wear)	1.39×10^{-2} (Wear)

Figure 3 shows that the mean unavailability of AFWPs with adverse effects in the component level is decreased radically up to quarterly. They are decreased from about 30% to 60 days and 40% to 90 days on the staggered test. The mean system unavailability with respect to the surveillance testing strategy are affected by random failure and human error rates. But not much affected by demand failure, as shown in Table 5.

The system unavailability of AFWS using IRRAS code in the system level are performed by the fault tree analysis. The fault trees for AFWS of YGN Unit

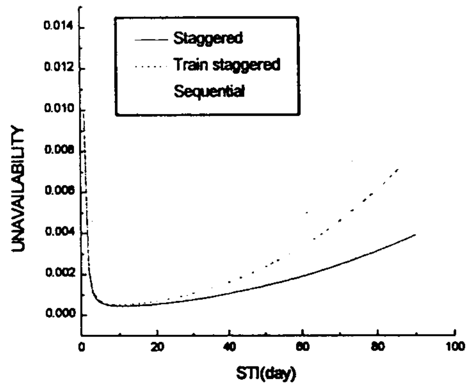

Fig. 3a. Unavailability Along with Surveillance Test Starategy(Wear)

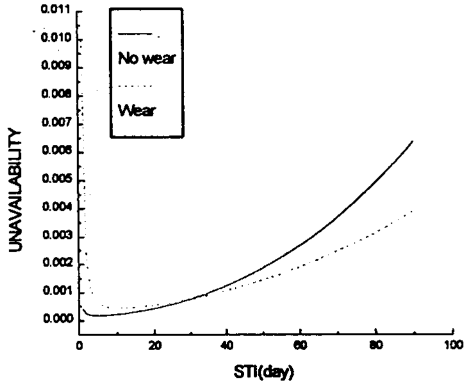

Fig. 3b. Unavailability of Staggered Test

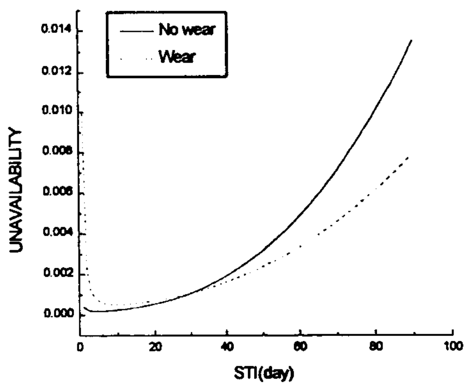

Fig. 3c. Unavailability of Train Staggered Test

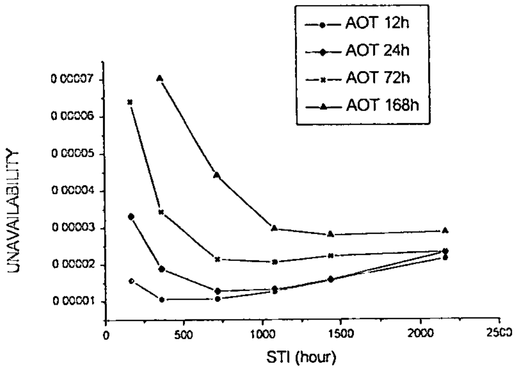

Fig. 4. Unavailability of AFWS ar Various AOT/STI

3&4 is adopted from the level I final PRA update report for YGN 3&4 published by KAERI in 1993[1]. These fault trees for AFWS consists of many subtrees representing the various significant systems such as electric power system, engineering safety feature actuation system, instrumentation and control system, etc. And these trees are built in the code by the connections of transit gates. The calculated system unavailabilities are shown in table 5 and figure 4. It is shown that are increased about 3.4% to 60 days and 9.1% to 90 days, as shown in table 6.

3. Conclusions

NRC recommended that the STI of AFW pumps need to be changed from monthly to quarterly on a staggered test basis, since the ASME code requires class 2 pumps, such as AFW pumps, be tested quarterly. It is described that the wear of AFW pumps is caused by recirculating water during tests through a line that has smaller diameter than presently recommended by pump manufacturers and the licensee burden is increased by monthly testing[2].

The proposed approach in this paper consists of the component level with adverse effects and the system level. The IRRAS code is utilized in the system level analysis. The STI of AFW pumps could be changed from monthly to quarterly on a staggered test basis. The optimal STI and AOT for the safety-significant components and systems can also be determined by this approach reflecting their characteristics such as adverse effects. It is shown that this methodology is very flexible in that it can be applied to any systems. It may also contribute to establishing a basis for the risk-based regulation.

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