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Groundbreaking safety enhancement based on digital I&C technology

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1. Introduction

Safety has been treated as an important issue in nuclear power plants (NPPs). Korea has set the core damage frequency (CDF) to the order of 10E-05 and 10E-6 per year for NPPs in operation and under construction, respectively, to meet the required safety margin. The importance of safety, however, has been even more emphasized in recent years, so a 10E-7 order of CDF is being targeted for future Korean NPPs. To meet this requirement, a new approach that can radically improve the safety of NPPs is required. In this study, two groundbreaking approaches for safety enhancement are introduced. One is availability improvement of standby safety component based on monitoring scheme and the other one is automation of feed and bleed (F&B) operation.

Since each component has its own failure probability, nuclear power plants (NPPs) have adopted redundancy and diversity concepts to reduce the failure probability of the entire system. This approach, however, increases system complexity and entails additional costs. 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 for the availability improvement of standby safety components should be developed.

F&B operation is the process to cool down the core using a safety depressurization system (SDS) and safety injection system (SIS) [1]. For F&B operation, operators must manually activate both systems based on very clear understanding about the plant status at that time. Because of these challenges, the failure probability of human operator is very high. Therefore, automation of this process is expected to reduce the failure probability of F&B initiation and to increase the plant safety.

2. Availability improvement of standby safety component

2.1 Management based strategies for component availability improvement

Currently, to maintain the availability of standby components, periodic surveillance tests are being applied to them [2]. Under this periodic operational test scheme, the unavailability of a standby component can be expressed schematically like Fig. 1. When the component is being tested, its intended function cannot be performed on demand because of the isolation procedures, such as a bypass from the ordinary path. In addition to this, if a failure occurs between periodic tests, the component is unavailable from this time to the next prearranged test due to its failure. Then, when the failed state is confirmed during the next test, additional unavailability occurs because of repair procedures.

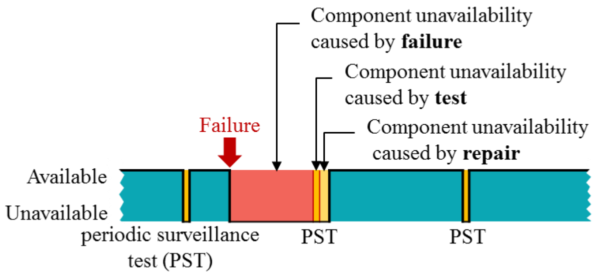

Fig. 1 Component unavailability under periodic surveillance test

Based on the periodic operational test structure, there might be two management based strategies for availability improvement. First, during standby or operation state, if failures in some elements are monitored and proper maintaining or substituting activities can be performed immediately, unavailability caused by failure can be reduced (online-status monitoring). Second, from the point of view of one standby turn, more frequent operational testing can reduce component unavailable time caused by failure because more frequent testing means earlier detection of failure (test interval adjustment). However, more frequent tests can lead to additional unavailable time caused by the testing itself and the additional failures caused by accumulated aging effects. Therefore, a general unavailability model considering component aging, test duration, and repair duration need to be developed.

2.2 General component unavailability model

To develop the general component unavailability, the aging effects need to be considered. At each test, the component may be worn down and deteriorate a little bit, so the effect of it accumulates along with the number of operations. This aging effect is named “test stress”. Waiting a long time may also deteriorate the condition of a component. This aging effect accumulating over time is named “standby stress”, and it can make failures occur more frequently. Kim. et al. [3] provided a well-organized mathematical foundation to reflect both stresses. When the both stresses are considered for a specific timing, component unavailability caused by failure can be expressed like Eq. 1.

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

$$t_n = \sum_0^{n-1} I_i \quad for\ n \geq 1,\ t_0 = 0 \qquad (2)$$

$$\rho(n) = \rho_0 + \rho_0 p_1 n \qquad (3)$$

$$\lambda(n,t) = \lambda_0 + \lambda_0 p_2 n + \alpha(t_n + t) \qquad (4)$$

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

where,
$q_f(n,t)$: Component unavailability caused by failure
t_n: Elapsed time since its installation
$\rho(n)$: Failure probability for failures occurring on demand
$\lambda(n,t)$: Standby failure rate 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
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

2.3 Reflection of the availability improvement strategies

Fig. 2 shows the interrelation between strategies for availability improvement of standby component. In order to reflect the effects of each strategy together, the unavailability model should be modified by applying the effects of each online status monitoring strategy, and the modified model can be utilized for test interval adjustment strategy with the operational information. By doing so, all the strategies can be combined together.

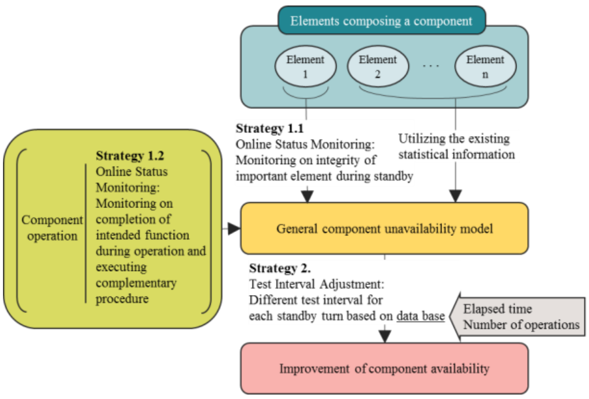

Fig. 2 Interrelation of strategies for availability improvement of standby component

The feasibility of the proposed strategies is demonstrated via a case study for an MOV and a CV. As a result of the analysis, the average unavailability of the valves for their expected lifetimes can be greatly reduced to 51.28% and 12.36%, respectively, when compared to the cases with no improvement strategies. From the comparison between the MOV and CV cases, it is confirmed that the test interval adjustment strategy is meaningful as an auxiliary means for the online status monitoring strategy.

3. Automated feed and bleed operation

3.1 Approaches for F&B automation

Automated function has two roles: first, performing the F&B operation automatically, second, predicting whether the reactor can be cooled down and core is not damaged after the F&B operation is initiated. For the first role, automated F&B operation will be developed using automation schemes (classical control schemes, fuzzy control, etc.). For the second role, detailed thermohydraulic modeling for identifying the necessity and success conditions for F&B operation initiation is performed using thermohydraulic modeling tools (MARS, CFD, etc.). In order to estimate the risk effects of automation, a dynamic probabilistic safety assessment (PSA) model can be utilized.

3.2 Development process of F&B automation and effect analysis

On the identification process of plant conditions needing F&B operation, a situation, that has secondary side failure with loss of coolant accident, is assumed as a representative case. Then various break timings (0 s, 3000 s, and 5000 s) and sizes (0.5 in, 1.0 in, 2.0 in, and 3.0 in) are set for analysis, as the pressure of primary loop is very important to identify the situations which need F&B operation and these two factors can affect the pressure change. In addition to this, availability of SIS components is also very important. Therefore, according to the combinations of break size, timing, and availability of high pressure safety injection (HPSI) pumps, the situations needing F&B operation are identified. Fig. 3 shows one of the thermohydraulic analysis results.

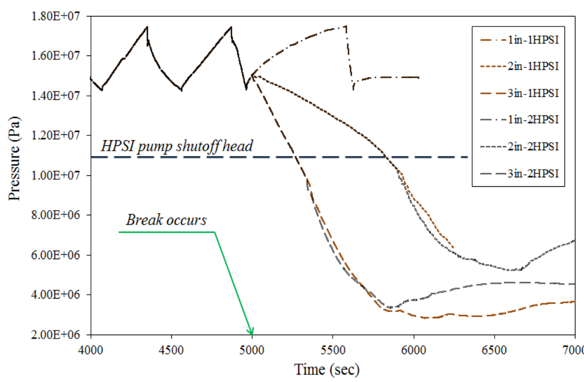

Fig. 3 Primary loop pressure based on the break size and the availability of the SIS components when a LOCA occurs at 5000s and an F&B operation is not initiated.

The guidance of F&B operation includes a number of steps following the opening of the SDS valves before reaching a SCS. However, conventional operation strategy in EOP does not cover all necessary conditions of F&B operation. In the case of small LOCA and failure of secondary side, the pressurizer safety valve (PSV) may not be opened. In this case, the F&B operation cannot be initiated since there is no direction in emergency operating procedure (EOP) even though the plant condition needs F&B operation. Hence, in this paper, an advanced operating strategies of F&B operation is suggested for the situations identified through thermohydraulic analysis.

If the automated function initiates F&B operation instead of operators, the human error probability (HEP) of initiating F&B operation can be replaced with failure probability of automated function in the PSA model. Therefore, as a sensitivity studies, 1.0E-1 to 1.0E-5 range of failure probability for F&B operation is reflected **by considering the early (1.46E-1) and late (5.69E-3) HEP for F&B operation.** Then, the difference of the CDF between original and modified are compared as shown in Fig. 4. If the failure of automated function is lower than failure probability of SDS (3.258E-3), the CDF is changed just a little bit. Therefore, the failure probability of automated function is necessary to lower than 0.001 based on the results from sensitivity study.

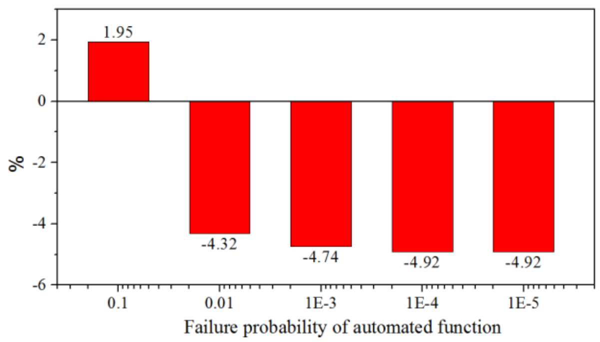

Fig. 4 Changes of core damage frequency differences according to the failure probability of automated function

4. Concluding remarks

Two groundbreaking approaches for safety enhancement of NPP are introduced. In case of the methodologies for availability improvement of standby component, while the proposed schemes were developed for the availability improvement, this scheme has potential applicability to other research areas because it can provide the most realistic availability of standby components 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 PSA for more realistic and accurate analysis, and risk-informed regulations.

In case of automation of F&B operation, just a specific situation is assumed to analysis. However, there might be various kinds of situation needing F&B operation and factors to be considered. Therefore, in order to quantify the actual effects of F&B operation under the combined accident, the research from definition of combined accident to development of dynamic PSA modeling for combined accident using the detailed thermal hydraulic modeling are needed. Especially, dynamic PSA can model accident sequences and calculate their probabilities through integrated, interactive, time-dependent, probabilistic and deterministic models of plant systems, thermal-hydraulic processes, and operator behavior in accident conditions. Based on the dynamic PSA modeling, the progression of the accident including quantitative timing of events and plant parameters for a given sequence would make the results more straight-forward to understand if it is intrinsic in the model and treatment of human interaction and mitigation can be improved.

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