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A Reliability Analysis of HHSIS of KNU 5,6,7 and 8 Following the Removal of s-signal from Charging/Safety Injection Pump Mini-flow Line Valves

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충전/안전주입 펌프 순환배관의 안전주입신호 제거에 따른 원자력 5,6,7,8 호기의 고압안전주입계통의 신뢰도 분석

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Abstract

The objective of this study is to evaluate the reliability of the High Head Safety Injection System (HHIS) of KNU 5, 6, 7 and 8 following the removal of safety injection signal (s-signal) from the mini-flow bypass line valves of charging/safety injection pumps. The unavailability of HHSIS and the rupture probability of a charging/safety injection pump have been computed for two different cases; with s-signal on and removed. The results show that when the s-signal is removed from the mini-flow bypass line valves, the unavailability of HHSIS slightly increases while the rupture probability of a charging/safety injection pump is significantly reduced. Hence, based upon the results of this study we conclude that it is more reasonable to remove the s-signal from the mini-flow bypass line valves of KNU 5,6,7 and 8 in the normal plant operation. And to improve the availability of HHSIS, the modification of operational procedures and the emphasis on operator training are recommended.

요　　약

본 연구의 목적은 충전/안전주입 펌프 최소순환관으로부터 안전주입신호(s-신호)를 제거함에 따른 원자력 5,6,7,8호기의 고압안전주입계통(HHSIS)의 신뢰도를 분석, 평가하는 것이다. 계산은 s-신호를 제거한 경우와 제거하지 않은 경우에 대하여 각각 수행되었다. 각 경우에 대하여 s-신호 발생시 고압안전주입계통의 이용불능도와 충전/안전주입 펌프의 파손확률이 계산되었다. 계산결과에 따르면, s-신호를 제거함에 따라 고압안전주입계통의 이용불능도는 미세하게 증가하였으며 반면에 충전/안전주입 펌프의 파손확률은 크게 감소하였다. 따라서 여러가지 측면에서 충전/안전주입 펌프의 최소순환관으로부터 s-신호를 제거하고 운전하는 것이 합당하다는 것이 밝혀졌으며, 고압안전주입계통의 이용불능도를 줄이기 위하여 운전절차를 개선하고 운전원의 훈련 및 교육을 강화할 것을 추천한다.

1. Introduction

After TMI-2 accident, the efforts to introduce the Probabilistic Safety Assessment (PSA) technique to the safety assessment of nuclear power plants have gradually increased and the results of PSA influence greatly on the determination of quantitative safety goals. In this study, the unavailability of High Head Safety Injection System (HHSIS) and the rupture probability of charging/safety injection pump have been computed using the PSA technique.

To prevent the rupture or damage of a charging/safety injection pump caused by some accidents or operator errors, a design modification has been applied to KNU 5,6,7 and 8. It is removal of the safety injection signal (s-signal) from the charging/safety injection pump mini-flow bypass line isolation valves to prevent the pumps from deadheading by keeping the bypass line continuously opened. But this design change imposes a potential risk of failure in keeping the Peak Cladding Temperature (PCT) criteria of 2,200°F following the Small Break LOCA because the safety injection flow may be insufficient due to the existence of recirculation flow. On the other hand, if the s-signal closes the mini-flow lines as originally designed the safety injection flow is sufficient for adequate core cooling but the rupture probability of a charging/safety injection pump caused by deadheading and/or inadvertent discharge path closure will increase. To analyze these reciprocal situations, the unavailability of HHSIS and the rupture probability of a charging/safety injection pump must be quantified and compared for two cases; s-signal on and removed. The step by step computation for this study has followed the process of PSA technique as shown in Fig. 1.

2. Descriptions of Failure Events

A simplified flow diagram of HHSIS is shown in Fig. 2. The safety injection pumps (P091, P092, P093) of HHSIS are used as reactor coolant pumps as a part of Chemical and Volume Control System (CVCS) in normal plant operation. A charging/safety injection pump is always in operation for CVCS charging and the other two pumps are in standby. In general, pump P091 is in operation and P092 and P093 are designed to operate by the s-signal. To protect the pumps, there exists the minimum flow bypass recirculation line which branches off at the location between the pump discharge head and the discharge check valve. The minimum flow of 60 gpm is required through this line. This mini-flow line is used as the flow path during test of the charging/safety injection pump.

When the s-signal is initiated in the nuclear power plant, the safety injection system (SIS) operates automatically. At first, the Volume Control Tank (VCT) discharge line is isolated by the closure of valves LV115-C and LV115-E and the Refueling Water Storage Tank (RWST) discharge line valves LV115-B and LV115-D are opened automatically and thereby the suction of the charging/safety injection pumps are diverted to the RWST. The CVCS charging line valves HV36 and HV37 are also automatically closed and all of the discharg flow contributes only to safety injection. Next, two standby pumps P092 and P093

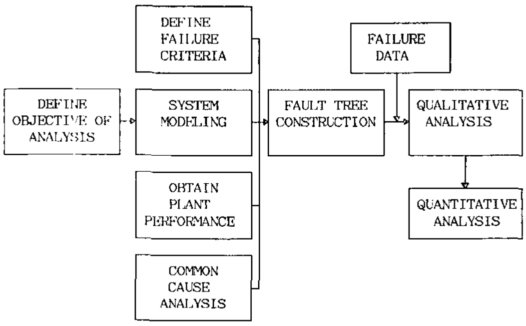

Fig. 1. The Process of Probabilistic Safety Assessment

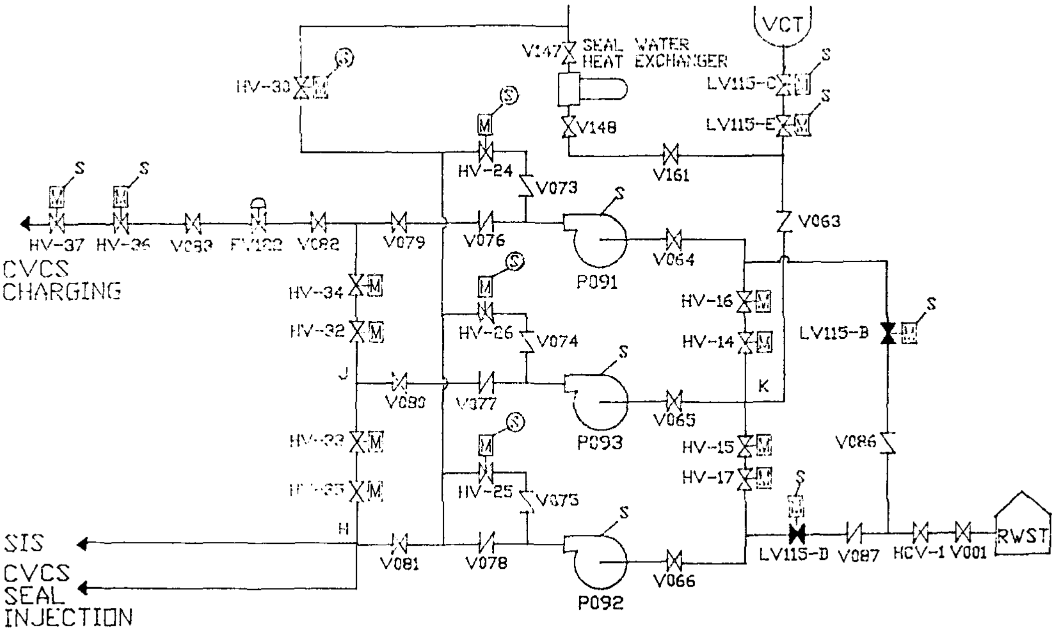

Fig. 2. Safety Injection System

start automatically. The operator never fail to stop P093 to prevent excessive buildup of flow and to secure the redundancy of the pumps after he makes sure that all the three pumps are in operation. Before KNU 5,6,7 and 8 adopt the design modification, the mini-flow line isolation valves HV24, HV25, HV26 and HV30 are designed to be closed upon receiving the s-signal to stop the recirculation flow and to maximize the safety injection flow. At present the s-signal is removed from the mini-flow line isolation valves.

Two types of severe accidents are considered in this study. In case of SBLOCA, it is assumed that only a charging/safety injection pump operates in compliance with the single failure criteria and the designed flow is sufficient to keep the PCT below 2,200°F provided that the mini-flow bypass line is isolated upon receiving the s-signal. However, if the mini-flow line fails to be isolated the safety injection flow may not be sufficient to keep the PCT criteria because of bypass flow through this mini-f-low line. In case of High Energy Line Break (HELB) accident, the s-signal is initiated by the depressurization of the RCS and the safety injection starts. However, as the safety injection flow is amassed the RCS pressure rises again and it may exceed the shutoff pressure of the charging/safety injection pump. This high RCS pressure may damage the pump. As the number of operating pumps increases this damage becomes more serious. But this kind of pump rupture can be considered to be very rare since the charging/safety injection pumps of KNU 5,6,7 and 8 are designed to operate under normal oeprating pressure (2,250 psig) and the shutoff pressure of these pumps is 2,800 psig (higher than the open pressure of PORV, 2,485 psig).

The other type of important event is the charging/safety injection pump rupture due to the inadvertent closure of discharge path. This event occurs only when the safety injection flow path to RCS fails to remain open and its mini-flow line is simultaneously closed. If the mini-flow line is closed on receiving the s-signal as originally designed, the rupture of the charging/safety injection pump depends solely on the closure of this flow path and the rupture probability is relatively high. Particularly, when the spurious s-signal occurs during the charging/safety injection pump test, it isolates the mini-flow lines and there is no discharge flow path, which results in the rupture of pump. It is observed that the frequency of spurious s-signal in the nuclear power plant becomes high and the possibility of pump damage due to this scenario has become a very serious problem.

When the s-signal is removed from the mini-flow line isolation valves, the mini-flow lines are always left opened irrespective of the s-signal. In this case, timely oepratore action to close the mini-flow line valves after SBLOCA guarantees sufficent safety injection flow. (We assumed the mission time of 10 minutes after the s-signal is initiated.)

The rupture probability of charging/safety injection pump caused by both deadheading and discharge path closure is significantly reduced because of the continuous existence of mini-flow line. However the unavailability of HHSIS is expected to increase due to the reduced safety injection flow. Hence it must be analyze whether the reduced safety injection flow is sufficient to cool the core or not following the SBLOCA. If the reduced flow appears to be insufficient, timely operator action of closing the mini-flow line valves to recover sufficient safety injection flow should be enhanced and in fact, this operator action is an important factor in this study.

3. Data Base

One of the most important tasks in reliability analysis is the collection and evaluation of the reliability data. Reliability data are represented as the point values of failure probabilities and are divided into following two categories; generic and plant specific data. Generic data are obtained through the synthesis of various experiences of plant oepration and existing data sources with the aids of opinions of experts. Generic data have some advantages in a sense that the failure data of rare events can be estimated based on such a many other data of failure events, but it is difficult to be faithful to the characteristic of the specific plant. On the other hand, plant specific data can reflect the characteristic of a plant such as some specific components and various operating codi-tions but it is difficult to collect these data enough to treat statistically.

In this study, both generic data and plant specific data are employed. The data on test & maintenance and operational procedures are calculated by accepting plant specific data and the other data are obtained from existing generic data sources. Generic data sources used in this study are;

1) All of the mechanical failure data are obtained from IREP, NUREG/CR-2728 (1983).

2) Data on human errors and control circuit faults are obtained from BNL, Seabrook PRA data, NUREG/CR-3531(1984).

3) Other data are obtained from EPRI, Oconee PRA, NSAC-60 (1984) and KOPEC PRA data source.

Plant specific data are used in calculating the unavailabilities of the pumps and valves during test & maintenance. The unavailability of a component during test & maintenance is given by

$$Q_{TM} = Q_T + Q_M,$$

$$Q_T = \frac{\text{test outage time}}{\text{test interval}},$$

$$Q_M = \frac{F \times (\text{maintenance outage time})}{720},$$

where F is 0.091 for pump and 0.02 for valve. Plant specific data of KNU 5 & 6 on test & maintenance and the calculated unavailabilities are listed in Table 1.

During test & maintenance, since the charging/safety injection pump and its mini-flow line valve are connected in series in the same flow path, the pump is unavailable when its mini-flow line valve is in test & maintenance, vice versa. For this

Table 1. Unavailabilities Due to Test & Maintenance

Component	Pump	Valve
Test period	3 months	18 months
Test outage time	30 minutes	29 minutes
Maintenance outage time	19 hours	7 hours
Unavailability	2.63 E-03	2.20 E-04

reason, these two events can be treated as a single event and the unavailability of the valve can be added to that of the pump. Therefore the probability that the charging/safety injection pump is unavailable due to test & maintenance at the time of s-signal initiation can be expressed as

$$Q_{TM} = (Q_{TM})_{pump} + (Q_{TM})_{valve}.$$

It is very likely that the unavailability of a system heavily depends on the failure probabilities of some specific components. If it is true, to improve the reliabilities of these components is very important. The failure probability of a component is a function of its test period and it increases with longer test period. If the test period is taken to be shorter, the unavailability due to test & maintenance increases while the failure probability of that component decreases, thus this reciprocity must be optimized in consideration of the characteristic of the component.

4. Fault Tree Analysis

Top events are defined for two cases, with s-signal on and removed. For each case, two top events are cosntructed as follows;

1) HHSIS unavailability when the s-signal is initiated and

2) charging/safety injection pump rupture probability when the s-signal is initiated.,

For basic events, mechanical failure of components, the unavailabilities due to test & maintenance, control circuit fault, failure of electric power supply, failure of cooling system, human errors and common cause failures are involved. In this study, common cause failures are considered on valves and pumps by using β-factor method. Total failure rate is divided into independent failure rate λ_i and common cause failure rate λ_c. Here, β is defined as

$$\beta \equiv \frac{\lambda_c}{\lambda} = \frac{\lambda_c}{\lambda_i + \lambda_c},$$

so

$$\lambda_c = \frac{\beta}{1-\beta} \lambda_i,$$

and if we find the β value, common cause failure rate is easily incorporated. The advantage of β-factor method is not only that existing experience data can be used directly but also that this method can be applied directly to fault tree analysis. Common cause failures of charging/safety injection pumps and valves which receive the s-signal and in the mini-flow line are considered. The β values are determined from the EPRI-NP-3967, classification system of common cause failures;

1) For charging/safety injection pump; 0.17

2) Motor-operated valves; 0.08

We have performed the qualitative analysis by using the computer code SETS with rare event approximation and cut-off value of 10^{-8}.

The unavailability of j-th minimal cut-set, Q_{jc} is expressed as

$$Q_{jc} = \prod_{i=1}^{n_c} \{q_i\}^{\alpha_{i,jc}},$$

where n_c = the number of basic events in fault tree,

q_i = failure probability of i-th basic event

$\alpha_i, j_c = 1$, if the i-th basic event belongs to j-th minimal cut-set,

0, otherwise And the overall system unavailability can be calculated as follows;

$$Q_s = 1 - \prod_{j=1}^{n_m} \{1 - Q_{jc}\},$$

where n_m = the number of minimal cut-sets.

Some basic events are major contributors to the

Table 2. Results of Uncertainty Analysis.

Case	5%	Point Mean	Mean	Median	95%
I	2.575×10^{-4}	1.782×10^{-3}	1.751×10^{-3}	1.015×10^{-3}	5.325×10^{-3}
II	5.709×10^{-3}	1.179×10^{-2}	1.194×10^{-2}	1.067×10^{-2}	2.194×10^{-2}
III	2.712×10^{-4}	1.813×10^{-3}	1.887×10^{-3}	1.093×10^{-3}	5.700×10^{-3}
IV	7.514×10^{-5}	5.063×10^{-4}	5.605×10^{-4}	2.921×10^{-4}	1.731×10^{-3}

overall system unavailability irrespective of the magnitude of their failure probabilities. If it is ture, the overall system unavailability is highly sensitive to the variation of the failure probabilities of these basic events. This effect can be quantified by the importance measure. The computer code IMPORTANCE has been used to measure the basic event importance. By ranking these importances, the weakness of system could be found and the best imporvement could be derived. The Fussel-Vesely method in which the importance is weighted by the unavailabilities of minimal cut-sets was applied. The Fussel-Vesely importance measure of i-th basic event is given by

$$M_i=\frac{\Sigma_j Q_{jc}^{(i)}}{Q_s},$$

where $Q_{jc}^{(i)}$ = unavailability of j-th minimal cut-set which includes i-th basic event.

Q_s = overall system unavailability.

This represents the ratio of the sum of unavailabilities of minimal cut-sets which include the i-th basic event to the overall system unavailability. The Fussel-Vesely importance measure of the j-th minimal cut-set is given by

$$M_{jc}=\frac{Q_{jc}}{Q_s}.$$

IMPORTANCE accepts SETS output as its input.

5. Results and Conclusions

The results of study are summarized as follows;

1) The unavailability of HHSIS with s-signal on is 1.782×10^{-3} and important basic events are CCF of charging/safety injection pumps, CCF of the RWST discharge line valves, failure of s-signal and electric power supply.

2) The rupture probability of a charging/safety injection pump with s-signal on is 1.179×10^{-2} and important basic events are human errors that the operator fails to open manual valves in the suction and discharge lines of the pumps after test & maintenance.

3) The unavailability of HHSIS with s-signal removed increases slightly to 1.813×10^{-3} and important basic events are similar to those of s-signal on case except that the importance of basic event that the operator fails to close the mini-flow line valves within 10 minutes becomes higher.

4) The rupture probability of a charging/safety injection pump with s-signal removed is significantly reduced to 5.063×10^{-4} and the important basic events are CCF of RWST discharge line valves and failure of s-singal.

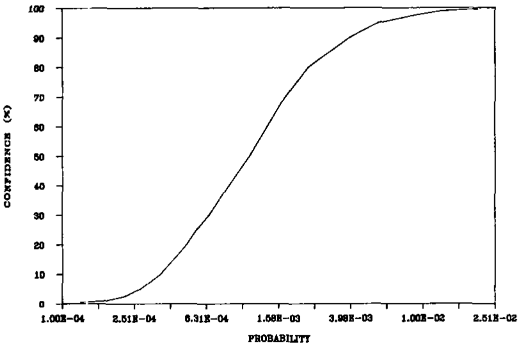

Fig. 3. Uncertainty Analysis of Case III.

Uncertainty analysis was performed by using the Monte Carlo uncertainty analysis code CONINT which was developed from SAMPLE code in KAERI, 1982. The results are listed in Table 2 and

Fig. 3. Case I, II, III and IV represent 1), 2), 3) and 4), respectively.

Based upon the results of this study, following conclusions apply;

1) The rupture probability of charging/safety injection pumps is reduced a great deal (by a factor of 23.3) while the unavailability of HHSIS increases slightly (about 1.7%) as the s-signal is removed. Thus, it is recommended to remove the s-signal from the mini-flow line valves.

2) The most noticeable basic event influencing on the HHSIS unavailability is the operator error that he fails to close the mini-flow line valves within 10 minutes following SBLOCA. It is assumed that this action is sufficient and necessary to revocer sufficient safety injection flow to cool the core. If the safety injection flow is proven to be sufficient in spite of the continuous existence of bypass flow (this is true with the results of Accident Analysis), removal of s-signal does not influence on HHSIS unavailability.

3) To minimize the operator errors, following actions and design changes are recommended;

a) Control logic improvements such as the automatic closing of the mini-flow line valves when only one charging/safety injection pump is available.

b) Improvement of operator accessibility to the manual valves.

c) Adoption of the intensive qualification and training programs.

d) Upgrading of operational procedures.

4) The removal of s-signal is also recommened to protect the charging/safety injection pumps against rupture by spurious s-signal during test & maint. or operator errors.

Acknowledgement

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