Transactions of the Korean Nuclear Society Spring Meeting
Chuncheon, Korea, May 25-26 2006

Calculation of the Incremental Conditional Core Damage Probability on the Extension of Allowed Outage Time

Dae Il Kang and Sang Hoon Han
Integrated Safety Assessment Division, Korea Atomic Energy Research Institute
150, Duckjin-Dong, Yuseong-Gu, Daejon, Korea, 305-353, dikang@kaeri.re.kr

1. Introduction

RG 1.177 [1] requires that the conditional risk (incremental conditional core damage probability and incremental conditional large early release probability: ICCDP and ICLERP), given that a specific component is out of service (OOS), be quantified for a permanent change of the allowed outage time (AOT) of a safety system. An AOT is the length of time that a particular component or system is permitted to be OOS while the plant is operating. The ICCDP is defined as [1]:

ICCDP = [(conditional CDF with the subject equipment OOS)- (baseline CDF with nominal expected equipment unavailabilities)] *[duration of the single AOT under consideration] (1)

Any event enabling the component OOS can initiate the time clock for the limiting condition of operation for a nuclear power plant. Thus, the largest ICCDP among the ICCDPs estimated from any occurrence of the basic events for the component fault tree should be selected for determining whether the AOT can be extended or not. If the component is under a preventive maintenance, the conditional risk can be straightforwardly calculated without changing the CCF probability. The main concern is the estimations of the CCF probability because there are the possibilities of the failures of other similar components due to the same root causes. The quantifications of the risk, given that a subject equipment is in a failed state, are performed by setting the identified event of subject equipment to TRUE. The CCF probabilities are also changed according to the identified failure cause. In the previous studies [2,3], however, the ICCDP was quantified with the consideration of the possibility of a simultaneous occurrence of two CCF events. Based on the above, we derived the formulas of the CCF probabilities for the cases where a specific component is in a failed state and we presented sample calculation results of the ICCDP for the low pressure safety injection system (LPSIS) of Ulchin Unit 3.

2. Estimation of Conditional CCF probability

Suppose a system consisting of two similar components "A" and "B". We assume that the success criterion of the system is 1 out of 2, that is, one component must succeed for the successful operation of the system. The basic events for the component fault tree are assumed to be "fail to start", "fail to run", "unavailable due to maintenance", "fail to start due to a CCF", and "fail to run due to a CCF". The failure of the system is expressed as the following Boolean algebra:

$$S_{fail} = A_T*B_T \approx A_{FS}*B_{FS} + A_{FS}*B_{FR} + A_{FS}*B_{MA} + A_{FR}*B_{FS} + A_{FR}*B_{FR} + A_{FR}*B_{MA} + A_{MA}*B_{FS} + A_{MA}*B_{FR} + A_{MA}*B_{MA} + C_{AB-FS} + C_{AB-FR} \quad (2)$$

where,

X_{FS} denotes the independent cause failure (ICF) event for "fail to start",

X_{FR} denotes the ICF event for "fail to run",

X_{MA} denotes the ICF event for "unavailable due to maintenance",

C_{XY-FS} denotes the CCF event of components X and Y for "fail to start", and

C_{XY-FR} denotes the CCF event of components X and Y for "fail to run"

In Eq. (2), basic events contributing to the failure of each component are mutually exclusive (for example, $A_{FS}*C_{AB-FR}= 0$) [4]. We assume that the probabilities of similar events involving similar components are the same. That is, assuming that P(x) is the probability of event "X", and

$P(A_T)=P(B_T)=Q_T, P(A_{FS})=P(B_{FS})=Q_{1FS}$,
$P(A_{MA})=P(B_{MA})= Q_{1MA}$,
$P(C_{AB-FS})=Q_{2FS}$, $P(C_{AB-FR})=Q_{2FR}$

In the CCF analysis by using the β-factor, the MGL Parameters, or the Alpha factor methods, each parameter is defined for each failure mode of the component. With the β-factor or the MGL method, Q_{1FS}, Q_{2FS}, Q_{1FR}, and Q_{2FR} are represented as below [4]:

$$Q_{1FS}= (1-\beta_{FS})Q_{TFS},\ Q_{1FR}= (1-\beta_{FR})Q_{TFR},$$
$$Q_{2FS}= \beta_{FS}Q_{TFS},\ Q_{2FR}= \beta_{FR}Q_{TFR} \quad (3)$$

where, $P(A_{TFS})=P(B_{TFS}) \approx Q_{TFS}= Q_{1FS} + Q_{2FS}$
$P(A_{TFR})=P(B_{TFR}) \approx Q_{TFR}= Q_{1FR} + Q_{2FR}$

We assume that an event of "fail to start" for the component "A" including the possibility of the CCF is assumed to have occurred. In other words, any basic event "A_{FS}" or "C_{AB-FS}" can occur. Then, Eq(2) is given by

$$P(S_{fail} | A_{TFS}) \approx P(A_{FS}*B_{FS} | A_{TFS})+P(A_{FS}*B_{FR} | A_{TFS})+P(A_{FS}*B_{MA} | A_{TFS})+P(C_{AB-FS} | A_{TFS}) \quad (4)$$

From Eq. (4), the conditional CCF probability can be represented as

$$P(C_{AB-FS} | A_{TFS})=Q_{2FS}/Q_{TFS}=\beta_{FS} \quad (5)$$

If an event of "fail to run" has occurred, the same approach for the case of the event of "fails to start" can be used. Then, the conditional CCF probability is

$$P(C_{AB-FR} | A_{TFR}) = Q_{2FR}/Q_{TFR}=\beta_{FR} \quad (6)$$

If the failure mode for the specific component failure is unknown, any basic event "A_{FS}", "A_{FR}", "C_{AB-FS}", or "C_{AB-FR}" can occur. Suppose the Boolean expression of "A_{TFSR}" represents the relation $A_{TFSR} = A_{FS} + A_{FR} + C_{AB\text{-}FS} + C_{AB\text{-}FR}$. Given that "$A_{TFSR}$" has occurred, Eq.(2) is given by

$$P(S_{fail} | A_{TFSR}) \approx P(A_{FSR}*B_{FSR} | A_{TFSR}) + P(A_{FSR}*B_{MA} | A_{TFSR}) + P(C_{AB\text{-}FS} | A_{TFSR}) + P(C_{AB\text{-}FR} | A_{TFSR}) \quad (7)$$

Let us define the modified MGL parameters β'_{FS}, β'_{FR}, and β_{FSR} as below:

$$P(C_{AB\text{-}FS}|A_{TFSR})+P(C_{AB\text{-}FR}|A_{TFSR})=(Q_{2FS}+Q_{2FR})/Q_{TFSR} =\beta_{FSR}=\beta_{FS}*Q_{TFS}/Q_{TFSR}+\beta_{FR}*Q_{TFR}/Q_{TFSR}=\beta'_{FS}+\beta'_{FR} \quad (8)$$

where,

$$P(A_{TFSR})=P(B_{TFSR})=Q_{TFSR}=Q_{1FS}+Q_{2FS}+Q_{1FR}+Q_{2FR},$$
$$\beta'_{FS}=\beta_{FS}*Q_{TFS}/Q_{TFSR},\ \beta'_{FR}=\beta_{FR}*Q_{TFR}/Q_{TFSR} \quad (9)$$

3. Calculation of ICCDP

The Low Pressure Safety Injection System (LPSIS) for the Ulchin Unit 3 was selected for the example calculation of the ICCDP. The LPSIS consists of two 100% capacity redundant pumps and associated valves. The technical specifications of the Ulchin Unit 3 say that one LPSIS pump must be restored within 3 days in the case that it is inoperable. The basic events of LPSIS pump 1 except for the supporting systems are shown in Figure 1. The present AOT of the LPSIS is planned to be extended from 3 days to 7 days.

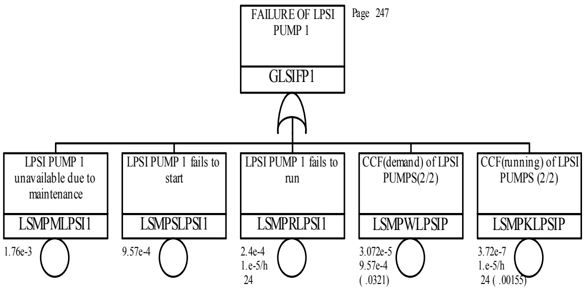

Figure 1. Fault tree of Ulchin Unit 3 LPSIS pump 1

Table 1 shows the estimated CCF probability and ICCDP on the extension of the AOT for the LPSIS pump. We assume that the LPSI pump A is OOS. The ICCDP for the case of the preventive maintenance was calculated without changing the CCF probability. For the cases of the event occurrences of "fails to start" and "fail to run", the CCF probabilities were estimated by using Eqs. (5) and (6), respectively. In the event that the failure mode was unknown, the CCF probabilities were estimated by using Eq.(9). If the possibility of a simultaneous occurrence of two CCF events was considered as in the previous studies [2,3], the CCF probabilities were estimated as the ordinary β_{FS} and β_{FR}, respectively.

As shown in Table 1, the largest CCF probabilities and the ICCDP were estimated for the case that the possibility of a simultaneous occurrence of two CCF events was assumed. In the event that the failure mode is unknown, the conditional CCF probabilities, β'_{FS} and β'_{FR}, are smaller than the ordinary β_{FS} and β_{FR}. The ICCDP was estimated as an intermediate value between that of "fails to run" and that of "fail to start". If the ICCDP calculations should include all failure modes of the component, Eq. (9) should be used for the estimation of the CCF probability. Consequently, the ICCDP for "fails to start" was selected for determining whether the AOT of the LPSIS pump could be extended or not.

Table 1. CCF probability and ICCDP

Cases	CCF probability		ICCDP
	Fail to start	Fail to run	
previous studies	3.21E-02	1.55E-03	8.82E-09
preventive maintenance	3.07E-05	3.72E-07	3.64E-09
fail to start	3.21E-02	3.72E-07	8.44E-09
fail to run	3.07E-05	1.55E-03	3.83E-09
failure mode is unknown	2.58E-02	3.03E-04	7.48E-09

4. Conclusions

This paper presents the formulas of the CCF probabilities for the cases where a specific component is in a failed state and the calculation results of the ICCDP for the LPSIS pump of Ulchin Unit 3. As the identified failure mode of a specific component can lead to the consideration of a possibility of a CCF event for the same failure mode, the assumption that simultaneous occurrence of the two CCF events could be possible is a conservative approach. If the possibilities of a simultaneous occurrences of all the CCF events should be considered, the conditional CCF probabilities are to be estimated as the modified β's, smaller than the ordinary βs. The ICCDP of the event of "fails to start" for the LPSIS pump was estimated as the largest in determining the extension of its AOT. However, there is a negligible difference between the ICCDP for the previous studies and the selected ICCDP.

Acknowledgement

This work was carried out under the Long-term Nuclear R&D Program sponsored by the MOST of Korea.

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