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Sensitivity Analysis of Simplified CCF Application in a Fault Tree with the Different Design Configuration

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1. Introduction

Common Cause Failure

The failure or unavailable state of more than one component during the mission time and due to the **same shared cause** in PRA.

Root Cause The most basic reasons for the component failure.

Coupling Factor The Characteristic of group of component as same casual mechanism of failure.

- CCF results from the coexistence of two main factors ; a root cause and a coupling factor. That creates the condition for multiple components to be affected by the same cause.
- The CCF modeling becomes complicated and huge in advanced nuclear power plant. Because of the redundant systems and components for the safe operation.
- The simplified CCF modeling is incorporated into the fault tree modeling. Calculation based on the alpha factor model introduced in the NUREG/CR-5485.

2. Methods and Results

2.1 Common Cause Impacting Components

- The **C**ommon **C**ause **C**omponent **G**roup (CCCG) consist of **C**ommon **C**ause **B**asic **E**vents (CCBEs).
- **CCBEs** involves failure of a specific set of components due to a common cause.
- **Formula (1)** : To calculate the number of common cause impacting k components.

$$N_k^{(m)} = \binom{m}{k} = {}_mC_k = \frac{m!}{k!(m-k)!}, \quad 1 \le k \le m$$

m = size of CCCG.

$N_k^{(m)}$ = the number of common cause impacting of k components.

Total number of CCBEs is significantly increase with increasing CCCG size.

Table I: The number of common cause impacting *k* components

$N_k^{(m)}$ \ m	2	3	4	5	6	7	8
$N_1^{(m)}$	2	3	4	5	6	7	8
$N_2^{(m)}$	1	3	6	10	15	21	28
$N_3^{(m)}$		1	4	10	20	35	56
$N_4^{(m)}$			1	5	15	35	70
$N_5^{(m)}$				1	6	21	56
$N_6^{(m)}$					1	7	28
$N_7^{(m)}$						1	8
$N_8^{(m)}$							1
Total	3	7	15	31	63	127	255

2. Methods and Results

2.2 Simplified CCF Probability Calculation

Formula (2) : The CCF Probability developed by Alpha-Factor model in NUREG/CR-5485.

for a staggered testing

$$Q_k^{(m)} = \frac{1}{\binom{m-1}{k-1}} \alpha_k Q_t$$

m = size of CCCG.

Q_t = Total failure probability of each component.

α_k = Fraction of the total probability of failure event.

Formula (3) : The simplified CCF Method is simplification by summing alpha factor.

for a staggered testing

This method can reduce the total number of CCBEs in one CCCG.

$$Q_S^{(m)} = \sum_{k=i}^{n} \alpha_k Q_t, \quad 1 < i < n \leq m$$

i = The start number of simplification group.

n = The end number of simplification group.

2. Methods and Results

2.3 Case for Comparison of CCF calculation

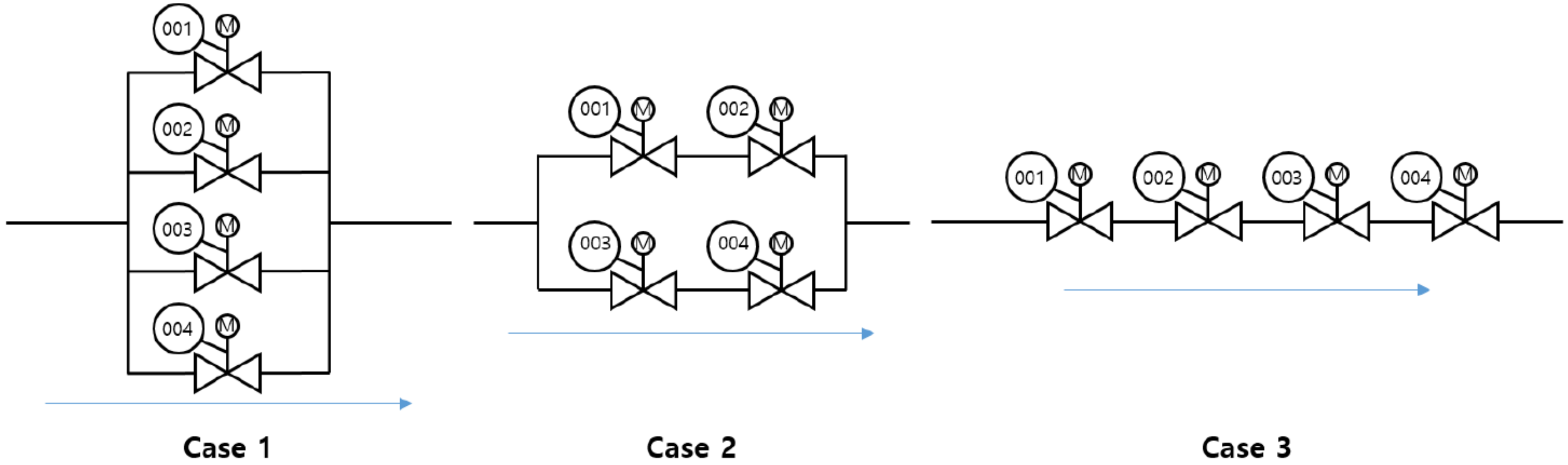


Fig. 1. Three cases composed to four valves

Case 1 : MOVs are arranged **in parallel**.
The failure of **all the four valves** will cause the train failure.

Case 2 : **Two lines** are arranged **in parallel**, each line **contains two MOVs** in series.
The failure of **three or more valves** will cause the train failure.
Two valves that **one in each line** also will cause the train failure.

Case 3 : MOVs are arranged **in series**.
The failure of **only one valve** will cause the train failure.

2. Methods and Results

2.4 Comparison of CCF Calculation Method

- The CCF probabilities of each case of trains are calculated by following three methods.
- The Date of each CCF calculation Method are shown in each table.

Method1. Base Model
- General CCF Calculation Method

Method2. 1-Simplified Model
- 2/4+3/4+4/4 CCF: Simplified CCF Method
- In formula (3), *i*=2, *n*=4

Method3. 2-Simplified Model
- 2/4 CCF: General CCF Calculation Method
- 3/4 + 4/4 CCF: Simplified CCF Method
- In formula (3), *i*=3, *n*=4

Table II: Data of General CCF Calculation (Method1)

Alpha Factor		CCF Parameter	$Q_k^{(4)}$
α_1	9.75E-01	-	-
α_2	1.54E-02	5.13E-03	2.16E-06
α_3	6.50E-03	2.17E-03	9.13E-07
α_4	3.37E-03	3.37E-03	1.42E-06

Table III: Data of 1-Simplified CCF Calculation (Method2)

Alpha Factor		CCF Parameter	$Q_S^{(4)}$
α_1	9.75E-01	-	-
α_2	1.54E-02	2.53E-02*	1.06E-05*
α_3	6.50E-03		
α_4	3.37E-03		

Note. * Calculated by Simplified Method

Table IV: Data of 2-Simplified CCF Calculation (Method3)

Alpha Factor		CCF Parameter	$Q_S^{(4)}$
α_1	9.75E-01	-	-
α_2	1.54E-02	5.13E-03	2.16E-06
α_3	6.50E-03	9.87E-03*	4.15E-06*
α_4	3.37E-03		

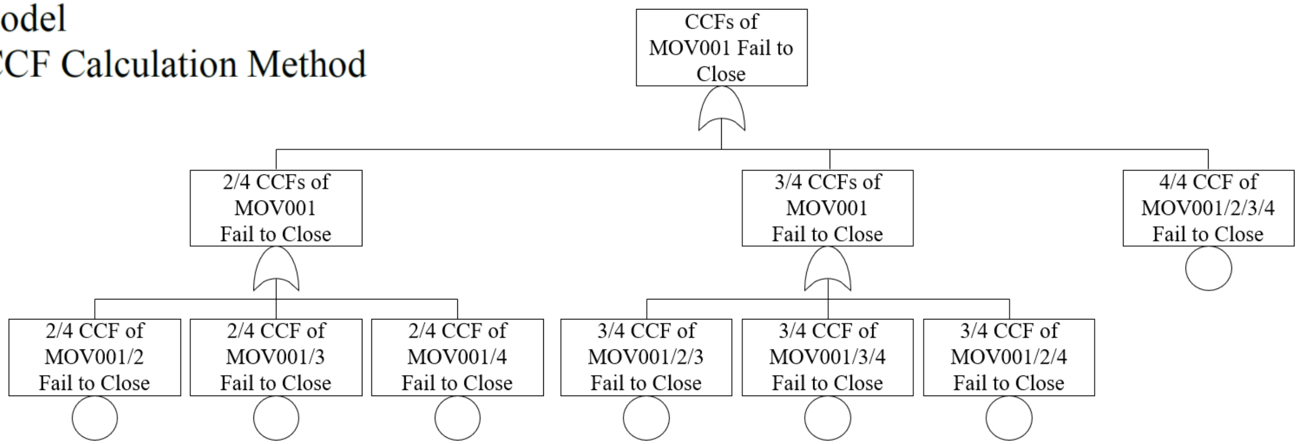
Note. * Calculated by Simplified Method

2. Methods and Results

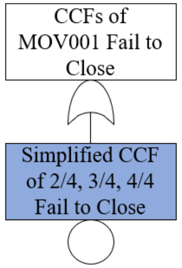
2.4 Comparison of CCF Calculation Method

The Fault Tree modeling of each Method are shown in following diagram.

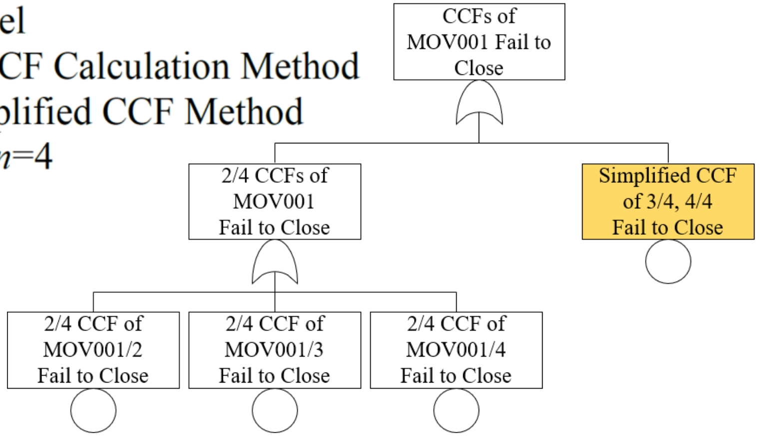
Method1. Base Model
- General CCF Calculation Method



Method2. 1-Simplified Model
- 2/4+3/4+4/4 CCF: Simplified CCF Method
- In formula (3), i=2, n=4



Method3. 2-Simplified Model
- 2/4 CCF: General CCF Calculation Method
- 3/4 + 4/4 CCF: Simplified CCF Method
- In formula (3), i=3, n=4



2. Methods and Results

2.5 Results of Comparison

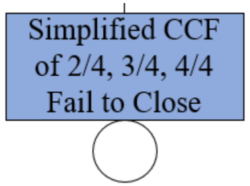
Table V: Result of CCF Calculation Method Comparison for Each Case

	Case 1		Case 2		Case 3	
Method	Prob.	Deviation	Prob.	Deviation	Prob.	Deviation
Method1 ; Base Model	1.42E-06	-	1.44E-05	-	1.70E-03	-
Method2 ; 1-Simplified	1.06E-05	+650%	1.14E-05	-21%	1.70E-03	-0.43%
Method3 ; 2-Simplified	4.15E-06	+193%	1.35E-05	-6%	1.70E-03	-0.05%

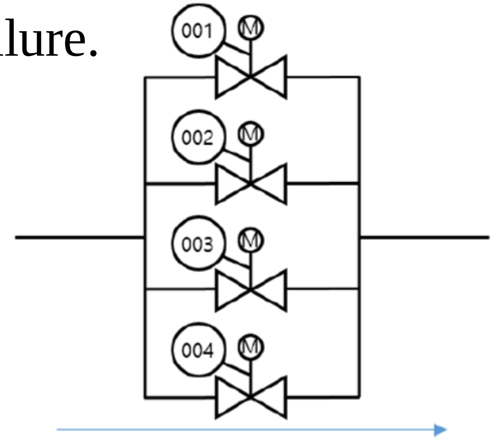
Case 1. MOVs are arranged in parallel

- The deviations of probability for CCFs are the highest, because **the impact of the CCF events is dominant** for parallel configuration failure.

- When using Method2, the Simplified CCF event is the only event of common cause failure.



- The Simplified CCF calculation method is very conservative in Case 1.



Case 1

2. Methods and Results

2.5 Results of Comparison

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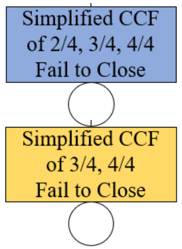
Method3 ; 2-Simplified	4.15E-06	+193%	1.35E-05	-6%	1.70E-03	-0.05%

Case 2. 2 lines are arranged in parallel that contains 2 MOVs are arranged in series

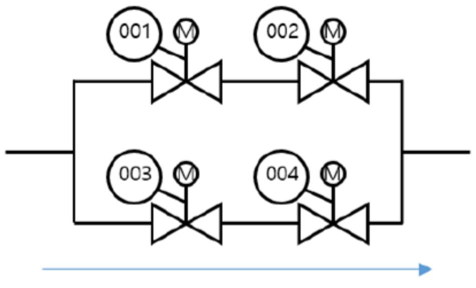
- The deviations of probability for CCFs are quietly high, because of **insufficient consideration** of CCF events.
  - Failure of two or more valves except for two valves failure in same line causes the failure of this case.

    In Method2, CCF event of V001/V002/V003 is considered 'Simplified CCF of 2/4, 3/4, 4/4 Fail to Close'

    In Method3, CCF event of V001/V002/V003 is considered 'Simplified CCF of 3/4, 4/4 Fail to Close'



  - These CCF event is not considered in Method2 because one Simplified CCF event is considered only.



Case 2

- The Simplified CCF calculation method is estimated lower than base model in Case 2.

2. Methods and Results

2.5 Results of Comparison

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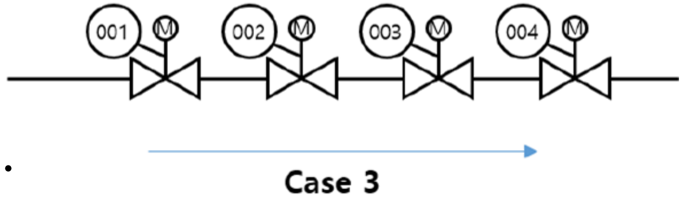
Method3 ; 2-Simplified	4.15E-06	+193%	1.35E-05	-6%	1.70E-03	-0.05%

Case 3. MOVs are arranged in series

- The deviations of probability for CCFs are the lowest, because **the impact of each component failure is higher than CCF events** for series configuration failure.



- The results of **using Simplified Method are very similar** with Method1.

- The Simplified CCF calculation method has been well applied in Case 3.

3. Conclusions

- The sensitivity study has been performed to understand the effectiveness of the Simplified CCF modeling with different train design configurations.
  - In the parallel configuration model like Case 1, the Simplified CCF Calculation is estimated to be very conservative.
  - The components are placed in series like Case 2 and Case 3, it is estimated to be non-conservative because the CCF events are less considered.

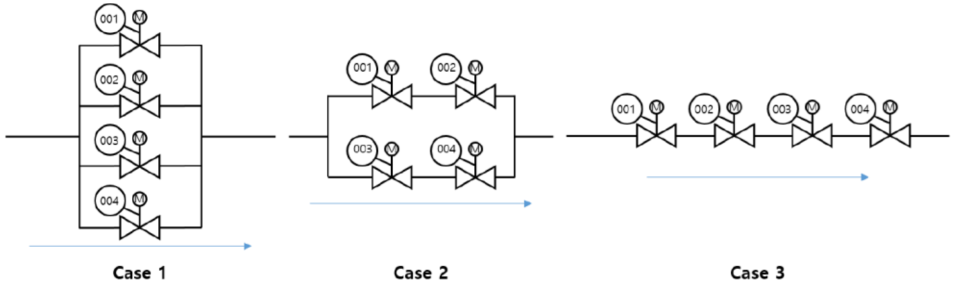


Fig. 1. Three cases composed to four valves

- A PRA for an advanced nuclear power plant includes a lot of CCCGs. It consist of many components due to its redundant design.
- If the Simplified CCF Calculation Method is applied to PRA model in these conditions, it is necessary to consider very cautiously.

REFERENCES

[1] Mosleh, A., INEEL, Guidelines on Modeling Common-Cause Failures in Probabilistic Risk Assessment, NUREG/CR-5485, 1999.
[2] U.S. Nuclear Regulatory Commission, Component Reliability Data Sheets 2015 Update, 2017.
[3] U.S. Nuclear Regulatory Commission, CCF Parameter Estimations 2010, 2012.