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ORIGINAL RESEARCH

Asymmetrical Common-Cause Failures Analysis Method Applied in Fusion Reactors

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Abstract Fusion reactors like the International Thermonuclear Experimental Reactor (ITER) are generally complex systems, which demand reliability analysis. Common-Cause Failures (CCF) are increasingly important in the reliability analysis of these systems because of the widespread redundancy or similar components in them. However, despite the wide research in CCF, there has been little research on the handling of asymmetries of CCF that is inevitable in ITER. A concept of Multi-Common-Cause Failures (MCCF) and its key assumptions are discussed in this paper. On the basis of MCCF and the assumptions, a transition method named Common-Cause Breakdown Structure (CCBS) was designed to manage the asymmetrical CCF. The CCBS method can be easily applied to most fault tree analysis codes because the CCF treated by CCBS can be handled by traditional CCF models. A redundant system example was modeled and calculated in the reliability and probabilistic safety analysis program RiskA developed by FDS Team. The analysis results for water pumps redundant system applied in Tokamak cooling water system show that CCBS method is adequate and effective.

Keywords Reliability analysis · Asymmetrical common-cause failures · Fault tree · Tokamak cooling water system · RiskA

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Introduction

The International Thermonuclear Experimental Reactor (ITER) [1] is a very large and complex system, which demand reliability analysis to ensure safe operation. ITER has 17 test ports in total, in which 3 of the standard ports dedicated for 6 test blanket modules (TBM) designed by different countries. All TBM cooling systems were assigned in the south east corner of the Tokamak cooling water system (TCWS) vault. Some of the subsystems of ITER are very similar, which will generate Common-Cause Failures (CCF). For example, cooling water subsystems (CWS), measure and remote handling subsystems in Chinese helium cooled ceramic breeder (HCCB) or dual functional lithium–lead (DFLL) TBM [2] would also be applied in many other subsystems of ITER. CCF of these subsystems need to be analyzed in their reliability analysis. In the methods of reliability analysis and probabilistic safety assessment, CCF usually refer to cases that two or more components fail at the same time or fail one by one irrevocably in a short time for one or more common causes. For example, analogous valves, circuit breakers, pumps and generators are widely used in a same system, and they will generally subject to CCF results from same designing, operational environment or other common errors [3]. Researches on the CCF with the symmetrical assumption are very comprehensive [4, 5], which include the studies of CCF parameters, CCF models and CCF handling in fault tree analysis (FTA) codes [6–9], etc. At present the symmetrical CCF analytical methods have gradually become a standard procedure [3, 10].

However, TBM and other similar subsystems in ITER will generally have some different characteristics, which will result in asymmetries in their CCF. In fact, all CCF have some asymmetries caused by the inevitable differences in design principles, manufacturing and processing, storage, transportation, installation, operation and maintenance, working environment, etc. Furthermore, in order to improve reliability as far as possible, redundant components or facilities are often different in the above aspects. For example, valves and pumps that are different in driving motors, running histories or applied at pipes with different fluids [10–12], these components will subject to CCF with asymmetries. These asymmetries sometimes are small enough to be ignored by symmetrical assumptions in order to reduce the number of probabilities that need to be estimated in the CCF analysis [3], but other times they need to be considered to avoid excessive high or low result of reliability analysis. When the CCF do not satisfy the symmetrical assumption, they are generally referred to as asymmetrical CCF. That is, the independent failure probabilities of these components are not exactly the same; or the probabilities of CCF events combined two components in a CCF component group will depend on the specific components but not only on the number of components combined [3, 10]. However, there has been little research conducted on asymmetrical CCF. Some examples of the asymmetrical CCF were mentioned in NUREG/CR-4780 in 1988, including the modeling method of asymmetrical CCF that add some events to or subtract some events from the traditional CCF model, but the corresponding parameter estimation method was not supplied by these reports. Jo proposed a modeling method in 2005 [11], but the deviation of this method had much to do with the CCF asymmetry rate, which largely limited the scope of its application. Kang proposed an approximate formula method in 2009 [12], in which a CCF event is decomposed to asymmetrical part and symmetrical part then modeled them respectively; In his paper, Kang also supplied parameter estimation methods of Basic Parameter Model (BPM) and Alpha Factor Model (AFM). Yet just like Jo's methods, Kang's formula cannot be applied to the CCF analyses of different types of components with different probabilities. An explicit method based on modified Beta Factor Model (BFM) for modeling an event within different CCF groups was proposed in 2012 by Dusko Kancev [13], but besides possibly unreasonable increasing of the dependent portion, the method was also restricted to the CCF model and the same component types. In 2010, Xing Liudong [14] proposed a method to analyze probabilistic CCF (PCCF) in systems with an external common-cause where different components within a CCF group fail with different probabilities, and successively proposed two methods to address PCCF in systems with multiple external or internal common-cause in 2014 [15]. However, these PCCF methods can not utilize traditional symmetrical CCF models that are widely applied in the CCF analysis of nuclear reactors, such as AFM. Furthermore, for fusion reactors, it is hard to collect enough information to estimate those probabilities demanded by PCCF methods in the analysis of the components and system reliabilities. But these papers are very enlightening for the method proposed in this paper.

In order to meet the demands of the asymmetrical CCF analysis, a transition method named Common-cause Breakdown Structure (CCBS) was proposed to manage the asymmetrical CCF, which include those CCF of different types of components. The asymmetrical CCF events treated by CCBS can be handled by traditional CCF models such as AFM, multiple greek letter model, etc. This method can be easily applied to most FTA codes. The simulation tests were carried on reliability and probabilistic safety assessment program RiskA, one of the series of integrated nuclear energy software [16, 17] developed by FDS Team. RiskA had been applied to Experimental Advanced Superconducting Tokamak EAST's reliability analysis [18], design of fusion-driven subcritical system [19] and FDS series fusion reactors [20–22], International Thermonuclear Experimental Reactor ITER-TBM's safety analysis [2], China LEAd-based Reactor (CLEAR), Third Qinshan nuclear power plant risk monitor (TQRM), etc. The results show that the asymmetrical CCF events can be handled by CCBS method adequately.

Methodology

The CCBS method will be presented without model dependence as far as possible, but in some necessary occasions, CCF model of Basic Parameter Model (BPM) will be used because BPM is easy to be understood and can be converted to other CCF models conveniently.

CCBS Method

Two key assumptions of the CCBS method are introduced firstly. The first assumption can be expressed as Eq. (1). The total probability of a CCF component can be divided into two parts, one is the independent part, and the other is the CCF part. Here, $P_T(A)$ is the total failure probability of basic event (BE) A representing a CCF component, $P_0(A_0)$ is the independent failure probability of A, and $P_{\text{ccf}}(A_{\text{ccf}})$ is the total CCF probability of A.

$$P_T(A) = P_0(A_0) + P_{\text{ccf}}(A_{\text{ccf}}) \tag{1}$$

The second assumption is that a single common-cause results in the same CCF probability part of every component impacted by it. This assumption is clearly put in Eq. (2), where basic event A and B represents any of the two components affected by a same common failure cause

j. In Eq. (2), j is any one of m common causes that impact the analyzed system.

$$P_{\mathrm{ccf}}(A_j) = P_{\mathrm{ccf}}(B_j), j = 1, 2, \ldots, m \tag{2}$$

Generally, A and B will be putted into a CCF component group (CCCG) as shown in Fig. 1 when their failures result from same common-causes. Here C_{AB} is a compound CCF event which represents both A and B fails. Therefore, Eq. (3) can be deduced according to Eqs. (1) and (2).

These assumptions are elaborately abstracted from the symmetrical assumptions. They are not only weakened but also reasonable and true in most cases. These assumptions only bring some errors in rare instances, such as in the case where the components affected by the CCF have a slightly different mechanism in the response to the common-cause and this difference is so tiny that it does not need to be considered in the analysis and these components still be put into a same CCCG. However, these errors can be reduced to appropriate degree by regulating the CCCGs establishing process.

$$\begin{aligned} P_T(A) &= P_0(A_0) + P_{\mathrm{ccf}}(A_{\mathrm{ccf}}) \\ &= P_0(A_0) + P_{\mathrm{ccf}}(C_{AB}), \\ P_T(B) &= P_0(B_0) + P_{\mathrm{ccf}}(C_{AB}) \end{aligned} \tag{3}$$

On the basis of above assumptions, the principium of the Common-cause Breakdown Structure (CCBS) method can be explained as bellow. When basic event A is affected by m common causes, it can be broken down to $n + 1$(here $n <= m$) events, i.e., A_0, A_1, A_2,…, A_n. Here A_0 is the representation of A failing independently, and A_1 to A_n belong to n CCF component groups respectively ($CCCG_1$ to $CCCG_n$). Thus A becomes a Multi-Common-Cause Failures (MCCF) event. In contrast, BE that has not been broken down is called normal CCF event in this paper. It should be noted that as A_1 to A_n are not real existent BEs, their single failure parts will be ignored and added to A_0 that will not change in the breaking down process. Therefore A_1 to A_n represent only the CCF probabilities resulted from the n CCCGs. In order to ensure the correctness, this breaking down should be carried out according to the analysis of CCF statistical data, component characteristics, CCF mechanisms, etc.

Furthermore, the assigning of BE A to CCCGs should be subjected to a principle that the CCF portions of different CCCGs should be mutually exclusive. That is, in the CCF part of A, which generally resulted from multiple failure

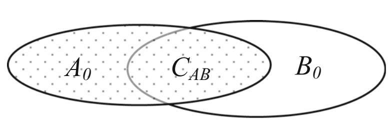

Fig. 1 A CCCG of A and B

mechanisms, these different failure mechanisms ought to be mutually exclusive when they belong to different CCCGs. Because they partition the failure space of A according to the impact on other components in the different CCCGs.

According to Probability theory, this principle can be expressed in Eq. (4). Here i is one of the n CCCGs that A is assigned to. As a result, the construction of these multi CCCGs are much different from Jo and Kang's methods. Then according to Eqs. (1) and (4), and the total probability of A is shown as Eq. (5).

$$P_{\mathrm{ccf}}(A_{\mathrm{ccf}}) = \sum_{i=1}^{n} P_{\mathrm{ccf}}(A_i) \tag{4}$$

$$P_{\mathrm{T}}(A) = P_0(A_0) + P_1(A_1) + P_2(A_2) + \cdots + P_n(A_n) \tag{5}$$

Here $P_{\mathrm{T}}(A)$ is the total failure probability of A; $P_0(A_0)$ is the probability of A_0, representing A fails independently; $P_{\mathrm{i}}(A_{\mathrm{i}})$ is the CCF probability of A brought by $CCCG_{\mathrm{i}}$, which is the probability of A_{i}. Then $P_{\mathrm{i}}(A_{\mathrm{i}})$ can be expressed as Eq. (6) where $1 <= i <= n$. In the Eqs. (6)–(8), θ_i represents the ratio of the CCF probability brought by $CCCG_{\mathrm{i}}$ to the total probability of basic event A.

$$P_i(A_i) = P_{\mathrm{T}}(A) * \theta_i, i = 1, 2, 3, \ldots, n. \tag{6}$$

Thus, conclusion can be made that the summation of all θ_i is always less than or equal to 1, as shown in the Eq. (7). Then probability of A_0 can be putted as Eq. (8). The summation of θ_{i} is possibly equal to 1 in some special cases and these cases can also be handled by CCBS method. Because P_0 (A_0) in Eq. (5) could be zero if all the failure causes of A are common shared with other basic events while those events are also modeled in this CCF analysis. According to Eq. (7), the risk of possible increasing of the CCF portion is avoided. In fact, the dominating of CCF portion over the independent portion only suggests that the assigning of A to CCCGs is not in accord with the actual situation and rectification should be made to it, for example, these CCF are not mutually exclusive.

$$(\theta_1 + \theta_2 + \cdots + \theta_n) \le 1 \tag{7}$$

$$P_0(A_0) = P_{\mathrm{T}}(A) * (1 - \theta_1 - \theta_2 - \cdots - \theta_n) \tag{8}$$

After the CCBS transition, event A_i becomes a normal CCF event. In each of the $CCCG_{\mathrm{i}}$, each BE fails due to exactly the same or approximately same common-causes, which is very the situation of the well-known symmetrical assumptions given the independent failure probabilities of BEs in a same CCCG are the same. Therefore, these CCCGs can be analyzed by the traditional CCF models like AFM. Most importantly, from the above reasoning and description, it can be deduced that CCBS method has no CCF model dependence, which means it can be used in cases of the CCCGs adopting different CCF models.

Moreover, the CCBS method can be used not only for the CCF analyses of same type components with same total failure probabilities but also for different type components with different total failure probabilities. Finally, the error introduced by CCBS depends on the suitability and subtle degree of the break-down of the basic event A, and forasmuch, errors can be minished to an acceptable degree by adjusting the CCCGs establishing in the CCF analysis process.

Formulas for Traditional Representative CCF Models

On the basis of CCBS method, the calculation formulas will be deduced for widely used CCF models, Multiple Greek Letter Model (MGLM) and Alpha Factor Model (AFM), which were recommended in NUREG/CR-5485. The formulas of $P_i(A_i)$ and θ_i for these CCF models are listed below. Formulas for other CCF models can also be easily deduced without changing of their parameter estimation methods. In the Eqs. (9)–(14), it is assumed that the CCCG_i has m BEs, and only A is a MCCF event. Here P_T is the total failure probability of A, Q_1 represents the single failure probability of a normal CCF event in the CCCG_i, $Q_k^{(m)}$ represents the probability of a normal CCF basic event involving k specific components in a CCCG of size m, and Q_T represents the total failure probability of normal CCF event. It should be noted that specific CCF events belonging to CCCG should be picked out in the parameter estimating process. Furthermore, there are special cases when more than one CCF BE is broken down to MCCF event, in which some CCCGs will only contain MCCF events. In those cases, all the MCCF events in CCCGs will only represents the CCF probabilities according to the principium of CCBS. Besides, the symmetry factor of f_r from Jo and Young's paper also can be used to adjust the estimating of CCF model parameters or impact vectors, which will be descripted explicitly in the following.

The $Q_k^{(m)}$ of MGLM is given by Eq. (9), where $\rho_1 = 1, \rho_2 = \beta^M, \rho_3 = \gamma, \rho_4 = \delta, \ldots, \rho_{m+1} = 0,$ and $1 \le k \le m$. Here β^M is the conditional probability of the cause of a BE failure will be shared by other BEs when one specific BE fails, and γ is the conditional probability of the cause of one or more BEs failure will be shared by two or some additional BEs when two specific BEs fail, etc. For the MGLM, formulas of $P_i(A_i)$ and θ_i are shown in Eq. (10).

$$Q_k^{(m)} = \frac{(m-k)! * (k-1)!}{(m-1)!} * \prod_{i=1}^{k} \rho_i * \left(1-\rho_{k+1}\right) * Q_\mathrm{T} \quad (9)$$

$$\begin{aligned} P_i(A_i) &= Q_\mathrm{T} - Q_1 = \beta^\mathrm{M} * Q_\mathrm{T}, \theta_i = P_i(A_i)/P_T \\ &= \beta^\mathrm{M} * Q_\mathrm{T}/P_\mathrm{T} \end{aligned} \quad (10)$$

The AFM defines CCF probabilities from a set of failure probabilities ratios α_k and the total BE failure probability Q_T. α_k is fraction of the total probability of normal CCF events that occur in the CCCG involving failure of k BEs due to a common cause. The $Q_k^{(m)}$ of AFM is given by Eq. (11) for staggered testing and Eq. (12) for non-staggered testing. And the formulas of $P_i(A_i)$ and θ_i for the AFM are shown in Eq. (13) for staggered testing and Eq. (14) for non-staggered testing.

$$Q_k^{(m)} = \frac{(m-k)! * (k-1)! * \alpha_k * Q_\mathrm{T}}{(m-1)!} \quad (11)$$

$$Q_k^{(m)} = \frac{k * (m-k)! * (k-1)! * \alpha_k * Q_T}{(m-1)! * \alpha_\mathrm{t}}, \alpha_\mathrm{t} \equiv \sum_{k=1}^{m} k\alpha_k \quad (12)$$

$$\begin{aligned} P_i(A_i) &= (1-\alpha_1) * Q_\mathrm{T}, \theta_i = P_i(A_i)/P_\mathrm{T} \\ &= (1-\alpha_1) * Q_\mathrm{T}/P_\mathrm{T} \end{aligned} \quad (13)$$

$$\begin{aligned} P_i(A_i) &= \left(\sum_{k=2}^{m} k * \alpha_k\right) * Q_\mathrm{T}, \theta_i = P_i(A_i)/P_\mathrm{T} \\ &= \left(\sum_{k=2}^{m} k * \alpha_k\right) * Q_\mathrm{T}/P_\mathrm{T} \end{aligned} \quad (14)$$

A Simple Example

A simple example of assigning A to multiple CCCGs is brought forth in Fig. 2.

The 3 CCCGs models are $\{A_1, B\}$, $\{A_2, C\}$ and $\{A_3, D\}$ for the part I of Fig. 2. According to Eq. (3), $P_1(A_1) = P(C_{AB})$, $P_2(A_2) = P(C_{AC})$ and $P_3(A_3) = P(C_{AD})$, Eq. (15) can be deduced from Eq. (5). Then Eq. (16) is a special form of Eq. (7). It can be seen from part I that C_{AB}, C_{AC} and C_{AD} will always be part of A. Therefore, Eq. (7) will be always true given CCCG assigning subjected to the above principium, no matter how many CCCGs A is assigned to.

$$P_T(A) = P_0(A_0) + P(C_{AB}) + P(C_{AC}) + P(C_{AD}) \quad (15)$$

$$(\theta_1 + \theta_2 + \theta_3) \le 1 \quad (16)$$

As for the fault tree (FT) modeling, BE A will become a transfer CCF fault tree with a top "OR" logic gate, and there will be 4 events inputs under the gate A_0, C_{AB}, C_{AC} and C_{AD}. This modeling in FT is based on the above assumptions and principium of CCBS. The FT for whole system of A, B, C and D was built in RiskA, which can be show as Fig. 3 given any one of the 4 component operating successfully will ensure the system function. The original minimal cutsets (MCS) of the system fault tree include 8 cutsets, but 4 minor cutsets of the type $C_{AB} \cdot C_{AC}$ are identically zero after the mutually exclusive treatment process.

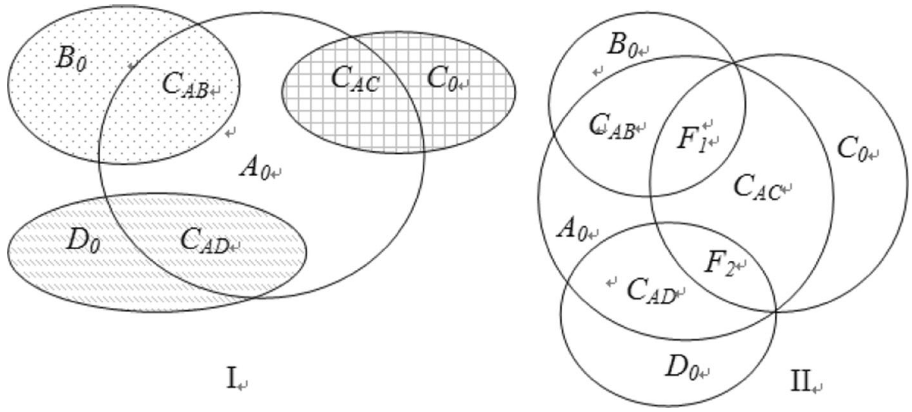

Fig. 2 Assigning event A to multiple CCCGs

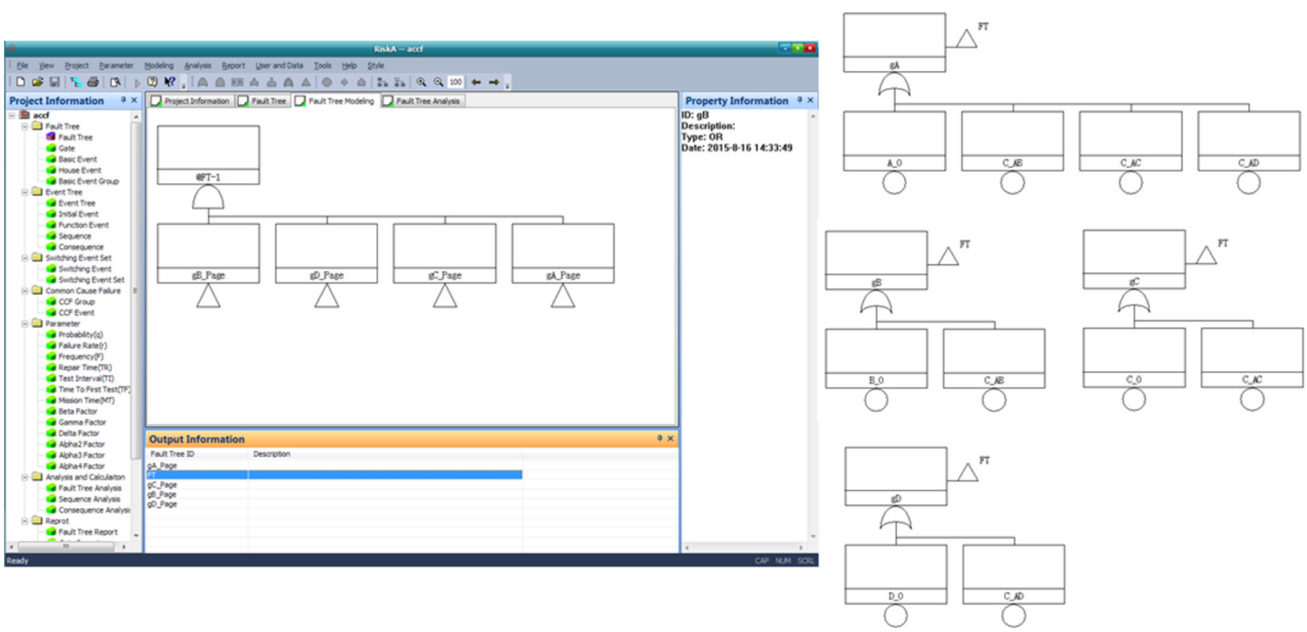

Fig. 3 Main FT of the system and 4 CCF transfer FT pages in RiskA

However, for the part II of Fig. 2, because the above 3 CCCGs are not mutually exclusive, Eq. (4) is not true for this case. Then Eqs. (15) and (16) cannot be reasoned out. According to part II, the regions of C_{AB} and C_{AC} have an overlap area of F_1. Similarly, C_{AC} and C_{AD} also have an overlap area of F_2. If the sum area of F_1 and F_2 is larger than that of A_0, the summation of 3 CCF portions will be greater than 1. Actually, this phenomenon suggests that the above CCCGs establishing is not appropriate for part II. One proper 5 CCCGs model establishing case can be $\{A_1, B_1\}$, $\{A_2, B_2, C_2\}$, $\{A_3, C_3\}$, $\{A_4, C_4, D_4\}$ and $\{A_5, D_5\}$. Here is no mark of C_1, D_1, D_2, and D_3 for modeling convenience. According to the principium of CCBS, A_1 to A_5 represent the CCF portions resulted from these 5 CCCGs.

Thus, the new corresponding probability of the CCF portion from CCCG $\{A_1, B_1\}$ can be expressed as Eq. (17). Here $P(C_{AB}^{new})$ deduced from 5 CCCGs model represents the area of C_{AB} after F_1 is subtracted from it, and the area of total C_{AB} is represented by $P(C_{AB})$ in Eq. (15) deduced from 3 CCCGs model.

$$P(A_1B_1) = P\left(C_{AB}^{new}\right) = P(C_{AB}) - P(F_1) \tag{17}$$

The CCF portions of $\{A_3, C_3\}$ and $\{A_5, D_5\}$ also should be analogously treated as in Eqs. (18) and (19). In the meantime, F_1 and F_2 will be the CCF portion of A from $\{A_2, B_2, C_2\}$ and $\{A_4, C_4, D_4\}$ respectively. Thus, the total failure probability of A can be expressed as Eq. (20). Then Eq. (21) is a special form of Eq. (7).

$$P(A_3C_3) = P\left(C_{AC}^{new}\right) = P(C_{AC}) - P(F_1) - P(F_2) \tag{18}$$

$$P(A_5D_5) = P\left(C_{AD}^{new}\right) = P(C_{AD}) - P(F_2) \tag{19}$$

$$P_T(A) = P_0(A_0) + P\left(C_{AB}^{new}\right) + P\left(C_{AC}^{new}\right) + P\left(C_{AD}^{new}\right) + P(F_1) + P(F_2) \quad (20)$$

$$(\theta_1 + \theta_2 + \theta_3 + \theta_4 + \theta_5) \leq 1 \quad (21)$$

It should be noted here that, in general, the total failure probabilities of basic events A, B, C and D are different from each other, i.e., $P_T(B) \neq P_T(C) \neq P_T(A) \neq P_T(D)$. Therefore CCBS can be used in a wider scope, such as the asymmetrical CCF analyses for different types of components whose total failure probabilities are much different.

Results

The CCBS method can be applied to CCF components with different failure probabilities, but for convenient comparison with other methods, the CCF of same type events with a same independent failure probability were to be analyzed in this paper.

System Description

Pumps and valves are widely applied in Tokamak Cooling Water System (TCWS) and other subsystems of ITER. TCWS provides enough cooling for removing heat from test blankets, shield, etc. Normally multiple cooling loops are applied to accomplish this function. The typical components of a pump include the pump itself, motor driver, circuit breaker, lubrication or cooling systems, and any sensors, controls, etc. The main components of a valve are the valve itself and the operator, including their internal piece-part components. Therefore, the asymmetries for pumps and valves may come from the differences of driving factors, operating environment, running history, etc.

Without loss of generality, an asymmetrical redundant cooling water system with 3 similar water pumps A, B and C was considered. The total failure probability of a water pump is set as $Q_T = 0.00045$ from the failure data of IAEA-TECDOC-478 approved by ITER. The summary of average impact vectors is shown in Table 1 from the water pump CCF data of NUREG/CR-5497 [23], in which the total number of independent failure events is 318 and that of CCF events is 61. Here the symmetry factor for this asymmetrical redundant system is set as $f_r = n_2^{CCCG1}/\left(n_2^{CCCG1} + n_2^{CCCG2}\right) = 0.92$ without changing its meaning defined by Jo and Kang's paper.

Table 1 Summary of average impact vectors

CCCG size m	Adj. ind. events	N_1	N_2	N_3
2	129.01	32.3127	6.0422	–
3	193.51	37.7868	10.6786	2.4781

As for the MGLM and AFM used, the CCF model parameters estimating values of 2 and 3 components CCCGs are shown in Table 2. According to these models definitions in the above context and NUREG/CR-4780, equations for estimating parameters are given by Eqs. (22) and (23), in which, n_k is the number of events involving k basic events in a failed state.

$$\beta^M = \frac{\sum_{k=2}^{m} n_k}{\sum_{k=1}^{m} n_k}, \gamma = \frac{\sum_{k=3}^{m} n_k}{\sum_{k=2}^{m} n_k}, \delta = \frac{\sum_{k=4}^{m} n_k}{\sum_{k=3}^{m} n_k} \quad (22)$$

$$\alpha_k = \frac{n_k}{\sum_{k=1}^{m} n_k}, k = 1, 2, \ldots, m \quad (23)$$

Optimistic Method

The optimistic analysis method was done according to NUREG/CR-5485. In this method, only A and B were considered as CCF events in a CCF group of {A, B}, and C would be an independent event. Thus the CCF factors between A and C will be ignored, and it is the same for the CCF between B and C. This method will result in a lower system failure probability than the actual system failure probability.

Table 3 shows the results of A and B calculated by MGLM according to Eq. (9). In Tables 3, 4, 7, and 8, Q_1 is the single independent failure probability of a CCF BE in a CCCG, and Q_i ($i > 1$) is the failure probability of i specific CCF basic events fail togather in the CCCG.

Conservative Method

For a conservative analysis method, A, B and C will all be considered in a CCF group of {A, B, C} according to in NUREG/CR-5485. Thus some of the CCF factors that only exists between A and B will be expanded to affect C. This method will result in a higher system failure probability than the actual probability.

Table 4 shows the results A, B and C calculated by non-staggered AFM according to Eq. (12).

Table 2 Model parameters values

CCCG size m	Factor name	Values
2(MGLM)	1-β	9.64E−1
	β	3.61E−2
3(AFM)	α_1	9.46E−1
	α_2	4.37E−2
	α_3	1.01E−2

Table 3 Optimistic method results

Events	Expression	Values
A_0, B_0	Q_1	4.34E−4
C_{AB}	Q_2	1.62E−5

Table 4 Conservative method results

Events	Expression	Values
A_0, B_0, C_0	Q_1	4.00E−4
C_{AB}, C_{AC}, C_{BC}	Q_2	1.85E−5
C_{ABC}	Q_3	1.28E−5

CCBS Method

It is assumed that the number of total failure events of C is a little bit smaller than that of A and B, or A and B should be impacted by more common-causes according to the analysis of components failure. For the CCBS method, A and B will be considered as MCCF events. Therefore 2 CCCG should be considered {A_1, B_1, C} and {A_2, B_2}. The $CCCG_1$ of {A_1, B_1, C} will be calculated by the non-staggered AFM according to Eq. (12), and the $CCCG_2$ of {A_2, B_2} will be calculated by the MGLM according to Eq. (9). The CCF probabilities can be recalculated according to the CCBS method and the symmetry factor f_r. The numbers of independent events (Adj. Ind. Events) will not change according to CCBS principium, while considering the asymmetry between A, B and C. The other average impact vectors in Table 1 were adjusted to Table 5 according to symmetry factor f_r without changing the total failure probabilities of A and B (i.e., $Q_T = 0.00045$). Then the CCF parameters of these two CCCGs were also estimated again as Table 6 according to Eqs. (22) and (23).

Therefore, according to the proposed CCBS method, analysis results are shown in Table 7. Finally, the results of Optimistic method, CCBS and Conservative method are compared in Table 8.

Table 5 Summary of adjusted average impact vectors

CCCG number	Adj. ind. events	N_1	N_2	N_3
1	193.51	34.7639	9.8243	2.2799
2	129.01	2.5850	0.4834	–

Table 6 Model parameters adjusted values

CCCG number	Factor name	Values
1	β	3.66E-3
2	α_1	9.54E-1
	α_2	4.10E-2
	α_3	9.52E-3

Table 7 CCBS Results

Events	Expression	Values
A_2B_2	Q_2 ($CCCG_2$)	1.65E−6
A_1, B_1, C_1	Q_1	4.03E−4
A_1B_1, A_1C, B_1C	Q_2 ($CCCG_1$)	1.74E−5
A_1B_1C	Q_3	1.21E−5
A, B	$Q_1 + 2Q_2 + Q_3 + A_2B_2$	4.50E−5
C	$Q_1 + 2Q_2 + Q_3$	4.48E−4

Table 8 Final results comparison

Analysis methods	Unavailability value of the system
Optimistic method	1.58E−6
CCBS	1.50E−5
Conservative method	1.58E−5

Discussion

In general, for asymmetrical common-cause failures, there are three analyzing methods and one modeling method, but they are all restricted by the CCF models and components types. The method CCBS is proposed for transition from asymmetrical CCF to a symmetrical one.

From Table 8, it can be seen that the system unavailability was 1.58×10^{-6} for the optimistic method, for the conservative method, it was 1.58×10^{-5}, and for the CCBS method, it was 1.50×10^{-5}. The result of the CCBS was between that of the conservative method and optimistic method, which proves that the result of CCBS is more closed to the true failure probability of the redundant system.

From the reasoning equations, example and the calculation process of cooling water system, the conclusion can be made that CCBS method is not restricted by the CCF models. In other words, CCBS can treat the CCCG that adopt different CCF models. Besides, CCBS method is based on concise and reasonable assumptions and principium that are meticulously abstracted from the symmetrical assumptions and much closer to the CCF facts. Foremost, CCBS has no restriction for the different components types whose total failure probabilities are much different, which is inevitable in ITER subsystems. Moreover, CCBS can be adopted conveniently by FTA codes given the CCCGs parameters, because these CCCGs can be analyzed by traditional CCF models after treating with CCBS method.

However, this method will bring some errors in rare instances while these errors can be reduced to an accepted degree by regulating the CCCGs establishing. And the CCF parameters estimating will become more complex, because the specific CCF events belong to each of the CCCGs have to be picked out in the estimating process, or the applying of symmetry factor of f_r to help adjust the existing values of the parameters or impact vectors.

Conclusions

A transition analysis method named CCBS for asymmetrical common-cause failures was proposed in this paper. This method includes two important assumptions and principium in the process of breaking down the CCF portion of a component into several parts. The CCBS method is applied to the reliability analysis of an asymmetrical cooling water system with three similar water pumps applied in Tokamak Cooling Water System. At the same time, traditional optimistic and conservative methods are also applied for comparison. The effectiveness and applying scope is verified by the example and application results. In the future, the CCBS method will be applied in RiskA program, and reliability analysis with Asymmetrical CCF will be done for the Chinese DFLL TBM to ensure the systems reliability.

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