

Common cause failure analysis of PWR containment spray system by GO-FLOW methodology

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HIGHLIGHTS

- Identification of particular causes of failure for common cause failure analysis.
- Evaluation of dynamic reliability of PWR containment sprays system (standard case).
- Selection of important parameters by sensitivity analysis for CCF analysis.
- Calculated dynamic reliability has significantly worsened than that of standard case.
- GO-FLOW with it advance function can be used alternatively to FAT and ET tree.

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ABSTRACT

Common cause failure (CCF) is the simultaneous failure of multiple components due to some particular cause of failure and has long been recognized as an important issue in the probabilistic safety assessment (PSA). Sometimes CCFs have an important contribution to system unreliability. In this study, Common Cause Failure has been considered in the reliability analysis and procedure of CCF analysis is treated by GO-FLOW methodology. As the sample system, PWR containment spray system has been taken. It is shown that dynamic reliability of the containment spray system has been significantly decreased by common cause failures.

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1. Introduction

Common cause failure (CCF) is the simultaneous failure of multiple components due to some particular cause of failure and sometimes has an important contribution to system unreliability (Tang et al., 2005). The particular cause of failure can be classified as (i) external factor (loss of offsite power, earthquake, fire, flooding, tsunami as well as human-cause events such as sabotage, terrorism, airplane collision, etc.) and (ii) internal factors (such as maintenance error, human error, loss of water source, loss of command signal, design fabrication and physical environment (high temp and pressure, etc.)) (Yoshikawa et al., 2012).

In CCFs analysis, if the logical relation between cause and consequences is a clear, then explicit model can be used (fault tree analysis and event tree analysis) (Matsuoka and Kobayashi, 1997). However, if it is difficult to find such explicit relation, the

parametric models of common cause failures such as beta factor, Binomial failure rate (BFR), Multiple Greek Letter model (MGL), etc. may be applied for taking into account of implicit common cause factors. Such implicit CCFs may exist in the system configuration with redundant components, and it can affect the reliability of the system's operation. Therefore, it is important to consider the common cause failure (CCF) in evaluation of reliability of many safety systems of the nuclear power plants.

In this study, common cause failure is additionally considered for the authors' previous evaluation of dynamic reliability for PWR containment spray system by the GO-FLOW methodology (Hashim et al., 2012), where no special consideration was taken for the possibility of CCF. The GO-FLOW method is the success-oriented system analysis technique (Matsuoka and Kobayashi, 1988), which can be used to evaluate the system reliability/availability by considering many types of parametric models of CCF. In the GO-FLOW, the analysis program automatically takes into account system configuration and evaluates the effects of CCFs.

The GO-FLOW methodology has following significant features.

(i) The GO-FLOW chart corresponds to the physical layout of a system and is easy to construct and validate, (ii) Alterations and updates of a GO-FLOW chart are easily made, (iii) A GO-FLOW chart

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Nomenclature

CCF	Common Cause Failure
PSA	Probabilistic Safety Assessment
CCWS	Component of Cooling Water System
CPAS	Containment Pressure Activation System
CRS	Containment Recirculation Sump
CSHEX	Containment Spray Water Heat EXchanger
CSP	Containment Spray Pump
CSS	Containment Spray System
IAEA	International Atomic Energy Agency
RWST	Refueling Water Storage Tank
SAT	Spray Additive Tank
USNRC	United States Nuclear Regulatory Commission
MGL	Multiple Greek Letter Model
BFR	Binomial Failure Rate

contains all possible systems operational states, and (iv) The analysis is performed by one GO-FLOW chart and one computer run (Matsuoka and Kobayashi, 1988).

The authors have started their discussion from the summary of evaluation of dynamic reliability for PWR containment spray system from the previous conducted study and remainder of paper explain the common cause failure analysis for PWR containment spray system.

2. Summary of example practice for evaluation of dynamic reliability

2.1. Function of PWR containment spray system and its GO-FLOW modeling

Containment spray system (CSS) has a function to decrease the containment pressure during the large loss of coolant accidents (LOCA) to attain the design pressure within the containment vessel (atmospheric pressure). CSS traps radioactive inorganic iodine to wash down into the containment sump by spraying the borated cooling water. Sodium hydroxide (NaOH) solution of about 30% concentration is added from spray additive tank (SAT). The configuration of a PWR containment spray system employed is illustrated in Fig. 1, (Japan Nuclear Energy Safety Organization (JNES), 2005). The design of CSS has redundancy according to single criteria and consists of containment spray pumps (CSP), containment heat Exchangers (CSHEX), refueling water storage tank (RWST), spray additive tank (SAT), containment recirculation sump (CRS), and also motor operated and check valves, etc. In the CSS, there is a test line which is designed to allow periodical tests and inspections to verify the operability and integrity depending upon the importance of safety (Japan Nuclear Energy Safety Organization (JNES), 2005). CSHEXs are cooled by component of cooling water system (CCWS). RWST is designed to provide the borated water which is pressurized with nitrogen. The NaOH solution makes water slightly alkali to enhance absorption of radioactive iodine and to prevent corrosion of the vessel during long-term cooling after the accident. In the configuration of CSS, there are two phases (injection phase and recirculation phase), and detail of both phases has been explained in the author's previous study given in reference (Hashim et al., 2012).

For GO-FLOW modeling of CSS, two lines redundancy case is considered as the standard case in which test line and component of cooling water system (CCWS) are neglected shown in Fig. 2. In this model following assumptions are made: two CSP pumps and two heat Exchangers (CSHEX), and eight motor operated valves, each valve corresponding to each line. RWST, SAT, CSHEX and CRS are

passive components, which have no need of any power source for actuation. CSP is active one, which needs the source for actuation, and it should open in both phases. Motor-operated valves from M1 to M8 are also active ones, which have open and close state (Hashim et al., 2012). In the GO-FLOW model, the control system is also shown. In the control system of containment spray system, P is containment spray activation signal and L is the low level water signal of RWST. During the LOCA, M1 to M4 and CSP A and B are open on the receipt of high containment pressure signal (injection phase) and M5 to M8 and CSP A and B are open on the receipt of low level water signal of RWST and water source is switched to containment recirculation sump(CRS)(recirculation phase)(Hashim et al., 2012). In the control system, solid and dotted arrows represent the open and close state of components respectively in respective phase.

2.2. Result of GO-FLOW calculation (standard case)

The GO-FLOW chart of the PWR containment spray system is shown in Fig. 3 in which two phases are considered. For phase 1 (injection phase), RWST, SAT, two CSP (A and B) and four motor-operated valves from M1 to M4 are needed and for phase 2, SUMP, CSHEX, A and B, two CSP (A and B) and four motor operated valves from M5 to M8 are required.

The time span of phase one is 0–1800 s and that for second phase is 1800–3600 s. The value of time is taken on assumption base, and it may be vary for different PWR plants. For Conventional four loop PWR, the time point 1800 s for shifting from phase 1 to 2 is taken that water storage should be large enough to cover the needed time for continuous injection of water by both ECCS and containment spray for a large break LOCA in the cold leg. In GO-FLOW chart analysis, 10 time points were declared by operator number 4. The operation within the system is demanded five time points for phase 1 and five time points for phase 2.

The time point 1 is an initial state and at a time point 2, the system operation is demanded in phase 1. In the GO-FLOW chart, the operators, 26, 34 and 53 present the output signal, and these output signals give the result of GO-FLOW analysis. This analysis result can be consists of successful probability of the system. The operation of components and reliability data which is assigned in the GO-FLOW analysis is given in Table 1 (USNRC: Wash 1400 NUREG -75/014, 1975 and IAEA, TECDOC-508, 1989).

The failure probability curve versus time is shown in Fig. 4. The failure probability is very small in phase 1 and discontinuously increases from the beginning of phase 2, because the availability or reliability of a nuclear power plants has greatly affected by failures of the subsystems or components which are responsible for reliable power production.

3. Common cause failure analysis of PWR containment spray system

3.1. Classification of dependent events

The CCF events included in plant logic models represent those inter-component dependencies which are potentially significant, and whose mechanisms are not explicitly represented within the logic model (event trees and fault trees) of the plant (IAEA: IAEA-TECDOC-648, 1989). An event in which a component state occurs, causally unrelated to any other component state is considered as an independent event and if an event is not independent, it is defined as a dependent event shown in Fig. 5 (USNRC, 1988, NUREG/CR-4780).

The type of dependent events based on their impact on a PSA model is given in Table 2 (USNRC, NUREG/CR-4780, 1988). This categorization provides the way to identify the nature and scope

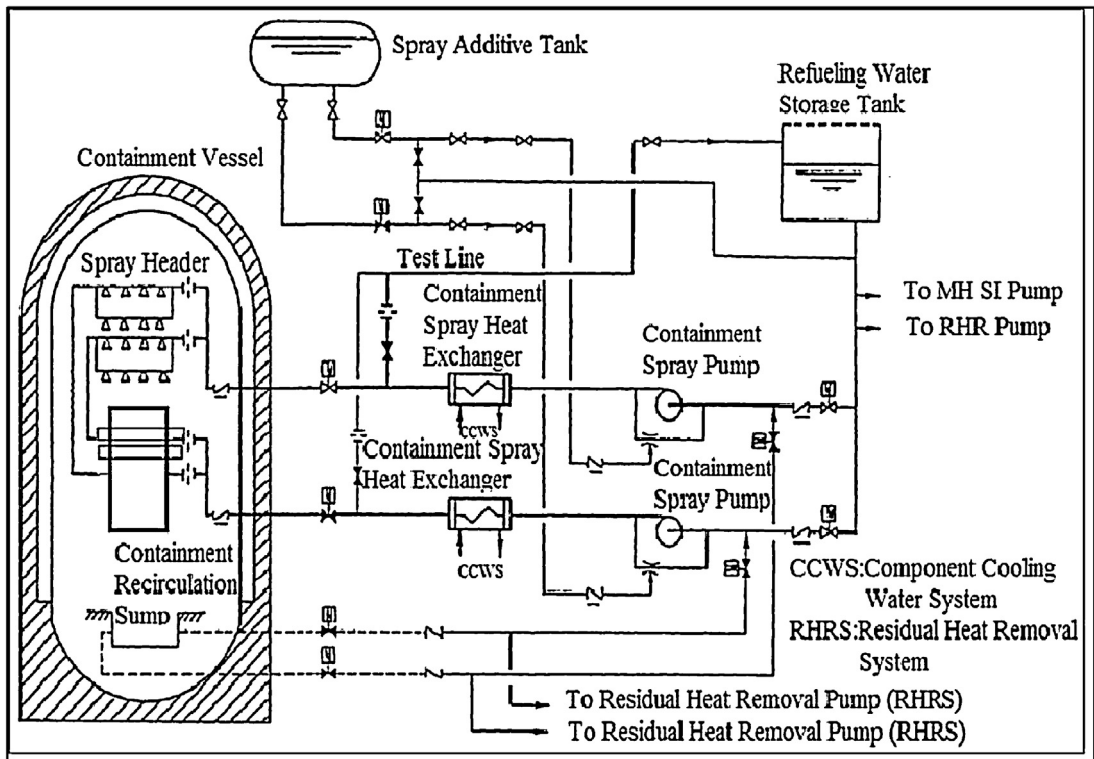


Fig. 1. Containment spray system of PWR plant.

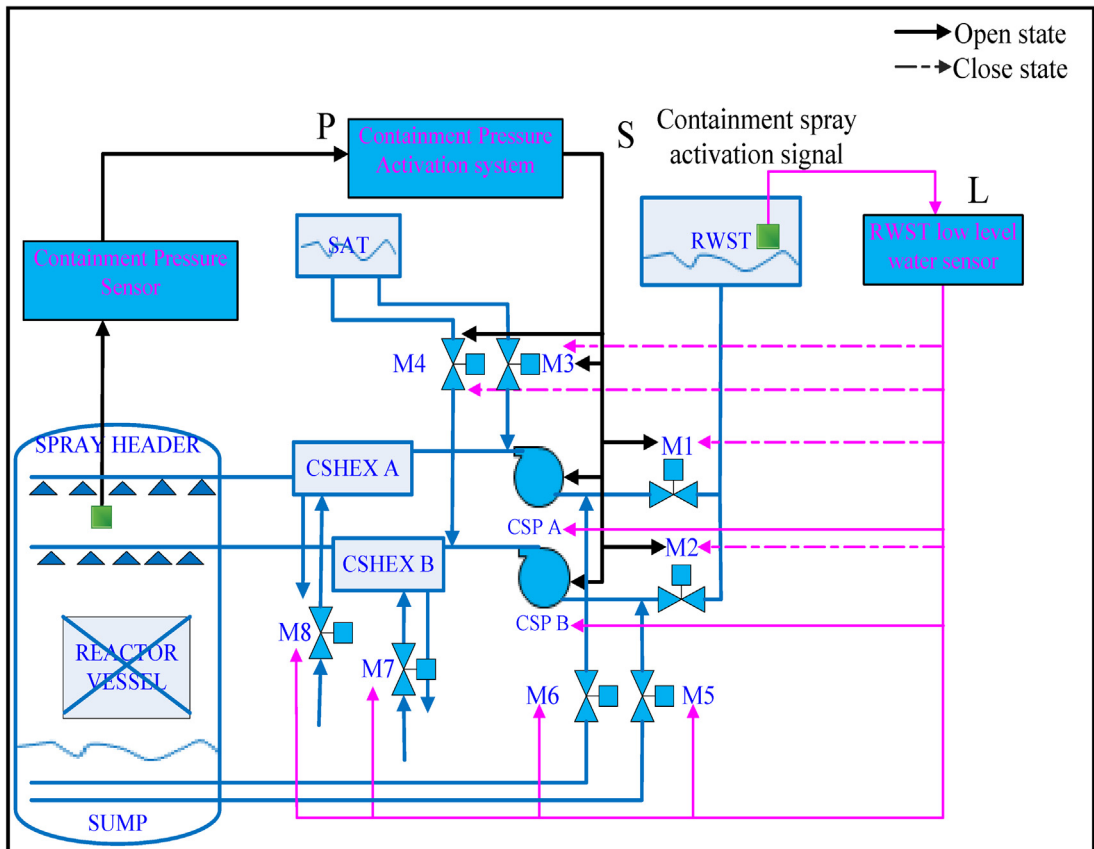


Fig. 2. GO-FLOW model of containment spray system (standard case).

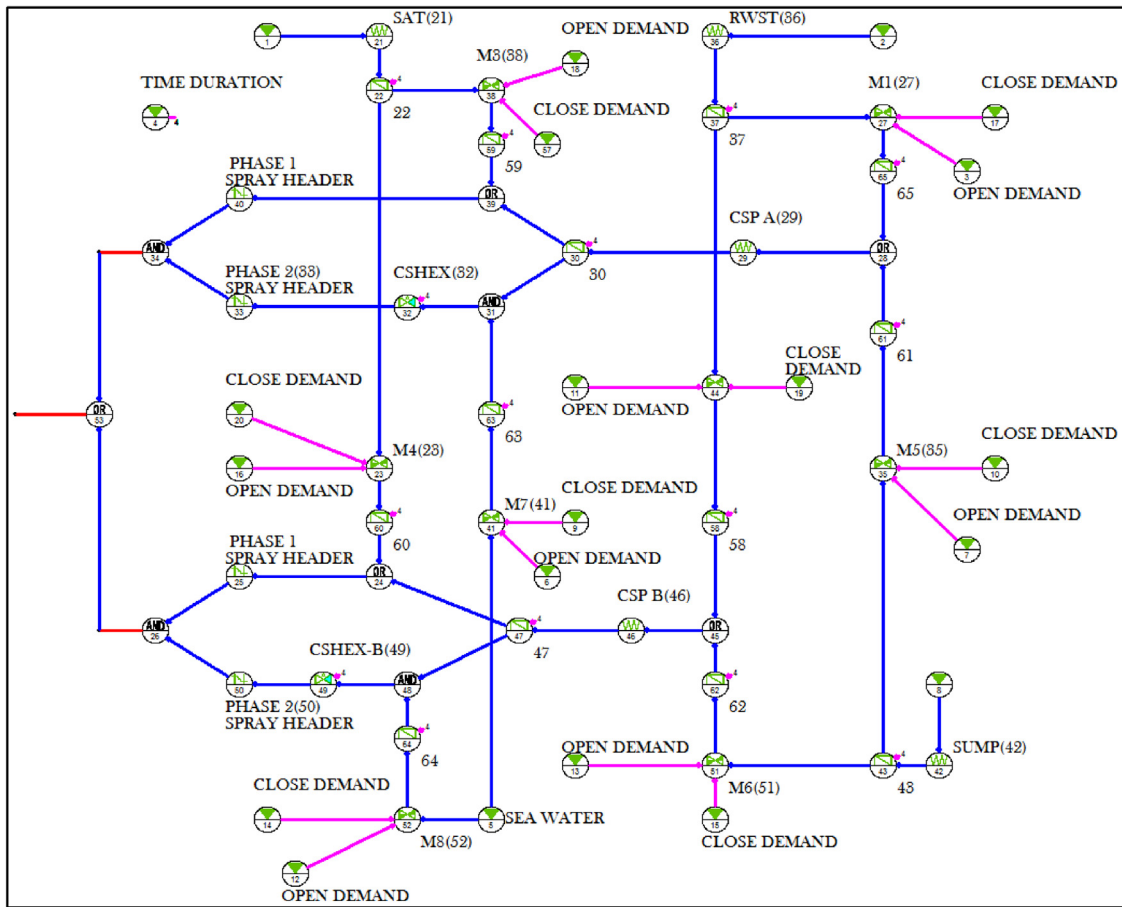


Fig. 3. GO-FLOW chart PWR containment spray system (Standard case).

Table 1
Operation and failure rate used in the present analysis.

Components	Kind	Success probability or failure rate	Phase 1	Phase 2
RWST	Passive	$P_g = 0.999999, \lambda_o = 1 \times 10^{-5}/s$	On	Off
SAT	Passive	$P_g = 0.99, \lambda_o = 1 \times 10^{-5}/s$	On	Off
CRS	Passive	$P_g = 0.999999, \lambda_o = 1 \times 10^{-5}/s$	Off	On
CSHEX	Passive	$\lambda_o = 1 \times 10^{-8}/s$	Off	On
CSP	Active	$P_g = 0.99, \lambda_o = 1 \times 10^{-5}/s$	On	On
M1, M2, M3, M4	Active (Open and close action)	$P_o = 0.96/\text{demand}, P_c = 1.0/\text{demand}, P_p = 0.96, \lambda_o = 1 \times 10^{-8}/s, \lambda_c = 1 \times 10^{-8}/s$	On	Off
M5, M6, M7, M8	Active (Open and close action)	$P_o = 0.96/\text{demand}, P_c = 0.96/\text{demand}, P_p = 0.0, \lambda_o = 1 \times 10^{-8}/s, \lambda_c = 1 \times 10^{-8}/s$	Off	On

of dependent's events analysis in a PSA. In this categorization, the dependent's events are considered not only in quantification, but also in the definition of accident sequences in a PSA.

According to PSA procedure guide, dependent events can be categorized: (i) Common cause initiating events, (ii) Intersystem

dependencies, and (iii) Intrasystems dependencies and other dependent events determined by these three possibilities were further subdivided, as shown in Table 2.

The Common Cause events are the subset of dependent events in which two or more component fault states exist at the same time.

Table 2
Types of dependent events on their impact on a PSA model (USNRC, NUREG/CR-4780, 1988).

Dependent event type	Characteristics	Subsystem (coupling mechanism)	Example (trigger events)
Common cause initiating event	Causes a plant transient and increases unavailability of one or more mitigating systems	Functional Spatial human	Loss of offsite power Earthquake, Maintenance error shorting out instrument bus
Intersystem dependency	Causes a dependency in a joint event probability involving two or more systems	Functional spatial human	Coolant charging fails because component cooling fails, Fire causes loss of equipment of two systems, Operator error causes loss of two systems
Intercomponent (intrasystems) dependency	Causes a dependency in a joint event probability involving two or more components	Functional Spatial human	Battery loss charge after it is run beyond capacity, Fire causes loss of redundant pumps, Design error present in redundant pump controls

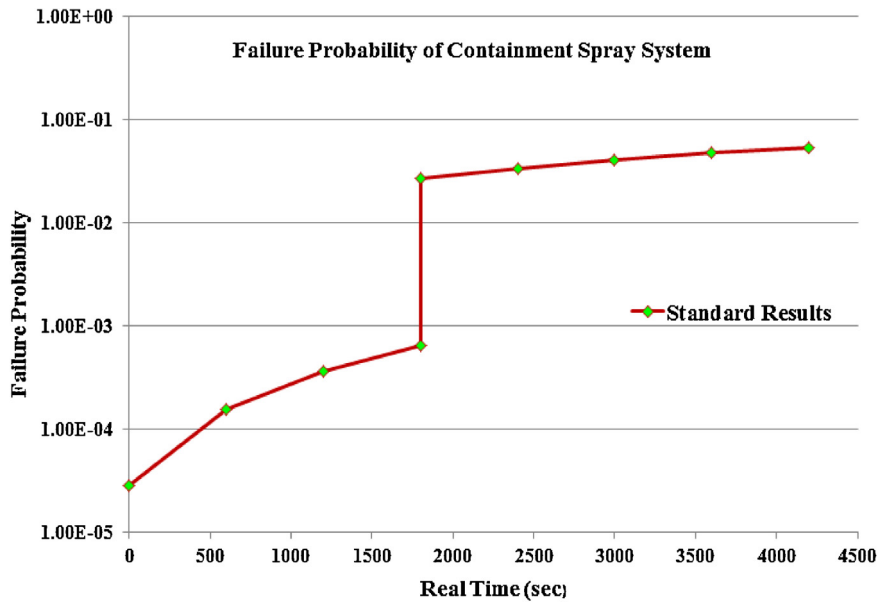


Fig. 4. Failure probability curve versus time of PWR containment spray system (standard case).

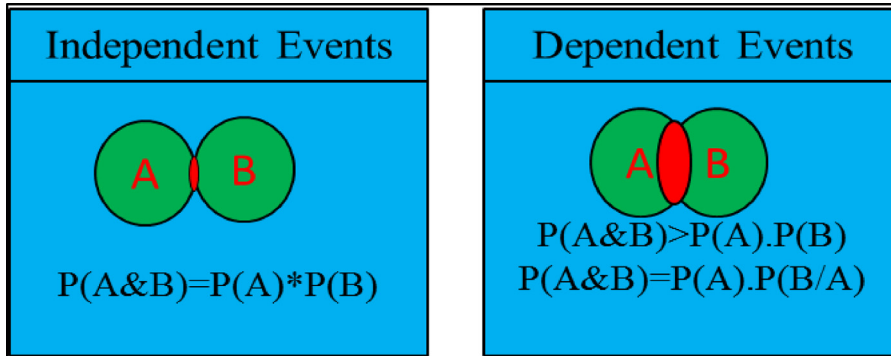


Fig. 5. Independent and dependent events.

The physical elements of a dependent event are shown in Fig. 6. That presents the root cause events and their propagation (coupling mechanism) to multiple equipment items or components.

There are four general types of root causes, (i) hardware, (ii) human, (iii) environmental, and (iv) external to the plant and three broad categories of coupling mechanisms, (i) functional equipments (connected equipment and nonconnected equipment), (ii) spatial couplings (spatial proximity, linked equipment), and (iii) human couplings.

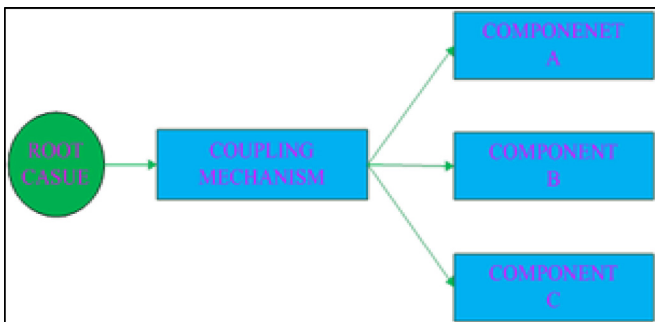


Fig. 6. Physical element of dependent events.

3.2. Treatment of common cause by GO-FLOW methodology

In the CCFs, there are more than one common cause and many possible combinations of component failures for a specific common cause. The analysis becomes impractical if all the common causes are treated at the same time. Therefore, each common cause is separately evaluated, and the total system unavailability is obtained by summing up contribution from each CCF (Matsuoka and Kobayashi, 1997).

If there are two basic events X and Y (failure events) which are subjected to common cause. A system failure S is expressed in the following general Boolean algebraic equation

$$S(X, Y) = (XE + YF + XYG).H + K \tag{1}$$

From E to K are some Boolean algebraic terms not suffered by common cause. The basic events X, and Y are decomposed into independent events and a common cause failure as follows,

$$X = X_i + C_{XY}, \quad Y = Y_i + C_{XY} \tag{2}$$

Substitute the above relations into Eq. (1), and rearrange it.

$$S(X, Y) = S(X_i, Y_i) + C_{XY}(E + F + G).H \tag{3}$$

where $S(X_i, Y_i)$ means that basic events X and Y are replaced by independent failure events X_i and Y_i , respectively.

Table 3
Calculations of CCF for group 1, 2 and 3.

Group 1 and 2		Group 3	
Operators (type 35)	22, 37 and 30, 47	Operators (type 26)	41, 51, and 52
Failure rate	$(\lambda_o) = 1 \times 10^{-5}/s$	Failure probability	0.04
Beta-factor	$(\beta) = 0.4$	Beta-factor	$(\beta) = 0.4$
Common cause failure (CCF)	$(\lambda_o) = 4 \times 10^{-6}/s$	Common cause failure (CCF)	$1 - 0.04 \times 0.4 = 0.984$
Independent failure	$(\lambda_o) = 6 \times 10^{-6}/s$	Independent failure of open and close action	$1 - 0.04 \times 0.6 = 0.976$
Common cause failure contribution P (CCF)	$1 - \exp(-\beta\lambda t) = 1 - \exp(-0.000004t)$	Common cause failure contribution P (CCF)	$0.04\beta = 0.04 \times 0.4 = 0.016$

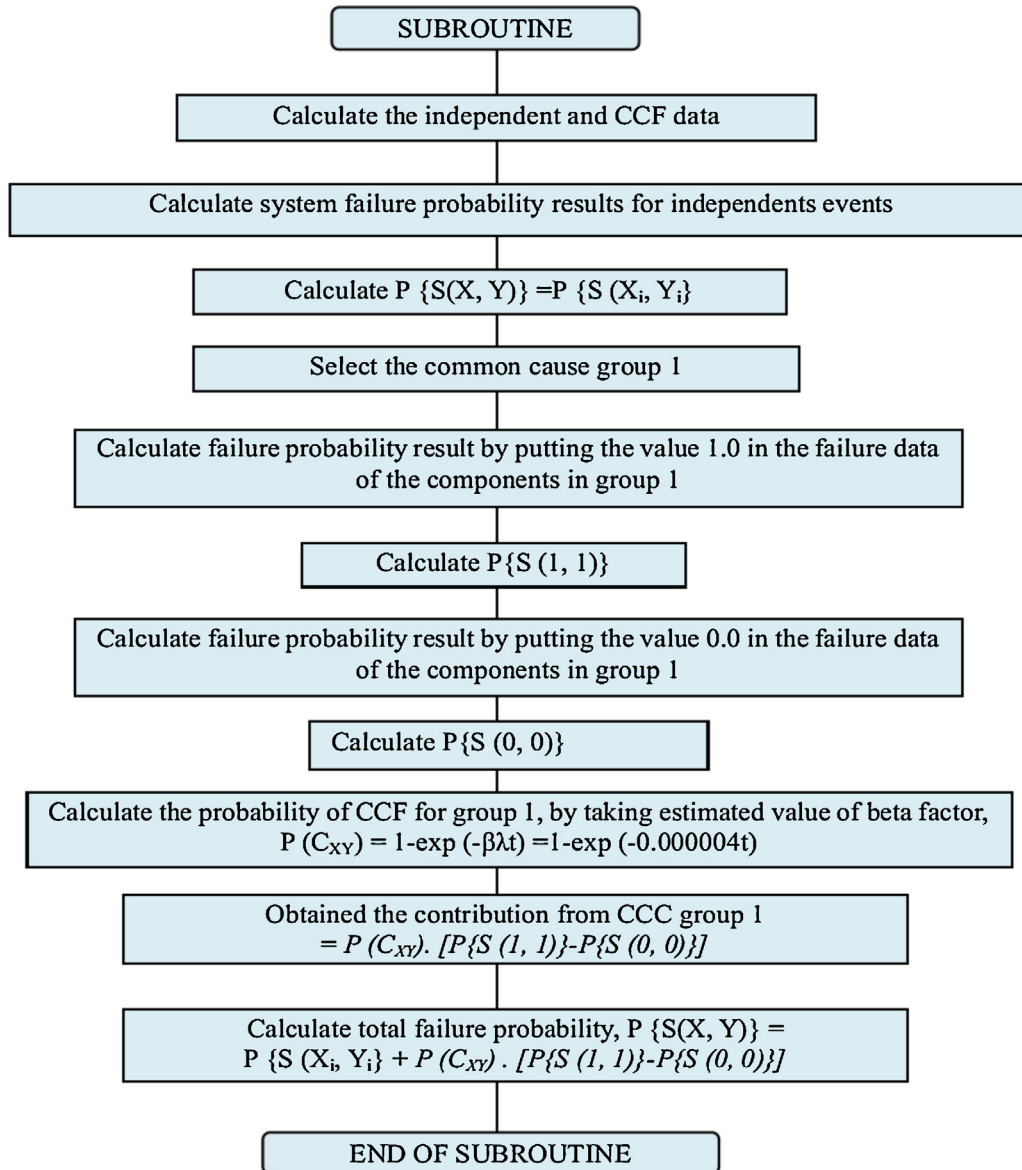


Fig. 7. Analysis steps for CCF group1 (beta factor model).

Table 4
Results of common cause failures for PWR containment spray system.

Time point (s)	Standard results without CCF	Independent failure (I)	CCC Group 1 (G ₁)	CCC Group 2 (G ₂)	CCC Group 3 (G ₃)	Total I + G ₁ + G ₂ + G ₃
1	0.00E+00	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0
2	2.85E-05	2.85E-05	0.00E+0	0.00E+0	0.00E+0	2.85E-05
3	1.58E-04	9.67E-05	2.40E-03	3.61E-05	0.00E+00	2.53E-03
4	3.65E-04	1.93E-04	4.79E-03	8.86E-05	0.00E+00	5.07E-03
5	6.48E-04	3.17E-04	7.17E-03	1.57E-04	0.00E+00	7.65E-03
6	2.67E-02	2.26E-02	7.02E-03	7.01E-03	1.57E-02	5.23E-02
7	3.35E-02	2.89E-02	9.28E-03	9.28E-03	1.56E-02	6.30E-02
8	4.03E-02	3.52E-02	1.15E-02	1.15E-02	1.55E-02	7.37E-02
9	4.71E-02	4.14E-02	1.37E-02	1.37E-02	1.54E-02	8.43E-02
10	5.40E-02	4.77E-02	1.59E-02	1.59E-02	1.53E-02	9.47E-02

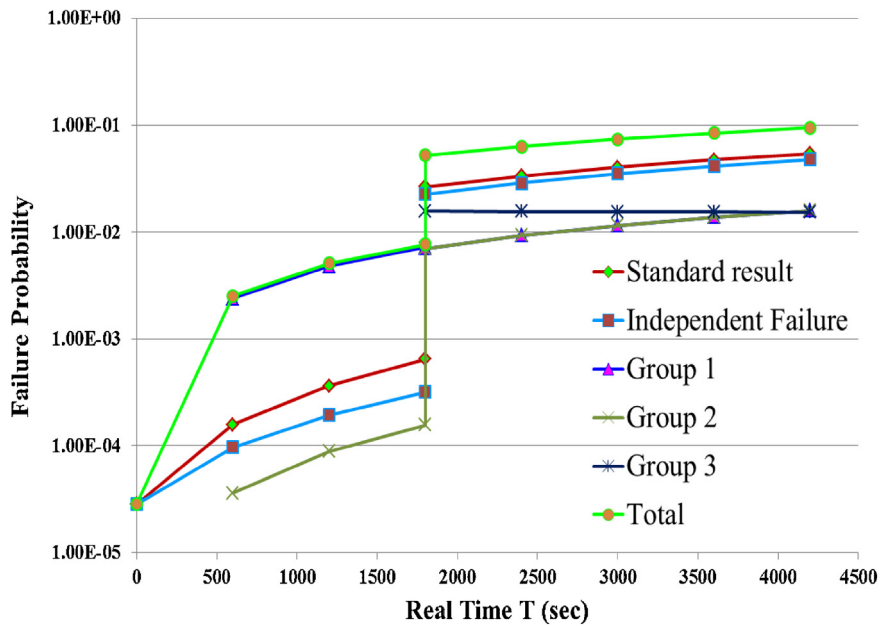


Fig. 8. Results of common cause failure analysis for PWR containment spray system.

In the expression of failure probability, the above equation can be written as.

$$P\{S(X, Y)\} = P\{S(X_i, Y_i)\} + P\{C_{XY}\} \cdot [P\{S(1, 1)\} - P\{S(0, 0)\}] \quad (4)$$

where $P\{S(1, 1)\}$ and $P\{S(0, 0)\}$ means the system failure probability when occurrence probabilities of basic events X and Y are replaced by 1.0 and 0.0, respectively. The first term is the contribution from the independent events, and the second term is from the common cause event C_{XY} .

The general formula is obtained as the next equation

$$P\{S(X, Y, \dots)\} = P\{S(X_i, Y_i, \dots)\} + \sum_{C_j} \sum_{m=2}^N \sum_m \{C_{jm}\} \times [P\{1, 1, \dots\} - P\{0, 0, \dots\}] \quad (5)$$

where the summations are performed on the common cause kinds C_j number of suffered components N , and the possible combination of m components (Matsuoka and Kobayashi, 1997). For CCF analysis by using above equation, it is necessary to know about the source and nature common cause failure for containment spray system

In this authors' example study, the previous GO-FLOW analysis with no consideration of CCF is taken as the standard case. And for considering CCFs, contributions of CCFs to the failure probability of several redundant systems were considered by adding additional failure probability by beta factor model to those of the standard case for various important equipments to perform safety functions in case of LOCA accident. The values of the beta factors were taken upon the basis of failure mode with its empirical data for each component.

For the first step of the CCF analysis is identification of several common cause groups, which are more responsible for failure probability of the system. In the present study, common cause groups were identified by conducting sensitivity analysis to the standard case. It was concluded that the following three groups of equipments were major contributions to the failure probability of the containment spray system of the order of significance. The groups 1 and 3 contribute in phase 1 and 2 respectively and group 2 contribute in both phases. There are many possible combinations of component's failures for a specific common cause. These three

common cause groups are combined due to same failure mode and same contribution of system failure probability. The analysis becomes impractical if all failures are treated at the same time in a single analysis model such as the fault tree model because large numbers of minimal cut sets are produced.

Group 1: Spray additive tank (SAT, operator 22) and Refueling Water Storage Tank (RWST, operator 37). The nature of failure or failure mode is "Failure during usage."

Group 2: Two containment spray pumps (CSP, Operators 30 and 47) and failure mode is "Failure during usage"

Group 3: Three motor-operated valves (M6 to M8, Operators 41, 51, and 52) and failure mode is "Failure in open and close action"

3.3. Calculation of common cause failure effects by GO-FLOW

The calculations of CCF for each group are given by the Table 3 in which operator 22, 37 and 30, 47 presents CCF group 1 and 2 respectively. These operators are type 35 operators and were considered to increase the failure probability by the simultaneous failure during usage. Similarly, operators 41, 51, 52 presents the group 3 of which are type 26 operators were considered to increase the failure probability by the simultaneous failure to open and close action.

- (i) The procedure of CCF analysis in the GO-FLOW methodology consists of the following steps.
- (ii) Construction of GO-FLOW chart of the containment spray system in which CCFs need not be explicitly expressed.
- (iii) Obtain the system failure probability for independent events
- (iv) Identify the common cause components groups
- (v) Select the parametric models such as β -factor model and Multiple Greek Letter model (MGL) etc.
- (vi) Take the estimated value of the parametric model based on failure mode
- (vii) Obtain the contribution from a specific common cause.
- (viii) Repeat the steps from (ii) to (v) for all common causes groups.
- (ix) Sump up to the contributions from all the common causes groups

- (x) Compare the CCF result with results of system failure probability of standard case (Matsuoka and Kobayashi, 1997).

Fig. 7 shows the analysis steps for CCFs by the β -factor model in the GO-FLOW analysis program for group 1. All the components belong to the same CCF group fail at the same time in the β -factor model and analysis procedure has a few steps in comparison with the steps for other models.

Similarly, above all analysis steps can be applied for others CCF groups and results of dependency between simultaneous failures of components caused by a specific common cause is adequately treated in a system logic model by the formulation of Eq. (5) that gives the contribution from all CCFs groups.

The procedure assures that the resulting logic model of a system is complete with respect to all possible ways that common cause events could impact the system (Matsuoka and Kobayashi, 1997).

3.4. Discussion on the calculated results

The common cause failure analysis results are given in Table 4 and shown in Fig. 8. The analysis results consists standard result that is whole system failure without common cause failure, failure probability of independent events and the contribution of common cause failures with three groups.

The final Results (total) is obtained by adding the results of independent failures (I) and contribution of three groups (G1, G2, G3). From Table 4, it is shown that the large contribution to system failure probability is from first two groups while 3rd groups only contribute in phase 2. The result of 3rd group is slightly decreases due to failures of the components and subsystems which are responsible for a reliable power production. Results of the calculated common cause contributions by GO-FLOW of the above three groups and independent failures are added to the failure probability curve of standard case of containment spray system. And thus calculated dynamic reliability has significantly worsen than that of standard case, i.e., without considering the CCF, where major CCF contributions to system failure probability were the simultaneous failure of two water tanks, two containment spray pump and three motor operated valves. The common cause failures are the biggest part when calculating the dynamical probability of failure for redundant safety integrity systems. The CCFs can occur, when a random hardware failure leads to failure of several components.

4. Conclusion

In this study, Common cause failures have been considered in dynamical reliability analysis of the PWR containment spray system by GO-FLOW methodology. The GO-FLOW analysis program can evaluate CCFs effects from the information for the CCF groups by considering many types of parametric models of CCF. Though premature, the presented example calculation by GO-FLOW shows the importance of considering CCF for the evaluation of system reliability for the safety systems with high redundancy. It has been shown that reliability of safety-related subsystem has significantly decreased by considering common cause failure. For further study, the collection, classification and analysis of failure data are important issues for the more practical evaluation of reliability of safety systems of NPP than presented by this example study.

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