A NEW METHOD TO DETECT RECOVERY EVENT COMBINATIONS IN MCSS

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Human Reliability Analysis (HRA) methods require that the Probabilistic Safety Assessment (PSA) analyst finds whole significant combinations of recovery events in minimal cut sets (MCSs) so that dependencies among recovery events in each minimal cut set should be analyzed and evaluated. Identification of recovery event combinations is a very difficult task since there are so many minimal cut sets and many complex combinations of recovery events that it is not easy to generate whole minimal cut sets. In many cases, there may be millions of combinations that results in huge minimal cut sets. Furthermore, this calculation is very slow, or even frequently fails. The purpose of this study is to develop a better way to do provide this information of recovery event combinations. A new method that was developed in this study is very flexible and very effective for generating recovery event combinations in minimal cut sets. Features of this new method are

1. *Cut set initiators that are mapped into minimal cut sets with TRUE recovery events are introduced in this paper. Then, mapping equations from cut set initiators to random failure events are appended to the original fault tree.*
2. *By solving this fault tree with all the recovery events, all the possible minimal cut sets and recovery event combinations can be calculated with much less difficulty than by solving the original fault tree. It is accomplished by the fact that the occurrences of events in the minimal cut sets are significantly reduced by replacing random failure events with cut set initiators. Thus, the recovery event combinations in these minimal cut sets can be easily found.*
3. *By selecting one or a few chosen cut set initiator(s) and all the recovery events, and setting the other cut set initiators to FALSE, minimal cut sets that have selected cut set initiator(s) can be quickly calculated, and recovery event combinations connected to the cut set initiator(s) can be easily obtained.*
4. *It is easy to implement this method into any fault tree solver by appending mapping equations from cut set initiators to random failure events to the given fault tree, and selectively turning off/on the cut set initiators.*

I. INTRODUCTION

Probabilistic Safety Assessment (PSA) has developed over the last decades into a fairly standardized and rigorous activity that is used routinely by utilities that operate nuclear power plants. The continued development and application of this technology requires ongoing research activities to identify improved methods to more efficiently address known limitations in the methods, as well as incorporating new methods that take advantage of new and upcoming computational resources.

US Electric Power Research Institute (EPRI) has performed several research activities that address PSA methods development in a variety of specific targeted areas, such as fire and seismic risk, human reliability, or component data collection. These research activities may develop mathematical methods, engineering analyses, and business processes. The research activities are directed toward the specific issues of implementing the methods and strategies on a computational platform, identifying the features and enhancements to EPRI tools that would be necessary to realize significant improvements to the risk assessments performed by the end user.

Fault tree analysis is extensively and successfully applied to the risk assessment of safety-critical systems such as nuclear, chemical and aerospace systems. The fault tree analysis is being used together with an event tree analysis in PSA of nuclear power plants. Fault tree solvers for a PSA are mostly based on the cutset-based algorithm. They generate minimal cut sets (MCSs) from a fault tree. The most popular fault tree solver in the PSA industry is FTREX.

Current Human Reliability Analysis (HRA) methods expect that the PSA analyst finds whole significant combinations of recovery events in minimal cut sets so that dependencies among recovery events in each minimal cut set should be analyzed and evaluated.

II. NEEDS OF NEW METHOD

In a PSA, minimal cut sets that reflect accident sequences of nuclear power plant are generated using fault tree and event tree logic. Minimal cut set is defined as a minimal set of component, equipment, and function failures that results in an undesired condition of a nuclear power plant such as core damage. A typical minimal cut set for core damage represents an accident sequence that consists of (1) an initiating event, (2) basic events (component failures of mitigation systems), and (3) recovery events (failures of operator actions). The recovery event is a human reliability analysis event (or HRA event) that the operator fails to restore one or more failed components in the minimal cut sets. The probability of recovery event is a human error probability (HEP).

Nominally, the detection of recovery event combinations is done by setting all the HEPs to 1.0 and then solving the logic by fault tree solver such as FTREX, then extracting the minimal cut sets containing two or more recovery events. Here is a practical question "is there a better way to do this?" or "is there a way to get all of the combinations of recovery events that are significant without solving the entire fault tree or with efficiently solving the fault tree?".

The purpose of this study is to develop a better way to do provide this information of recovery event combinations. A new method was developed in this study. This new method is explained and demonstrated in Sections III and IV. This method is very flexible and very effective for generating recovery event combinations in minimal cut sets.

III. METHOD TO FIND RECOVERY EVENT COMBINATIONS

Let us illustrate a fault tree that has recovery events.

$$\begin{aligned} CDF &= G1 + G4 \\ G1 &= G2 * G3 \\ G2 &= A * B + A * C + B * C \\ G3 &= H1 * H2 + H1 * H3 \\ G4 &= A * B * C * H2 * H3 \ . \end{aligned} \tag{1}$$

Here, $\{H1, H2, H3\}$ are recovery events, and $\{A, B, C\}$ are random failure events that require operator actions $\{H1, H2, H3\}$. This fault tree has seven minimal cut sets

$$CDF = (AB + AC + BC)(H1H2 + H1H3) + ABCH2H3 \ . \tag{2}$$

In a real PSA fault tree for core damage, the identification of recovery event combinations is done by setting all the HEPs to 1.0, generating minimal cut sets from this fault tree, and then extracting minimal cut sets that contain two or more recovery events. However, it is not easy to generate minimal cut sets after setting recovery event probabilities to the value 1.0 since this results in huge minimal cut sets. In order to overcome this problem, a new method is developed in this study. The developed method is as follows:

<u>(Step 1)</u>

Generate minimal cut sets after setting all the recovery events $\{H1, H2, H3\}$ to TRUE. Please note that the last cut set $\{ABCH2H3\}$ in Eq. (1) is subsumed into the other minimal cut sets.

$$CDF = AB + AC + BC \ . \tag{3}$$

<u>(Step 2)</u>

Develop mapping equations from cut set initiators to random failure events as

$$\begin{aligned} A &= \%M1 + \%M2 + \%N \\ B &= \%M1 + \%M3 + \%N \\ C &= \%M2 + \%M3 + \%N \ . \end{aligned} \tag{4}$$

Here, cut set initiators $\{\%M1, \%M2, \%M3\}$ are introduced for indexing minimal cut sets $\{AB, AC, BC\}$, respectively.

$$\begin{aligned} \%M1 &= AB \\ \%M2 &= AC \\ \%M3 &= BC \\ \%N &= \text{dummy cut set initiator.} \end{aligned} \tag{5}$$

Here, $\%N$ is a dummy cut set initiator for the minimal cut set(s) that is not in Eq. (3). That is, $\%N$ is a dummy cut set initiator for $\{ABCH2H3\}$ that is subsumed in Eq. (3). As shown in Eqs. (3) to (5), basic event A is in the two minimal cut sets $\{\%M1, \%M2\}$, basic event B exists in the two minimal cut sets $\{\%M1, \%M3\}$, and basic event C is in the two minimal cut sets $\{\%M2, \%M3\}$.

Probabilities/frequencies of the cut set initiators are

$$\begin{aligned} &P(\%M1) = P(AB) \\ &P(\%M2) = P(AC) \\ &P(\%M3) = P(BC) \\ &P(\%N) = Max\big(P(\%M1), P(\%M2), P(\%M3)\big) \ . \end{aligned} \tag{6}$$

(Step 3)

Replace events $\{A, B, C\}$ with cut set initiators by appending mapping logics in Eq. (4) to the original fault tree in Eq. (1). By appending mapping equations from cut set initiators to random failure events, events $\{A, B, C\}$ become gates in a new fault tree.

$$\begin{aligned} &CDF = G1 + G4 \\ &G1 = G2 * G3 \\ &G2 = A * B + A * C + B * C \\ &G3 = H1 * \ H2 + H1 * H3 \\ &G4 = A * B * C * H2 * H3 \\ &A = \%M1 + \%M2 + \%N \\ &B = \%M1 + \%M3 + \%N \\ &C = \%M2 + \%M3 + \%N \, . \end{aligned} \tag{7}$$

Please note that dummy cut set initiator $\%N$ is additionally mapped into all random failure events.

(Step 4)

Generate minimal cut sets. When this fault tree is solved, generated minimal cut sets are

$$CDF = (\%M1 + \%M2 + \%M3 + \%N)(H1H2 + H1H3) + \%NH2H3 \ . \tag{8}$$

Possible recovery combinations $\{H1H2, H1H3, H2H3\}$ in Eq. (8) are identical to those in Eq. (2), and the size of whole minimal cut set structure in Eq. (8) is much smaller than in Eq. (2) in a real PSA fault tree.

When the fault tree in Eq. (7) is so complex that it cannot be solved, minimal cut sets for each cut set initiator in $\{\%M1, \%M2, \%M3, \%N\}$ can be sequentially generated by turning off all the other cut set initiators. For example, if the fault tree is solved for $\{\%M1\}$, $\{\%M2\}$, and $\{\%M3\}$, respectively, after setting the other cut set initiators to FALSE, the final minimal cut sets are

$$CDF \ = \%M1(H1H2 + H1H3) \tag{9}$$

$$CDF \ = \%M2(H1H2 + H1H3) \tag{10}$$

$$CDF \ = \%M3(H1H2 + H1H3) \ . \tag{11}$$

Here, the recovery event combinations $\{H1H2, H1H3\}$ in Eqs. (9) to (11) reflect possible event combinations that are connected to the minimal cut sets $\{AB\}$, $\{AC\}$, and $\{BC\}$.

Similarly, if the fault tree is solved for $\{\%M1, \%M2\}$, $\{\%M1, \%M3\}$, and $\{\%M2, \%M3\}$, respectively, after setting the other cut set initiators to FALSE, the final minimal cut sets are

$$CDF \ = (\%M1 + \%M2) \ (H1H2 + H1H3) \tag{12}$$

$$CDF \ = (\%M1 + \%M3) \ (H1H2 + H1H3) \tag{13}$$

$$CDF \ = (\%M2 + \%M3) \ (H1H2 + H1H3) \ . \tag{14}$$

Please note that there is no way to get part of minimal cut sets by turning off/on the events with the original fault tree.

If the fault tree is solved for $\%N$ after setting $\{\%M1, \%M2, \%M3\}$ to FALSE, the final minimal cut sets are

$$CDF = \%N(H1H2 + H1H3 + H2H3) \ . \tag{15}$$

As mentioned above, $\%N$ is an intentionally introduced dummy initiator for cut sets such as $\{ABCH2H3\}$ that is subsumed in Eq. (3). Without this dummy initiator $\%N$, the combination $\{ABCH2H3\}$ cannot be found.

IV. APPLICATIONS

This Section demonstrates the strength of the developed method that is explained in Section III. The developed method was tested with a complex fault tree in TABLE I. In order to define cut set initiators, minimal cut sets are calculated from the fault tree in TABLE I after setting all the recovery events to TRUE (Step 1). Major minimal cut sets are listed in TABLE II.

TABLE I. Tested Fault Tree

Gates	47,514
Events	7,815
Negates	143
Complemented Events	0
Initiator	43
HRA events	185

TABLE II. Calculated MCSs (HRA events = TRUE)

Cutset Prob.	Event 1	Event 2	Event 3	Event 4	Event 5	Event 6
1.2719E-03	%LOSP	1DGDGG4001---X	LOSP	PAV		
4.7141E-04	%LOSP	1AC--ARUN-LS-FCC	FL-TRNAEQP-RUN	LOSP	PAV	
3.6445E-04	%LOSP	1DGDGG4001---M	LOSP	PAV		
3.1821E-04	%LOSP	1AFPTP4001---A	LOSP	PAV		
2.5867E-04	%LOSP	1AFPTP4001---X	LOSP	PAV		
8.6060E-05	%LOSP	1AFPTP4001---M	LOSP	PAV		
6.4786E-05	%LOSP	1DGDGG4001---A	LOSP	PAV		
5.9023E-05	%LOSP	1ACCBAA0219--K	LOSP	PAV		
5.9023E-05	%LOSP	1ACCBAA0205--D	LOSP	PAV		
5.3474E-05	%LOSP	1ACCBAB0501--K	LOSP	PAV		
5.3474E-05	%LOSP	1ACCBAB1501--K	LOSP	PAV		
4.5422E-05	%LOSP	1AC--APRUN-LSFCC	FL-TRNAEQP-P-RUN	LOSP	PAV	
2.5662E-05	%LOSP	1TTPMG-------F	CON-SSBO	CONSLOCAT	LOSP	PAV
2.4953E-05	%LOSP	1AFXV015-----P	LOSP	PAV		
1.8615E-05	%LOSP	1DGXV038FXFR-P	LOSP	NACR2HR	PAV	
1.7805E-05	%LOSP	1DGDGU1SU2---XCC	LOSP	PAV	RCPSL-21GPM	
1.7527E-05	%LOSP	1SWFN-A-1234-M	LOSP	PAV		

As listed in TABLE III, the minimal cut sets in TABLE II are mapped into cut set initiators (Step 2). Then, mapping equations from cut set initiators to random failure events are appended to the given fault tree in TABLE I (Step 3), and the new fault tree is solved for each cut set initiator (Step 4).

TABLE III. Created Mapping from TABLE II

Cut set initiator	Probability	Member
%%N	1.271870e-003	
%%M1	1.271870e-003	%LOSP 1DGDGG4001---X LOSP PAV
%%M2	4.714110e-004	%LOSP 1AC--ARUN-LS-FCC FL-TRNAEQP-RUN LOSP PAV
%%M3	3.644517e-004	%LOSP 1DGDGG4001---M LOSP PAV
%%M4	3.182088e-004	%LOSP 1AFPTP4001---A LOSP PAV
%%M5	2.586730e-004	%LOSP 1AFPTP4001---X LOSP PAV
%%M6	8.606009e-005	%LOSP 1AFPTP4001---M LOSP PAV
%%M7	6.478629e-005	%LOSP 1DGDGG4001---A LOSP PAV
%%M8	5.902260e-005	%LOSP 1ACCBAA0219--K LOSP PAV
%%M9	5.902260e-005	%LOSP 1ACCBAA0205--D LOSP PAV
%%M10	5.347448e-005	%LOSP 1ACCBAB0501--K LOSP PAV
%%M11	5.347448e-005	%LOSP 1ACCBAB1501--K LOSP PAV
%%M12	4.542174e-005	%LOSP 1AC--APRUN-LSFCC FL-TRNAEQP-P-RUN LOSP PAV
%%M13	2.566200e-005	%LOSP 1TTPMG-------F CON-SSBO CONSLOCAT LOSP PAV
%%M14	2.495270e-005	%LOSP 1AFXV015-----P LOSP PAV
%%M15	1.861472e-005	%LOSP 1DGXV038FXFR-P LOSP NACR2HR PAV
%%M16	1.780487e-005	%LOSP 1DGDGU1SU2---XCC LOSP PAV RCPSL-21GPM
%%M17	1.752715e-005	%LOSP 1SWFN-A-1234-M LOSP PAV
%%M18	1.360086e-005	%LOSP 1AFMVHV5106--D LOSP PAV
%%M19	1.298497e-005	%LOSP 1DCBYAD1B----M LOSP PAV

This fault tree that has cut set initiators is solved for each cut set initiator $\{\%\%\boldsymbol{M1}, \%\%\boldsymbol{M2}, \%\%\boldsymbol{M3}\}$ by setting all the other initiators to FALSE (Step 4). The results are summarized in TABLEs IV to VI. Various recovery event combinations for each cut set initiator can be collected from the compact structure of minimal cut sets in TABLEs IV to VI. Then, dependencies among recovery events in each minimal cut set can be analyzed and evaluated.

TABLE IV. Calculated MCSs with Mapping (%%M1, others cut set initiators=FALSE, HEP=1.0)

Cutset Prob.	Event 1	Event 2	Event 3	Event 4	Event 5	Event 6
1.2719E-03	%%M1	OA-ALIGNPW-G-H	OA-COG--FRH1-H	OA-MISPAF5094H	OA-XTIE-DGS-GH	
1.2719E-03	%%M1	OA-ALIGNPW-G-H	OA-MISPAF5094H	OA-XTIE-DGS-GH	OAR_LTFB-TRA-H	
1.2719E-03	%%M1	OA-ALIGNPW-G-H	OA-MISPAF5094H	OA-XTIE-DGS-GH	OAB_TR-------H	
3.8156E-04	%%M1	OA-MISPAF5094H	OA-XTIE-DGS-GH	OAR_LTFB-TRA-H	WILSON-SWYD-LOSP	
3.8156E-04	%%M1	OA-MISPAF5094H	OA-XTIE-DGS-GH	OAB_TR-------H	WILSON-SWYD-LOSP	
3.8156E-04	%%M1	OA-COG--FRH1-H	OA-MISPAF5094H	OA-XTIE-DGS-GH	WILSON-SWYD-LOSP	
5.6634E-05	%%M1	1DCBYND1B----M	OA-MISPAF5094H	OA-XTIE-DGS-GH	OAB_TR-------H	
5.6634E-05	%%M1	1DCBYND1B----M	OA-COG--FRH1-H	OA-MISPAF5094H	OA-XTIE-DGS-GH	
5.6634E-05	%%M1	1DCBYND1B----M	OA-MISPAF5094H	OA-XTIE-DGS-GH	OAR_LTFB-TRA-H	
1.2452E-05	%%M1	1DGDGU2DG----M	OA-ALIGNPW-G-H	OA-MISPAF5094H	OAB_TR-------H	
1.2452E-05	%%M1	1DGDGU2DG----M	OA-ALIGNPW-G-H	OA-MISPAF5094H	OAR_LTFB-TRA-H	
1.2452E-05	%%M1	1DGDGU2DG----M	OA-ALIGNPW-G-H	OA-COG--FRH1-H	OA-MISPAF5094H	
5.5326E-06	%%M1	1RCPORV0456A-D	OA-ALIGNPW-G-H	OA-MISPAF5094H	OA-XTIE-DGS-GH	
4.0451E-06	%%M1	1CPPMCCPB----M	FL-CCP-PMPB-NR	OA-ALIGNPW-G-H	OA-MISPAF5094H	OA-XTIE-DGS-GH
3.7355E-06	%%M1	1DGDGU2DG----M	OA-MISPAF5094H	OAR_LTFB-TRA-H	WILSON-SWYD-LOSP	
3.7355E-06	%%M1	1DGDGU2DG----M	OA-COG--FRH1-H	OA-MISPAF5094H	WILSON-SWYD-LOSP	
3.7355E-06	%%M1	1DGDGU2DG----M	OA-MISPAF5094H	OAB_TR-------H	WILSON-SWYD-LOSP	
3.3654E-06	%%M1	1LPPMRHRB----A	OA-ALIGNPW-G-H	OA-MISPAF5094H	OA-XTIE-DGS-GH	

TABLE V. Calculated MCSs with Mapping (%%M2, others cut set initiators=FALSE, HEP=1.0)

Cutset Prob.	Event 1	Event 2	Event 3	Event 4	Event 5	Event 6
4.7141E-04	%%M2	OA-ALIGNPW-G-H	OA-MISPAF5094H	OA-XTIE-DGS-GH	OAB_TR-------H	
4.7141E-04	%%M2	OA-ALIGNPW-G-H	OA-COG--FRH1-H	OA-MISPAF5094H	OA-XTIE-DGS-GH	
4.7141E-04	%%M2	OA-ALIGNPW-G-H	OA-MISPAF5094H	OA-XTIE-DGS-GH	OAR_LTFB-TRA-H	
1.4142E-04	%%M2	OA-MISPAF5094H	OA-XTIE-DGS-GH	OAR_LTFB-TRA-H	WILSON-SWYD-LOSP	
1.4142E-04	%%M2	OA-MISPAF5094H	OA-XTIE-DGS-GH	OAB_TR-------H	WILSON-SWYD-LOSP	
1.4142E-04	%%M2	OA-COG--FRH1-H	OA-MISPAF5094H	OA-XTIE-DGS-GH	WILSON-SWYD-LOSP	
2.0991E-05	%%M2	1DCBYND1B----M	OA-MISPAF5094H	OA-XTIE-DGS-GH	OAB_TR-------H	
2.0991E-05	%%M2	1DCBYND1B----M	OA-COG--FRH1-H	OA-MISPAF5094H	OA-XTIE-DGS-GH	
2.0991E-05	%%M2	1DCBYND1B----M	OA-MISPAF5094H	OA-XTIE-DGS-GH	OAR_LTFB-TRA-H	
4.6151E-06	%%M2	1DGDGU2DG----M	OA-ALIGNPW-G-H	OA-COG--FRH1-H	OA-MISPAF5094H	
4.6151E-06	%%M2	1DGDGU2DG----M	OA-ALIGNPW-G-H	OA-MISPAF5094H	OAR_LTFB-TRA-H	
4.6151E-06	%%M2	1DGDGU2DG----M	OA-ALIGNPW-G-H	OA-MISPAF5094H	OAB_TR-------H	
2.0506E-06	%%M2	1RCPORV0456A-D	OA-ALIGNPW-G-H	OA-MISPAF5094H	OA-XTIE-DGS-GH	
1.4993E-06	%%M2	1CPPMCCPB----M	FL-CCP-PMPB-NR	OA-ALIGNPW-G-H	OA-MISPAF5094H	OA-XTIE-DGS-GH
1.3845E-06	%%M2	1DGDGU2DG----M	OA-COG--FRH1-H	OA-MISPAF5094H	WILSON-SWYD-LOSP	
1.3845E-06	%%M2	1DGDGU2DG----M	OA-MISPAF5094H	OAR_LTFB-TRA-H	WILSON-SWYD-LOSP	
1.3845E-06	%%M2	1DGDGU2DG----M	OA-MISPAF5094H	OAB_TR-------H	WILSON-SWYD-LOSP	
1.2474E-06	%%M2	1LPPMRHRB----A	OA-ALIGNPW-G-H	OA-MISPAF5094H	OA-XTIE-DGS-GH	

TABLE VI. Calculated MCSs with Mapping (%%M3, others cut set initiators=FALSE, HEP=1.0)

Cutset Prob.	Event 1	Event 2	Event 3	Event 4	Event 5	Event 6
3.6445E-04	%%M3	OA-ALIGNPW-G-H	OA-MISPAF5094H	OA-XTIE-DGS-GH	OAB_TR-------H	
3.6445E-04	%%M3	OA-ALIGNPW-G-H	OA-COG--FRH1-H	OA-MISPAF5094H	OA-XTIE-DGS-GH	
3.6445E-04	%%M3	OA-ALIGNPW-G-H	OA-MISPAF5094H	OA-XTIE-DGS-GH	OAR_LTFB-TRA-H	
1.0934E-04	%%M3	OA-MISPAF5094H	OA-XTIE-DGS-GH	OAR_LTFB-TRA-H	WILSON-SWYD-LOSP	
1.0934E-04	%%M3	OA-COG--FRH1-H	OA-MISPAF5094H	OA-XTIE-DGS-GH	WILSON-SWYD-LOSP	
1.0934E-04	%%M3	OA-MISPAF5094H	OA-XTIE-DGS-GH	OAB_TR-------H	WILSON-SWYD-LOSP	
1.6228E-05	%%M3	1DCBYND1B----M	OA-COG--FRH1-H	OA-MISPAF5094H	OA-XTIE-DGS-GH	
1.6228E-05	%%M3	1DCBYND1B----M	OA-MISPAF5094H	OA-XTIE-DGS-GH	OAB_TR-------H	
1.6228E-05	%%M3	1DCBYND1B----M	OA-MISPAF5094H	OA-XTIE-DGS-GH	OAR_LTFB-TRA-H	
3.5680E-06	%%M3	1DGDGU2DG----M	OA-ALIGNPW-G-H	OA-COG--FRH1-H	OA-MISPAF5094H	
3.5680E-06	%%M3	1DGDGU2DG----M	OA-ALIGNPW-G-H	OA-MISPAF5094H	OAB_TR-------H	
3.5680E-06	%%M3	1DGDGU2DG----M	OA-ALIGNPW-G-H	OA-MISPAF5094H	OAR_LTFB-TRA-H	
1.5854E-06	%%M3	1RCPORV0456A-D	OA-ALIGNPW-G-H	OA-MISPAF5094H	OA-XTIE-DGS-GH	
1.0704E-06	%%M3	1DGDGU2DG----M	OA-COG--FRH1-H	OA-MISPAF5094H	WILSON-SWYD-LOSP	
1.0704E-06	%%M3	1DGDGU2DG----M	OA-MISPAF5094H	OAR_LTFB-TRA-H	WILSON-SWYD-LOSP	
1.0704E-06	%%M3	1DGDGU2DG----M	OA-MISPAF5094H	OAB_TR-------H	WILSON-SWYD-LOSP	
9.6434E-07	%%M3	1LPPMRHRB----A	OA-ALIGNPW-G-H	OA-MISPAF5094H	OA-XTIE-DGS-GH	
9.2009E-07	%%M3	1DGDGU2DG----A	OA-ALIGNPW-G-H	OA-MISPAF5094H	OAR_LTFB-TRA-H	

Furthermore, by selecting a few chosen cut set initiators and turning off the other cut set initiators, minimal cut sets of the selected cut set initiators can be quickly calculated, and recovery event combinations that are connected to these cut sets are easily collected.

V. CONCLUSIONS

As explained in the previous Sections, the developed method is very flexible and very effective in order to generate the whole combinations of recovery events (or fire failure events) in minimal cut sets. The features and strengths of the developed method are summarized as

1. Cut set initiators that are mapped into minimal cut sets with TRUE recovery events are introduced in this paper. Then, these mapping equations from cut set initiators to random failure events are appended to the original fault tree.
2. By solving this fault tree with all the recovery events, all the possible minimal cut sets and recovery event combinations can be calculated with much less difficulty than by solving the original fault tree. It is accomplished by the fact that the occurrences of events in the minimal cut sets are significantly reduced by replacing random failure events with cut set initiators. Thus, the recovery event combinations in these minimal cut sets can be easily found and collected.
3. By selecting one or a few chosen cut set initiators and all the recovery events, and setting the other cut set initiators to FALSE, minimal cut sets that have the selected cut set initiator(s) can be quickly calculated, and the recovery event combinations connected to the cut set initiator(s) can be easily obtained. Please note that there is no way to calculate these specific minimal cut sets and recovery event combinations by turning off/on the random failure events in the original fault tree.
4. It is easy to implement this developed method into any fault tree solver by appending mapping equations from cut set initiators to random failure events to the given fault tree, and selectively turning off/on the cut set initiators.

REFERENCES

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