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TITLE A SYSTEMS ANALYSIS APPROACH TO PROBABILISTIC MODELING OF FAULT TREES

AUTHOR(S) R. J. Bartholomew, Group WX-11
Clifford R. Qualls, Ph.D., Dept. of Mathematics and Statistics
University of New Mexico, Albuquerque, NM 87131

SUBMITTED TO 8th International Conference on "Structural Mechanics in Reactor Technology," Brussels (Belgium)

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A SYSTEMS ANALYSIS APPROACH TO PROBABILISTIC MODELING OF FAULT TREES

by

Robert J. Bartholomew, Ph.D.
Los Alamos National Laboratory
Los Alamos, New Mexico, U.S.A.

Clifford R. Qualls, Ph.D.
Department of Mathematics and Statistics
University of New Mexico
Albuquerque, New Mexico, U.S.A.

Abstract

A method of probabilistic modeling of fault tree logic combined with stochastic process theory (Markov modeling) has been developed. Systems are then quantitatively analyzed probabilistically in terms of their failure mechanisms including common cause/common mode effects and time dependent failure and/or repair rate effects that include synergistic and propagational mechanisms. The modeling procedure results in a state vector set of first order, linear, inhomogeneous, differential equations describing the time dependent probabilities of failure described by the fault tree. The solutions of this Failure Mode State Variable (FMSV) model are cumulative probability distribution functions of the system. A method of appropriate synthesis of subsystems to form larger systems is developed, and applied to practical nuclear power safety systems.

1. Introduction

Nuclear reactor power technology development has widely used the fault tree as a tool for assessing safety, reliability, and risk. A fault tree depicts the occurrence of basic events (initiators or causes) that cause undesirable intermediate, and finally, top events representing system or component failures, where these events are modeled stochastically. The initiators (roots) of the fault tree pass through an interconnected (branched) system of Boolean OR and AND gates to which respectively apply the fourth and fifth axioms of

order, linear, inhomogeneous, differential equations describing the time dependent probabilities of failure described by the fault tree. The solutions of this Failure Mode State Variable (FMSV) model are cumulative probability distribution functions of the system. A method of appropriate synthesis of subsystems to form larger systems is developed, and applied to practical nuclear power safety systems.

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2. Method of Analysis

Using the disjoint property of Markov states S_i; $i = 0,1,\ldots,m$, a set of Adjoint states $\hat{S}_i$; $i = 0,1,\ldots,m$ was formulated comprising successive unions of the S_i in which all combinations of occurrences of basic events were depicted. The $\hat{S}_0$ state was chosen to represent S_m, the occurrence of all n basic events ($m = 2^n - 1$). The $\hat{S}_m$ state was chosen to represent Ω or the union of all of the S_i. The intermediate $\hat{S}_i$; $i = 1,2,\ldots m-1$ represent all of the combinations of occurrences of any one, any two, etc. basic events. There is a transformation matrix $\underline{E}$ for the probability state vector transformation equation ($\hat{\underline{P}}(t) = \underline{E}\,\underline{P}(t)$). The transformation $\underline{E}$ is one-to-one and an m^{th}-order Markov model of the form:

$$\dot{\underline{P}}(t) = \underline{A}\,\underline{P}(t),\ t > 0 \quad ; \quad \underline{P}(0) \qquad (1)$$

is transformed to the Adjoint state model

$$\dot{\hat{\underline{P}}}(t) = \hat{\underline{A}}\,\hat{\underline{P}}(t),\ t > 0 \quad ; \quad \hat{\underline{P}}(0) \qquad (2)$$

by the similarity transformation

$$\hat{\underline{A}} = \underline{E}\,\underline{A}\,\underline{E}^{-1}\ . \qquad (3)$$

Three generic fault trees each having two failure modes (inputs to the top gate) comprising two, three, or four statistically independent (S-independent) initiators together with common cause and/or common mode S-independent initiators were developed. These are shown in Fig. 1. In addition to the common cause/common mode events that result in S-dependent failure modes we included time dependent, synergistic failure-repair rate S-dependencies between these modes. We also developed a propagational failure rate S-dependency for a three-identical-component model. The fourth, eighth, and sixteenth order Markov and Adjoint state models are formulated. Using generalized state variable simulation models drawn from modern control system theory, a new model called the Failure Mode State Variable (FMSV) inhomogeneous model was formulated and found to have a general mathematical form. For example, the state variable analog simulation general form and four different two component models are shown in Fig. 2. A subsystem fault tree synthesis methodology was developed where lifetime cumulative distribution functions (ℓcdf's) of the subsystem top event occurrence probabilities are curve fit with single term decaying exponential functions two, three, or four statistically independent (S-independent) initiators together with common cause and/or common mode S-independent initiators were developed. These are shown in Fig. 1. In addition to the common cause/common mode events that result in S-dependent failure modes we included time dependent, synergistic failure-repair rate S-dependencies between these modes. We also developed a propagational failure rate S-dependency for a three-identical-component model. The fourth, eighth, and sixteenth order Markov and Adjoint state models are formulated. Using generalized state variable simulation models drawn from modern control system theory, a new model called the Failure Mode State Variable (FMSV) inhomogeneous model was formulated and found to have a general mathematical form. For example, the state variable analog simulation general form and four different two component models are shown in Fig. 2. A subsystem fault tree synthesis methodology was developed where lifetime cumulative distribution functions (ℓcdf's) of the subsystem top event occurrence probabilities are curve fit with single term decaying exponential functions $(1 - e^{-\lambda_{TOP} t}, t > 0)$, and become inputs to the larger system fault trees, properly accounting for common cause/common mode dependencies.

3. Applications and Results

Engineered safety systems in nuclear reactor technology are analyzed by the FMSV method. A simplified reactor shutdown (SCRAM) system (Bartholomew [3]) was computer simulated, and the ℓcdf's were calculated (Fig. 3). A more detailed system fault tree (Fig. 4a) discussed by Caldarola and Wickenhauser [4], and comprising 30 initiators (some of which are common cause/common mode) was computer simulated using the generic fault tree models for subsystem portions (Figs. 4b, 4c). Approximate failure mode and top event ℓcdf's were calculated assuming no repair mechanisms. The approximate failure mode and top event failure rates are listed in Table I.

4. Conclusions

1. The FMSV method gives time dependent solutions of generic fault trees more directly than does the probability expansion of minimal cut sets.
2. The FMSV method for two initiators with common cause and having three kinds of failure-repair rate coupling mechanisms is readily computer simulated by generalized state variable techniques. A three identical component "jump" failure rate dependency can also be included.
3. The fault tree synthesis method utilizing generic subsystem fault trees is a practical approximate alternative to minimal cut set expansion for large fault trees, and retains engineering modeling interpretation and control of components, subsystems, and complete systems reliabilities.

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B

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[2] Shooman, M. L., Probabilistic Reliability: an Engineering Approach (McGraw-Hill, NY, 1968) pp. 61-67.

[3] Bartholomew, R. J., "A State Space Method of Fault Tree Analysis with Applications" (Ph.D. Dissertation, University of New Mexico, July 1984) LA-10298-T, December 1984, Chapter 5, pp. 87-94.

[4] Caldarola, L. and A. Wickenhauser, "Recent Advancements in Fault Tree Methodology at Karlsruhe," in Nuclear Systems Reliability and Risk Assessment, J. B. Fussell and G. R. Burdick, Eds. (SIAM, 1977) pp. 518-542.

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[3] Bartholomew, R. J., "A State Space Method of Fault Tree Analysis with Applications" (Ph.D. Dissertation, University of New Mexico, July 1984) LA-10298-T, December 1984, Chapter 5, pp. 87-94.

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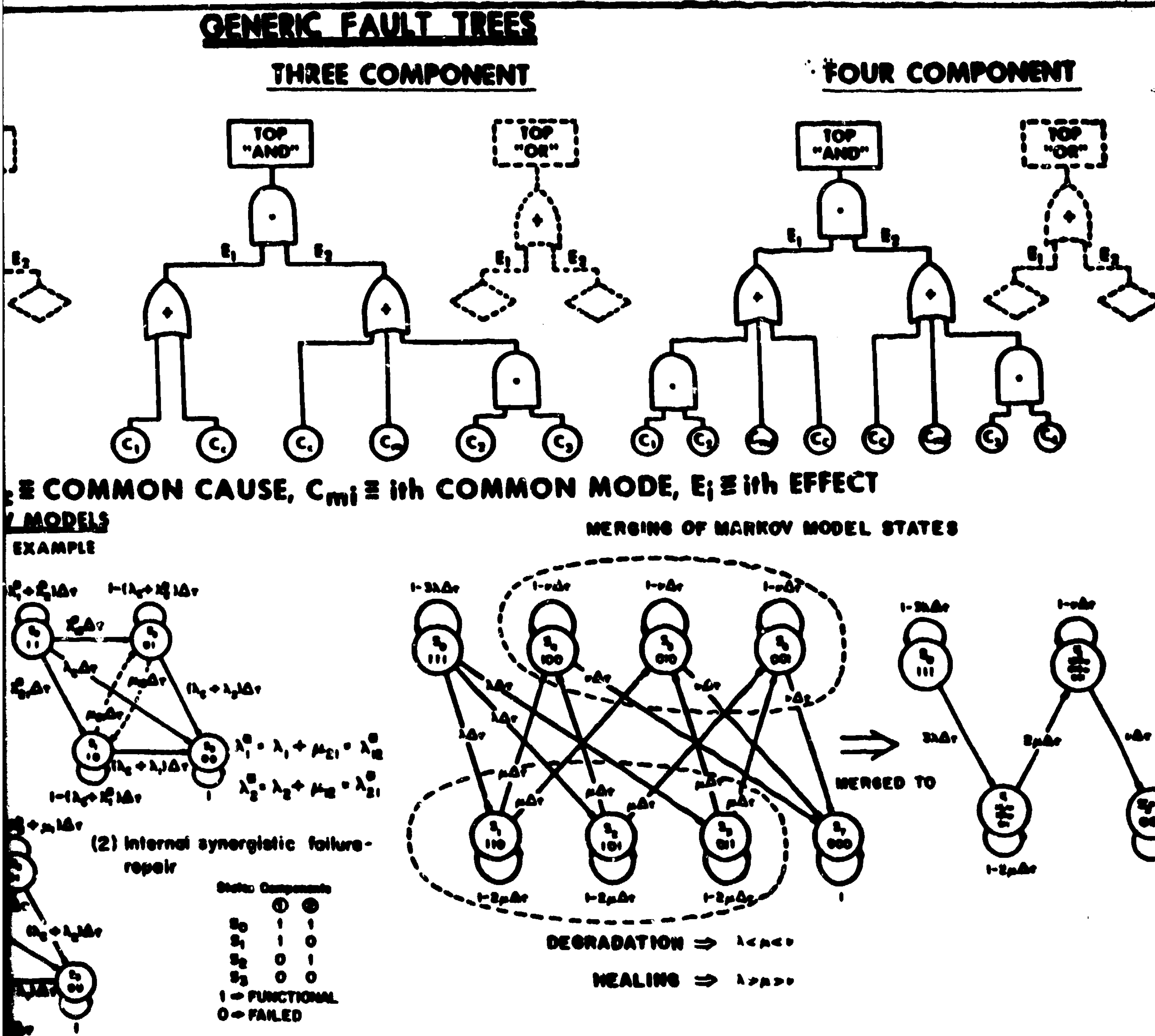
V. Your code number should be written in the top right-hand corner and the name of the senior author on the left-hand side.



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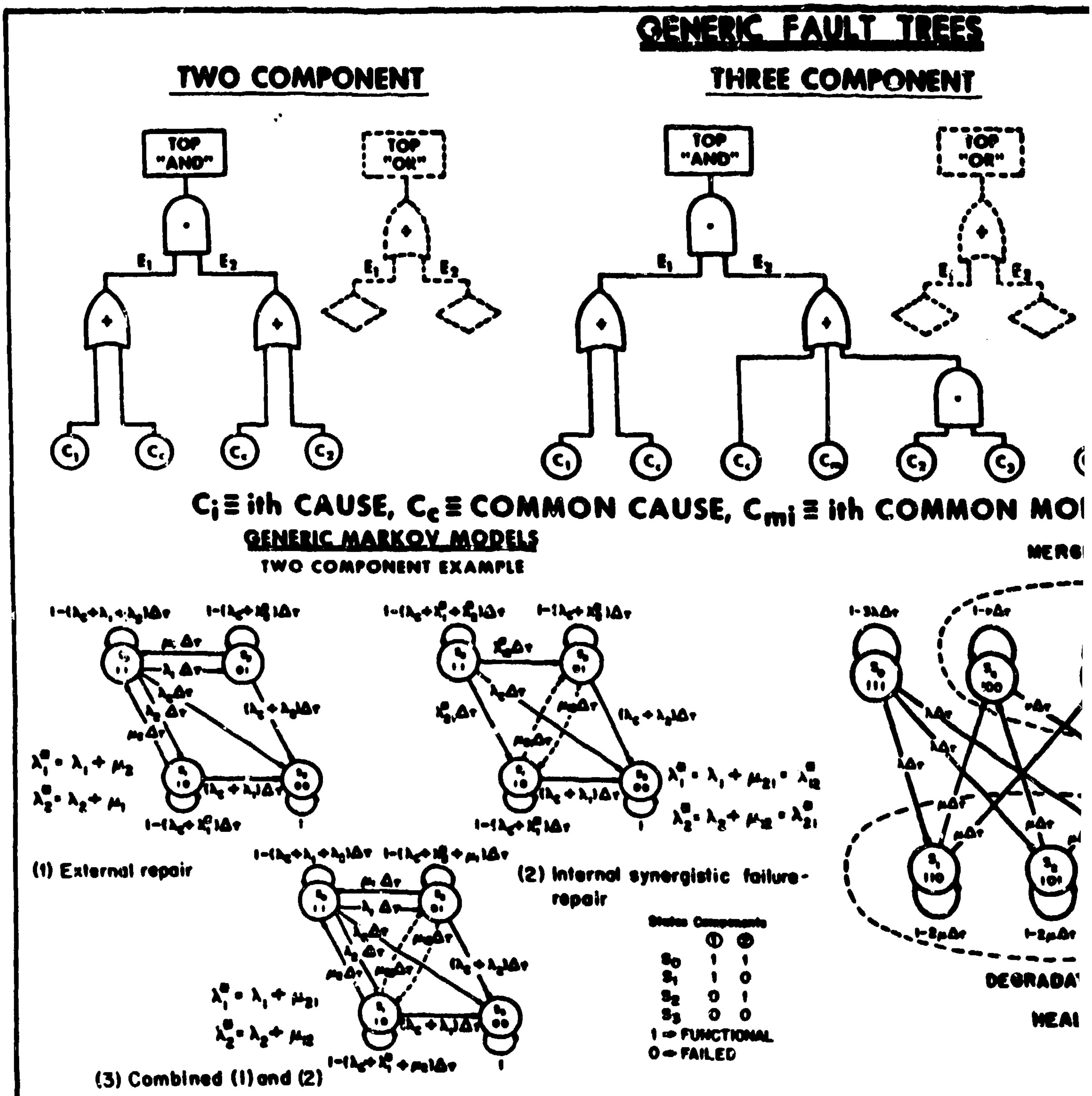


Figure 1. Generic fault trees and Markov models for subsystems synt.he

SIMILARITY TRANSFORMATION FOR INTERNAL SYNERGISTIC FAILURE-REPAIR RATE COUPLING

TWO COMPONENT EXAMPLE

$$\dot{\xi}(t)=A\xi(t),\ t\geq 0,\ \text{given } \xi(0) \Rightarrow \dot{\xi}'(t)=SAS^{-1}\xi'(t)=A'\xi'(t),\ t\geq 0,\ \text{given } \xi'(0) \text{ with } \xi'(t)=S\xi(t)$$

$$\begin{bmatrix}\dot{\xi}_0\\ \dot{\xi}_1\\ \dot{\xi}_2\\ \dot{\xi}_3\end{bmatrix}=\begin{bmatrix}-(\lambda_c+\lambda_1^0+\lambda_2^0) & 0 & 0 & 0\\ \lambda_{21}^0 & -(\lambda_c+\lambda_1^0) & \mu_{12} & 0\\ \lambda_{12}^0 & \mu_{21} & -(\lambda_c+\lambda_2^0) & 0\\ \lambda_c & (\lambda_c+\lambda_1) & (\lambda_c+\lambda_2) & 0\end{bmatrix}\begin{bmatrix}\xi_0\\ \xi_1\\ \xi_2\\ \xi_3\end{bmatrix}$$

$$\xi(t)=[\xi_0(t)\ \xi_1(t)\ \xi_2(t)\ \xi_3(t)]^T,\quad \lambda_1^0=\lambda_1+\mu_{21}=\lambda_{12}^0,\quad \lambda_2^0=\lambda_2+\mu_{12}=\lambda_{21}^0$$

$$\Rightarrow \begin{bmatrix}\dot{\xi}'_0\\ \dot{\xi}'_1\\ \dot{\xi}'_2\\ \dot{\xi}'_3\end{bmatrix}=\begin{bmatrix}-(\lambda_c+\lambda_1+\lambda_2) & \lambda_2 & \lambda_1 & \lambda_c\\ \mu_{12} & -(\lambda_c+\lambda_1^0+\mu_{12}) & 0 & (\lambda_c+\lambda_1^0)\\ \mu_{21} & 0 & -(\lambda_c+\lambda_2^0+\mu_{21}) & (\lambda_c+\lambda_2^0)\\ 0 & 0 & 0 & 0\end{bmatrix}\begin{bmatrix}\xi'_0\\ \xi'_1\\ \xi'_2\\ \xi'_3\end{bmatrix}$$

$$\xi'(t)=[\xi'_0(t)\ \xi'_1(t)\ \xi'_2(t)\ 1]^T,\quad A\neq A' \text{ unless } \mu_{21}=\mu_{12}=0$$

THE FAILURE MODE STATE VARIABLE MODEL FOR SYNERGISTIC FAILURE-REPAIR RATE COUPLING

TWO COMPONENT EXAMPLE

$\xi(t)=\Pr\{\text{both } C_1 \text{ and } C_2 \text{ occur or } C_c \text{ occurs in } [0,t]\}=T_{OR}(t)$

$\xi(t)=\Pr\{C_1 \text{ or } C_c \text{ occur in } [0,t]\}=\xi(t)$

$\eta(t)=\Pr\{C_2 \text{ or } C_c \text{ occur in } [0,t]\}=\eta(t)$

$\xi(t)=1.0,\ t\geq 0$

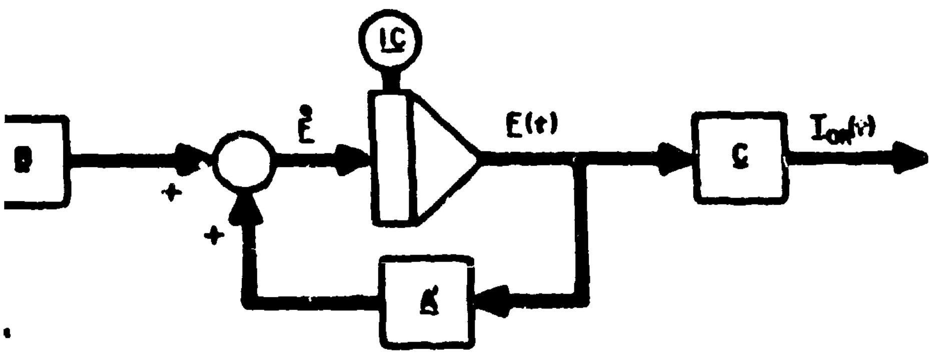
Thus, the FMSV model of the form $\dot{E}=AE+Bu(t),\ E(0),\ T_{OR}(t)$ is:

$$\begin{bmatrix}\dot{\xi}\\ \dot{\eta}\\ \dot{T}_{OR}\end{bmatrix}=\begin{bmatrix}-(\lambda_c+\lambda_1'+\mu_{21}) & 0 & \mu_{12}\\ 0 & -(\lambda_c+\lambda_2'+\mu_{12}) & \mu_{21}\\ \lambda_2 & \lambda_1 & -(\lambda_c+\lambda_1+\lambda_2)\end{bmatrix}\begin{bmatrix}\xi\\ \eta\\ T_{OR}\end{bmatrix}+\begin{bmatrix}\lambda_c+\lambda_1' & 0 & 0 & 0\\ \lambda_c+\lambda_2' & 0 & 0 & 0\\ \lambda_c & 0 & 0 & 0\end{bmatrix}\begin{bmatrix}1\\ 1-e^{-\lambda_1 t}\\ 1-e^{-\lambda_2 t}\\ 1-e^{-\lambda_c t}\end{bmatrix}$$

$$E(0)=[\xi(0)\ \eta(0)\ T_{OR}(0)]^T,\quad \lambda_1'=\lambda_1+\mu_{21},\ \lambda_2'=\lambda_2+\mu_{12}$$

$$T_{OR}(t)=[1\ \ 1\ \ -1]E(t)+[0\ 0\ 0\ 0]u(t)$$

FAILURE MODE STATE VECTOR (FMSV) MODELS



(1) ... REPAIR

$$\begin{bmatrix} \cdots & \mu_1\\ \cdots & \mu_2\\ \cdots & -(\lambda_c+\lambda_1+\lambda_2)\end{bmatrix}$$

(2) INTERNAL SYNERGISTIC FAILURE-REPAIR

$$A=\begin{bmatrix}-(\lambda_c+\lambda_1'+\mu_{21}) & 0 & \mu_{12}\\ 0 & -(\lambda_c+\lambda_2'+\mu_{12}) & \mu_{21}\\ \lambda_2 & \lambda_1 & -(\lambda_c+\lambda_1+\lambda_2)\end{bmatrix}$$

(3) COMBINED (1) AND (2)

$$A=\begin{bmatrix}-(\lambda_c+\lambda_1+\mu_{12}) & \mu_{21} & (\mu_1+\mu_{12}-\mu_{21})\\ \mu_{12} & -(\lambda_c+\lambda_2+\mu_{21}) & (\mu_2+\mu_{21}-\mu_{12})\\ \lambda_2 & \lambda_1 & -(\lambda_c+\lambda_1+\lambda_2)\end{bmatrix}$$

(4) SEQUENTIAL 'JUMP' FAILURE RATE DEPENDENCY AMONG THREE IDENTICAL COMPONENTS

$$A=\begin{bmatrix}-3\lambda & 0 & 0\\ 2\mu & -2\mu & 0\\ 0 & \nu & -\nu\end{bmatrix}$$

$$E(t)=[\xi(t)\ \eta(t)\ T_{OR}(t)]^T,\ IC=[\xi(0)\ \eta(0)\ T_{OR}(0)]^T,\ u(t)=[1\ \ 1-e^{-\lambda_1 t}\ \ 1-e^{-\lambda_2 t}\ \ 1-e^{-\lambda_c t}]^T$$

$$B=\begin{bmatrix}\lambda_c+\lambda_1' & 0 & 0 & 0\\ \lambda_c+\lambda_2' & 0 & 0 & 0\\ \lambda_c & 0 & 0 & 0\end{bmatrix}\qquad B=\begin{bmatrix}\lambda_c+\lambda_1 & 0 & 0 & 0\\ \lambda_c+\lambda_2 & 0 & 0 & 0\\ \lambda_c & 0 & 0 & 0\end{bmatrix}$$

$$C=[1\ \ 1\ \ -1]\qquad C=[1\ \ 1\ \ -1]$$

$$\lambda_1'=\lambda_1+\mu_{21},\ \lambda_2'=\lambda_2+\mu_{12}\qquad \lambda_1=\lambda_1+\mu_1,\ \lambda_2=\lambda_2+\mu_2$$

$$E(t)=[\xi_1(t)\ \xi_2(t)\ \xi_3(t)]^T,\quad IC=[\xi_1(0)\ \xi_2(0)\ \xi_3(0)]^T,\quad u(t)=[1\ 0\ 0]^T$$

$$B=\begin{bmatrix}3\lambda & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix}$$

For failure defined:
(1) only one of three,
(2) only two of three, or
(3) all three,
$T_{OR}(t)=[T_1(t)\ T_2(t)\ T_3(t)]^T$, and

$$C=\begin{bmatrix}1 & -1 & 0\\ 0 & 1 & -1\\ 0 & 0 & 1\end{bmatrix}.$$

...pment of Failure Mode State Vector (FMSV)
...ds of two components fault trees having statistical dependencies.

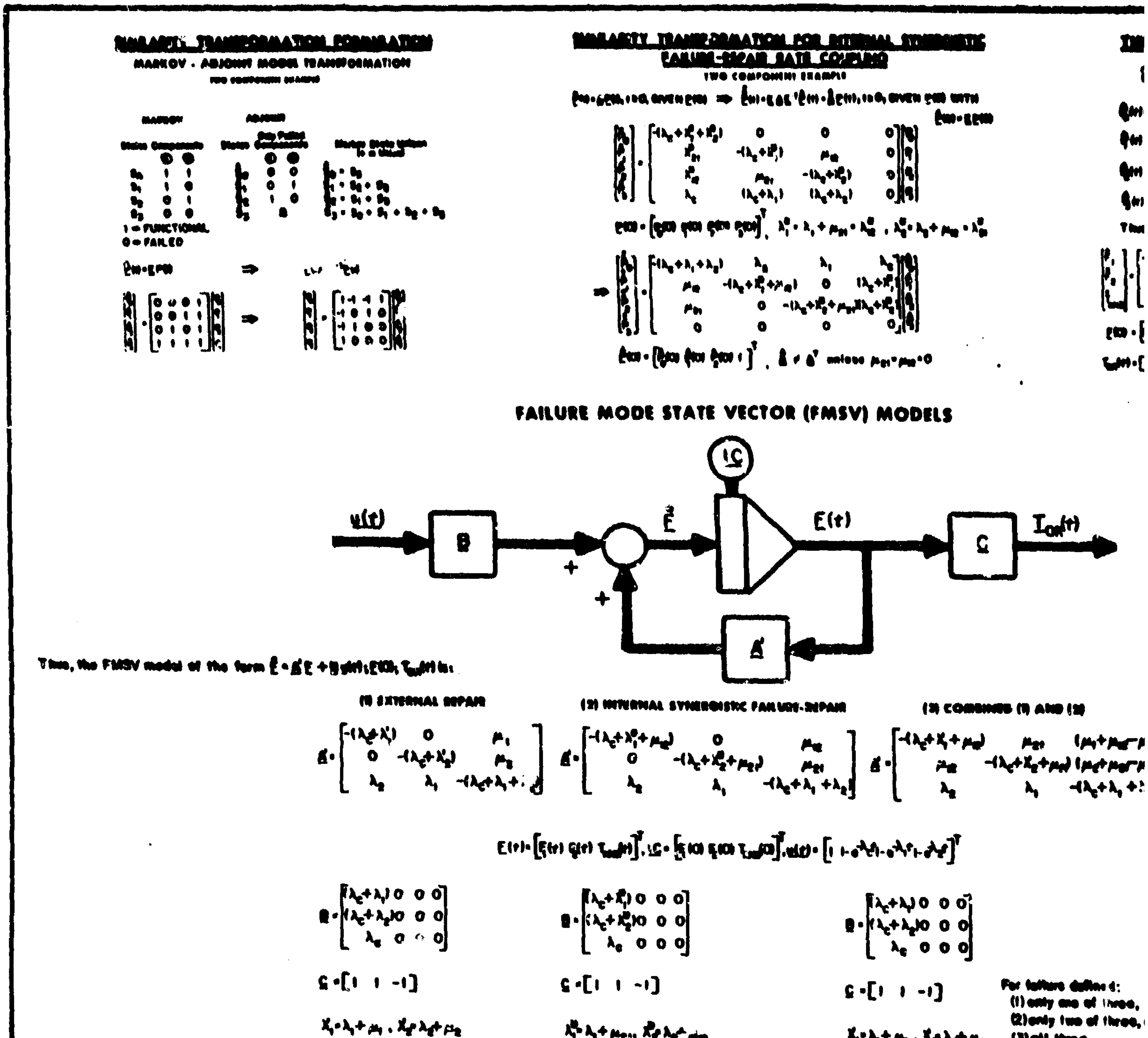
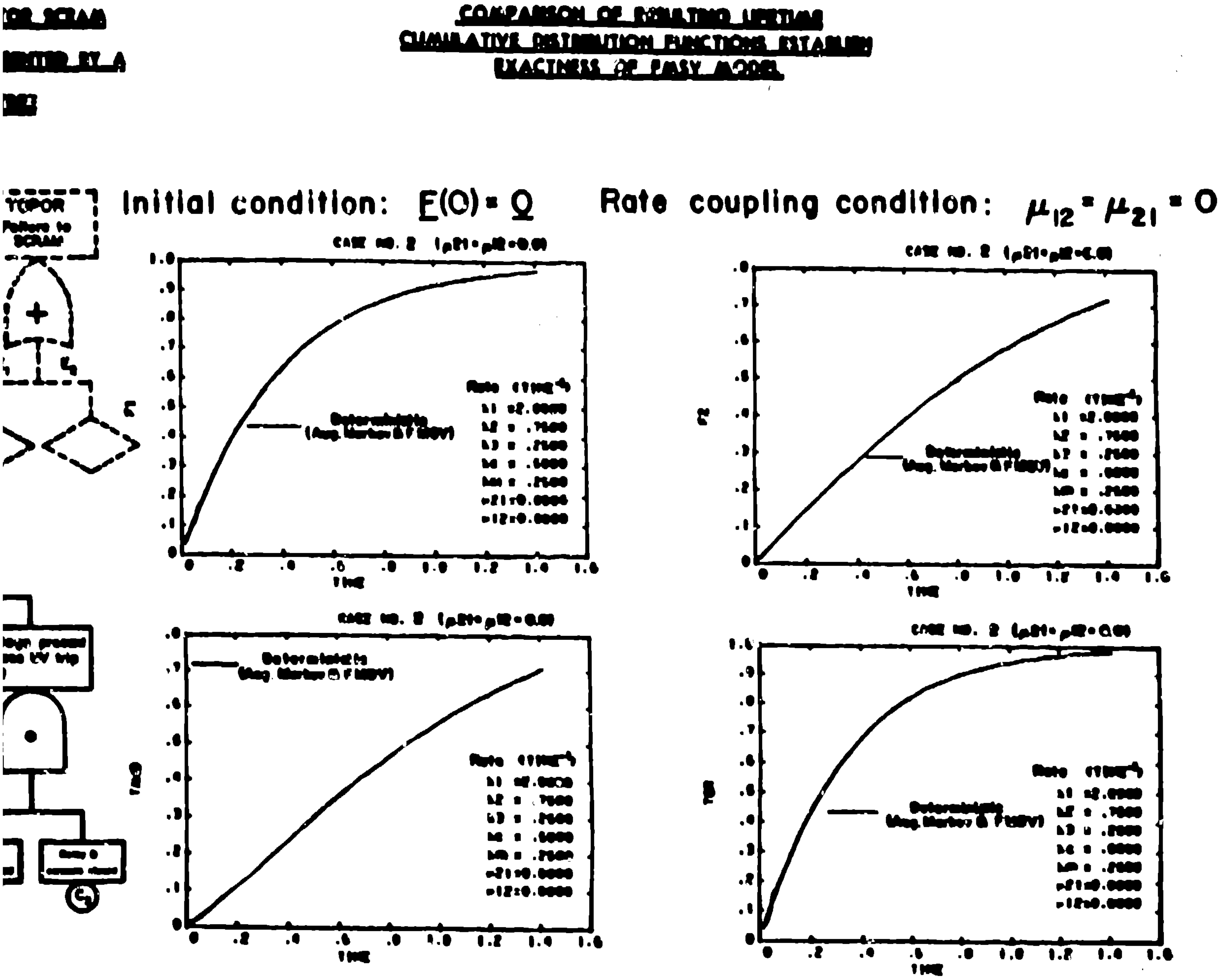


Figure 2. Mathematical development of Failure Mode State Vector (FMSV) models for four kinds of two components fault trees having statistical dependen



simplified reactor shutdown (SCRAM) system fault tree and resulting time
pendent failure probability solutions comparison.

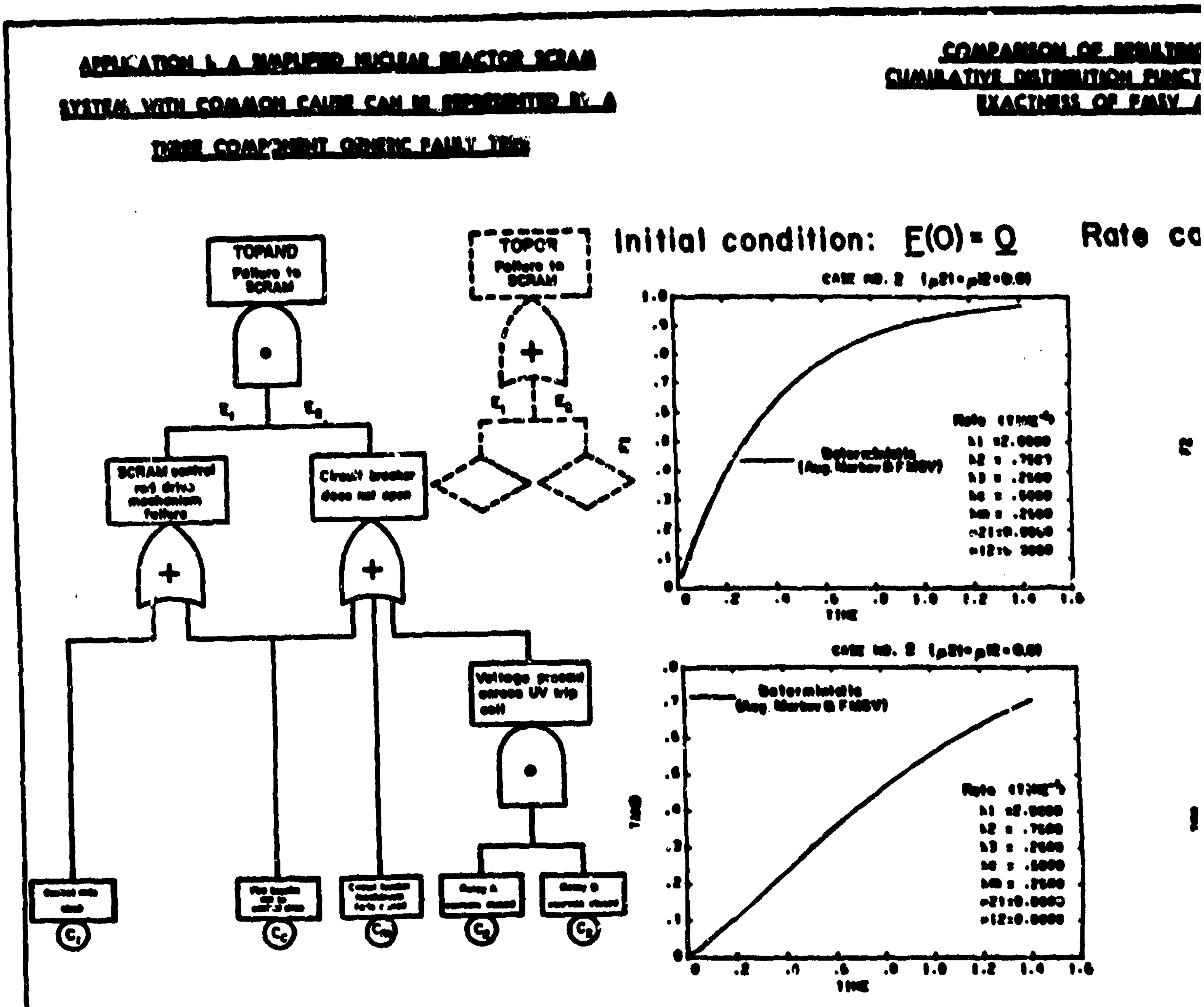
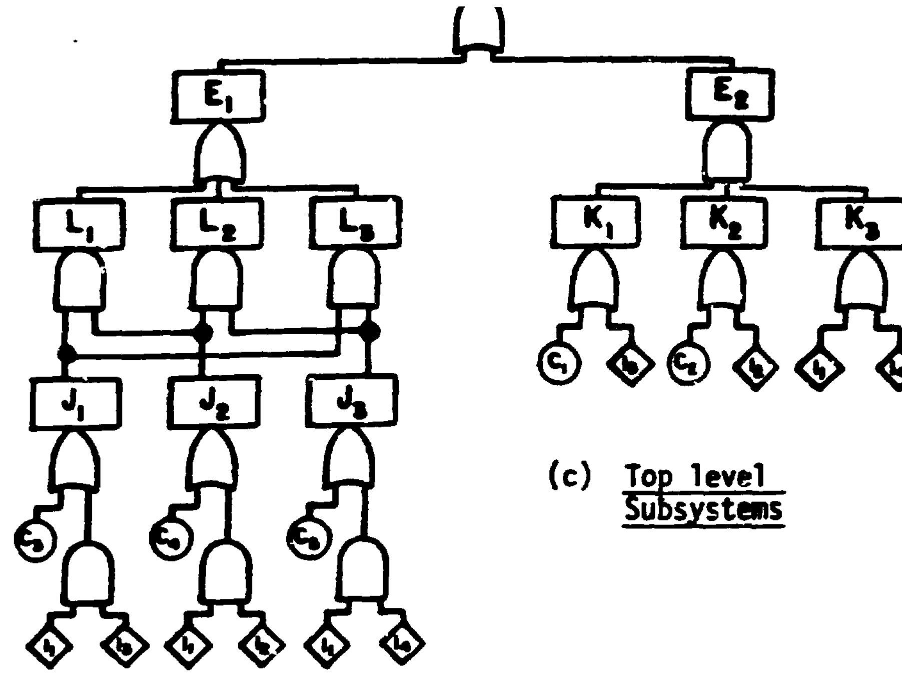
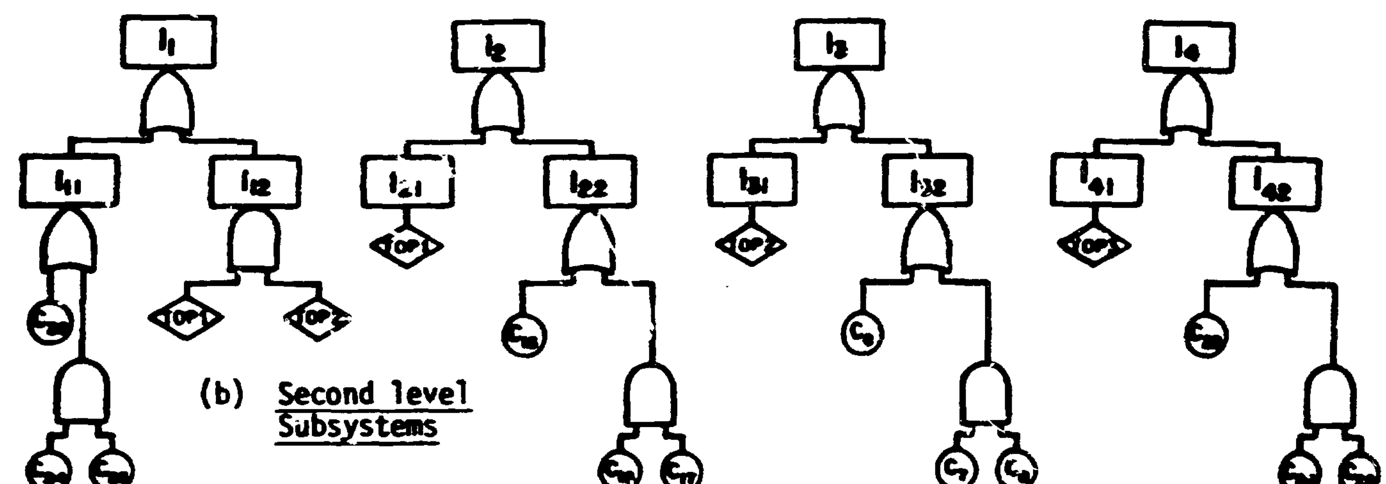


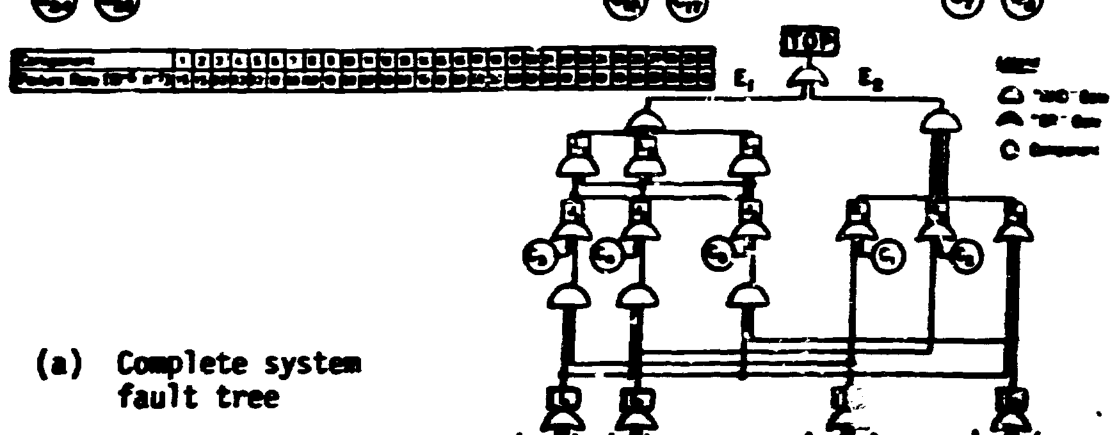
Figure 3. A simplified reactor shutdown (SCRAM) system fault tree and dependent failure probability solutions comparison.



(c) Top level Subsystems



(b) Second level Subsystems



(a) Complete system fault tree

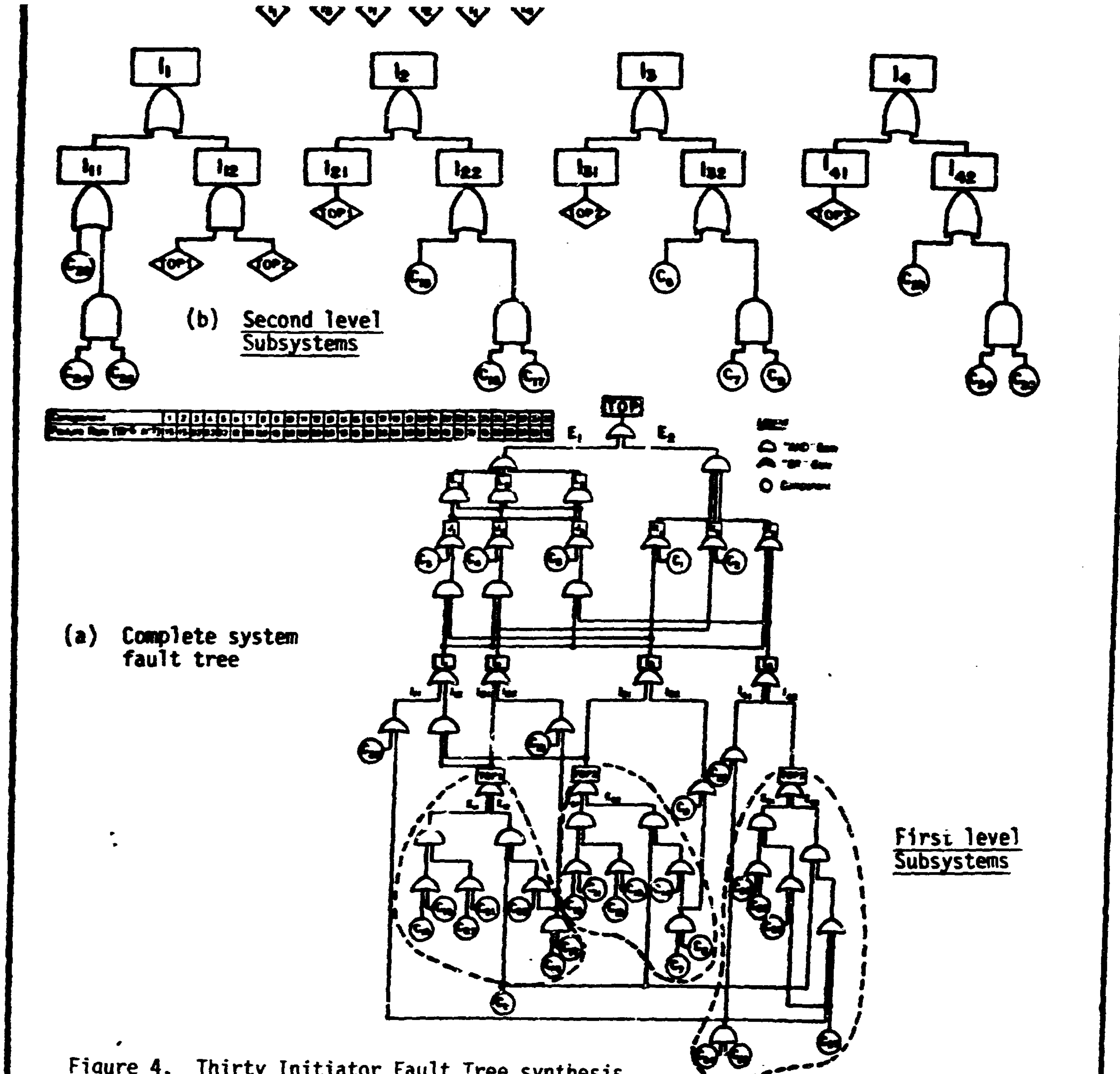


Figure 4. Thirty Initiator Fault Tree synthesis example.

TABLE I

ANALYSIS AND SYNTHESIS OF THIRTY BASIC EVENT FAULT TREE

SYSTEM	CONTRIBUTING EVENTS	GENERIC FAULT TREES: No. of Components	GENERIC FAULT TREES: Kind of Event	GENERIC FAULT TREES: Kind of S-Dependencies	APPROX. EFFECTIVE OCCURRENCE RATES $[10^{-6}\ h^{-1}]$
FIRST LEVEL					
Failure Mode E_{11}	$(C_{18}$ or $C_{19})$ and $(C_{20}$ or $C_{21})$	2	TOPAND	None	57.47
Failure Mode E_{12}	C_9 and $(C_{22}$ or C_{16} and $C_{17})$	3	TOPAND	$CM(C_{22})$	3.16
TOP Event TOP1	E_{11} or E_{12}	-	TOPOR	---	60.63
Failure Mode E_{21}	$(C_{10}$ or $C_{11})$ and $(C_{12}$ or $C_{13})$	2	TOPAND	None	57.47
Failure Mode E_{22}	C_9 and $(C_{14}$ or C_7 and $C_8)$	3	TOPAND	$CM(C_{14})$	3.16
TOP Event TOP2	E_{21} or E_{22}	-	TOPOR	---	60.63
Failure Mode E_{31}	$(C_{26}$ or $C_{27})$ and $(C_{28}$ or $C_{29})$	2	TOPAND	None	57.47
Failure Mode E_{32}	C_9 and $(C_{27}$ or C_{24} and $C_{25})$	3	TOPAND	$CM(C_{27})$	4.70
TOP Event TOP3	E_{31} or E_{32}	-	TOPOR	---	62.17
SECOND LEVEL (initiators and approximated 1st level TOP events assumed S-independent)					
Failure Mode I_{11}	C_{30} or C_{24} and C_{25}	2	TOPOR	$CM(C_{30})$	11.18
Failure Mode I_{12}	TOP1 and TOP2	2	TOPAND		27.04
Intermediate I_1	I_{11} or I_{12}	-	TOPOR	---	38.22
Failure Mode I_{21}	TOP1 or				60.63
Failure Mode I_{22}	$(C_{15}$ or C_{16} and $C_{17})$	3	TOPOR	$CM(C_{15})$	
Intermediate I_2	I_{21} or I_{22}	-	TOPOR	---	90.53
Failure Mode I_{31}	TOP2 or				60.63
Failure Mode I_{32}	$(C_6$ or C_7 and $C_8)$	3	TOPOR	$CM(C_6)$	
Intermediate I_3	I_{31} or I_{32}	-	TOPOR	---	90.53
Failure Mode I_{41}	TOP3 or				62.17
Failure Mode I_{42}	$(C_{23}$ or C_{24} and $C_{25})$	3	TOPOR	$CM(C_{23})$	
Intermediate I_4	I_{41} or I_{42}	-	TOPOR	---	73.34
TOP LEVEL (initiators, approximated 2nd level I's, and propagated I's through AND gates assumed S-independent)					
Intermediate J_1	I_1 and I_3 or C_3	2	TOPAND	$CC(C_3)$	24.33
Intermediate J_2	I_1 and I_2 or C_4	2	TOPAND	$CC(C_4)$	24.33
Intermediate J_3	I_1 and I_4 or C_5	2	TOPAND	$CC(C_5)$	21.29
Intermediate K_1	C_1 or I_3	2	TOPOR	None	92.03
Intermediate K_2	C_2 or I_2	2	TOPOR	None	92.03
Intermediate K_3	I_1 or I_4	2	TOPOR	None	111.56
2 of 3 L_1	J_1 and J_2	-	TOPAND	None	48.66
2 of 3 L_2	J_2 and J_3	-	TOPAND	None	45.61
2 of 3 L_3	J_1 and J_3	-	TOPAND	None	45.61
Failure Mode E_1	J_1 and J_2 or J_2 and J_3 or J_1 and J_3	3	TOPOR	2 of 3	9.06
[illegible]	K_1 and K_2 and K_3	3	TOPAND	Neglected	19.08
					[illegible]

TABLE I

ANALYSIS AND SYNTHESIS OF THIRTY BASIC EVENT FAULT TREE

SYSTEM	CONTRIBUTING EVENTS	GENERIC FAULT TREES No. of Components	GENERIC FAULT TREES Kind of Event	GENERIC FAULT TREES Kind of S-Dependencies	APPROX. EFFECTIVE OCCURRENCE RATES $[10^{-6}\ h^{-1}]$
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TOP Event TOP1	E_{11} or E_{12}	-	TOPOR	---	60.63
Failure Mode E_{21}	$(C_{10}$ or $C_{11})$ and $(C_{12}$ or $C_{13})$	2	TOPAND	None	57.47
Failure Mode E_{22}	C_9 and $(C_{14}$ or C_7 and $C_8)$	3	TOPAND	CM(C_{14})	3.16
TOP Event TOP2	E_{21} or E_{22}	-	TOPOR	---	60.63
Failure Mode E_{31}	$(C_{26}$ or $C_{27})$ and $(C_{28}$ or $C_{29})$	2	TOPAND	None	57.47
Failure Mode E_{32}	C_9 and $(C_{27}$ or C_{24} and $C_{25})$	3	TOPAND	CM(C_{27})	4.70
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SECOND LEVEL (initiators and approximated 1st level TOP events assumed S-independent)					
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Failure Mode I_{12}	TOP1 and TOP2	2	TOPAND		27.04
Intermediate I_1	I_{11} or I_{12}	-	TOPOR	---	38.22
Failure Mode I_{21}	TOP1 or				60.63
Failure Mode I_{22}	$(C_{15}$ or C_{16} and $C_{17})$	3	TOPOR	CM(C_{15})	
Intermediate I_2	I_{21} or I_{22}	-	TOPOR	---	90.53
Failure Mode I_{31}	TOP2 or				60.63
Failure Mode I_{32}	$(C_6$ or C_7 and $C_8)$	3	TOPOR	CM(C_6)	
Intermediate I_3	I_{31} or I_{32}	-	TOPOR	---	90.53
Failure Mode I_{41}	TOP3 or				62.17
Failure Mode I_{42}	$(C_{23}$ or C_{24} and $C_{25})$	3	TOPOR	CM(C_{23})	
Intermediate I_4	I_{41} or I_{42}	-	TOPOR	---	73.34
TOP LEVEL (initiators, approximated 2nd level I's, and propagated I's through AND gates assumed S-independent)					
Intermediate J_1	I_1 and I_3 or C_3	2	TOPAND	CC(C_3)	24.33
Intermediate J_2	I_1 and I_2 or C_4	2	TOPAND	CC(C_4)	24.33
Intermediate J_3	I_1 and I_4 or C_5	2	TOPAND	CC(C_5)	21.29
Intermediate K_1	C_1 or I_3	2	TOPOR	None	92.03
Intermediate K_2	C_2 or I_2	2	TOPOR	None	92.03
Intermediate K_3	I_1 or I_4	2	TOPOR	None	111.56
2 of 3 L_1	J_1 and J_2	-	TOPAND	None	48.66
2 of 3 L_2	J_2 and J_3	-	TOPAND	None	45.61
2 of 3 L_3	J_1 and J_3	-	TOPAND	None	45.61
Failure Mode E_1	J_1 and J_2 or J_2 and J_3 or J_1 and J_3	3	TOPOR	2 of 3	9.06
Failure Mode E_2	K_1 and K_2 and K_3	3	TOPAND	Neglected	19.06
TOP	E_1 or E_2	-	TOPOR	---	28.16

CM = Common Mode *CC = Common Cause*