NASA Technical Memorandum 100524

NASA-TM-100524 19880008006

EXAMPLES OF NONCONSERVATISM IN THE CARE III PROGRAM

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January 1988

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INTRODUCTION

As fault-tolerant computer systems grow in complexity, assessment of the reliability of such systems similarly increases in difficulty. Realistic models of fault-tolerant systems can easily have several thousands of states. As models get larger, though, manual derivation of the exact unreliability or even the manual derivation of an approximation for the unreliability becomes impracticable. Thus, the reliability of a system based on a large or complex model has to be calculated numerically.

Markov models of highly reliable, fault-tolerant computer systems typically have both slow and fast transition rates -- the slow rates corresponding to fault arrivals and the fast rates corresponding to a system's response (such as reconfiguration) to a fault. To calculate the death-state probabilities and, hence, the reliability of a system based on such a Markov model, a system of stiff differential equations must be solved. However, the solution of a system of stiff differential equations is plagued with numerical difficulties. Thus, other approaches have been developed to estimate reliability.

To estimate the reliability of state-of-the-art fault-tolerant computer architectures, automated tools such as CARE III (Computer-Aided Reliability Estimation), SURE (Semi-Markov Unreliability Range Evaluator), PAWS (Padė Approximation With Scaling), and STEM (Scaled Taylor Exponential Matrix) have been created (ref. 1 and 2). CARE III has been developed over several years estimate the reliability of a system based on a given model. Since these tools were developed to assess highly reliable, fault-tolerant systems, the solutions to the reliability models should be sufficiently accurate to permit engineering judgements to be made about the system under study. Overestimation of reliability can support acceptance of a system with inadequate reliability while underestimation can support rejection of a well-designed system.

During the testing of the SURE program, the unreliability estimates given by CARE III, PAWS, and STEM were used to check the accuracy of the bounds that the SURE program gives on the unreliability of a system based on a semi-Markov model. Some of the answers given by CARE III differed by several orders of magnitude from the answers given by SURE, PAWS, and STEM; and, even more importantly, the answers given by CARE III for several test cases were not conservative in comparison to the other estimates. In each case, the CARE III program did not give any warning that the estimates may not be accurate or conservative.

Descriptions of CARE III, SURE, PAWS, and STEM

The CARE III reliability analysis tool was originally codeveloped by the Raytheon Company and the NASA Langley Research Center. This program implements a solution technique that incorporates behavioral decomposition and aggregation to evaluate the reliability of systems. The solution technique reduces the solution of a complex model to the solution of two relatively simpler models: a coverage model that is a semi-Markov process, and a reliability model that is a non-homogeneous, Markov process (ref. 3). This solution technique involves an approximation which is not characterized via a mathematical error analysis in the program. Figure 1 shows CARE III's single fault-handling (coverage) model. Although several types of fault-handling behavior can be represented by the CARE III model, the models in this report are very basic constructions. To simplify CARE III's fault-handling model, the following parameter values were used; $P_B = 0$, $P_A = 1$, $c = 1$, $\rho = 0$, and $\varepsilon = 0$. Since these parameters either can not be measured or are very difficult to measure, these values are typically used. With these parameter values, the fault-handling model reduces to the simple model shown in figure 2.

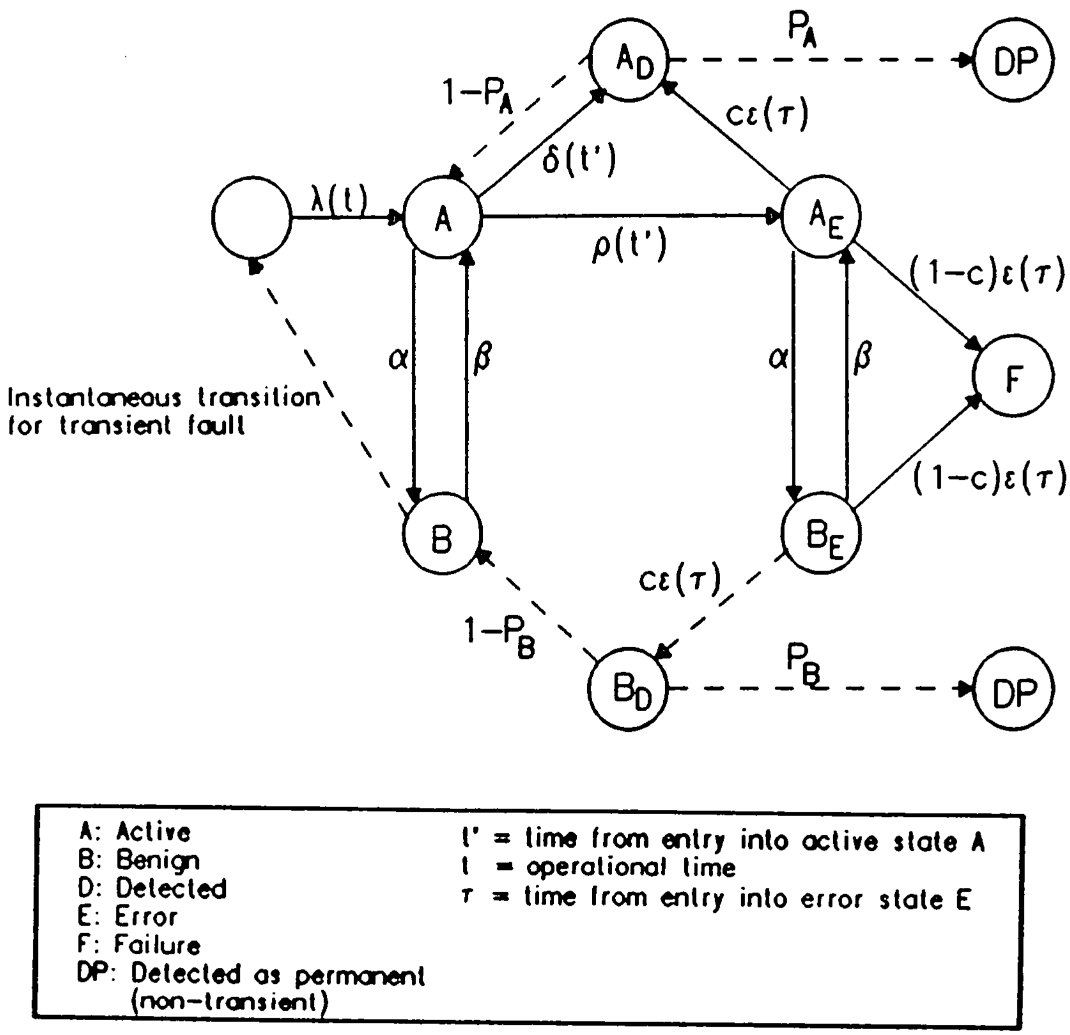

Figure 1.- CARE III'S single fault-handling model.

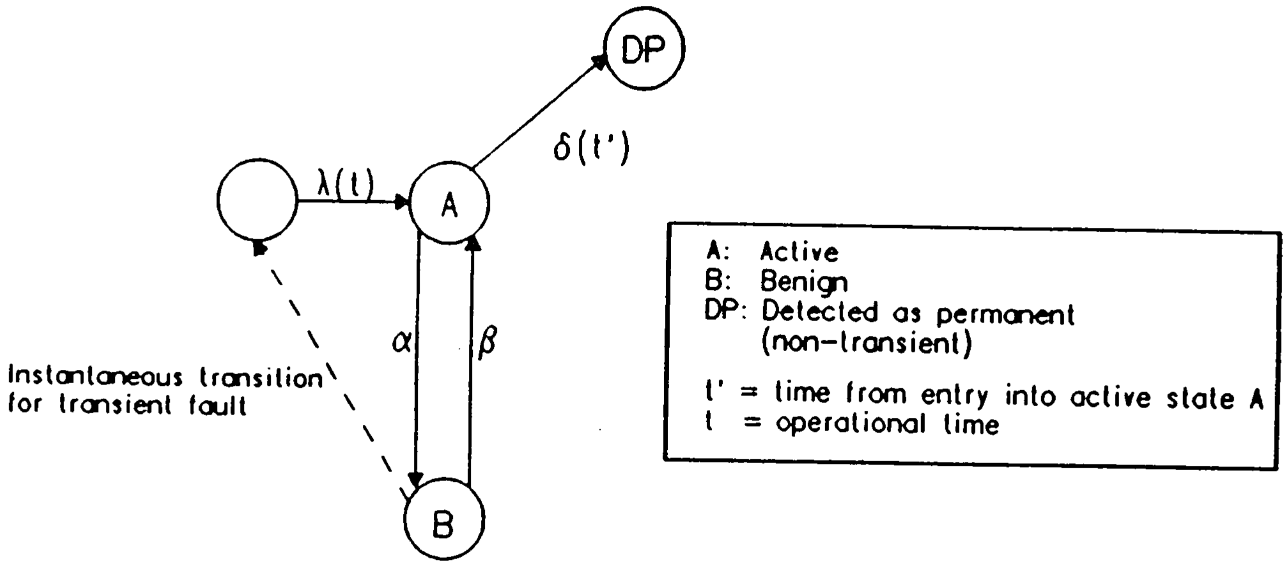

Figure 2.- CARE III's single fault-handling model simplified.

To solve both the fault-handling and fault-occurrence models, numerical integration techniques are used. To input a model into CARE III, fault trees are used to describe the fault-occurrence behavior, and the fault-handling behavior is described by the parameters of the semi-Markov model. Since a semi-Markov model is included in CARE III, distributions other than the exponential can be used to describe fault-handling behavior. For the models given in this report, though, only exponential transition rates were considered.

The SURE program provides an alternative approach to the difficult task of solving convolution integrals traditionally used to determine the reliability of a system modeled by a semi-Markov model. SURE gives lower and upper bounds, developed by White (ref. 4), on the death-state probabilities of a semi-Markov model. Using these bounds on the individual death-state probabilities, lower and upper bounds on the total unreliability of a modeled system are determined;

and, these bounds have been demonstrated to be mathematically rigorous (ref. 4). Since the bounds implemented in SURE are algebraic in form, they are relatively simple to compute. Hence, the numerical stability problems that often occur when solving systems of stiff differential equations do not exist in this program. Models are input to SURE by simply enumerating all of the state transitions in the model.

The PAWS program is used to compute the reliability of a pure Markov model. As mentioned above, the reliability of a system modeled with a pure Markov model can be determined by solving a system of differential equations. PAWS uses a combination of Padė approximations, scaling, and squaring techniques to compute a matrix exponential needed to solve this system of equations and, hence, determine the death-state probabilities of a Markov model (ref. 5). In fact, this method of finding the matrix exponential is considered to be one of the most efficient algorithms known (ref. 6). A conservative estimate of the number of digits of accuracy in the unreliability estimate is also given along with the output of the death-state probabilities. PAWS is limited, though, to pure Markov models and can not handle very large models (models with more than 300 states). PAWS also uses the same input format as SURE.

Another reliability analysis tool called STEM (Scaled Taylor Exponential Matrix) which was developed at NASA Langley Research Center does have the capability to compute the exact death state probabilities for Markov models as large as 1000 states. The underlying mathematics in STEM involves the calculation of the matrix exponential where the matrix exponential is defined via a Taylor series (ref. 7 and 8). The Taylor series is truncated in the program, and a conservative error estimate of the truncation is produced. The

STEM program uses the same input language as SURE and outputs the death-state probabilities along with the error estimate.

The following three models were used in testing of the SURE program. For each of the examples, the system is described and the Markov model is presented along with a table that gives the final unreliability estimates from SURE, PAWS, STEM, and CARE III. The number of digits of accuracy that are reported for PAWS and STEM are given in brackets beside the corresponding unreliability estimate. The input files used with each tool for the first three models are located in the appendix. The input files used with the last two models are very similar to the input files for model 3 since the systems in each of these examples are basically the same structure. A range of parameter values were used when running each model in order to show the region where the CARE III estimates become nonconservative. The mission time used in each test case was 10 hours. The cases where CARE III overestimates the reliability of the modeled system by underestimating the unreliability are marked in the tables with an "#" symbol.

Example 1: Simple Triad

The first example is a Markov model of a triad of components with no spares. The system degrades with a component failure rate λ and a fault-recovery rate δ. Only permanent faults are considered. Two faults that arrive before the system can reconfigure will cause system failure; and, only one functioning component is necessary for the system to be operational. The model for this example is given in figure 3.

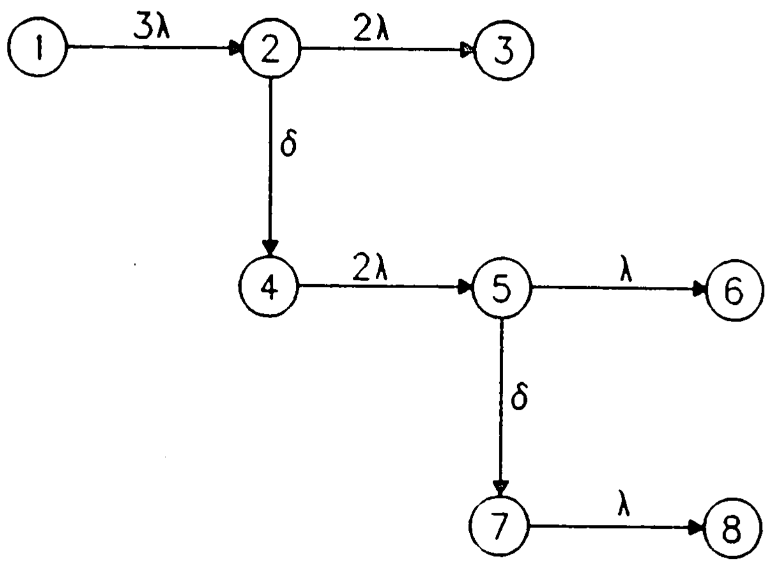

Figure 3.- Model 1: Markov model of a triplex with permanent faults.

Table 1.- Comparison of SURE, PAWS, STEM, and CARE III for Model 1

PARAMETERS	SURE BOUNDS	Total System Unreliability Given by Each Tool PAWS	STEM	CARE III	CARE III*
λ= 1e-03 δ= 1e+02	(1.42254e-06, 1.60300e-06)	1.57267e-06 [9]	1.57267e-06 [4]	1.57588e-06	1.57588e-06
λ= 1e-04 δ= 1e+08	(9.98495e-10, 1.00001e-09)	9.98507e-10 [3]	9.98507e-10 [4]	9.98501e-10	9.98501e-10
λ= 1e-6 δ= 1e+2	(5.48422e-13, 6.01003e-13)	6.00388e-13 [9]	6.00388e-13 [4]	6.00658e-13	6.00658e-13
λ= 7e-7 δ= 1e+4	(3.25497e-15, 3.28301e-15)	3.28293e-15 [7]	3.28293e-15 [3]	3.29291e-15	3.29291e-15
λ= 6e-7 δ= 1e+4	(2.35560e-15, 2.37601e-15)	2.37595e-15 [7]	2.37595e-15 [3]	2.38329e-15	2.38329e-15
λ= 5e-7 δ= 1e+4	(1.61096e-15, 1.62500e-15)	1.62497e-15 [7]	1.62497e-15 [3]	1.24599e-16#	1.63006e-15
λ= 1e-7 δ= 1e+2	(5.47623e-15, 6.00100e-15)	5.99499e-15 [9]	5.99499e-15 [4]	9.99999e-19#	5.99766e-15
λ= 1e-7 δ= 1e+4	(6.04593e-17, 6.10000e-17)	6.09993e-17 [7]	6.09993e-17 [3]	9.99999e-19#	6.12029e-17
λ= 1e-7 δ= 1e+8	(1.00599e-18, 1.00600e-18)	1.00600e-18 [3]	1.00600e-18 [4]	9.99999e-19#	1.00602e-18
λ= 5e-7 δ= 1e+3	(1.47007e-14, 1.51250e-14)	1.51233e-14 [8]	1.51233e-14 [5]	1.24999e-16#	1.51289e-14
λ= 1e-08 δ= 1e+02	(5.47543e-17, 6.00010e-17)	5.99410e-17 [9]	5.99410e-17 [4]	1.00000e-21#	5.99676e-17

The unreliability estimates listed under the CARE III column were obtained by running CARE III with all of the default run-time parameters while the values in the CARE III* column were obtained by dramatically reducing one of CARE III's run-time parameters PSTRNC.[1] When the above test cases were run with CARE III with the default run-time parameters, many of the resulting unreliability estimates in cases where λ was very small differed from the other estimates by several orders of magnitude. These estimates were not conservative, and no warning messages were output. In some of the cases, though, the portion of unreliability that CARE III attributed to fault handling was reported to be 0. This information served as a clue that varying the value of PSTRNC, which is used in controlling the calculation of the fault-handling unreliability, may affect CARE III's estimate. All of the run-time parameter values were varied; however, only variation of PSTRNC yielded any significant change in CARE III's output. Reducing the PSTRNC parameter, whose default value is 10^{-10}, to 10^{-30} enabled CARE III to give a conservative reliability estimate in each of the test cases shown.

Example 2: Critical-pair Five-plex

Example 2 consists of a system of five components that are critically paired and are susceptible to intermittent faults. The parameters of the model, shown in figure 4 are defined as follows: λ is the fault-arrival rate, α is the rate at which an intermittent fault goes from the active to benign state, β is the

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1 The PSTRNC parameter is used to limit the number of fault vectors that CARE III uses in computing the fault-handling unreliability. Only the fault vectors whose module depletion probability is less than PSTRNC will be included in the fault-handling unreliability calculation (p. 31, ref. 1).

rate at which an intermittent fault goes from the benign to active state, and δ is the permanent fault-recovery rate.

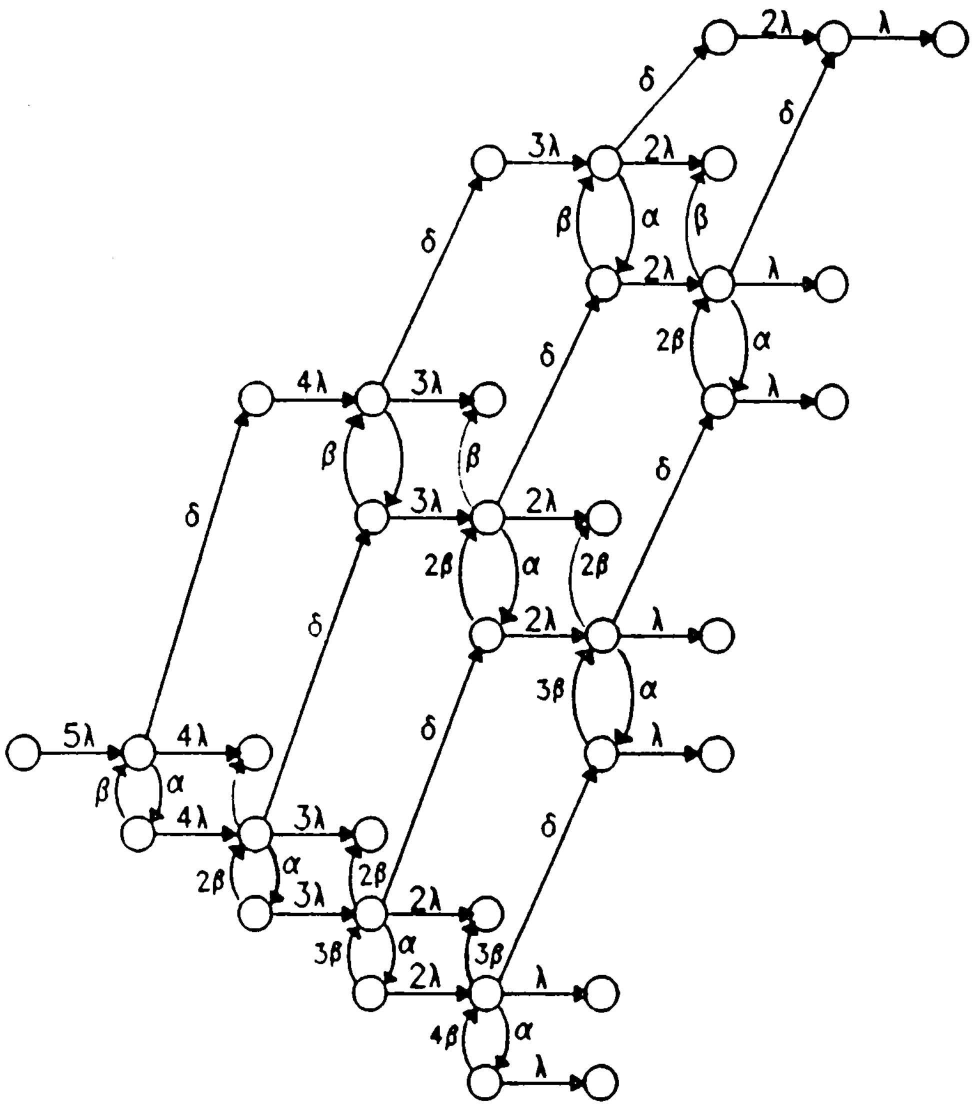

Figure 4.- Model 2: Critical pair 5-plex with intermittent faults.

Table 2.- Comparison of SURE, PAWS, STEM and CARE III for Model 2.

PARAMETERS	SURE BOUNDS	Total System Unreliability Given by Each Tool PAWS	STEM	CARE III	CARE III*
λ= 1e-6 σ= 3.6e-3 β= 1e-2 δ= 3.6e+6	(5.55288e-17, 5.55564e-17)	5.55550e-17 [4]	5.55550e-17 [2]	5.57649e-17	5.57658e-17
λ= 1e-6 σ= 3.6e-2 β= 1e+1 δ= 3.6e+2	(5.29698e-13, 5.55674e-13)	5.55449e-13 [7]	5.55449e-13 [4]	5.57028e-13	5.57036e-13
λ= 1e-6 σ= 3.6e-1 β= 1e-1 δ= 3.6e+2	(5.29530e-13, 5.55417e-13)	5.55249e-13 [7]	5.55249e-13 [4]	5.53959e-13*	5.53967e-13*
λ= 2e-7 σ= 3.6e-3 β= 3.6e-2 δ= 3.6e+1	(1.90313e-13, 2.22230e-13)	2.21589e-13 [8]	2.21589e-13 [6]	3.19998e-29*	2.21615e-13
λ= 1e-7 σ= 3.6 β= 1e-1 δ= 3.6e+2	(5.28272e-15, 5.54082e-15)	5.53926e-15 [7]	5.53926e-15 [4]	9.99998e-31*	5.50788e-15*
λ= 1e-8 σ= 1e-1 β= 1e+2 δ= 1e+6	(1.99821e-20, 2.00000e-20)	2.00000e-20 [4]	2.00000e-20 [3]	1.00000e-35*	2.00275e-20
λ= 1e-4 σ= 1e+2 β= 1e+1 δ= 1e+3	(2.13068e-09, 2.19804e-09)	2.19131e-09 [6]	2.19131e-09 [5]	2.18797e-09*	2.18797e-09*

The appendix of CARE III's users guide (D-2, ref. 1) states that separation of the values of the fault-handling parameters by more than two or three orders of magnitude may cause numerical inaccuracies; but, the nature of the inaccuracies are not explained. Since some of the above test cases infringe on this caveat, CARE III's estimates in these cases might be expected to differ from the estimates given by SURE, PAWS, and STEM. However, the last case in particular contains rates that are readily accepted as reasonable rates for highly reliable, fault-tolerant computer systems modeled with CARE III.

The results listed under the CARE III* column were obtained by reducing the

PSTRNC parameter of the program. As in example 1, many of the unreliability estimates given by CARE III when the default run-time parameters were used (shown in the first CARE III column) deviated from the other results by several orders of magnitude. No warning messages were output by CARE III to alert the user that the reliability estimate is not conservative, although, as in example 1, the amount of unreliability attributed to fault handling was reported to be 0.

In some of the cases where CARE III overestimated the reliability, the fault-arrival rate λ was very small. This fault-arrival rate is a somewhat smaller failure rate than is typically assumed for components of a computer system. However, with the rapid evolution of electronic components, failure rates of this magnitude are now being assigned to components as can be seen in the failure rates suggested for the avionic reliability study for the Entry Research Vehicle.[2] No suggestions were made in the user's guide or the program's output to decrease the PSTRNC parameter in cases where the fault-arrival rate was very small. However, CARE III user's guide states that the range for the λ parameter includes all values > 0.0 (p. 43 ref. 1). Once the PSTRNC value was reduced, though, the portion of unreliability that CARE III attributed to fault handling increased; and, the final reliability estimate tended to converge to the estimates given by PAWS, STEM, and SURE in several of the cases.

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2 Dzwonczyk, M.; Adams, S.; McKinney, M.; Esielionis, J.: Avionic Reliability Study for the Entry Research Vehicle. ERV-87-05, January 23, 1987.

The CARE III* estimates may be considered good enough for use by engineering judgement since these estimates are very close to the estimates given by the other tools. However, some of the CARE III* estimates were still not conservative compared to the PAWS and STEM estimates which agree to at least 6 digits. More importantly, the reason CARE III's estimates in these cases do not converge to a conservative estimate is not evident.

Example 3: Triad with Transient Faults

Model 3, in figure 5, is a triad of components susceptible to transient faults. Two faults which occur before recovery can take place will cause system failure; otherwise, the system degrades until there are no more functioning components. The fault-arrival rate is given by λ, the fault-recovery rate is given by δ, and the transient fault-recovery rate is given by α.

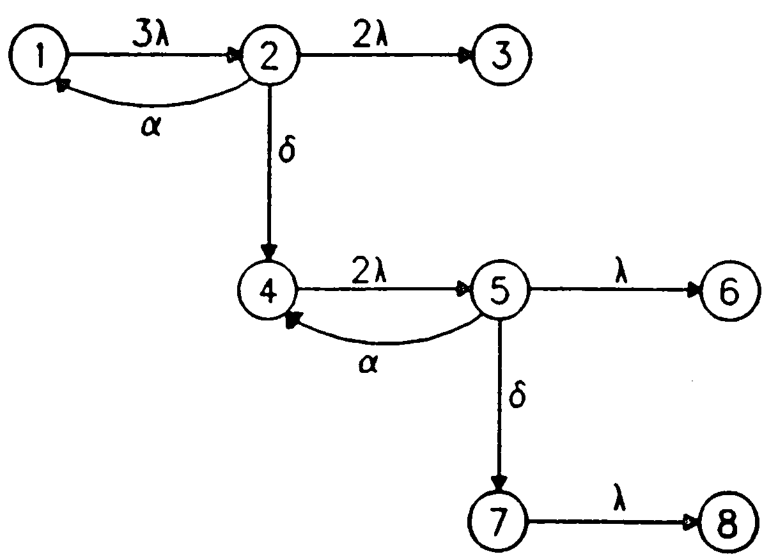

Figure 5.- Model 3: Triad with transient faults.

Table 3.- Comparison of SURE, PAWS, STEM, and CARE III for Model 3.

PARAMETERS	Total System Unreliability Given by Each Tool			
	SURE BOUNDS	PAWS	STEM	CARE III
λ= 1e-03 δ= 1e+05 α= 1e+03	(9.65236e-07, 9.81015e-07)	9.66415e-07 [6]	9.66415e-07 [4]	9.63961e-07#
λ= 1e-08 δ= 1e+07 α= 1e+02	(1.59975e-21, 1.59997e-21)	1.59997e-21 [4]	1.59997e-21 [3]	1.31233e-21#
λ= 1e-04 δ= 1e+04 α= 1e-01	(1.05275e-09, 1.06001e-09)	1.05836e-09 [7]	1.05836e-09 [3]	1.03322e-09#
λ= 1e-06 δ= 1e+03 α= 1e-02	(5.92900e-14, 6.09997e-14)	6.09922e-14 [7]	6.09922e-14 [5]	3.10625e-14#
λ= 1e-04 δ= 1e+03 α= 1e+00	(1.55489e-09, 1.59771e-09)	1.59465e-09 [8]	1.59465e-09 [5]	1.29556e-09#
λ= 1e-05 δ= 1e+02 α= 1e+05	(5.97717e-14, 5.99500e-14)	5.99410e-14 [6]	5.99410e-14 [4]	1.69753e-14#

In all of the test cases, the unreliability estimates given by CARE III are not conservative. No warning messages or any other indication was given by CARE III in any of these cases to inform the user that the unreliability estimate may not be conservative. Many attempts were made by varying the run-time parameters to get CARE III to give a conservative estimate; but, the estimates were the same regardless of the variation in the run-time parameters.

The following two models were not a part of the testing of the SURE program. These two models were developed to serve as a preliminary investigation of the error in the transient model seen in example 3. The next two models are simple critical-pair configurations as in example 3 except these next models contain more components to test the hypothesis that as the size of the model increases, so does the CARE III's error in analyzing the transient model.

Example 4: 7-Plex with Transient Faults

Model 4, in figure 6, is a system of 7 identical components susceptible to transient faults. Two faults which occur before recovery can take place will cause system failure; otherwise, the system degrades until there are no more functioning components. The fault-arrival rate is λ, the fault-recovery rate is δ, and the transient fault-recovery rate is α.

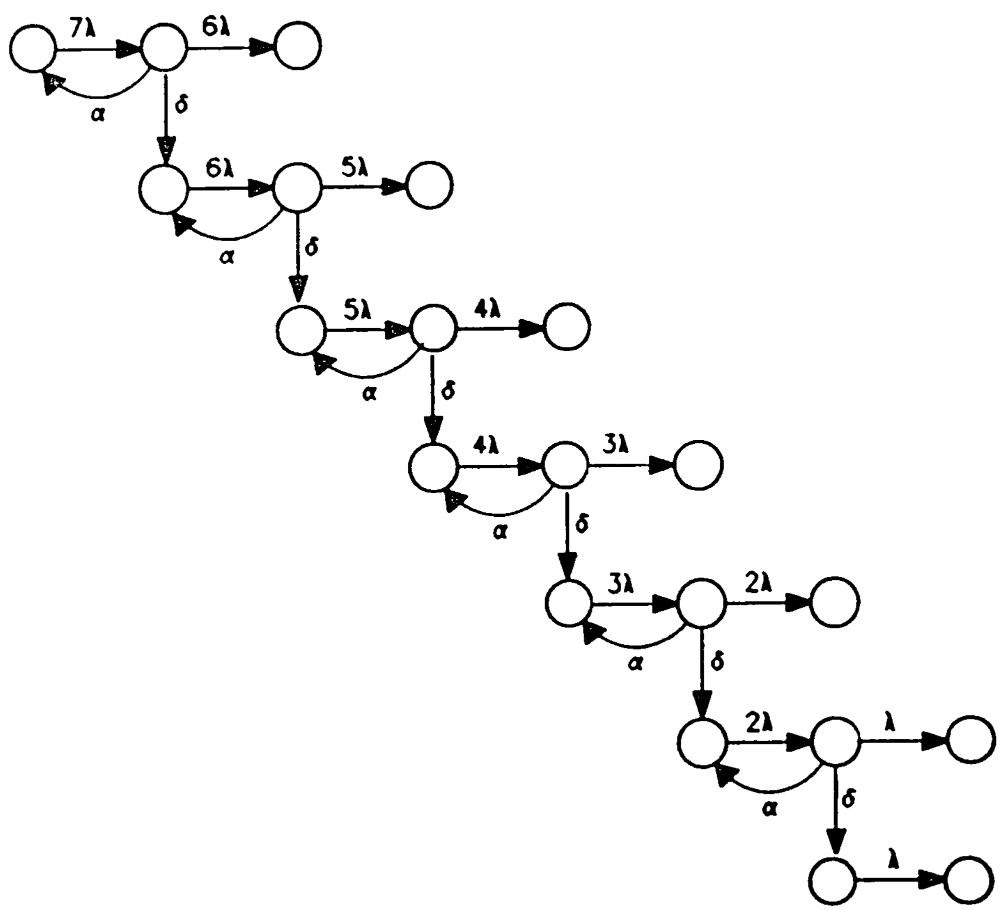

Figure 6.- Model 4: 7-Plex with transient faults.

Table 4.- Comparison of SURE, PAWS, STEM, and CARE III for Model 4.

PARAMETERS	Total System Unreliability Given by Each Tool SURE BOUNDS	PAWS	STEM	CARE III
λ= 1e-4 δ= 1e+3 σ= 1e+4	(3.78529e-10, 3.83123e-10)	3.81780e-10 [7]	3.81780e-10 [3]	6.28699e-11#
λ= 1e-7 δ= 1e+2 σ= 1e+4	(4.12149e-16, 4.15843e-16)	4.15837e-16 [7]	4.15837e-16 [3]	6.49649e-17#
λ= 1e-8 δ= 1e+5 σ= 1e+2	(4.18395e-19, 4.19581e-19)	4.19580e-19 [6]	4.19580e-19 [4]	7.01660e-20#
λ= 1e-6 δ= 1e+1 σ= 1e+4	(4.15838e-14, 4.19595e-14)	4.19576e-14 [7]	4.19576e-14 [3]	5.06318e-15#
λ= 1e-7 δ= 1e+5 σ= 1e+6	(3.81493e-18, 3.81819e-18)	3.81818e-18 [5]	3.81818e-18 [5]	6.38098e-19#
λ= 1e-5 δ= 1e+3 σ= 1e+6	(4.19205e-14, 4.19727e-14)	4.19580e-14 [5]	4.19580e-14 [3]	5.28975e-15#
λ= 1e-4 δ= 1e+5 σ= 1e+3	(4.14259e-11, 4.16887e-11)	4.15430e-11 [6]	4.15430e-11 [4]	6.94510e-12#

Recall from example 3 that CARE III's unreliability estimates agreed with the estimates from the other tools to at least one significant digit in several of the test cases. However, as seen in table 4, CARE III's estimates differ from the other estimates for the above model by almost an order of magnitude in each test case.

Example 5: 12-Plex with Transient Faults

Model 5, in figure 7, is a system of 12 identical components that is susceptible to transient faults. Two faults which occur before recovery can take place will cause system failure; otherwise, the system degrades until there are no more functioning components. The fault-arrival rate is λ, the fault-recovery rate is δ, and the transient fault-recovery rate is α.

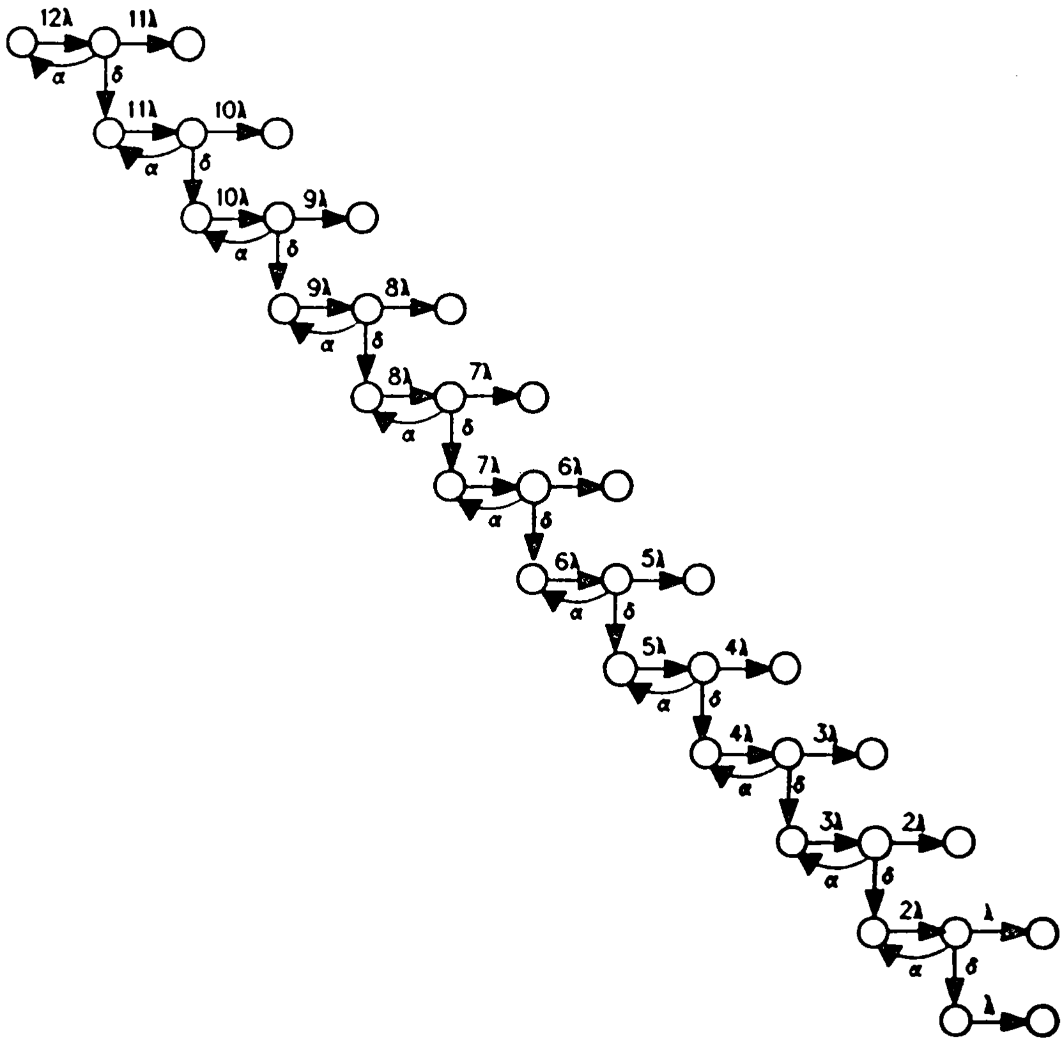

Figure 7.- Model 5: 12-Plex with transient faults.

Table 5.- Comparison of SURE, PAWS, STEM, and CARE III for Model 5.

PARAMETERS	Total System Unreliability Given by Each Tool SURE BOUNDS	PAWS	STEM	CARE III
λ= 1e-4 δ= 1e+3 α= 1e+4	(1.18964e-09, 1.20712e-09)	1.19988e-09 [7]	1.19988e-09 [3]	1.07777e-10#
λ= 1e-7 δ= 1e+2 α= 1e+4	(1.29533e-15, 1.30694e-15)	1.30692e-15 [7]	1.30692e-15 [3]	1.11368e-16#
λ= 1e-8 δ= 1e+5 α= 1e+2	(1.31495e-18, 1.31868e-18)	1.31868e-18 [6]	1.31868e-18 [4]	1.20284e-19#
λ= 1e-6 δ= 1e+1 α= 1e+4	(1.30692e-13, 1.31876e-13)	1.31867e-13 [7]	1.31867e-13 [3]	8.67973e-15#
λ= 1e-7 δ= 1e+5 α= 1e+6	(1.19898e-17, 1.20001e-17)	1.20000e-17 [5]	1.20000e-17 [5]	1.09388e-18#
λ= 1e-5 δ= 1e+3 α= 1e+6	(1.31750e-13, 1.31847e-13)	1.31868e-13 [5]	1.31868e-13 [3]	9.06815e-15#
λ= 1e-4 δ= 1e+5 α= 1e+3	(1.30193e-10, 1.31350e-10)	1.30564e-10 [6]	1.30564e-10 [4]	1.19059e-11#

In each of these test cases, CARE III's unreliability estimates differ from the other estimates by more than an order of magnitude. Although examples 4 and 5 are still elementary models, they do indicate that as a model that incorporates transient faults increases in size, the error in CARE III's unreliability estimate also increases.

CONCLUSIONS

There are parameter regions in CARE III which cause the program to severely overestimate the reliability of a modeled system without warning the user. The source of the error in the CARE III estimates is not known; however, in the case of models that consider transient fault occurrences, the error appears to increase as larger models are analyzed. The CARE III user's guide states many restrictions, assumptions, and constraints that should be observed when using the program. However, there are many subtleties involved when modeling a system with CARE III. CARE III program also does not explicitly test for some of the parameter regions where the program does not perform correctly. Consequently, even an experienced user of CARE III unaware of all of the many subtleties of the program could easily generate wrong answers without any warning.

APPENDIX

The following is the input file used with SURE, PAWS, and STEM for model 1.

```
1,2= 3*LAMBDA;
2,3= 2*LAMBDA;
2,4= FAST DELTA;
4,5= 2*LAMBDA;
5,6= LAMBDA;
5,7= FAST DELTA;
7,8= LAMBDA;

RUN;
```

The input file used with CARE III for model 1 follows.

```
$FHMNAMES
     FHMNAME(1)= 'PERMANENT'
$END
$FLTTYP
     NFTYPS=1,
     ALP=       0.0    ,
     BET=       0.0    ,
     DEL=    1.0e+02   ,
     RHO=       0.0    ,
     EPS=       0.0    ,
     IDELF=       1    ,
     IRHOF=       1    ,
     IEPSF=       1    ,
     MARKOV=      1    ,
     PA=        1.0    ,
     PB=        0.0    ,
     C=         1.0    ,
     LGTMST=T
$END
$STGNAMES
     STGNAME(1)= 'PROCESSORS'
$END
$STAGES
     NSTGES=1,
     N =  3,
     M =  1,
     NSUB=   0,
     MSUB=   0,
     LC=  0,
     IRLPCD=1,
     RLPLOT=F,IAXSRL=2
$END
$FLTCAT
     NFCATS=1,
     JTYP(1,1)=  1,
     OMG(1,1)=       1.0    ,
     RLM(1,1)= 1.000000E-03
$END
$RNTIME
     FT=  10.0000    ,ITBASE=1,
     PSTRNC= 0.100000E-09,
     QPTRNC= 0.100000E-01,
     NPSBRN=20,
     CKDATA=T,
     SYSFLG=F,CPLFLG=T
$END
MODEL 1
1 3 4 4
1 1 3
4  2 1 2 3
```

The following is the input file used with SURE, PAWS, and STEM for model 2.

```
1,2 = 5*LAMBDA;
2,3 = 4*LAMBDA;
2,4 = FAST ALPHA;
4,2 = BETA;
4,5 = 4*LAMBDA;
5,6 = 3*LAMBDA;
5,3 = BETA;
5,7 = FAST ALPHA;
7,5 = 2*BETA;
7,8 = 3*LAMBDA;
8,9 = 2*LAMBDA;
8,6 = 2*BETA;
8,10 = FAST ALPHA;
10,8 = 3*BETA;
10,11 = 2*LAMBDA;
11,12 = LAMBDA;
11,9 = 3*BETA;
11,13 = FAST ALPHA;
13,11 = 4*BETA;
13,14 = LAMBDA;
2,15 = FAST DELTA;
5,18 = FAST DELTA;
8,21 = FAST DELTA;
11,24 = FAST DELTA;
15,16 = 4*LAMBDA;
16,17 = 3*LAMBDA;
16,18 = FAST ALPHA;
18,16 = BETA;
18,19 = 3*LAMBDA;
19,20 = 2*LAMBDA;
19,17 = BETA;
19,21 = FAST ALPHA;
21,19 = 2*BETA;
21,22 = 2*LAMBDA;
22,23 = LAMBDA;
22,20 = 2*BETA;
22,24 = FAST ALPHA;
24,22 = 3*BETA;
24,25 = LAMBDA;
16,26 = FAST DELTA;
19,29 = FAST DELTA;
22,32 = FAST DELTA;
26,27 = 3*LAMBDA;
27,28 = 2*LAMBDA;
27,29 = FAST ALPHA;
29,27 = BETA;
29,30 = 2*LAMBDA;
30,31 = LAMBDA;
30,28 = BETA;
30,32 = FAST ALPHA;
32,30 = 2*BETA;
32,33 = LAMBDA;
27,34 = FAST DELTA;
30,35 = FAST DELTA;
34,35 = 2*LAMBDA;
35,36 = LAMBDA;
```

The following is the input file used with CARE III for model 2.

```
$FHMNAMES
     FHMNAME(1)= 'INTERMITTENT'
$END
$FLTTYP
     NFTYPS=1,
     ALP=   3.6e+5     ,
     BET=   1.0e-5     ,
     DEL=   3.6e+2     ,
     RHO=      0.0     ,
     EPS=      0.0     ,
     IDELF=      1     ,
     IRHOF=      1     ,
     IEPSF=      1     ,
     MARKOV=     1     ,
     PA=       1.0     ,
     PB=       0.0     ,
     C=        1.0     ,
     LGTMST=T
$END
$STGNAMES
     STGNAME(1)= 'PROCESSORS'
$END
$STAGES
     NSTGES=1,
     N =  5,
     M =  1,
     NSUB=   0,
     MSUB=   0,
     LC=  0,
     IRLPCD=1,
     RLPLOT=F,IAXSRL=2
$END
$FLTCAT
     NFCATS=1,
     JTYP(1,1)=  1,
     OMG(1,1)=       1.0     ,
     RLM(1,1)= 1.000000E-02
$END
$RNTIME
     FT=  10.0000     ,ITBASE=1,
     PSTRNC= 0.100000E-09,
     QPTRNC= 0.100000E-01,
     NPSBRN=20,
     CKDATA=T,
     SYSFLG=F,CPLFLG=T
$END
MODEL 2
1 5 6 6
1 1 5
6  2 1 2 3 4 5
```

The following is the input file used with SURE, PAWS, and STEM for model 3.

```
1,2 = 3*LAMBDA;
2,3 = 2*LAMBDA;
2,1 = ALPHA;
2,4 = FAST DELTA;
4,5 = 2*LAMBDA;
5,6 = LAMBDA;
5,4 = ALPHA;
5,7 = FAST DELTA;
7,8 = LAMBDA;

LIST = 2;
RUN;
```

The following is the input file used with CARE III for model 3.

```
 $FHMNAMES
      FHMNAME(1)= 'TRANSIENT'
 $END
 $FLTTYP
      NFTYPS=1,
      ALP=   1.0e+03    ,
      BET=       0.0    ,
      DEL=   1.0e+05    ,
      RHO=       0.0    ,
      EPS=       0.0    ,
      IDELF=       1    ,
      IRHOF=       1    ,
      IEPSF=       1    ,
      MARKOV=      1    ,
      PA=        1.0    ,
      PB=        0.0    ,
      C=         1.0    ,
      LGTMST=T
 $END
 $STGNAMES
      STGNAME(1)= 'PROCESSORS'
 $END
 $STAGES
      NSTGES=1,
      N =  3,
      M =  1,
      NSUB=   0,
      MSUB=   0,
      LC=  0,
      IRLPCD=1,
      RLPLOT=F,IAXSRL=2
 $END
 $FLTCAT
      NFCATS=1,
      JTYP(1,1)=  1,
      OMG(1,1)=       1.0     ,
      RLM(1,1)= 1.000000E-03
 $END
 $RNTIME
      FT=  10.0     ,ITBASE=1,
      PSTRNC= 0.100000E-30,
      QPTRNC= 0.100000E-10,
      NPSBRN=20,
      CKDATA=T,
      SYSFLG=F,CPLFLG=T
 $END
 MODEL 3
 1 3 4 4
 1 1 3
 4  2 1 2 3
```

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Report Documentation Page

National Aeronautics and Space Administration

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-100524		

4. Title and Subtitle	5. Report Date
Examples of Nonconservatism in the CARE III Program	January 1988
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Kelly J. Dotson	
	10. Work Unit No. 505-66-21-01
9. Performing Organization Name and Address	11. Contract or Grant No.
NASA Langley Research Center Hampton, VA 23665-5225	
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, DC 20546-0001	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This paper presents parameter regions in the CARE III (Computer-Aided Reliability Estimation vs. 3) computer program where the program overestimates the reliability of a modeled system without warning the user. Five simple models of fault-tolerant computer systems are analyzed; and, the parameter regions where reliability is overestimated are given. The source of the error in the reliability estimates for models which incorporate transient fault occurrences was not readily apparent. However, the source of much of the error for models with permanent and intermittent faults can be attributed to the choice of values for the run-time parameters of the program.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
CARE III Fault-tolerant Reliability Markov model	Unclassified - Unlimited Star Category 65

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
unclassified	unclassified	26	A03

NASA FORM 1626 OCT 86