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General Monte Carlo Reliability Simulation Code Including Common Mode Failures and HARP Fault/Error-Handling

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1. Introduction

Variance reduction techniques have made feasible the use of the Monte Carlo method to simulate even large state space governing Markov processes such as those encountered here in modeling systems for reliability and/or availability evaluation. The present version of our Monte Carlo program for computing system unreliability effectively uses two variance reduction techniques: forced transitions and failure biasing [1,2]. The structure of the program differs from earlier versions as it was written to be consistent with the HARP code which employs behavioral decomposition [3,4,5]. This enables us to impartially demonstrate the capability of our Markov Monte Carlo method versus the Runge-Kutta method used in the HARP code to solve the Markov chain in the reliability analysis. The HARP provides several models for system fault/error-handling (called FEHM's or coverage models) which are accessible by our program (see Appendix A) In addition to these coverage models we separately incorporate into our program the handling of common mode failures and take into account their influence on the overall system unreliability. A listing of our program appears in Appendix C. In Appendix D is a copy of a previous paper [2] which provides more or less a summary of our work prior to the inclusion of common mode failures into the reliability simulation. What appears in Section 1.1 is a brief account of our work including the implementation scheme of our most general common mode failure model. The equations which appear here are more program-specific and indicative of the coding implications involved with programming the more general equations which appear in the paper of Appendix D.

1.1. Transition Rates and Probabilities Including Common Mode Failures

Each step in the simulation of a Monte Carlo trial requires the computation of the total transition rate $\gamma_k(t)$ out of the present system state k. This rate is given explicitly by

$$\gamma_k(t) = \gamma_{ck}(t) + \gamma_{nk}(t) + \gamma_{sk}(t) + \gamma_{cm} \qquad (1\ 1)$$

where

$$\gamma_{ck}(t) = \sum_{j=1}^{M_k} C_{jk}\lambda_{jk}(t)$$

$$\gamma_{nk}(t) = \sum_{j=1}^{M_k} N_{jk}\lambda_{jk}(t)$$

$$\gamma_{sk}(t) = \sum_{j=1}^{M_k} S_{jk}\lambda_{jk}(t)$$

and

$$\gamma_{cm} = \sum_{j=1}^{M} \nu_j$$

For computing γ_{ck}, γ_{nk}, and γ_{sk}, the summations include only the M_k number of operational components in state k with respective component failure rates $\lambda_{jk}(t)$. (We clarify that $\lambda_{jk}(t)$ represents the failure rate of component j at simulation state k and time t in the Monte Carlo trial. It represents a more general transition rate in Appendix D.) The coefficients C_{jk}, N_{jk}, S_{jk}, and R_{jk} are computed using Harp fault/error-handling models as explained in Appendix A. R_{jk} does not appear in Eq (1.1) since this fraction of the failure rate does not contribute to the transition rate "out" of state k The rate γ_{cm} is the contribution of common mode failures, with event rates ν_j, to the total transition rate out of state k. Since we consider the event rates ν_j to be independent of time, γ_{cm} will have the same value for all states k For time-increasing failure rates we must also compute $\gamma_k(T)$ where T is the simulation mission time corresponding to the design life of the system. This state-dependent, time-independent rate is greater than the actual transition rate $\gamma_k(t)$ and must be used for sampling the distribution function of times to the next state transition in the Monte Carlo trial [6].

To determine the next system state (k+1) in the simulation of the Monte Carlo trial, we must compute the following conditional probabilities

$$P_c = \gamma_{ck}/\gamma_k(T)$$

$$P_n = \gamma_{nk}/\gamma_k(T)$$

$$P_s = \gamma_{sk}/\gamma_k(T)$$

$$P_{cm} = \gamma_{cm}/\gamma_k(T)$$

and

$$P_{st} = 1 - P_f \tag{1.2}$$

where

$$P_f = P_c + P_n + P_s + P_{cm} \tag{1.3}$$

If only constant component failure rates are used, the self-transition probability P_{st} will be zero since $\gamma_k(T)=\gamma_k(t)$. Otherwise for $\gamma_k(T)>\gamma_k(t)$, the probability for self-transition inherently corrects for the biasing introduced by needing to use $\gamma_k(T)$ to sample the time of the next state transition. If $\gamma_k(T)$ is much larger that $\gamma_k(t)$, then P_{st} will be large In this case, for the purpose of variance reduction, we failure bias the probabilities in Eq (1.2) in order to increase the total failure transition probability P_f in Eq (1.3) The biased probabilities are given by

$$BP_c = P_c\,(X/P_f)$$

$$BP_n = P_n\,(X/P_f)$$

$$BP_s = P_s\,(X/P_f)$$

$$BP_{cm} = P_{cm}\,(X/P_f)$$

and

$$BP_{st} = 1 - X \tag{1.4}$$

where the failure biasing factor X is input by the user and has a typical value of 0.5. We note that biasing is only used when $P_f < X$, and otherwise the probabilities in Eq (1.2) are used

The type of transition (component failure, near coincident fault, single point failure, common mode failure, or self-transition) is determined by completely dividing the unit interval into disjoint subintervals of lengths proportional to the probabilities in Eq. (1.2) or Eq. (1.4), and then drawing a uniform random number between 0 and 1. The subinterval in which the random number lies corresponds to the type of transition For self-transitions there is no change in the system state and the Monte Carlo trial continues, while single point failure and near coincident fault transitions are system failure states which terminate the Monte

Carlo trial For a component failure transition, the failed component is found by dividing the unit interval into subintervals proportional to the (operational) component failure rates $\lambda_{jk}(t)$ and again using a random value to pick an interval corresponding to the failed component. It is then determined whether the new system state defined by the failed component is a system failure state or not This is discused in Section 2.2. We next discuss in detail how we determine the next system state for a common mode failure transition.

If the type of transition corresponds to common mode failure, we first determine the event i which caused the failure by dividing the unit interval into lengths proportional to the various event rates v_i and then using a random value ζ to pick the event Explicitly, event i may be chosen by satisfying the condition

$$\left(\frac{v_1 + .. + v_{i-1}}{\gamma_{cm}}\right) \leq \zeta < \left(\frac{v_1 + ... + v_i}{\gamma_{cm}}\right)$$

over $i=1, .., M$ with v_0 defined to be zero.

For each event i there is defined a next state probability vector denoted

$$\mathbf{PV}_i = (P_1, ..., P_y, ..., P_{l_i})$$

The l_i next state probabilities for event i are normalized to sum to one. Corresponding to each P_j is an n-tuplet K_j defining the number of components from each group which fail. (Component groups are discussed in Section 2.1.) The next state (k+1) is defined by failing the number of components in K_j corresponding to the probability P_j picked using a random value per the usual interval sampling method. In the most general case the system modeler must specify l_i, PV_i, and the n-tuplets K_j ($j=1, ..., l_i$), as well as the rates v_i, for each common mode failure event i Other less general options are also available as discussed in Section 2 4.

2. System Modeling for Markov Monte Carlo Evaluation

This chapter describes in general the system modeling options and the required input to the Monte Carlo program. Upon first executing the Monte Carlo code, the user is presented with three options:

1) Input a new system model;
2) Edit the old input file;
3) Use the input file as is.

The program always reads the input from a file named INPMC.DAT. Caution should be exercised in selecting option 1) or 2) as these options will overwrite this input file If you want to save the old contents of the file it should be copied to a different file name. Option 1) should be used in order to interactively create the input file for a new system model, while option 2) allows the user to respecify portions of the system model without having to recreate the whole file. The editing options available are:

1) Edit component group specifications;
2) Edit minimum cut set specifications;
3) Edit the near coincident fault model;
4) Edit the common mode failure model;
5) Change the design life (mission) time;
6) Change no. of time intervals for graphing;
7) Change number of Monte Carlo histories;
8) Change the non-analog default values;
9) Quit editing / Run Monte Carlo simulation.

The following sections discuss the various options and their association, if any, with the HARP program.

2.1. Component Group Specification

Component groups are sets of one or more identical components operating in active parallel. By identical we mean that components from the same group have the same constant failure rate, or have the same Weibull parameters if time-dependent rates are being used. In the HARP nomenclature component groups are referred to as component types or stages of redundant components. Unlike the HARP which allows the option of specifying component repair rates, we instead allow the user to associate with each group a specified number of spare components which may be inserted into the system model in place of failed components. Insertion of spares is equivalent to instantaneous repair of failed components and is consistent with the method of behavioral decomposition which is particularly valid if repair rates are orders of magnitude greater than component failure rates. It is assumed that the spare component replaces the failed component in good-as-new condition. Thus, if time-dependent (increasing) Weibull rates are being used, the failure rate of the installed spare will be less than the rates of the other group components since it's been operational for less time. If constant failure rates are being used, then the spare simply resumes the failure rate of the original and there is no change in the total group failure rate. To complete the specification of component groups, the system modeler must give.

1) The total number of component groups;
2) The number of components in each group;
3) The number of spares available for each group;
4) A distinct name for each component group;
5) The constant failure rate of components from each group;
6) The Weibull modulus for components from each group;
7) The Weibull scale parameter for components from each group;
8) The HARP fault/error-handling model file name for each group.

The HARP provides the option of choosing among several time-dependent distributions for component failure rates. We, however, implement only a Weibull rate of the form

$$\lambda(t) = \left(\frac{m}{\theta}\right)\left(\frac{t}{\theta}\right)^{m-1}$$

where m is the Weibull modulus and θ is the Weibull scale parameter. If only a constant failure rate is required, then both the Weibull modulus and scale parameter should be given as zero in 6) and 7). However, a Weibull component failure rate may be specified with a constant failure rate offset, and in this case the value given for 5) need not be zero. The time-dependent self-transition sampling method which we implement [6] allows for the use of only time increasing Weibull rates, so given moduli must be greater than one. If no fault handling is desired for a group, NONE should be entered in 8) as the fault/error-handling model file name.

2.2. Minimum Cut Sets

At any time during the model simulation individual components are classified as being operational or failed. A failed component replaced by a spare is considered to be operational, while components which are not replaced remain failed. At the beginning of the simulation time all components are assumed to be operational. All possible combinations of operational and failed components form the possible states the system may be in during a simulation run. Altogether a system with N components has 2^N system states. Of these, we are interested in only two categories: states for which the system is operational, and the system failure states To determine the state of the system, we compare the set of all failed components with the specified minimum cut sets for the modeled system. Minimum cut sets identify groups of minimal number of components which must not all be failed if the system is to be operational [7]. Thus if we find that all components in a particular cut set are failed, then we know that the system has failed. To specify the minimum cut sets it is necessary to have the components uniquely ordered It is the convention in this work to sequentially number all the components (but not spares) beginning with Component 1 in Group 1 through to the last component in the highest numbered group. See for example how the components are numbered in the 3-processor/2-memory/1-bus reliability block diagram shown in Fig. 2.1 With the components numbered as such, the system modeler must evaluate the minimum cut sets and input them to the Monte Carlo program. For the 3P2M1B example, the minimum cut sets are: (6), (4,5), (1,2,3).

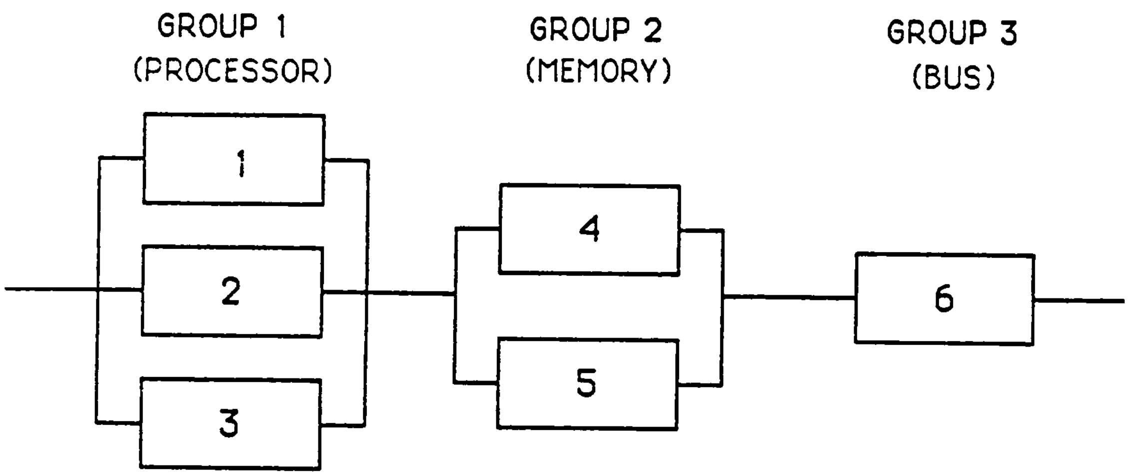


Figure 2.1. Reliability block diagram for 3P2M1B system model.

2.3. Near Coincident Faults

A near coincident fault (NCF) is a system failure event which occurs when the failure of a component interferes with the fault recovery process of the component just previously failed The HARP allows the system modeler to choose among four options for specifying the the NCF behavior of the system:

1) All inclusive NCF's;
2) Same component NCF's;
3) User defined NCF's;
4) No NCF's allowed.

Relying on values supplied by the HARP coverage models (see Appendix A), we have implemented these NCF options in our program in a manner consistent with that of the HARP. For type 1 NCF's, the failure of any component may fatally interfere with the fault recovery of any other component, whereas for type 2 NCF's, only a component failure within the same group could interfere with fault recovery of a component from that group. If neither of these types adequately characterizes the NCF behavior of the system, the user can explicitly define interfering component groups (option 3), or simply choose to ignore the occurrence of NCF's (option 4). Since the components in groups are identical, user defined NCF's can be specified in terms of group numbers with the understanding that the relationship given among groups applies actually to each of the individual components of the groups. Thus, for each component group, the system modeler can provide a listing of all the groups by number whose components can interfere with the fault recovery of a component from the particular group in question. For example, Fig. 2.2 shows user defined interfering groups for the 3P2M1B system model. In this case, a processor failure could interfere with fault recovery of another processor or with fault recovery from a memory error, while either another memory fault or a bus failure would interfere with memory fault recovery, but would not interfere with fault recovery of a processor failure.

Group Number	Group Name	Interfering Groups Listed By Number
1	processor	1
2	memory	1, 2, 3
3	bus	(none)

Figure 2.2. Interfering component groups for 3P2M1B system model

2.4. Common Mode Failures

A common mode failure (CMF) event occurs when more than one system component fails due to a single common cause (such as lightening, fire, explosion, vibration, flood, power failure, or faulty maintenance). In this work, CMF's are considered to be random events and can therefore be characterized as having constant CMF event rates. We allow the system modeler the option of specifying none or up to several different CMF events. Each event may be modeled using one of the following options to be discussed presently:

1) Beta-factor;
2) Random generated;
3) User defined;
4) System failure.

Since the ability to obtain CMF data is fairly limited, the CMF models presented here are rather loosely constructed so that the input data required is minimal.

2.4.1. Beta-Factor Model for Common Mode Failure Events

The β-factor model [7] can be applied to any number of the component groups To apply the model interactively, a component group number must first be selected If the component failure rate for this group is constant, the value is displayed and then the system modeler is asked to estimate what fraction β of the component failure rate is due to common cause The component failure rate is then reduced by this fractional amount and a new CMF event rate is established to make up the difference. Now the failure rate of components in the group consists of the sum of two parts an independent part which acts in parallel and a common mode part which acts in series The chance that only a single component fails is reduced by an amount now allotted to the chance that every component in the group could fail at once, thus causing immediate system failure. If the component failure rate for the group selected is a time dependent Weibull rate, then the β-factor model cannot be generally applied. In this case the user is asked to estimate a constant CMF event rate to act in series with the group components At any time, the total component failure rate is the sum of the Weibull rate plus the CMF event rate

2.4.2. Random Generated Common Mode Failure Events

For the β-factor model, a CMF event would fail all of the components in a group causing immediate system failure. This is a most severe type of CMF To model the uncertainty in the severity of a particular CMF event, the system modeler has the option of letting the number of components which fail due to a CMF event be random. To do this the modeler must specify a CMF event rate and also give the maximum number of components from each group which could be failed by this event. If the event occurs during simulation, the number of components from each group which fail is selected randomly between one and the maximum number specified (if greater than zero). In this case it is possible that a CMF event may not cause immediate system failure. If the system survives the CMF event, the components failed by the event remain failed No spares are used

2.4.3. User Defined Common Mode Failure Events

If more data is available regarding the occurrence of a particular CMF event, the system modeler may wish to specify a more detailed model for the event This is done interactively by first giving the CMF event rate Then the user is asked the number of next state possibilities expected if the event should happed to occur, and must specify probabilities for the likelihood of entering each of these states. These next state probabilities are automatically normalized to sum to one and stored as entries in the next state probability vector for the event. Each of the next state possibilities must in turn be specified by giving the number of components from each group which would be failed by the event. If the event occurs during simulation of the model, the next system state is determined by summing in order the entries of the probability vector until the sum exceeds a generated random value between 0 and 1. The latest entry position encountered while summing then corresponds to the next system state. It would be tedious to enter too many next state possibilities, and generally there is insufficient data available to do so. It may be appropriate to lump the many next state possibilities into just a few states One state could perhaps be specified to guarantee with a certain probability that system failure will occur, and two or three more states which have a chance of not being system failure states.

2.4.4. System Failure Common Mode Failure Events

The last option for modeling a CMF event is to treat the event as if it were an all inclusive NCF resulting in immediate system failure. In this case, just a constant CMF rate for the event must be specified. System failure CMF events can also be used to model single point failures as an alternative to relying on the HARP coverage models. A single point failure (SPF) occurs when fault handling does not prevent a component failure from causing immediate failure of the system

2.5. Other Modeling Parameters and Default Values

Before Monte Carlo simulation of the system model can begin, the user must specify the design life or mission time for the model. The units used for the design life should of course be consistent with the component failure rates and any CMF event rates Also the user must choose an integer (between 1 and 300) for the number of time intervals within the design life for reporting the system unreliability in discrete time steps for graphing. The number of Monte Carlo histories (or trials) to run must also be specified. In addition, the user has the option of changing two default values internal to the program: the so called "analog switch" and the failure biasing factor. The first involves the case-splitting method we implement [1] for sampling the distribution function of times to the next state transition. If during simulation of the model the expected number of state transitions within the remaining life time is large, normal analog sampling is used. Otherwise non-analog sampling from a modified distribution function forces transitions to occur within the remaining mission time. If the expected number of transitions is very small, rare event non-analog sampling is used and could continue forcing transitions indefinitely (if there are repair rates) or until the system reaches a failed state. We note that forcing transitions causes more of the Monte Carlo histories to end in system failure which helps to reduce the sampling variance, but has the potential of being computationally time consuming To improve run-time of the program, we arbitrarily switch to analog sampling exclusively after 90 percent of the mission time per history has been simulated. On some trial problems we have observed that the program runs most efficiently (highest figure of merit) when about two-thirds of the Monte Carlo histories end in system failure. To aid the user in setting the switch, the fraction of histories ending in system failure is displayed at the terminal after each run of the program. If it is too low, better results may be obtained by rerunning the program with the analog switch set higher to perhaps 95 percent. The failure biasing factor, on the other hand, is less critical than the analog switch Since our code employs behavioral decomposition with no repair rates, all state transitions are necessarily failure oriented so there is no need to bias the system toward failing If time dependent rates are used however, failure biasing may be significant due to the fact that the self-transition probability [6] may become large Even so the default value of 0.5 is likely to be sufficient in all cases where time dependent rates are being used. Further investigation is necessary regarding the optimal setting for these default values.

3. Example Models and Results

The Monte Carlo program writes the results of the unreliability calculations to a file named OUTMC.DAT. In addition to the overall mission time unreliability, the solution includes the unreliability attributed to each component group and for the total exhaustion of hardware including all groups, as well as the unreliability due to single point failures, near coincident faults, and common mode failures. To compute the SPF and NCF unreliabilities we rely on values supplied by the HARP coverage models (see Appendix A), whereas the unreliability due to CMF is computed directly by our program without using the HARP. File OUTGR DAT provides data for graphing the overall system unreliability plus or minus the standard deviation (68 percent confidence) over the specified number of time intervals within the design life. To avoid overwriting these two output files, they should be copied to a different file name before the Monte Carlo program is rerun The examples which follow demonstrate the use and capability of the Monte Carlo program. Both of the system models presented here are benchmark (tutorial) problems appearing in the HARP literature [4,5]. The results we present were computed on a Sun SPARCstation 1 We found that our program runs about twice as fast on the Sun than on the VAX 11/785 where the program was previously installed.

3.1. 3-Processor/2-Memory/1-Bus System model

The reliability block diagram for this model is shown in Fig. 2.1. Let the failure rate of each processor be 10^{-4}/hr, each memory unit be 10^{-5}/hr, and that of the bus be 10^{-6}/hr [4,5]. We wish first to consider some perfect-coverage (no HARP fault handling) examples which show the effect of using the various CMF event options. Suppose, for example, we model a processor CMF event using the β-factor model. Fig. 3 1 shows how this affects the overall system unreliability at 10 hours for values of β ranging from 0 to 20 percent. The analytic solution is trivial in this case and is also plotted in the figure to show the correctness of the Monte Carlo calculations For higher values of β, the chance of CMF of the processors and, hence, the probability of system failure is greater corresponding to the rise in system unreliability as seen in the figure. In Appendices B.1 and B.2 we provide listings of the Monte Carlo output files for the cases β=0 (no CMF's) and β=20 percent. Note that when using the β-factor model, the component failure rate is

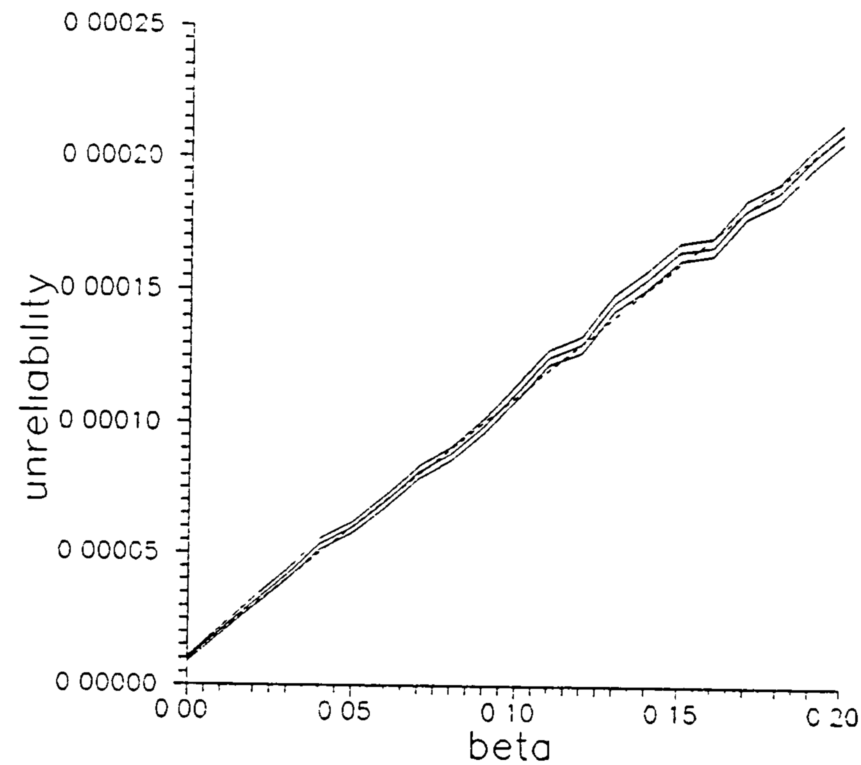


Figure 3.1. Plot of 3P2M1B system unreliability (and 68% confidence interval) at 10 hours with processor CMF's as β increases from 0 to 20 percent. The dotted line is the analytical solution.

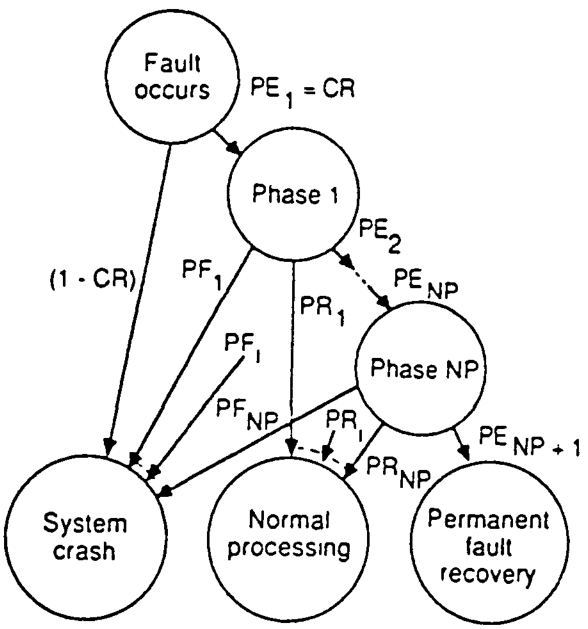
reduced by β-percent and a new CMF event rate is established to make up the difference. Thus in Appendix B.2, we see that the processor failure rate has been reduced by 20 percent from 10^{-4}/hr to 8×10^{-5}/hr, and the difference of 2×10^{-5}/hr became the transition rate for CMF Event 1. When using the other options to model CMF events, no component failure rates are modified in this manner. Instead, the user specifies a CMF event rate which acts in addition to any of the component rates previously specified. The impact of CMF's on the overall unreliability of the system can be varied according to the option used to model the event. For example, Table 3.1 compares the 3P2M1B perfect-coverage system unreliability at 10 hours in the case where no CMF's were allowed, and three cases which included a CMF event modeled by different options. In each of the three cases the CMF event rate was given as 10^{-6}/hr. For the random event case, the next state was specified as (3,2,0) which means that at most all three processors and both memory units could be failed if the event occurs. The random outcomes for the next state are then (1,1,0), (2,1,0), (3,1,0), (1,2,0), (2,2,0), and (3,2,0). Of these six, four are certain to be system failure states and thus the event has at least a two-thirds chance of causing system failure. On the other hand, the user defined event was arranged to have only a one-third chance or more of being the cause of system failure and so the unreliability in this case is less. The next state probability vector was given as (0.33, 0.27, 0.18, 0.22) and the corresponding next states as [(3,2,1), (2,0,0), (2,1,0), (1,1,0)]. The first state (3,2,1) guarantees a 33 percent chance of system failure, while the other states may or may not be system failure states depending on the state of individual components at the time the CMF event occurs. For the last case in Table 3 1, the CMF event had a 100 percent chance of causing system failure and so the unreliability in this case is the highest.

Output File	CMF Event	Unreliability
Appendix B.1	None	$(9.57 \pm 0.87) \times 10^{-6}$
Appendix B.3	Random Generated	$(1.69 \pm 0.12) \times 10^{-5}$
Appendix B.4	User Defined	$(1.26 \pm 0.10) \times 10^{-5}$
Appendix B.5	System Failure	$(2.03 \pm 0.13) \times 10^{-5}$

Table 3.1. Results showing the effects of using different CMF event options.

We next consider an imperfect-coverage 3P2M1B example utilizing the HARP fault/error-handling capabilities for modeling single point and near coincident faults For handling processor faults, we use the ARIES model shown in Fig. 3.2, and for memory faults the Probabilities and Moments model shown in Fig. 3.3. For handling NCF's, user-defined interfering groups as shown in Fig. 2.2 are specified Using the same component failure rates as before, Fig 3.4 shows the overall system unreliability as a function of time for two cases In the first case no

CMF's were allowed, and for the second case we included in the model specification a system failure CMF event with rate 10^{-6}/hr Including the CMF event increased the unreliability as seen in the figure. The detailed results for these two cases are provided in Appendices B 6 and B.7. In Appendix B.8 are imperfect-coverage results (without CMF's) for the 3P2M1B example using time-dependent rates rather than constant rates as before. A Weibull modulus of 2.5 was used for each of the components and the scale parameters were chosen so that the unreliability at 10 hours was comparable with the unreliability obtained when constant rates were used. The unreliability as a function of time for this case is plotted in Fig. 3.5. Using time-dependent rates increased the computational time by a factor of ten over the constant rate case.



Values required by HARP as input -

Probability that fault is transient	85
Mean duration of transient fault	05
Probability that fault is catastrophic	.001
Number of transient recovery phases	6

Phase	Duration	Effectiveness
1	01	0
2	02	1
3	03	.2
4	04	5
5	05	7
6	08	01

Coverage of permanent fault 85

Given that a fault occurs, the following parameters are derived from the above HARP input values -

CR probability that fault is noncatastrophic
PF probability that system crashes
PE probability that system enters recovery state
PR probability that transient recovery is successful

Figure 3.2. The ARIES transient-fault recovery model and parameterization for processors [5].

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PROBABILITIES AND MOMENTS

TRANSIENT RESTORATION EXIT
  EXIT PROBABILITY  9800
  FIRST MOMENT OF TIME TO EXIT   0
  SECOND MOMENT OF TIME TO EXIT   0
  THIRD MOMENT OF TIME TO EXIT  0

RECONFIGURATION COVERAGE EXIT
  EXIT PROBABILITY  1615e-01
  FIRST MOMENT OF TIME TO EXIT   0 4500
  SECOND MOMENT OF TIME TO EXIT   0 2500
  THIRD MOMENT OF TIME TO EXIT   0

SINGLE POINT FAILURE EXIT
  EXIT PROBABILITY  3850e-02
  FIRST MOMENT OF TIME TO EXIT   0
  SECOND MOMENT OF TIME TO EXIT   0
  THIRD MOMENT OF TIME TO EXIT   0
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Figure 3.3. Description of the FEHM for Memory Subsystem [5].

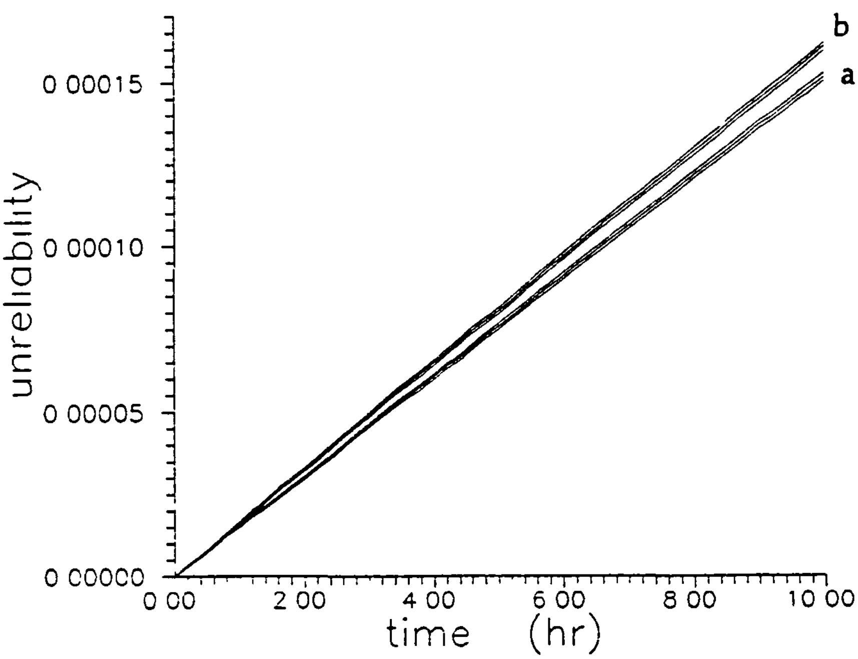

Figure 3.4. Plot of system unreliability (and 68% confidence interval) as a function of time for the 3P2M1B model with HARP fault handling for two cases: a) No common mode failures and b) A system failure common mode failure event with rate 10^{-6}.

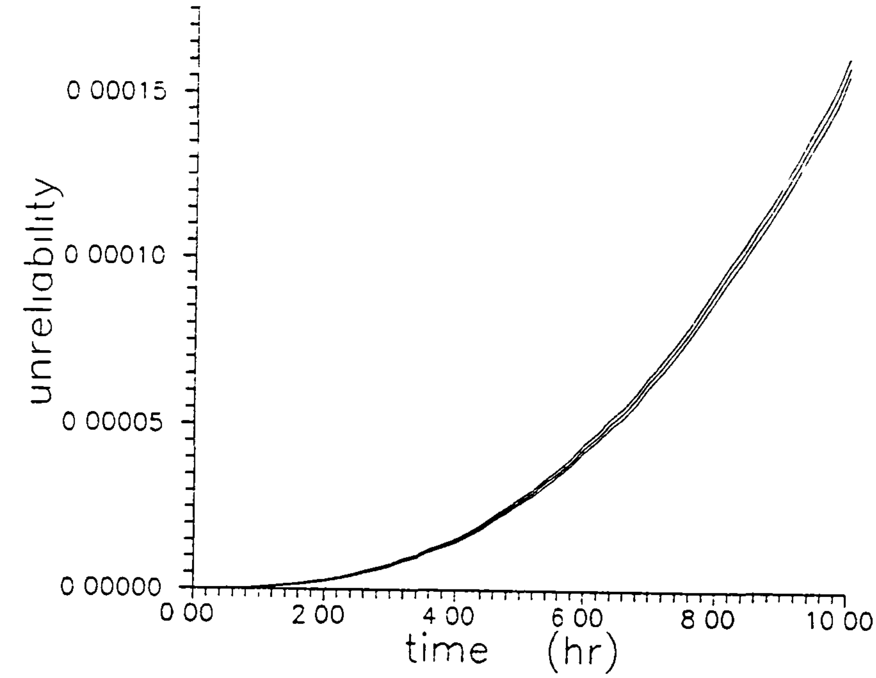

Figure 3.5. Plot of system unreliability (and 68% confidence interval) as a function of time for the 3P2M1B model using time-dependent component failure rates.

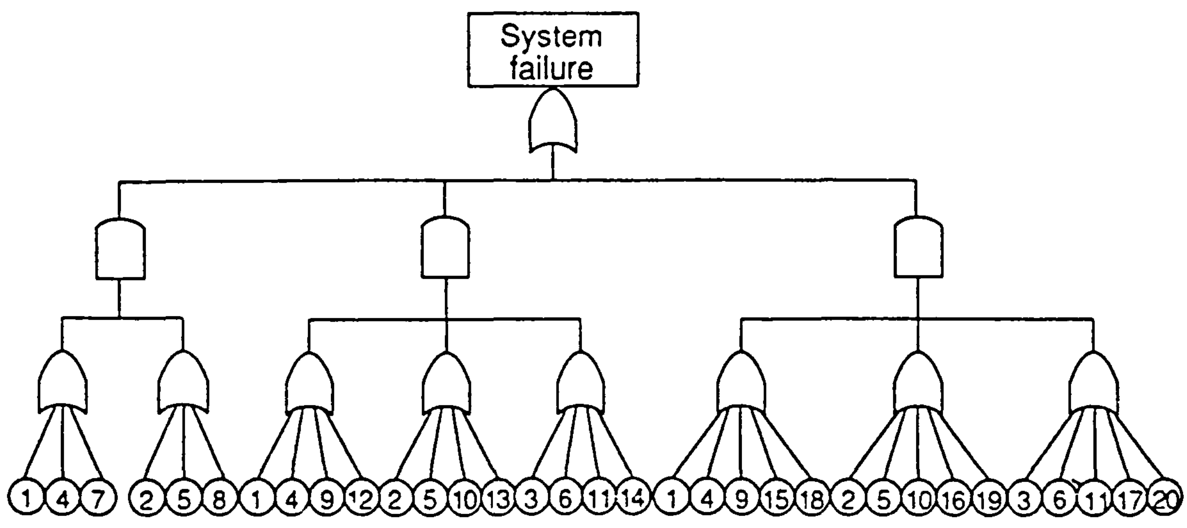

Figure 3.6. Fault tree representation of a fault tolerant jet engine control system. (If two basic event labels are the same, they represent the same component) [5].

3.2 Jet Engine Control System Model

To demonstrate the capability of the Monte Carlo method to simulate larger models, we consider next the jet engine control problem which has twenty components distributed among seven groups. The constant component failure rates are listed in Table 3.2. From the system fault tree shown in Fig. 3.6, we were able to determine 171 minimum cut sets. In the first example we use the HARP Markov version of the CARE III model shown in Fig. 3.7 for fault handling, with the error detectability for data collectors set at 0.97, and 0.99 for all other groups. The Monte Carlo solution is listed in Appendix B.9 It took just over 8 minutes to run 40,000 histories. The overall unreliability result of $(0.111 \pm 0.009) \times 10^{-4}$ compares well with the HARP result of 0.11153×10^{-4} [5]. In this example (which neglects NCF's), the single point failure probability contributes most significantly to the system unreliability. Rather than using the CARE III model, we also solved the problem using CMF's to equivalently model this single point failure probability We used the β-factor model with β set at 0.02 for data collectors and 0.01 for all other groups. The results for this case, given in Appendix B.10, are comparable with the results in Appendix B.9. To conclude the jet engine control examples, the plot in Fig. 3.8 shows the effect of using spare components. The cases plotted are perfect-coverage unreliability results (without HARP fault handling or CMF'S) in which no spares were used (Appendix B.11) as compared to a case in which two spare power supplies were available (Appendix B.12). Including the spare components increased the computational time by only 100 seconds over the no-spare case. The overall perfect-coverage unreliability at 10 hours with no spares was computed to be $(0.273 \pm 0.006) \times 10^{-6}$ in good agreement with the HARP result of 0.27088×10^{-6} [5].

Stage	Basic events	Failure rate
Power supplies	1,2,3	3.00×10^{-5}
Input controllers	4,5,6	1.50×10^{-5}
Data collectors	7,8	7.00×10^{-6}
CPU's	9,10,11	3.26×10^{-5}
1553 buses	12,13,14	1.00×10^{-5}
Output drivers	15.16,17	3.00×10^{-6}
Cross channel data link receivers	18 19,20	4.26×10^{-6}

Table 3.2 Description of Stages [groups] and Basic Events [components] for the Jet Engine Control System [5].

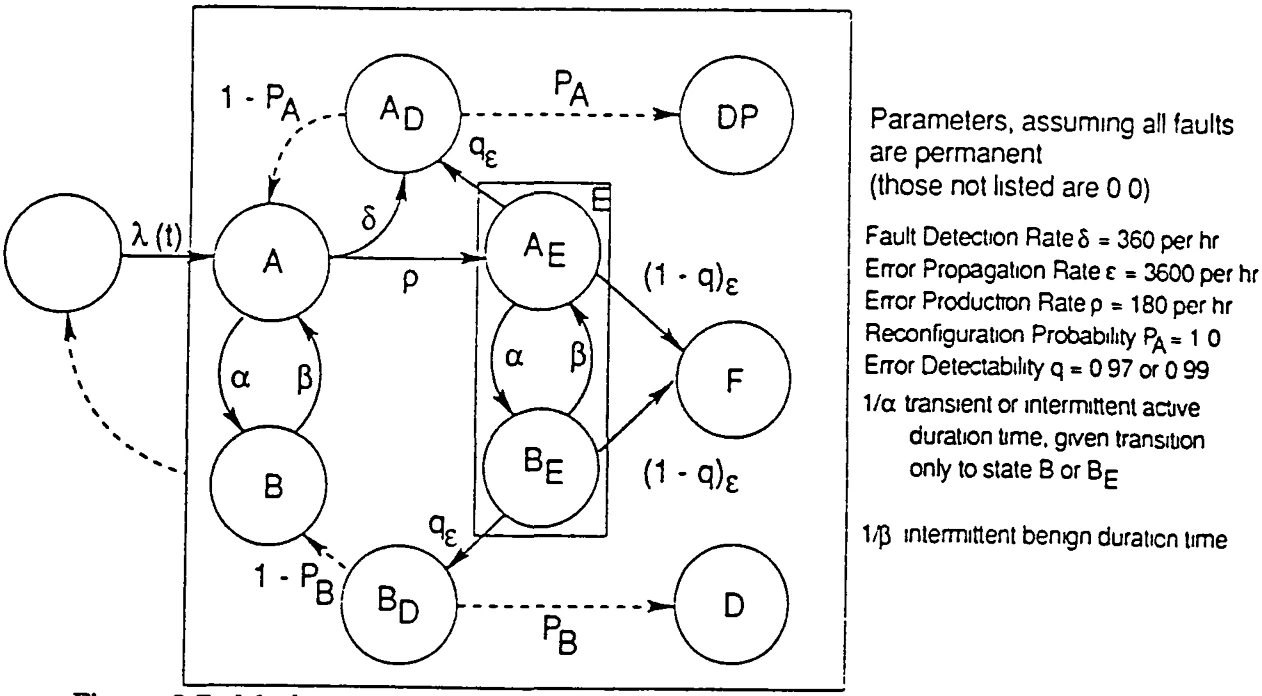

Figure 3.7. Markov version of the CARE III single-fault model [5].

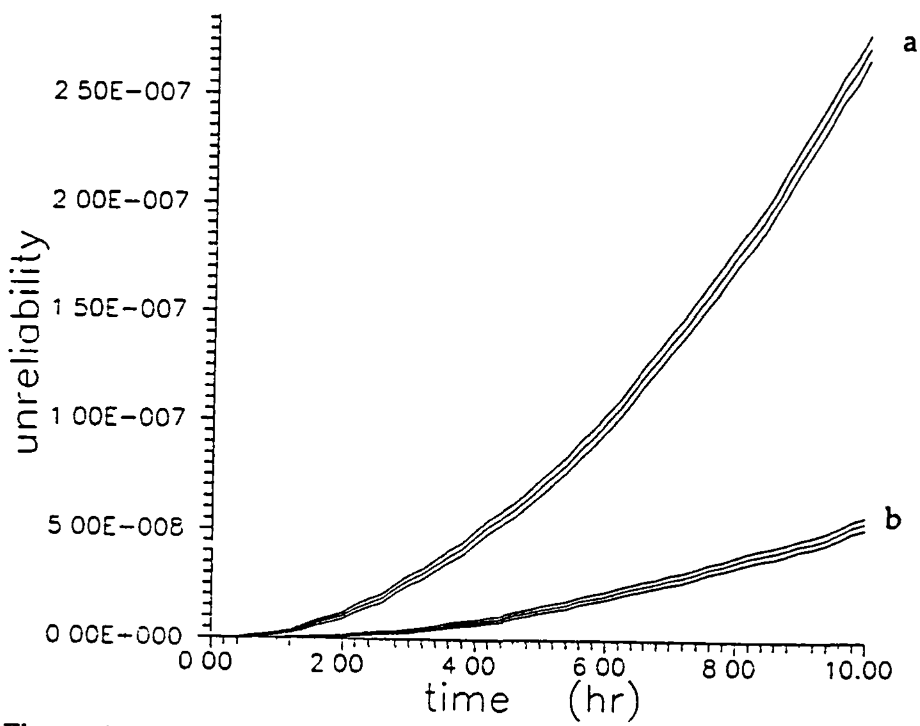

Figure 3.8 Plot of perfect-coverage system unreliability (and 68% confidence interval) as a function of time for the jet engine control model for two cases: a) No spare components and b) Two spare power supplies available.

References

1. Lewis, E. E., and Boehm, F., "Monte Carlo Simulation of Markov Unreliability Models," *Nuclear Engineering and Design*, Vol. 77, 1984, Pp. 49-62.

2. Lewis, E. E., Boehm, F., Kirsch, C., and Kelkhoff, B., "Monte Carlo Simulation of Complex System Mission Reliability," Proceedings of the 1989 Winter Simulation Conference, December 4-6, 1989, Washington D.C., Pp. 497-504.

3. Rothmann, Elizabeth M., Dugan, J. B., Trivedi, K. S., Boyd, Mark A., Mittal, Nitin, Bavuso, Salvatore J., "HARP, Hybrid Automated Reliability Predictor Introduction and Guide for Users," Version 6.1, Dept. of Computer Science, Duke University, May 1990.

4. Bavuso, S. J., Dugan, J. B., Trivedi, K. S., Rothmann, E. M., and Smith, W. E., "Analysis of Typical Fault-Tolerant Architectures Using HARP," *IEEE Transaction on Reliability*, Vol. R-36, No. 2, June 1987, Pp. 176-185.

5. Bavuso, S. J., Dugan, J. B., Trivedi, K., Rothmann, B., and Boyd, M., NASA Technical Paper 2760, 1987.

6. Lewis, E. E., Zhuguo, T., "Monte Carlo Reliability Modeling by Inhomogeneous Markov Precesses," *Reliability Engineering*, Vol. 16, 1986, Pp. 277-296.

7. Lewis, E. E., Introduction to Reliability Engineering, John Wiley Sons, New York, 1987, Pp. 225-228, 361-370.

Appendix A: Interfacing with the HARP

The HARP provides several coverage models (FEHM's) of varying complexity and applicability for handling transient, intermittent, and permanent faults [3]. The system modeler may apply an appropriate FEHM for handling component faults within a particular group. For each FEHM specified, our Monte Carlo program relies on the HARP for computing the (exit) probability R_o (transient restoration) that the system will recover from a transient fault, C_o (permanent coverage) that the system will be successfully reconfigured to eliminate a permanent (or intermittent or transient) fault, and S_o (single point failure) that the fault will cause system failure. These values (called exit probabilities) must then be adjusted to account for the state-dependent probability N that the system may fail due to a near coincident fault. For this purpose, the HARP also provides the first three moments in time (RM1, RM2, RM3, CM1, CM2, CM3, SM1, SM2, SM3) required to reach each exit (R, C, S) in the fault handling process. These moments are applied in a Taylor series expansion in order to get the state-dependent fault handling exit probability

$$R = R_o\left(1 - (\gamma_f)(RM1) + \frac{1}{2}(\gamma_f^2 - 2\,\dot{\gamma}_f)(RM2) - \frac{1}{6}(\gamma_f^3 - 6\,\gamma_f\,\dot{\gamma}_f + 3\,\ddot{\gamma}_f)(RM3)\right)$$

Likewise, C and S are computed. The NCF probability N is then equal to 1-R-C-S. For each component, the NCF rate γ_f is the sum of the failure rates (at the time of the fault) of all other (operational) components whose failure could interfere with the fault recovery process of that particular component. If only constant failure rates are used, the derivatives $\dot{\gamma}_f$ and $\ddot{\gamma}_f$ are zero which greatly simplifies the computation. The following is a listing of the Sun command file (called a makefile) used to compile and link our Monte Carlo source code file (mccode.f) to the appropriate HARP FEHM source files to form the executable file mcHARP.out.

```
mcHARP.out :
       f77 -dalign -o mcHARP.out \
       cfhmmc.f ari.f aries.f ariesinp.f \
       car.f care.f careinp.f cformat.f covfac.f devgen.f \
       dis.f distinp.f dists.f emp.f empir.f empirinp.f \
       espn.f espninp.f harpsim.f mom.f moments.f \
       mominp.f simdrv.f states.f mccode.f
```

The ".f" indicates Sun FORTRAN 77 source code. The HARP main program CFEHM in file cfhmmc.f was altered to allow users to only create or edit FEHM's and to run our Monte Carlo code as a subroutine of CFEHM The HARP subroutine COVNOM in file covfac.f is called by our code to get the exit probabilities and moments for each user-specified FEHM. The values returned by COVNOM are saved on a file named VALUES.DAT. Alternatively, our program can be run without interfacing with the HARP using the executable file mcpro.out compiled from the source code mcpro.f. In this case FEHM values can be read from the VALUES.DAT file or perfect-coverage values (C=1, R=S=N=0) can be used. In either version of the program, we separately implement the handling of common mode failures without using the HARP.

Appendix B

Monte Carlo Output Files for Example Problems

```
=======================================
 MONTE CARLO UNRELIABILITY CALCULATION      APPENDIX B.1
=======================================

 NUMBER OF COMPONENT GROUPS:  3

 NUMBER OF COMPONENTS IN GROUP processor     :  3
 NUMBER OF SPARES FOR GROUP processor        :  0
 FAILURE RATE FOR COMPONENT processor        :  0.1000D-03
 WEIBULL MODULUS OF COMPONENT processor      :  0.0000D+00
 SCALE PARAMETER OF COMPONENT processor      :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP processor     : NONE

 NUMBER OF COMPONENTS IN GROUP memory        :  2
 NUMBER OF SPARES FOR GROUP memory           :  0
 FAILURE RATE FOR COMPONENT memory           :  0.1000D-04
 WEIBULL MODULUS FOR COMPONENT memory        :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT memory        :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP memory        : NONE

 NUMBER OF COMPONENTS IN GROUP bus           :  1
 NUMBER OF SPARES FOR GROUP bus              :  0
 FAILURE RATE FOR COMPONENT bus              :  0.1000D-05
 WEIBULL MODULUS FOR COMPONENT bus           :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT bus           :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP bus           : NONE

 MISSION TIME FOR THIS MODEL:                   10.00
 NUMBER OF MONTE CARLO HISTORIES:               40000
 NEAR COINCIDENT FAULT MODEL:                   4


 UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 1
 ----------------------------------------------------
 UNRELIABILITY  =  0.9986245D-09 +/-  0.7795827D-11
 SAMPLE VARIANCE  =         0.2430997D-17
 COEFFICIENT OF VARIATION = 0.7806565D-02


 UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 2
 ----------------------------------------------------
 UNRELIABILITY  =  0.8598134D-08 +/-  0.1171477D-08
 SAMPLE VARIANCE  =         0.5489432D-13
 COEFFICIENT OF VARIATION = 0.1362478D+00


 UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 3
 ----------------------------------------------------
 UNRELIABILITY  =  0.9564956D-05 +/-  0.8741179D-06
 SAMPLE VARIANCE  =         0.3056328D-07
 COEFFICIENT OF VARIATION = 0.9138755D-01
```

```
OVERALL UNRELIABILITY DUE TO EXHAUSTION OF HARDWARE
---------------------------------------------------
UNRELIABILITY  =  0.9574552D-05 +/-  0.8741160D-06
SAMPLE VARIANCE  =         0.3056315D-07
COEFFICIENT OF VARIATION = 0.9129576D-01


UNRELIABILITY DUE TO SINGLE POINT FAILURE
-----------------------------------------

UNRELIABILITY  =  0.0000000D+00 +/-  0.0000000D+00
SAMPLE VARIANCE  =         0.0000000D+00
COEFFICIENT OF VARIATION = 0.0000000D+00


UNRELIABILITY DUE TO NEAR COINCIDENT FAULT
-----------------------------------------

UNRELIABILITY  =  0.0000000D+00 +/-  0.0000000D+00
SAMPLE VARIANCE  =         0.0000000D+00
COEFFICIENT OF VARIATION = 0.0000000D+00


UNRELIABILITY DUE TO COMMON MODE FAILURE
-----------------------------------------

UNRELIABILITY  =  0.0000000D+00 +/-  0.0000000D+00
SAMPLE VARIANCE  =         0.0000000D+00
COEFFICIENT OF VARIATION = 0.0000000D+00


OVERALL SYSTEM CALCULATION:
===========================

****************************************************
* UNRELIABILITY  =  0.9574552D-05 +/- 0.8741160D-06*
* SAMPLE VARIANCE  =        0.3056315D-07          *
* COEFFICIENT OF VARIATION= 0.9129576D-01          *
* FIGURE OF MERIT  =        0.1350635D+11          *
* TIME PER HISTORY =        0.2422500D-02          *
****************************************************

CPU CALCULTION TIME:   0.9690E+02 SECONDS
```

```
========================================
 MONTE CARLO UNRELIABILITY CALCULATION       APPENDIX B.2
========================================


 NUMBER OF COMPONENT GROUPS:  3

 NUMBER OF COMPONENTS IN GROUP processor     :  3
 NUMBER OF SPARES FOR GROUP processor        :  0
 FAILURE RATE OF COMPONENT processor         :  0.8000D-04
 WEIBULL MODULUS OF COMPONENT processor      :  0.0000D+00
 SCALE PARAMETER OF COMPONENT processor      :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP processor     : NONE

 NUMBER OF COMPONENTS IN GROUP memory        :  2
 NUMBER OF SPARES FOR GROUP memory           :  0
 FAILURE RATE OF COMPONENT memory            :  0.1000D-04
 WEIBULL MODULUS OF COMPONENT memory         :  0.0000D+00
 SCALE PARAMETER OF COMPONENT memory         :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP memory        : NONE

 NUMBER OF COMPONENTS IN GROUP bus           :  1
 NUMBER OF SPARES FOR GROUP bus              :  0
 FAILURE RATE OF COMPONENT bus               :  0.1000D-05
 WEIBULL MODULUS OF COMPONENT bus            :  0.0000D+00
 SCALE PARAMETER OF COMPONENT bus            :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP bus           : NONE

 TRANSITION RATE FOR CMF EVENT 1:               0.2000D-04
 MISSION TIME FOR THIS MODEL:                   10.00
 NUMBER OF MONTE CARLO HISTORIES:               40000
 NEAR COINCIDENT FAULT MODEL:                   4


 UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 1
 ----------------------------------------------------
 UNRELIABILITY  =  0.5066846D-09 +/-  0.5305886D-11
 SAMPLE VARIANCE  =         0.1126097D-17
 COEFFICIENT OF VARIATION = 0.1047177D-01


 UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 2
 ----------------------------------------------------
 UNRELIABILITY  =  0.1171366D-07 +/-  0.1249942D-08
 SAMPLE VARIANCE  =         0.6249418D-13
 COEFFICIENT OF VARIATION = 0.1067080D+00


 UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 3
 ----------------------------------------------------
 UNRELIABILITY  =  0.1048077D-04 +/-  0.8559085D-06
 SAMPLE VARIANCE  =         0.2930318D-07
 COEFFICIENT OF VARIATION = 0.8166465D-01
```

```
OVERALL UNRELIABILITY DUE TO EXHAUSTION OF HARDWARE
---------------------------------------------------
UNRELIABILITY  =  0.1049299D-04 +/-  0.8559057D-06
SAMPLE VARIANCE  =          0.2930298D-07
COEFFICIENT OF VARIATION = 0.8156927D-01


UNRELIABILITY DUE TO SINGLE POINT FAILURE
-----------------------------------------

UNRELIABILITY  =  0.0000000D+00 +/-  0.0000000D+00
SAMPLE VARIANCE  =          0.0000000D+00
COEFFICIENT OF VARIATION = 0.0000000D+00


UNRELIABILITY DUE TO NEAR COINCIDENT FAULT
-----------------------------------------

UNRELIABILITY  =  0.0000000D+00 +/-  0.0000000D+00
SAMPLE VARIANCE  =          0.0000000D+00
COEFFICIENT OF VARIATION = 0.0000000D+00


UNRELIABILITY DUE TO COMMON MODE FAILURE
-----------------------------------------

UNRELIABILITY  =  0.1992120D-03 +/-  0.3603330D-05
SAMPLE VARIANCE  =          0.5193595D-06
COEFFICIENT OF VARIATION = 0.1808791D-01


OVERALL SYSTEM CALCULATION:
===========================

****************************************************
* UNRELIABILITY  =  0.2097050D-03+/- 0.3689451D-05 *
* SAMPLE VARIANCE  =        0.5444818D-06          *
* COEFFICIENT OF VARIATION= 0.1759353D-01          *
* FIGURE OF MERIT  =        0.8079223D+09          *
* TIME PER HISTORY =        0.2273249D-02          *
****************************************************

CPU CALCULTION TIME:   0.9093E+02 SECONDS
```

```
=======================================
 MONTE CARLO UNRELIABILITY CALCULATION      APPENDIX B.3
=======================================

 NUMBER OF COMPONENT GROUPS:  3

 NUMBER OF COMPONENTS IN GROUP processor     :  3
 NUMBER OF SPARES FOR GROUP processor        :  0
 FAILURE RATE FOR COMPONENT processor        :  0.1000D-03
 WEIBULL MODULUS FOR COMPONENT processor     :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT processor     :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP processor     : NONE

 NUMBER OF COMPONENTS IN GROUP memory        :  2
 NUMBER OF SPARES FOR GROUP memory           :  0
 FAILURE RATE FOR COMPONENT memory           :  0.1000D-04
 WEIBULL MODULUS FOR COMPONENT memory        :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT memory        :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP memory        : NONE

 NUMBER OF COMPONENTS IN GROUP bus           :  1
 NUMBER OF SPARES FOR GROUP bus              :  0
 FAILURE RATE FOR COMPONENT bus              :  0.1000D-05
 WEIBULL MODULUS FOR COMPONENT bus           :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT bus           :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP bus           : NONE

 TRANSITION RATE FOR CMF EVENT 1:               0.1000D-05
 MISSION TIME FOR THIS MODEL:                   10.00
 NUMBER OF MONTE CARLO HISTORIES:               40000
 NEAR COINCIDENT FAULT MODEL:                   4


 UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 1
 ----------------------------------------------------
 UNRELIABILITY  =  0.1779548D-08 +/-  0.1950970D-09
 SAMPLE VARIANCE  =          0.1522514D-14
 COEFFICIENT OF VARIATION = 0.1096329D+00


 UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 2
 ----------------------------------------------------
 UNRELIABILITY  =  0.1124485D-07 +/-  0.1382043D-08
 SAMPLE VARIANCE  =          0.7640171D-13
 COEFFICIENT OF VARIATION = 0.1229045D+00


 UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 3
 ----------------------------------------------------
 UNRELIABILITY  =  0.9595793D-05 +/-  0.8768407D-06
 SAMPLE VARIANCE  =          0.3075399D-07
 COEFFICIENT OF VARIATION = 0.9137762D-01
```

```
OVERALL UNRELIABILITY DUE TO EXHAUSTION OF HARDWARE
---------------------------------------------------
UNRELIABILITY  =  0.9608817D-05 +/-  0.8768383D-06
SAMPLE VARIANCE  =           0.3075382D-07
COEFFICIENT OF VARIATION = 0.9125351D-01


UNRELIABILITY DUE TO SINGLE POINT FAILURE
-----------------------------------------

UNRELIABILITY  =  0.0000000D+00 +/-  0.0000000D+00
SAMPLE VARIANCE  =           0.0000000D+00
COEFFICIENT OF VARIATION = 0.0000000D+00


UNRELIABILITY DUE TO NEAR COINCIDENT FAULT
-----------------------------------------

UNRELIABILITY  =  0.0000000D+00 +/-  0.0000000D+00
SAMPLE VARIANCE  =           0.0000000D+00
COEFFICIENT OF VARIATION = 0.0000000D+00


UNRELIABILITY DUE TO COMMON MODE FAILURE
-----------------------------------------

UNRELIABILITY  =  0.7337463D-05 +/-  0.7670451D-06
SAMPLE VARIANCE  =           0.2353433D-07
COEFFICIENT OF VARIATION = 0.1045382D+00


OVERALL SYSTEM CALCULATION:
===========================

****************************************************
* UNRELIABILITY  =  0.1694628D-04 +/- 0.1163477D-05*
* SAMPLE VARIANCE  =       0.5414713D-07          *
* COEFFICIENT OF VARIATION= 0.6865677D-01         *
* FIGURE OF MERIT  =       0.7623612D+10          *
* TIME PER HISTORY =       0.2422500D-02          *
****************************************************


CPU CALCULATION TIME:   0.9690E+02 SECONDS
```

```
=====================================
 MONTE CARLO UNRELIABILITY CALCULATION      APPENDIX B.4
=====================================

 NUMBER OF COMPONENT GROUPS:  3

 NUMBER OF COMPONENTS IN GROUP processor     :  3
 NUMBER OF SPARES FOR GROUP processor        :  0
 FAILURE RATE FOR COMPONENT processor        :  0.1000D-03
 WEIBULL MODULUS FOR COMPONENT processor     :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT processor     :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP processor     : NONE

 NUMBER OF COMPONENTS IN GROUP memory        :  2
 NUMBER OF SPARES FOR GROUP memory           :  0
 FAILURE RATE FOR COMPONENT memory           :  0.1000D-04
 WEIBULL MODULUS FOR COMPONENT memory        :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT memory        :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP memory        : NONE

 NUMBER OF COMPONENTS IN GROUP bus           :  1
 NUMBER OF SPARES FOR GROUP bus              :  0
 FAILURE RATE FOR COMPONENT bus              :  0.1000D-05
 WEIBULL MODULUS FOR COMPONENT bus           :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT bus           :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP bus           : NONE

 TRANSITION RATE FOR CMF EVENT 1:               0.1000D-05
 MISSION TIME FOR THIS MODEL:                   10.00
 NUMBER OF MONTE CARLO HISTORIES:               40000
 NEAR COINCIDENT FAULT MODEL:                   4


 UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 1
 ----------------------------------------------------
 UNRELIABILITY  =  0.2965665D-08 +/-  0.3393513D-09
 SAMPLE VARIANCE  =         0.4606371D-14
 COEFFICIENT OF VARIATION = 0.1144267D+00


 UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 2
 ----------------------------------------------------
 UNRELIABILITY  =  0.1129167D-07 +/-  0.1351843D-08
 SAMPLE VARIANCE  =         0.7309915D-13
 COEFFICIENT OF VARIATION = 0.1197203D+00


 UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 3
 ----------------------------------------------------
 UNRELIABILITY  =  0.8870040D-05 +/-  0.8431265D-06
 SAMPLE VARIANCE  =         0.2843449D-07
 COEFFICIENT OF VARIATION = 0.9505330D-01
```

```
OVERALL UNRELIABILITY DUE TO EXHAUSTION OF HARDWARE
---------------------------------------------------
UNRELIABILITY  =  0.8884297D-05 +/-  0.8431239D-06
SAMPLE VARIANCE  =          0.2843432D-07
COEFFICIENT OF VARIATION = 0.9490047D-01


UNRELIABILITY DUE TO SINGLE POINT FAILURE
-----------------------------------------

UNRELIABILITY  =  0.0000000D+00 +/-  0.0000000D+00
SAMPLE VARIANCE  =          0.0000000D+00
COEFFICIENT OF VARIATION = 0.0000000D+00


UNRELIABILITY DUE TO NEAR COINCIDENT FAULT
-----------------------------------------

UNRELIABILITY  =  0.0000000D+00 +/-  0.0000000D+00
SAMPLE VARIANCE  =          0.0000000D+00
COEFFICIENT OF VARIATION = 0.0000000D+00


UNRELIABILITY DUE TO COMMON MODE FAILURE
-----------------------------------------

UNRELIABILITY  =  0.3716620D-05 +/-  0.5456628D-06
SAMPLE VARIANCE  =          0.1190992D-07
COEFFICIENT OF VARIATION = 0.1468170D+00


OVERALL SYSTEM CALCULATION:
===========================

****************************************************
* UNRELIABILITY  =  0.1260092D-04 +/- 0.1003471D-05*
* SAMPLE VARIANCE  =        0.4027820D-07          *
* COEFFICIENT OF VARIATION= 0.7963479D-01          *
* FIGURE OF MERIT  =        0.1024547D+11          *
* TIME PER HISTORY =        0.2423250D-02          *
****************************************************


CPU CALCULATION TIME:   0.9693E+02 SECONDS
```

```
=======================================
 MONTE CARLO UNRELIABILITY CALCULATION      APPENDIX B.5
=======================================

 NUMBER OF COMPONENT GROUPS:  3

 NUMBER OF COMPONENTS IN GROUP processor     :  3
 NUMBER OF SPARES FOR GROUP processor        :  0
 FAILURE RATE FOR COMPONENT processor        :  0.1000D-03
 WEIBULL MODULUS FOR COMPONENT processor     :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT processor     :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP processor     : NONE

 NUMBER OF COMPONENTS IN GROUP memory        :  2
 NUMBER OF SPARES FOR GROUP memory           :  0
 FAILURE RATE FOR COMPONENT memory           :  0.1000D-04
 WEIBULL MODULUS FOR COMPONENT memory        :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT memory        :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP memory        : NONE

 NUMBER OF COMPONENTS IN GROUP bus           :  1
 NUMBER OF SPARES FOR GROUP bus              :  0
 FAILURE RATE FOR COMPONENT bus              :  0.1000D-05
 WEIBULL MODULUS FOR COMPONENT bus           :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT bus           :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP bus           : NONE

 TRANSITION RATE FOR CMF EVENT 1:               0.1000D-05
 MISSION TIME FOR THIS MODEL:                   10.00
 NUMBER OF MONTE CARLO HISTORIES:               40000
 NEAR COINCIDENT FAULT MODEL:                   4

 UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 1
 ---------------------------------------------------
 UNRELIABILITY  =  0.1002237D-08 +/-  0.7883135D-11
 SAMPLE VARIANCE  =        0.2485753D-17
 COEFFICIENT OF VARIATION = 0.7865542D-02


 UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 2
 ---------------------------------------------------
 UNRELIABILITY  =  0.1053510D-07 +/-  0.1334953D-08
 SAMPLE VARIANCE  =        0.7128395D-13
 COEFFICIENT OF VARIATION = 0.1267147D+00


 UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 3
 ---------------------------------------------------
 UNRELIABILITY  =  0.9998374D-05 +/-  0.8950161D-06
 SAMPLE VARIANCE  =        0.3204215D-07
 COEFFICIENT OF VARIATION = 0.8951617D-01
```

```
OVERALL UNRELIABILITY DUE TO EXHAUSTION OF HARDWARE
---------------------------------------------------
UNRELIABILITY  =  0.1000991D-04 +/-  0.8950139D-06
SAMPLE VARIANCE  =          0.3204200D-07
COEFFICIENT OF VARIATION = 0.8941277D-01


UNRELIABILITY DUE TO SINGLE POINT FAILURE
-----------------------------------------

UNRELIABILITY  =  0.0000000D+00 +/-  0.0000000D+00
SAMPLE VARIANCE  =          0.0000000D+00
COEFFICIENT OF VARIATION = 0.0000000D+00


UNRELIABILITY DUE TO NEAR COINCIDENT FAULT
-----------------------------------------

UNRELIABILITY  =  0.0000000D+00 +/-  0.0000000D+00
SAMPLE VARIANCE  =          0.0000000D+00
COEFFICIENT OF VARIATION = 0.0000000D+00


UNRELIABILITY DUE TO COMMON MODE FAILURE
-----------------------------------------

UNRELIABILITY  =  0.1024021D-04 +/-  0.9057440D-06
SAMPLE VARIANCE  =          0.3281489D-07
COEFFICIENT OF VARIATION = 0.8844977D-01


OVERALL SYSTEM CALCULATION:
===========================

****************************************************
* UNRELIABILITY  =  0.2025012D-04 +/- 0.1271337D-05*
* SAMPLE VARIANCE  =        0.6465188D-07          *
* COEFFICIENT OF VARIATION= 0.6278169D-01          *
* FIGURE OF MERIT  =        0.6398120D+10          *
* TIME PER HISTORY =        0.2417500D-02          *
****************************************************


CPU CALCULATION TIME:   0.9670E+02 SECONDS
```

```
=======================================
 MONTE CARLO UNRELIABILITY CALCULATION      APPENDIX B.6
=======================================

 NUMBER OF COMPONENT GROUPS:  3

 NUMBER OF COMPONENTS IN GROUP processor     :  3
 NUMBER OF SPARES FOR GROUP processor        :  0
 FAILURE RATE FOR COMPONENT processor        :  0.1000D-03
 WEIBULL MODULUS FOR COMPONENT processor     :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT processor     :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP processor     : CFEHM.ARI

 NUMBER OF COMPONENTS IN GROUP memory        :  2
 NUMBER OF SPARES FOR GROUP memory           :  0
 FAILURE RATE FOR COMPONENT memory           :  0.1000D-04
 WEIBULL MODULUS FOR COMPONENT memory        :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT memory        :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP memory        : FEHM.MOM

 NUMBER OF COMPONENTS IN GROUP bus           :  1
 NUMBER OF SPARES FOR GROUP bus              :  0
 FAILURE RATE FOR COMPONENT bus              :  0.1000D-05
 WEIBULL MODULUS FOR COMPONENT bus           :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT bus           :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP bus           : NONE

 MISSION TIME FOR THIS MODEL:                   10.00
 NUMBER OF MONTE CARLO HISTORIES:               80000
 NEAR COINCIDENT FAULT MODEL:                   3

 UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 1
 ----------------------------------------------------
 UNRELIABILITY  =  0.6795463D-10 +/-  0.3831140D-12
 SAMPLE VARIANCE  =          0.1174211D-19
 COEFFICIENT OF VARIATION = 0.5637790D-02


 UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 2
 ----------------------------------------------------
 UNRELIABILITY  =  0.2249129D-09 +/-  0.4334561D-10
 SAMPLE VARIANCE  =          0.1503074D-15
 COEFFICIENT OF VARIATION = 0.1927218D+00


 UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 3
 ----------------------------------------------------
 UNRELIABILITY  =  0.9926839D-05 +/-  0.3395517D-06
 SAMPLE VARIANCE  =          0.9223627D-08
 COEFFICIENT OF VARIATION = 0.3420542D-01
```

```
OVERALL UNRELIABILITY DUE TO EXHAUSTION OF HARDWARE
---------------------------------------------------
UNRELIABILITY  =  0.9927132D-05 +/-  0.3395516D-06
SAMPLE VARIANCE  =           0.9223621D-08
COEFFICIENT OF VARIATION = 0.3420440D-01


UNRELIABILITY DUE TO SINGLE POINT FAILURE
-----------------------------------------

UNRELIABILITY  =  0.1414603D-03 +/-  0.1187693D-05
SAMPLE VARIANCE  =           0.1128492D-06
COEFFICIENT OF VARIATION = 0.8395945D-02


UNRELIABILITY DUE TO NEAR COINCIDENT FAULT
-----------------------------------------

UNRELIABILITY  =  0.2349318D-07 +/-  0.1660713D-07
SAMPLE VARIANCE  =           0.2206375D-10
COEFFICIENT OF VARIATION = 0.7068916D+00


UNRELIABILITY DUE TO COMMON MODE FAILURE
-----------------------------------------

UNRELIABILITY  =  0.0000000D+00 +/-  0.0000000D+00
SAMPLE VARIANCE  =           0.0000000D+00
COEFFICIENT OF VARIATION = 0.0000000D+00


OVERALL SYSTEM CALCULATION:
===========================

****************************************************
* UNRELIABILITY  =  0.1514109D-03+/- 0.1221061D-05 *
* SAMPLE VARIANCE  =       0.1192792D-06           *
* COEFFICIENT OF VARIATION= 0.8064548D-02          *
* FIGURE OF MERIT  =       0.2481392D+10           *
* TIME PER HISTORY =       0.3378625D-02           *
****************************************************


CPU CALCULATION TIME:   0.2703E+03 SECONDS
```

```
=======================================
 MONTE CARLO UNRELIABILITY CALCULATION      APPENDIX B.7
=======================================

 NUMBER OF COMPONENT GROUPS:  3

 NUMBER OF COMPONENTS IN GROUP processor     :  3
 NUMBER OF SPARES FOR GROUP processor        :  0
 FAILURE RATE FOR COMPONENT processor        :  0.1000D-03
 WEIBULL MODULUS FOR COMPONENT processor     :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT processor     :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP processor     : CFEHM.ARI

 NUMBER OF COMPONENTS IN GROUP memory        :  2
 NUMBER OF SPARES FOR GROUP memory           :  0
 FAILURE RATE FOR COMPONENT memory           :  0.1000D-04
 WEIBULL MODULUS FOR COMPONENT memory        :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT memory        :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP memory        : FEHM.MOM

 NUMBER OF COMPONENTS IN GROUP bus           :  1
 NUMBER OF SPARES FOR GROUP bus              :  0
 FAILURE RATE FOR COMPONENT bus              :  0.1000D-05
 WEIBULL MODULUS FOR COMPONENT bus           :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT bus           :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP bus           : NONE

 TRANSITION RATE FOR CMF EVENT 1:               0.1000D-05
 MISSION TIME FOR THIS MODEL:                   10.00
 NUMBER OF MONTE CARLO HISTORIES:               80000
 NEAR COINCIDENT FAULT MODEL:                   3


 UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 1
 ----------------------------------------------------
 UNRELIABILITY  =  0.6840191D-10 +/-  0.3939940D-12
 SAMPLE VARIANCE  =         0.1241850D-19
 COEFFICIENT OF VARIATION = 0.5759985D-02


 UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 2
 ----------------------------------------------------
 UNRELIABILITY  =  0.1009069D-09 +/-  0.2959416D-10
 SAMPLE VARIANCE  =         0.7006514D-16
 COEFFICIENT OF VARIATION = 0.2932818D+00


 UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 3
 ----------------------------------------------------
 UNRELIABILITY  =  0.1032902D-04 +/-  0.3481505D-06
 SAMPLE VARIANCE  =         0.9696702D-08
 COEFFICIENT OF VARIATION = 0.3370606D-01
```

```
OVERALL UNRELIABILITY DUE TO EXHAUSTION OF HARDWARE
---------------------------------------------------
UNRELIABILITY  =  0.1032919D-04 +/-  0.3481505D-06
SAMPLE VARIANCE  =          0.9696699D-08
COEFFICIENT OF VARIATION = 0.3370550D-01


UNRELIABILITY DUE TO SINGLE POINT FAILURE
-----------------------------------------

UNRELIABILITY  =  0.1402953D-03 +/-  0.1191037D-05
SAMPLE VARIANCE  =          0.1134856D-06
COEFFICIENT OF VARIATION = 0.8489499D-02


UNRELIABILITY DUE TO NEAR COINCIDENT FAULT
-----------------------------------------

UNRELIABILITY  =  0.3561280D-07 +/-  0.2055588D-07
SAMPLE VARIANCE  =          0.3380353D-10
COEFFICIENT OF VARIATION = 0.5772047D+00


UNRELIABILITY DUE TO COMMON MODE FAILURE
-----------------------------------------

UNRELIABILITY  =  0.9925506D-05 +/-  0.3413531D-06
SAMPLE VARIANCE  =          0.9321754D-08
COEFFICIENT OF VARIATION = 0.3439150D-01


OVERALL SYSTEM CALCULATION:
===========================

****************************************************
* UNRELIABILITY  =  0.1605857D-03+/- 0.1258164D-05 *
* SAMPLE VARIANCE  =        0.1266381D-06          *
* COEFFICIENT OF VARIATION= 0.7834845D-02          *
* FIGURE OF MERIT  =        0.2317904D+10          *
* TIME PER HISTORY =        0.3406750D-02          *
****************************************************


CPU CALCULATION TIME:   0.2725E+03 SECONDS
```

```
=======================================
 MONTE CARLO UNRELIABILITY CALCULATION       APPENDIX B.8
=======================================

 NUMBER OF COMPONENT GROUPS:  3

 NUMBER OF COMPONENTS IN GROUP PROCESSOR      :  3
 NUMBER OF SPARES FOR GROUP PROCESSOR         :  0
 FAILURE RATE FOR COMPONENT PROCESSOR         :  0.0000D+00
 WEIBULL MODULUS FOR COMPONENT PROCESSOR      :  0.2500D+01
 SCALE PARAMETER FOR COMPONENT PROCESSOR      :  0.1585D+03
 FAILURE HANDLING MODEL FOR GROUP PROCESSOR      : CFEHM.ARI

 NUMBER OF COMPONENTS IN GROUP MEMORY         :  2
 NUMBER OF SPARES FOR GROUP MEMORY            :  0
 FAILURE RATE FOR COMPONENT MEMORY            :  0.0000D+00
 WEIBULL MODULUS FOR COMPONENT MEMORY         :  0.2500D+01
 SCALE PARAMETER FOR COMPONENT MEMORY         :  0.3981D+03
 FAILURE HANDLING MODEL FOR GROUP MEMORY         : FEHM.MOM

 NUMBER OF COMPONENTS IN GROUP BUS            :  1
 NUMBER OF SPARES FOR GROUP BUS               :  0
 FAILURE RATE FOR COMPONENT BUS               :  0.0000D+00
 WEIBULL MODULUS FOR COMPONENT BUS            :  0.2500D+01
 SCALE PARAMETER FOR COMPONENT BUS            :  0.1000D+04
 FAILURE HANDLING MODEL FOR GROUP BUS            : NONE

 MISSION TIME FOR THIS MODEL:                    10.00
 NUMBER OF MONTE CARLO HISTORIES:                40000
 NEAR COINCIDENT FAULT MODEL:                    3

 UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 1
 ----------------------------------------------------
 UNRELIABILITY  =  0.6865636D-10 +/-  0.9973916D-12
 SAMPLE VARIANCE  =          0.3979160D-19
 COEFFICIENT OF VARIATION = 0.1452730D-01


 UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 2
 ----------------------------------------------------
 UNRELIABILITY  =  0.1048874D-09 +/-  0.5640234D-10
 SAMPLE VARIANCE  =          0.1272490D-15
 COEFFICIENT OF VARIATION = 0.5377417D+00


 UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 3
 ----------------------------------------------------
 UNRELIABILITY  =  0.1062913D-04 +/-  0.7428625D-06
 SAMPLE VARIANCE  =          0.2207379D-07
 COEFFICIENT OF VARIATION = 0.6988928D-01
```

```
OVERALL UNRELIABILITY DUE TO EXHAUSTION OF HARDWARE
---------------------------------------------------
UNRELIABILITY  =  0.1062931D-04 +/-  0.7428625D-06
SAMPLE VARIANCE  =          0.2207379D-07
COEFFICIENT OF VARIATION = 0.6988814D-01


UNRELIABILITY DUE TO SINGLE POINT FAILURE
-----------------------------------------

UNRELIABILITY  =  0.1482236D-03 +/-  0.2674119D-05
SAMPLE VARIANCE  =          0.2860364D-06
COEFFICIENT OF VARIATION = 0.1804111D-01


UNRELIABILITY DUE TO NEAR COINCIDENT FAULT
-----------------------------------------

UNRELIABILITY  =  0.6597022D-10 +/-  0.3892732D-10
SAMPLE VARIANCE  =          0.6061346D-16
COEFFICIENT OF VARIATION = 0.5900741D+00


UNRELIABILITY DUE TO COMMON MODE FAILURE
-----------------------------------------

UNRELIABILITY  =  0.0000000D+00 +/-  0.0000000D+00
SAMPLE VARIANCE  =          0.0000000D+00
COEFFICIENT OF VARIATION = 0.0000000D+00


OVERALL SYSTEM CALCULATION:
===========================

****************************************************
* UNRELIABILITY  =  0.1588530D-03 +/- 0.2761155D-05*
* SAMPLE VARIANCE  =        0.3049592D-06          *
* COEFFICIENT OF VARIATION= 0.1738183D-01          *
* FIGURE OF MERIT  =        0.9725659D+08          *
* TIME PER HISTORY =        0.3371625D-01          *
****************************************************


CPU CALCULATION TIME:   0.1349E+04 SECONDS
```

```
=======================================
 MONTE CARLO UNRELIABILITY CALCULATION      APPENDIX B.9
=======================================

 NUMBER OF COMPONENT GROUPS:  7

 NUMBER OF COMPONENTS IN GROUP POWER_SUPPLY :  3
 NUMBER OF SPARES FOR GROUP POWER_SUPPLY    :  0
 FAILURE RATE FOR COMPONENT POWER_SUPPLY    :  0.3000D-04
 WEIBULL MODULUS FOR COMPONENT POWER_SUPPLY :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT POWER_SUPPLY :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP POWER_SUPPLY : FEHM.CAR

 NUMBER OF COMPONENTS IN GROUP INPUT_CONT   :  3
 NUMBER OF SPARES FOR GROUP INPUT_CONT      :  0
 FAILURE RATE FOR COMPONENT INPUT_CONT      :  0.1500D-04
 WEIBULL MODULUS FOR COMPONENT INPUT_CONT   :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT INPUT_CONT   :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP INPUT_CONT   : FEHM.CAR

 NUMBER OF COMPONENTS IN GROUP DATA_COLL    :  2
 NUMBER OF SPARES FOR GROUP DATA_COLL       :  0
 FAILURE RATE FOR COMPONENT DATA_COLL       :  0.7000D-05
 WEIBULL MODULUS FOR COMPONENT DATA_COLL    :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT DATA_COLL    :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP DATA_COLL    : FEHMDC.CAR

 NUMBER OF COMPONENTS IN GROUP CPUs         :  3
 NUMBER OF SPARES FOR GROUP CPUs            :  0
 FAILURE RATE FOR COMPONENT CPUs            :  0.3260D-04
 WEIBULL MODULUS FOR COMPONENT CPUs         :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT CPUs         :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP CPUs         : FEHM.CAR

 NUMBER OF COMPONENTS IN GROUP BUSSES       :  3
 NUMBER OF SPARES FOR GROUP BUSSES          :  0
 FAILURE RATE FOR COMPONENT BUSSES          :  0.1000D-04
 WEIBULL MODULUS FOR COMPONENT BUSSES       :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT BUSSES       :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP BUSSES       : FEHM.CAR

 NUMBER OF COMPONENTS IN GROUP OUT_DRIVE    :  3
 NUMBER OF SPARES FOR GROUP OUT_DRIVE       :  0
 FAILURE RATE FOR COMPONENT OUT_DRIVE       :  0.3000D-05
 WEIBULL MODULUS FOR COMPONENT OUT_DRIVE    :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT OUT_DRIVE    :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP OUT_DRIVE    : FEHM.CAR

 NUMBER OF COMPONENTS IN GROUP DATA_RECVR   :  3
 NUMBER OF SPARES FOR GROUP DATA_RECVR      :  0
 FAILURE RATE FOR COMPONENT DATA_RECVR      :  0.4260D-05
 WEIBULL MODULUS FOR COMPONENT DATA_RECVR   :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT DATA_RECVR   :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP DATA_RECVR   : FEHM.CAR
```

```
MISSION TIME FOR THIS MODEL:                    10.00
NUMBER OF MONTE CARLO HISTORIES:                40000
NEAR COINCIDENT FAULT MODEL:                    4

UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 1
----------------------------------------------------
UNRELIABILITY  =  0.1575319D-06 +/-  0.4568704D-08
SAMPLE VARIANCE  =          0.8349223D-12
COEFFICIENT OF VARIATION = 0.2900177D-01


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 2
----------------------------------------------------
UNRELIABILITY  =  0.7653835D-07 +/-  0.3226820D-08
SAMPLE VARIANCE  =          0.4164947D-12
COEFFICIENT OF VARIATION = 0.4215952D-01


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 3
----------------------------------------------------
UNRELIABILITY  =  0.3168055D-07 +/-  0.2044750D-08
SAMPLE VARIANCE  =          0.1672402D-12
COEFFICIENT OF VARIATION = 0.6454277D-01


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 4
----------------------------------------------------
UNRELIABILITY  =  0.2512772D-09 +/-  0.7100021D-11
SAMPLE VARIANCE  =          0.2016412D-17
COEFFICIENT OF VARIATION = 0.2825573D-01


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 5
----------------------------------------------------
UNRELIABILITY  =  0.6682166D-10 +/-  0.3600505D-11
SAMPLE VARIANCE  =          0.5185454D-18
COEFFICIENT OF VARIATION = 0.5388230D-01


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 6
----------------------------------------------------
UNRELIABILITY  =  0.1771411D-10 +/-  0.1908958D-11
SAMPLE VARIANCE  =          0.1457648D-18
COEFFICIENT OF VARIATION = 0.1077648D+00


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 7
----------------------------------------------------
```

```
UNRELIABILITY  =  0.2519411D-10 +/-  0.2090592D-11
SAMPLE VARIANCE  =          0.1748229D-18
COEFFICIENT OF VARIATION = 0.8297939D-01


OVERALL UNRELIABILITY DUE TO EXHAUSTION OF HARDWARE
---------------------------------------------------
UNRELIABILITY  =  0.2661118D-06 +/-  0.5872654D-08
SAMPLE VARIANCE  =          0.1379523D-11
COEFFICIENT OF VARIATION = 0.2206837D-01


UNRELIABILITY DUE TO SINGLE POINT FAILURE
-----------------------------------------

UNRELIABILITY  =  0.1083749D-04 +/-  0.8972111D-06
SAMPLE VARIANCE  =          0.3219951D-07
COEFFICIENT OF VARIATION = 0.8278773D-01


UNRELIABILITY DUE TO NEAR COINCIDENT FAULT
-----------------------------------------

UNRELIABILITY  =  0.0000000D+00 +/-  0.0000000D+00
SAMPLE VARIANCE  =          0.0000000D+00
COEFFICIENT OF VARIATION = 0.0000000D+00


UNRELIABILITY DUE TO COMMON MODE FAILURE
-----------------------------------------

UNRELIABILITY  =  0.0000000D+00 +/-  0.0000000D+00
SAMPLE VARIANCE  =          0.0000000D+00
COEFFICIENT OF VARIATION = 0.0000000D+00


OVERALL SYSTEM CALCULATION:
===========================

***************************************************
* UNRELIABILITY  =  0.1110360D-04 +/- 0.8971499D-06*
* SAMPLE VARIANCE  =        0.3219512D-07          *
* COEFFICIENT OF VARIATION= 0.8079811D-01          *
* FIGURE OF MERIT  =        0.2576735D+10          *
* TIME PER HISTORY =        0.1205425D-01          *
***************************************************


CPU CALCULATION TIME:   0.4822E+03 SECONDS
```

```
=======================================
 MONTE CARLO UNRELIABILITY CALCULATION       APPENDIX B.10
=======================================

 NUMBER OF COMPONENT GROUPS:  7

 NUMBER OF COMPONENTS IN GROUP POWER_SUPPLY :  3
 NUMBER OF SPARES FOR GROUP POWER_SUPPLY    :  0
 FAILURE RATE FOR COMPONENT POWER_SUPPLY    :  0.2970D-04
 WEIBULL MODULUS FOR COMPONENT POWER_SUPPLY :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT POWER_SUPPLY :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP POWER_SUPPLY : NONE

 NUMBER OF COMPONENTS IN GROUP INPUT_CONT   :  3
 NUMBER OF SPARES FOR GROUP INPUT_CONT      :  0
 FAILURE RATE FOR COMPONENT INPUT_CONT      :  0.1485D-04
 WEIBULL MODULUS FOR COMPONENT INPUT_CONT   :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT INPUT_CONT   :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP INPUT_CONT   : NONE

 NUMBER OF COMPONENTS IN GROUP DATA_COLL    :  2
 NUMBER OF SPARES FOR GROUP DATA_COLL       :  0
 FAILURE RATE FOR COMPONENT DATA_COLL       :  0.6860D-05
 WEIBULL MODULUS FOR COMPONENT DATA_COLL    :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT DATA_COLL    :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP DATA_COLL    : NONE

 NUMBER OF COMPONENTS IN GROUP CPUs         :  3
 NUMBER OF SPARES FOR GROUP CPUs            :  0
 FAILURE RATE FOR COMPONENT CPUs            :  0.3227D-04
 WEIBULL MODULUS FOR COMPONENT CPUs         :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT CPUs         :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP CPUs         : NONE

 NUMBER OF COMPONENTS IN GROUP BUSSES       :  3
 NUMBER OF SPARES FOR GROUP BUSSES          :  0
 FAILURE RATE FOR COMPONENT BUSSES          :  0.9900D-05
 WEIBULL MODULUS FOR COMPONENT BUSSES       :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT BUSSES       :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP BUSSES       : NONE

 NUMBER OF COMPONENTS IN GROUP OUT_DRIVE    :  3
 NUMBER OF SPARES FOR GROUP OUT_DRIVE       :  0
 FAILURE RATE FOR COMPONENT OUT_DRIVE       :  0.2970D-05
 WEIBULL MODULUS FOR COMPONENT OUT_DRIVE    :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT OUT_DRIVE    :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP OUT_DRIVE    : NONE

 NUMBER OF COMPONENTS IN GROUP DATA_RECVR   :  3
 NUMBER OF SPARES FOR GROUP DATA_RECVR      :  0
 FAILURE RATE FOR COMPONENT DATA_RECVR      :  0.4217D-05
 WEIBULL MODULUS FOR COMPONENT DATA_RECVR   :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT DATA_RECVR   :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP DATA_RECVR   : NONE
```

```
TRANSITION RATE FOR CMF EVENT 1:             0.3000D-06
TRANSITION RATE FOR CMF EVENT 2:             0.1500D-06
TRANSITION RATE FOR CMF EVENT 3:             0.1400D-06
TRANSITION RATE FOR CMF EVENT 4:             0.3260D-06
TRANSITION RATE FOR CMF EVENT 5:             0.1000D-06
TRANSITION RATE FOR CMF EVENT 6:             0.3000D-07
TRANSITION RATE FOR CMF EVENT 7:             0.4260D-07
MISSION TIME FOR THIS MODEL:                 10.00
NUMBER OF MONTE CARLO HISTORIES:             40000
NEAR COINCIDENT FAULT MODEL:                 4

UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 1
----------------------------------------------------
UNRELIABILITY  =  0.1460247D-06 +/-  0.4345605D-08
SAMPLE VARIANCE  =        0.7553712D-12
COEFFICIENT OF VARIATION = 0.2975938D-01


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 2
----------------------------------------------------
UNRELIABILITY  =  0.7965129D-07 +/-  0.3273486D-08
SAMPLE VARIANCE  =        0.4286284D-12
COEFFICIENT OF VARIATION = 0.4109771D-01


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 3
----------------------------------------------------
UNRELIABILITY  =  0.3591877D-07 +/-  0.2193508D-08
SAMPLE VARIANCE  =        0.1924591D-12
COEFFICIENT OF VARIATION = 0.6106858D-01


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 4
----------------------------------------------------
UNRELIABILITY  =  0.2520444D-09 +/-  0.7033642D-11
SAMPLE VARIANCE  =        0.1978885D-17
COEFFICIENT OF VARIATION = 0.2790636D-01


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 5
----------------------------------------------------
UNRELIABILITY  =  0.6588514D-10 +/-  0.3593959D-11
SAMPLE VARIANCE  =        0.5166615D-18
COEFFICIENT OF VARIATION = 0.5454885D-01


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 6
----------------------------------------------------
UNRELIABILITY  =  0.2131856D-10 +/-  0.2046893D-11
```

```
SAMPLE VARIANCE  =           0.1675909D-18
COEFFICIENT OF VARIATION = 0.9601459D-01


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 7
----------------------------------------------------
UNRELIABILITY  =  0.2578768D-10 +/-  0.2109633D-11
SAMPLE VARIANCE  =           0.1780220D-18
COEFFICIENT OF VARIATION = 0.8180776D-01


OVERALL UNRELIABILITY DUE TO EXHAUSTION OF HARDWARE
---------------------------------------------------
UNRELIABILITY  =  0.2619598D-06 +/-  0.5780995D-08
SAMPLE VARIANCE  =           0.1336796D-11
COEFFICIENT OF VARIATION = 0.2206826D-01


UNRELIABILITY DUE TO SINGLE POINT FAILURE
-----------------------------------------

UNRELIABILITY  =  0.0000000D+00 +/-  0.0000000D+00
SAMPLE VARIANCE  =           0.0000000D+00
COEFFICIENT OF VARIATION = 0.0000000D+00


UNRELIABILITY DUE TO NEAR COINCIDENT FAULT
-----------------------------------------

UNRELIABILITY  =  0.0000000D+00 +/-  0.0000000D+00
SAMPLE VARIANCE  =           0.0000000D+00
COEFFICIENT OF VARIATION = 0.0000000D+00


UNRELIABILITY DUE TO COMMON MODE FAILURE
-----------------------------------------

UNRELIABILITY  =  0.1128292D-04 +/-  0.9122647D-06
SAMPLE VARIANCE  =           0.3328907D-07
COEFFICIENT OF VARIATION = 0.8085363D-01


OVERALL SYSTEM CALCULATION:
===========================

****************************************************
* UNRELIABILITY  =  0.1154488D-04 +/- 0.9122020D-06*
* SAMPLE VARIANCE  =       0.3328450D-07           *
* COEFFICIENT OF VARIATION= 0.7901359D-01          *
* FIGURE OF MERIT  =       0.2309790D+10           *
```

```
* TIME PER HISTORY =          0.1300725D-01           *
*******************************************************

CPU CALCULATION TIME:    0.5203E+03 SECONDS
```

```
=======================================
MONTE CARLO UNRELIABILITY CALCULATION      APPENDIX B.11
=======================================

NUMBER OF COMPONENT GROUPS:  7

NUMBER OF COMPONENTS IN GROUP POWER_SUPPLY :  3
NUMBER OF SPARES FOR GROUP POWER_SUPPLY    :  0
FAILURE RATE FOR COMPONENT POWER_SUPPLY    :  0.3000D-04
WEIBULL MODULUS FOR COMPONENT POWER_SUPPLY :  0.0000D+00
SCALE PARAMETER FOR COMPONENT POWER_SUPPLY :  0.0000D+00
FAILURE HANDLING MODEL FOR GROUP POWER_SUPPLY : NONE

NUMBER OF COMPONENTS IN GROUP INPUT_CONT   :  3
NUMBER OF SPARES FOR GROUP INPUT_CONT      :  0
FAILURE RATE FOR COMPONENT INPUT_CONT      :  0.1500D-04
WEIBULL MODULUS FOR COMPONENT INPUT_CONT   :  0.0000D+00
SCALE PARAMETER FOR COMPONENT INPUT_CONT   :  0.0000D+00
FAILURE HANDLING MODEL FOR GROUP INPUT_CONT   : NONE

NUMBER OF COMPONENTS IN GROUP DATA_COLL    :  2
NUMBER OF SPARES FOR GROUP DATA_COLL       :  0
FAILURE RATE FOR COMPONENT DATA_COLL       :  0.7000D-05
WEIBULL MODULUS FOR COMPONENT DATA_COLL    :  0.0000D+00
SCALE PARAMETER FOR COMPONENT DATA_COLL    :  0.0000D+00
FAILURE HANDLING MODEL FOR GROUP DATA_COLL    : NONE

NUMBER OF COMPONENTS IN GROUP CPUs         :  3
NUMBER OF SPARES FOR GROUP CPUs            :  0
FAILURE RATE FOR COMPONENT CPUs            :  0.3260D-04
WEIBULL MODULUS FOR COMPONENT CPUs         :  0.0000D+00
SCALE PARAMETER FOR COMPONENT CPUs         :  0.0000D+00
FAILURE HANDLING MODEL FOR GROUP CPUs         : NONE

NUMBER OF COMPONENTS IN GROUP BUSSES       :  3
NUMBER OF SPARES FOR GROUP BUSSES          :  0
FAILURE RATE FOR COMPONENT BUSSES          :  0.1000D-04
WEIBULL MODULUS FOR COMPONENT BUSSES       :  0.0000D+00
SCALE PARAMETER FOR COMPONENT BUSSES       :  0.0000D+00
FAILURE HANDLING MODEL FOR GROUP BUSSES       : NONE

NUMBER OF COMPONENTS IN GROUP OUT_DRIVE    :  3
NUMBER OF SPARES FOR GROUP OUT_DRIVE       :  0
FAILURE RATE FOR COMPONENT OUT_DRIVE       :  0.3000D-05
WEIBULL MODULUS FOR COMPONENT OUT_DRIVE    :  0.0000D+00
SCALE PARAMETER FOR COMPONENT OUT_DRIVE    :  0.0000D+00
FAILURE HANDLING MODEL FOR GROUP OUT_DRIVE    : NONE

NUMBER OF COMPONENTS IN GROUP DATA_RECVR   :  3
NUMBER OF SPARES FOR GROUP DATA_RECVR      :  0
FAILURE RATE FOR COMPONENT DATA_RECVR      :  0.4260D-05
WEIBULL MODULUS FOR COMPONENT DATA_RECVR   :  0.0000D+00
SCALE PARAMETER FOR COMPONENT DATA_RECVR   :  0.0000D+00
FAILURE HANDLING MODEL FOR GROUP DATA_RECVR   : NONE
```

```
MISSION TIME FOR THIS MODEL:                    10.00
NUMBER OF MONTE CARLO HISTORIES:                40000
NEAR COINCIDENT FAULT MODEL:                    4


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 1
----------------------------------------------------
UNRELIABILITY  =  0.1607696D-06 +/-  0.4634166D-08
SAMPLE VARIANCE  =         0.8590198D-12
COEFFICIENT OF VARIATION = 0.2882489D-01


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 2
----------------------------------------------------
UNRELIABILITY  =  0.7551111D-07 +/-  0.3207294D-08
SAMPLE VARIANCE  =         0.4114694D-12
COEFFICIENT OF VARIATION = 0.4247446D-01


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 3
----------------------------------------------------
UNRELIABILITY  =  0.3678941D-07 +/-  0.2235804D-08
SAMPLE VARIANCE  =         0.1999528D-12
COEFFICIENT OF VARIATION = 0.6077303D-01


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 4
----------------------------------------------------
UNRELIABILITY  =  0.2673268D-09 +/-  0.7314072D-11
SAMPLE VARIANCE  =         0.2139826D-17
COEFFICIENT OF VARIATION = 0.2736004D-01


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 5
----------------------------------------------------
UNRELIABILITY  =  0.7679503D-10 +/-  0.4012188D-11
SAMPLE VARIANCE  =         0.6439060D-18
COEFFICIENT OF VARIATION = 0.5224541D-01


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 6
----------------------------------------------------
UNRELIABILITY  =  0.2136010D-10 +/-  0.2097490D-11
SAMPLE VARIANCE  =         0.1759786D-18
COEFFICIENT OF VARIATION = 0.9819667D-01


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 7
----------------------------------------------------
```

```
UNRELIABILITY  =  0.2481696D-10 +/-  0.2095993D-11
SAMPLE VARIANCE  =           0.1757275D-18
COEFFICIENT OF VARIATION = 0.8445809D-01


OVERALL UNRELIABILITY DUE TO EXHAUSTION OF HARDWARE
---------------------------------------------------
UNRELIABILITY  =  0.2734604D-06 +/-  0.5976133D-08
SAMPLE VARIANCE  =           0.1428567D-11
COEFFICIENT OF VARIATION = 0.2185374D-01


UNRELIABILITY DUE TO SINGLE POINT FAILURE
-----------------------------------------

UNRELIABILITY  =  0.0000000D+00 +/-  0.0000000D+00
SAMPLE VARIANCE  =           0.0000000D+00
COEFFICIENT OF VARIATION = 0.0000000D+00


UNRELIABILITY DUE TO NEAR COINCIDENT FAULT
-----------------------------------------

UNRELIABILITY  =  0.0000000D+00 +/-  0.0000000D+00
SAMPLE VARIANCE  =           0.0000000D+00
COEFFICIENT OF VARIATION = 0.0000000D+00


UNRELIABILITY DUE TO COMMON MODE FAILURE
-----------------------------------------

UNRELIABILITY  =  0.0000000D+00 +/-  0.0000000D+00
SAMPLE VARIANCE  =           0.0000000D+00
COEFFICIENT OF VARIATION = 0.0000000D+00


OVERALL SYSTEM CALCULATION:
===========================

****************************************************
* UNRELIABILITY  =  0.2734604D-06 +/- 0.5976133D-08*
* SAMPLE VARIANCE  =         0.1428567D-11         *
* COEFFICIENT OF VARIATION= 0.2185374D-01          *
* FIGURE OF MERIT  =         0.5417450D+14         *
* TIME PER HISTORY =         0.1292125D-01         *
****************************************************


CPU CALCULATION TIME:   0.5168E+03 SECONDS
```

```
=========================================
 MONTE CARLO UNRELIABILITY CALCULATION       APPENDIX B.12
=========================================

 NUMBER OF COMPONENT GROUPS:  7

 NUMBER OF COMPONENTS IN GROUP POWER_SUPPLY :  3
 NUMBER OF SPARES FOR GROUP POWER_SUPPLY    :  2
 FAILURE RATE FOR COMPONENT POWER_SUPPLY    :  0.3000D-04
 WEIBULL MODULUS FOR COMPONENT POWER_SUPPLY :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT POWER_SUPPLY :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP POWER_SUPPLY : NONE

 NUMBER OF COMPONENTS IN GROUP INPUT_CONT   :  3
 NUMBER OF SPARES FOR GROUP INPUT_CONT      :  0
 FAILURE RATE FOR COMPONENT INPUT_CONT      :  0.1500D-04
 WEIBULL MODULUS FOR COMPONENT INPUT_CONT   :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT INPUT_CONT   :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP INPUT_CONT   : NONE

 NUMBER OF COMPONENTS IN GROUP DATA_COLL    :  2
 NUMBER OF SPARES FOR GROUP DATA_COLL       :  0
 FAILURE RATE FOR COMPONENT DATA_COLL       :  0.7000D-05
 WEIBULL MODULUS FOR COMPONENT DATA_COLL    :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT DATA_COLL    :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP DATA_COLL    : NONE

 NUMBER OF COMPONENTS IN GROUP CPUs         :  3
 NUMBER OF SPARES FOR GROUP CPUs            :  0
 FAILURE RATE FOR COMPONENT CPUs            :  0.3260D-04
 WEIBULL MODULUS FOR COMPONENT CPUs         :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT CPUs         :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP CPUs         : NONE

 NUMBER OF COMPONENTS IN GROUP BUSSES       :  3
 NUMBER OF SPARES FOR GROUP BUSSES          :  0
 FAILURE RATE FOR COMPONENT BUSSES          :  0.1000D-04
 WEIBULL MODULUS FOR COMPONENT BUSSES       :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT BUSSES       :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP BUSSES       : NONE

 NUMBER OF COMPONENTS IN GROUP OUT_DRIVE    :  3
 NUMBER OF SPARES FOR GROUP OUT_DRIVE       :  0
 FAILURE RATE FOR COMPONENT OUT_DRIVE       :  0.3000D-05
 WEIBULL MODULUS FOR COMPONENT OUT_DRIVE    :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT OUT_DRIVE    :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP OUT_DRIVE    : NONE

 NUMBER OF COMPONENTS IN GROUP DATA_RECVR   :  3
 NUMBER OF SPARES FOR GROUP DATA_RECVR      :  0
 FAILURE RATE FOR COMPONENT DATA_RECVR      :  0.4260D-05
 WEIBULL MODULUS FOR COMPONENT DATA_RECVR   :  0.0000D+00
 SCALE PARAMETER FOR COMPONENT DATA_RECVR   :  0.0000D+00
 FAILURE HANDLING MODEL FOR GROUP DATA_RECVR   : NONE
```

```
MISSION TIME FOR THIS MODEL:                    10.00
NUMBER OF MONTE CARLO HISTORIES:                40000
NEAR COINCIDENT FAULT MODEL:                    4

UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 1
----------------------------------------------------
UNRELIABILITY  =  0.1851200D-13 +/-  0.2509484D-14
SAMPLE VARIANCE  =          0.2519004D-24
COEFFICIENT OF VARIATION = 0.1355599D+00


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 2
----------------------------------------------------
UNRELIABILITY  =  0.3767722D-07 +/-  0.2326881D-08
SAMPLE VARIANCE  =          0.2165750D-12
COEFFICIENT OF VARIATION = 0.6175829D-01


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 3
----------------------------------------------------
UNRELIABILITY  =  0.1691256D-07 +/-  0.1530143D-08
SAMPLE VARIANCE  =          0.9365352D-13
COEFFICIENT OF VARIATION = 0.9047379D-01


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 4
----------------------------------------------------
UNRELIABILITY  =  0.1280122D-09 +/-  0.5206921D-11
SAMPLE VARIANCE  =          0.1084481D-17
COEFFICIENT OF VARIATION = 0.4067520D-01


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 5
----------------------------------------------------
UNRELIABILITY  =  0.3241568D-10 +/-  0.2544685D-11
SAMPLE VARIANCE  =          0.2590168D-18
COEFFICIENT OF VARIATION = 0.7850165D-01


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 6
----------------------------------------------------
UNRELIABILITY  =  0.6442319D-11 +/-  0.1077866D-11
SAMPLE VARIANCE  =          0.4647177D-19
COEFFICIENT OF VARIATION = 0.1673102D+00


UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP 7
----------------------------------------------------
```

```
UNRELIABILITY  =  0.1157005D-10 +/-  0.1513996D-11
SAMPLE VARIANCE  =          0.9168740D-19
COEFFICIENT OF VARIATION = 0.1308547D+00


OVERALL UNRELIABILITY DUE TO EXHAUSTION OF HARDWARE
---------------------------------------------------
UNRELIABILITY  =  0.5476824D-07 +/-  0.2779101D-08
SAMPLE VARIANCE  =          0.3089361D-12
COEFFICIENT OF VARIATION = 0.5074293D-01


UNRELIABILITY DUE TO SINGLE POINT FAILURE
-----------------------------------------

UNRELIABILITY  =  0.0000000D+00 +/-  0.0000000D+00
SAMPLE VARIANCE  =          0.0000000D+00
COEFFICIENT OF VARIATION = 0.0000000D+00


UNRELIABILITY DUE TO NEAR COINCIDENT FAULT
-----------------------------------------

UNRELIABILITY  =  0.0000000D+00 +/-  0.0000000D+00
SAMPLE VARIANCE  =          0.0000000D+00
COEFFICIENT OF VARIATION = 0.0000000D+00


UNRELIABILITY DUE TO COMMON MODE FAILURE
-----------------------------------------

UNRELIABILITY  =  0.0000000D+00 +/-  0.0000000D+00
SAMPLE VARIANCE  =          0.0000000D+00
COEFFICIENT OF VARIATION = 0.0000000D+00


OVERALL SYSTEM CALCULATION:
===========================

****************************************************
* UNRELIABILITY  =  0.5476824D-07 +/- 0.2779101D-08*
* SAMPLE VARIANCE  =        0.3089361D-12          *
* COEFFICIENT OF VARIATION= 0.5074293D-01          *
* FIGURE OF MERIT  =        0.2099916D+15          *
* TIME PER HISTORY =        0.1541450D-01          *
****************************************************


CPU CALCULATION TIME:   0.6166E+03 SECONDS
```

Appendix C

Listing of Monte Carlo Unreliability Program

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```
C*********************************************************************C
C*                                                                   *C
C*      Subroutine MAINMC                        MARVIN E. PLATT     *C
C*                                               SUMMER 1990         *C
C*                                               EARLIER VERSIONS BY:*C
C*                                                  FRANZ BOEHM      *C
C*                                                  CHRISTOPH KIRSCH *C
C*                                                  BARBARA KELKHOFF *C
C*      Abstract:                                                    *C
C*                                                                   *C
C*          This subroutine is called from CFEHM whenever the        *C
C*          user wants to perform a Monte Carlo calculation.         *C
C*                                                                   *C
C*      Calling sequence:                                            *C
C*                                                                   *C
C*          CALL MAINMC                                              *C
C*                                                                   *C
C*      Subroutines called:                                          *C
C*                                                                   *C
C*          INPUT          Creates an input file for the             *C
C*                         Monte Carlo calculation, or               *C
C*                         reads the input from a previous           *C
C*                         file or edits a previous file.            *C
C*                                                                   *C
C*          NAMCC          Performs the non-analog Monte Carlo       *C
C*                         simulation of system unreliability.       *C
C*                                                                   *C
C*          OUTPUT         Evaluates the unreliabilities (with the   *C
C*                         tallies from NAMCC) and writes the        *C
C*                         solution to an output file.               *C
C*                                                                   *C
C*      Functions called:  None called.                              *C
C*                                                                   *C
C*********************************************************************C
C*
      SUBROUTINE MAINMC
C*
      REAL TIMSET,TIMSTP,TARRY(2)
C*
      PARAMETER (MD=20,IMD=300)
C*
      CHARACTER*13 FHMNAM(MD),GRPNAM(MD)
C*
      DOUBLE PRECISION FR,RM,ALPHA,ZETA,ETA,ANSW,
     *                 X,TALCC,TALSP,RTCMF,PV,
     *                 TALNC,TALCM,DL,TTAL
C*
      DIMENSION NUMPV(MD),RTCMF(MD),TALCC(2,IMD),TALSP(2,IMD),
     *          FR(MD),RM(3,MD),ALPHA(3,MD),TALNC(2,IMD),
     *          MCSNUM(MD),MCSET(3*IMD),NIG(IMD),
     *          INCG(MD),TTAL(2,MD),TALCM(2,IMD),
     *          ISPARO(MD),INCLSV(MD),PV(IMD),NXSTAT(IMD*MD)
C*
```

```
      DATA ZETA,ETA/1D-2,3D0/
C*
      OPEN (1,FILE='INPMC.DAT',STATUS='UNKNOWN')
      OPEN (2,FILE='OUTMC.DAT',STATUS='UNKNOWN')
      REWIND 1
      REWIND 2
C*
      CALL INPUT(MD,IMD,NOCG,INCG,NOC,FR,RM,ALPHA,
     *           DL,NOH,NOTI,MCSNUM,MCSET,LMCS,IDIM,
     *           NEAR,NIG,ID,INCLSV,FHMNAM,ANSW,X,
     *           NCMF,NUMPV,RTCMF,IC,PV,NXSTAT,
     *           GRPNAM,ISPAR0)
C*
C*       Set CPU time
C*
      TIMSET=DTIME(TARRY)
C*
      CALL NAMCC(NOH,NOCG,INCG,NOC,NOTI,NEAR,ZETA,ETA,
     *           ANSW,X,DL,LMCS,IDIM,MCSNUM,MCSET,NIG,ID,
     *           INCLSV,FHMNAM,FR,RM,ALPHA,ISPAR0,
     *           NCMF,NUMPV,RTCMF,IC,PV,NXSTAT,
     *           TALCC,TALSP,TALNC,TALCM,TTAL)
C*
C*       Get CPU time
C*
      TIMSTP=DTIME(TARRY)
C*
      CALL OUTPUT(NOCG,INCG,FR,RM,ALPHA,RTCMF,DL,NOH,
     *            NCMF,NEAR,TALCC,TALSP,TALNC,TALCM,TTAL,
     *            TIMSTP,NOTI,ISPAR0,FHMNAM,GRPNAM)
C*
      WRITE(2,200) ' CPU CALCULATION TIME:',TIMSTP,' SECONDS'
 200  FORMAT(1X//A,E13.4,A)
C*
      CLOSE (1)
      CLOSE (2)
C     RETURN
      END
C*
C*3456789012345678901234567890123456789012345678901234567890123456789*C
C*                                                                   *C
C*    Subroutine NAMCC()                                             *C
C*                                                                   *C
C*      Subroutine NAMCC performs the non-analog Monte Carlo         *C
C*      unreliability simulation.  The code allows for constant      *C
C*      or time dependent (Weibull) component failure rates.         *C
C*      In addition to the HARP coverage models, we implement        *C
C*      the handling of common mode failures.  Component repair      *C
C*      rates are not used, however spare components can be          *C
C*      specified for each component group.  Insertion of spares     *C
C*      is equivalent to instantaneous repair and is consistent      *C
C*      with the method of behavioral decomposition employed.        *C
C*                                                                   *C
```

```
C*      Input Parameters:                                            *C
C*        NOH ... Number of Monte Carlo histories.                   *C
C*        NOCG .. Number of component groups.                        *C
C*        INCG .. Number of components in each group (initially).    *C
C*        NOC ... Total number of components in the system model.    *C
C*        NOTI .. Number of time intervals for graphing.             *C
C*        NEAR .. Identifies the near coincident fault model.        *C
C*        ZETA .. Lower parameter for case splitting.                *C
C*        ETA ... Upper parameter for case splitting.                *C
C*        ANSW .. Value for the "analog switch."                     *C
C*        X ..... Parameter for failure biasing.                     *C
C*        DL .... Design life (mission time) for the system.         *C
C*        LMCS .. Number of components in largest minimum cut set.   *C
C*        IDIM .. Working dimension of array MCSET.                  *C
C*        MCSNUM. Number of singlets, doublets, ... , (LMCS)-lets.   *C
C*        MCSET.. Array containing the minimum cut sets.             *C
C*        NIG ... Array for NCF user-defined interfering groups.     *C
C*        ID .... Working dimension of array NIG.                    *C
C*        INCLSV. Set to 1 (from 0) for self-interfering groups.     *C
C*        FHMNAM. Fault/error-handling model name for each group.    *C
C*        FR .... Constant failure rate of group components.         *C
C*        ALPHA.. Weibull failure rate coefs. (0th-2nd derivatives). *C
C*        RM .... Exp. power for Weibull rate (0th-2nd derivatives). *C
C*        ISPARO. Number of spare components for each group.         *C
C*        NCMF .. Number of specified common mode failure events.    *C
C*        NUMPV.. Number of next state possibilities for CMF events. *C
C*        RTCMF.. Array of common mode failure rates.                *C
C*        IC .... Working dimension of array PV.                     *C
C*        PV .... Array of next state probabilities for CMF events.  *C
C*        NXSTAT. Array specifying next states for CMF events.       *C
C*      Output Parameters:                                           *C
C*        TALCC.. Unreliability tally for exhaustion of hardware.    *C
C*        TALSP.. Unreliability tally for single point failure.      *C
C*        TALNC.. Unreliability tally for near coincident faults.    *C
C*        TALCM.. Unreliability tally for common mode failures.      *C
C*        TTAL .. Unreliability tally for each component group.      *C
C* --------------------------------------------------------------- *C

        SUBROUTINE NAMCC(NOH,NOCG,INCG,NOC,NOTI,NEAR,ZETA,ETA,
     *                    ANSW,X,DL,LMCS,IDIM,MCSNUM,MCSET,NIG,ID,
     *                    INCLSV,FHMNAM,FR,RM,ALPHA,ISPARO,
     *                    NCMF,NUMPV,RTCMF,IC,PV,NXSTAT,
     *                    TALCC,TALSP,TALNC,TALCM,TTAL)
C*
        PARAMETER (MD=20,IMD=300)
C*
        CHARACTER*13 FHMNAM(NOCG)
        LOGICAL YES,NO
        CHARACTER*3 CH
C*
        DOUBLE PRECISION FR,RM,ALPHA,ZETA,ETA,ANSW,X,
     *                    TF,TALCC,TALSP,TALNC,TALCM,
     *                    TTAL,TIME,DL,TI,TI0
```

```
C*
      DOUBLE PRECISION TL,DT,W,NFRATE,WGAM0,
     *                 NFRAT2,NFRAT3,R,S,N,C,GAM0,
     *                 RN,TT,W1,SUMC,SUMN,SUMS,
     *                 SUMNFR,PC,PN,PS,PST,PF,W2F,
     *                 W2R,BPC,BPS,BPN,BPST,PCM,BPCM

      DOUBLE PRECISION SUM,FRT0,RTCMF,PV,SUMCMF,
     *                 FRFUNC,RAN1,CD,SD,RD,CC,
     *                 RM1,RM2,RM3,CM1,CM2,CM3,SM1,
     *                 SM2,SM3,RMOM,CMOM,SMOM
C*
      DIMENSION MCSNUM(LMCS),MCSET(IDIM),FR(NOCG),
     *          RM(3,NOCG),ALPHA(3,NOCG),INCG(NOCG),
     *          TF(IMD),TI(IMD),NXSTAT(IC*NOCG),PV(IC),
     *          TI0(IMD),NIG(ID),ISOIC(IMD),NCIG(MD),
     *          CD(MD),SD(MD),RD(MD),CC(MD)

      DIMENSION RMOM(3,MD),CMOM(3,MD),SMOM(3,MD),SUMNFR(3,MD),
     *          RTCMF(NCMF),TTAL(2,NOCG),TALCC(2,NOTI),
     *          TALSP(2,NOTI),TALNC(2,NOTI),TALCM(2,NOTI),
     *          NUMPV(NCMF),ISPAR(MD),ISPAR0(NOCG),INCLSV(NOCG)
C*
      OPEN (7,FILE='VALUES.DAT',STATUS='UNKNOWN')
      REWIND 7
C*
C*    Initialize the calculation.
C*    Compute the unreliability at time intervals DT:
C*
      DT=DL/DBLE(NOTI)
      DO 8 I=1,NOTI
         TALCC(1,I)=0D0
         TALCC(2,I)=0D0
         TALSP(1,I)=0D0
         TALSP(2,I)=0D0
         TALNC(1,I)=0D0
         TALNC(2,I)=0D0
         TALCM(1,I)=0D0
         TALCM(2,I)=0D0
 8    CONTINUE
      DO 13 I=1,NOCG
         TTAL(1,I)=0D0
         TTAL(2,I)=0D0
 13   CONTINUE
      NHF=0
      NHFS=0
      NHFN=0
      NHFCM=0
C*
C*    Get the state independent values for the first three
C*    moments to exit (RMOM,CMOM,SMOM) as well as the state
C*    independent FEHM exit probabilities (RD,CD,SD):
C*
```

```
 4      PRINT*
        PRINT*,' DO YOU WANT TO USE FEHM EXIT'
        PRINT*,' PROBABILITIES AND MOMENTS FROM'
        PRINT*,' FILE VALUES.DAT (Y/N) ?'
        READ*, CH
        YES=(CH(1:1).EQ.'Y').OR.(CH(1:1).EQ.'y')
        NO=(CH(1:1).EQ.'N').OR.(CH(1:1).EQ.'n')
C*
        IF (NO) THEN
C*
        DO 1 I=1,NOCG
           IF (FHMNAM(I).EQ.'NONE') THEN
C*            ---use perfect-coverage values---
              SD(I)=0D0
              CD(I)=1D0
              RD(I)=0D0
              RMOM(1,I)=0D0
              RMOM(2,I)=0D0
              RMOM(3,I)=0D0
              CMOM(1,I)=0D0
              CMOM(2,I)=0D0
              CMOM(3,I)=0D0
              SMOM(1,I)=0D0
              SMOM(2,I)=0D0
              SMOM(3,I)=0D0
           ELSE
C*            ---fault/error-handling using the HARP code---
              NFRATE=0D0
              NFRAT2=0D0
              CALL COVNOM(FHMNAM(I),NFRATE,NFRAT2,C,N,
     *                    S,R,RM1,RM2,RM3,CM1,CM2,CM3,
     *                    SM1,SM2,SM3)
              CD(I)=C
              SD(I)=S
              RD(I)=R
              RMOM(1,I)=RM1
              RMOM(2,I)=RM2
              RMOM(3,I)=RM3
              CMOM(1,I)=CM1
              CMOM(2,I)=CM2
              CMOM(3,I)=CM3
              SMOM(1,I)=SM1
              SMOM(2,I)=SM2
              SMOM(3,I)=SM3
           END IF
C*
C*         Write these values on a file:
C*
           WRITE(7,*) CD(I)
           WRITE(7,*) SD(I)
           WRITE(7,*) RD(I)
           WRITE(7,*) RMOM(1,I)
           WRITE(7,*) RMOM(2,I)
```

```
          WRITE(7,*) RMOM(3,I)
          WRITE(7,*) CMOM(1,I)
          WRITE(7,*) CMOM(2,I)
          WRITE(7,*) CMOM(3,I)
          WRITE(7,*) SMOM(1,I)
          WRITE(7,*) SMOM(2,I)
          WRITE(7,*) SMOM(3,I)
 1      CONTINUE
C*
        ELSE IF (YES) THEN
C*
C*      Read the exit probabilities and moments from a file:
C*
        DO 2 I=1,NOCG
           READ(7,*) CD(I)
           READ(7,*) SD(I)
           READ(7,*) RD(I)
           READ(7,*) RMOM(1,I)
           READ(7,*) RMOM(2,I)
           READ(7,*) RMOM(3,I)
           READ(7,*) CMOM(1,I)
           READ(7,*) CMOM(2,I)
           READ(7,*) CMOM(3,I)
           READ(7,*) SMOM(1,I)
           READ(7,*) SMOM(2,I)
           READ(7,*) SMOM(3,I)
 2      CONTINUE
C*
        ELSE
           GO TO 4
        END IF
C*
C*
        PRINT*,' SYSTEM MODEL COMPLETE.'
        PRINT*,' FAULT HANDLING TERMINATED.'
        PRINT*,' MONTE CARLO CALCULATION BEGINS:'
C*
C*      Sum the total transition rate due to common mode failure:
C*
        SUMCMF=0D0
        DO 25 I=1,NCMF
            SUMCMF=SUMCMF+RTCMF(I)
 25     CONTINUE
C*                        ---begin Monte Carlo simulation loop---
        DO 10 I1=1,NOH
C*
C*         Initialize a new history.
C*         Set the time, time left, trial weight, system state, and
C*         the number of operational and spare components per group:
C*
           TIME=0D0
           TL=DL
           W=1D0
```

```
          ISYS=0
          DO 15 I=1,NOCG
             NCIG(I)=INCG(I)
             ISPAR(I)=ISPAR0(I)
 15       CONTINUE
C*
C*        Initialize the state of individual components as operational
C*        at time zero (TI0) and also initialize the time (TI) at which
C*        spare components are switched in as operational:
C*
          DO 20 J=1,NOC
             ISOIC(J)=1
             TI0(J)=0D0
             TI(J)=0D0
 20       CONTINUE
C*        ---NFC is a tally for the number of failed components---
          NFC=0
C*
C*        Non-analog Monte Carlo simulation: if you want to solve
C*        the system with analog Monte Carlo only, set IANAC=1.
C*
          IANAC=0
C*
C*        Initialization for history I1 completed.  Statement number
C*        999 is the entry point for simulating the next state
C*        transition of the Monte Carlo history:
C*
 999      CONTINUE
C*
C*        Calculate the total transition rate GAM0 at the design
C*        life time DL (for self-transition sampling method [6]):
C*        ---GAM0 is a state-dependent but time-independent value---
C*
          CALL SETNFR(NOCG,INCG,NIG,ID,NOC,ISOIC,
     *                FR,ALPHA,RM,TI0,DL,SUMNFR)
          GAM0=SUMCMF
          K=0
          DO 35 I=1,NOCG
             DO 30 J=1,INCG(I)
                K=K+1
                IF (ISOIC(K).NE.0) THEN
C*
C*              ---component K is operational---
C*              Get fault handling probability sum N+S+CC(K)=1-R.
C*              Only this fraction of the failure rate of component
C*              K contributes to the total transition rate "out"
C*              of the present system state.
C*
                   R=0D0
                   IF (NCIG(I) .GT. 1) THEN
                      CALL NCFRT(FHMNAM(I),NEAR,INCLSV(I),
     *                     FR(I),ALPHA,RM,I,TI0(K),DL,SUMNFR,
     *                     NFRATE,NFRAT2,NFRAT3)
```

```
                        R=RD(I)*(1D0-NFRATE*RMOM(1,I)
     *                          +NFRAT2*RMOM(2,I)-NFRAT3*RMOM(3,I))
                        IF (R .GT. 1D0) R=1D0
                     END IF
C*                   ---get failure rate of component K at time DL---
                     FRT0=FRFUNC(FR(I),ALPHA(1,I),RM(1,I),TI0(k),DL)
C*                   ---sum the total next state transition rate---
                     GAM0=GAM0+(1D0-R)*FRT0
                  END IF
 30            CONTINUE
 35         CONTINUE
C*
C*          Sample the time to the next transition TT. The sampling
C*          method switchs to analog exclusively after ANSW-
C*          percent of the design life DL has been simulated.
C*
            RN=RAN1(ISEED)
            CALL NXTIME(ETA,ZETA,IANAC,RN,TL,GAM0,W1,TT)
            IF (TIME .GT. (ANSW*DL)) IANAC=1
            TIME=TIME+TT
C*
C*          Terminate the history if there is no more time remaining:
C*
            TL=TL-TT
            IF (TL .LE. 0D0) GO TO 10
C*
C*          Calculate the probabilities of the transition being of type
C*          component failure PC, single point failure PS, near coincident
C*          fault PN, common mode failure PCM, or self-transition PST:
C*
            CALL SETNFR(NOCG,INCG,NIG,ID,NOC,ISOIC,
     *                  FR,ALPHA,RM,TI,TIME,SUMNFR)
            SUMC=0D0
            SUMN=0D0
            SUMS=0D0
            K=0
            DO 45 I=1,NOCG
               DO 40 J=1,INCG(I)
                  K=K+1
                  IF (ISOIC(K).NE.0) THEN
C*
C*                Get fault handling exits N, S, CC(K), R:
C*                ---TIME-TI(K) is operational time of comp. K---
C*
                     IF (NCIG(I) .GT.1) THEN
                        CALL NCFRT(FHMNAM(I),NEAR,INCLSV(I),
     *                       FR(I),ALPHA,RM,I,TI(K),TIME,SUMNFR,
     *                       NFRATE,NFRAT2,NFRAT3)
                        R=RD(I)*(1D0-NFRATE*RMOM(1,I)
     *                          +NFRAT2*RMOM(2,I)-NFRAT3*RMOM(3,I))
                        CC(K)=CD(I)*(1D0-NFRATE*CMOM(1,I)
     *                          +NFRAT2*CMOM(2,I)-NFRAT3*CMOM(3,I))
                        S=SD(I)*(1D0-NFRATE*SMOM(1,I)
```

```
     *                          +NFRAT2*SMOM(2,I)-NFRAT3*SMOM(3,I))
                          N=1D0-R-CC(K)-S
                          IF (N .LT. 0) N=0D0
                       ELSE
                          N=0D0
                          S=0D0
                          CC(K)=1D0
                       END IF
C*                     ---get the current failure rate of comp. K---
                       TF(K)=FRFUNC(FR(I),ALPHA(1,I),RM(1,I),TI(K),TIME)
C*                     ---sum time-dependent next state transition rates
C*                        for each exit type (permanent-coverage, near
C*                        coincident fault, and single point failure---
                       SUMC=SUMC+TF(K)*CC(K)
                       SUMN=SUMN+TF(K)*N
                       SUMS=SUMS+TF(K)*S
                    END IF
 40              CONTINUE
 45           CONTINUE
C*            ---if only constant component rates are used GAM0 is equal
C*               to SUMC+SUMN+SUMS+SUMCMF and thus the probability for self-
C*               transition PST is zero, otherwise GAM0 is greater than
C*               SUMC+SUMN+SUMS+SUMCMF and self-transitions are probable---
              PC=SUMC/GAM0
              PN=SUMN/GAM0
              PS=SUMS/GAM0
              PCM=SUMCMF/GAM0
              PF=PC+PN+PS+PCM
              PST=1D0-PF
              IF (PST .LE. 1D-30) PST=0D0
C*
C*            Calculate the weights and biased probabilities of the
C*            transition being of type component failure BPC, single
C*            point failure BPS, near coincident fault BPN, self-
C*            transition BPST, or common mode failure BPCM.
C*
              IF ((PF.GT.X).OR.(PF.LE.1D-30).OR.(IANAC.EQ.1)) THEN
C*               ---no failure biasing---
                 W2F=1D0
                 W2R=1D0
                 BPC=PC
                 BPS=PS
                 BPN=PN
                 BPCM=PCM
                 BPST=PST
              ELSE
C*               ---bias the failure probability sum PF to equal X---
                 BPST=1D0-X
                 W2R=PST/BPST
                 W2F=PF/X
                 BPN=PN/W2F
                 BPS=PS/W2F
                 BPC=PC/W2F
```

```
            BPCM=PCM/W2F
         END IF
C*
C*       Sample the type of the transition (component failure,
C*       single point failure, near coincident fault, self-
C*       transition, or common mode failure):
C*
         SUM=0D0
         WGAM0=GAM0*W2F
         RN=RAN1(ISEED)
         IF (RN.LT.BPC) THEN
C*
C*          Search for component failure transition:
C*
            K=0
            DO 51 I=1,NOCG
              DO 50 J=1,INCG(I)
                 K=K+1
                 IF (ISOIC(K) .NE. 0) THEN
                    SUM=SUM+TF(K)*CC(K)/WGAM0
                    IF (RN .LT. SUM) THEN
C*
C*                     Failed component found--insert a spare
C*                     component if available, else tag the
C*                     component as failed:
C*
                        IF (ISPAR(I) .NE. 0) THEN
                            ISPAR(I)=ISPAR(I)-1
                            TI(K)=TIME
                        ELSE
                            NCIG(I)=NCIG(I)-1
                            ISOIC(K)=0
                            NFC=NFC+1
                        END IF
C*
C*                      Weight history and check for system failure:
C*
                        W=W*W1*W2F
                        ISYS=ISTATE(ISOIC,NOC,MCSNUM,LMCS,
     *                              MCSET,IDIM,NFC)
                        IF (ISYS .EQ. 1) THEN
C*
C*                         System failure:  terminate history.
C*
C*                         Compile tallies for each component group:
C*
                           TTAL(1,I)=TTAL(1,I)+W
                           TTAL(2,I)=TTAL(2,I)+W*W
C*
C*                         Compile overall tallies for
C*                         permanent-coverage exit:
C*
                           NHF=NHF+1
```

```
                          M=INT(TIME/DT)+1
                          TALCC(1,M)=TALCC(1,M)+W
                          TALCC(2,M)=TALCC(2,M)+W*W
C*                        ---start a new history---
                          GO TO 10
                       END IF
C*                     ---continue sampling---
                       GO TO 999
                    END IF
                 END IF
 50           CONTINUE
 51         CONTINUE
         END IF
C*
         IF (RN .LT.(BPC+BPCM)) THEN
C*
C*          Search for common mode failure transition:
C*
            SUM=BPC+RTCMF(1)/WGAM0
            I=1
            K=0
            DO WHILE (SUM .LE. RN)
               I=I+1
               SUM=SUM+RTCMF(I)/WGAM0
               K=K+NUMPV(I-1)
            END DO
C*
C*          Common mode failure I found, search for the next state:
C*
            RN=RAN1(ISEED)
            SUM=0D0
            DO WHILE (SUM .LE. RN)
               K=K+1
               SUM=SUM+PV(K)
            END DO
C*
C*          Next state K for CMF event I found.
C*          Fail components corresponding to this state:
C*
            KN=(K-1)*NOCG
            K=0
            DO 65 I=1,NOCG
               KN=KN+1
               M=0
               M0=NXSTAT(KN)
C*             ---negative value implies random generated case---
               IF (M0 .LT. 0) M0=INT(RAN1(ISEED)*ABS(M0))+1
               DO 60 J=1,INCG(I)
                  K=K+1
                  IF (M .GE. M0) GO TO 60
                  IF (ISOIC(K) .NE. 0) THEN
C*                   ---tag components as failed---
                     M=M+1
```

```
                    NCIG(I)=NCIG(I)-1
                    ISOIC(K)=0
                    NFC=NFC+1
                 END IF
 60            CONTINUE
 65         CONTINUE
C*
C*          Weight history and check for system failure:
C*
            W=W*W1*W2F
            ISYS=ISTATE(ISOIC,NOC,MCSNUM,LMCS,MCSET,IDIM,NFC)
            IF (ISYS .EQ. 1) THEN
               M=INT(TIME/DT)+1
               TALCM(1,M)=TALCM(1,M)+W
               TALCM(2,M)=TALCM(2,M)+W*W
               NHFCM=NHFCM+1
C*             ---start a new history---
               GO TO 10
            END IF
C*          ---continue sampling---
            GO TO 999
         END IF
C*
         IF (RN .LT. (BPC+BPCM+BPS)) THEN
C*
C*           Transition is of type single point failure,
C*           therefore: system failed, terminate history.
C*
            W=W*W1*W2F
            NHFS=NHFS+1
            M=INT(TIME/DT)+1
            TALSP(1,M)=TALSP(1,M)+W
            TALSP(2,M)=TALSP(2,M)+W*W
C*          ---start a new history---
            GO TO 10
         END IF
C*
         IF (RN .LT.(BPC+BPCM+BPS+BPN)) THEN
C*
C*           Transition is of type near coincident fault,
C*           therefore: system failed, terminate history.
C*
             W=W*W1*W2F
             NHFN=NHFN+1
             M=INT(TIME/DT)+1
             TALNC(1,M)=TALNC(1,M)+W
             TALNC(2,M)=TALNC(2,M)+W*W
C*          ---start a new history---
             GO TO 10
         END IF
C*
C*       Else transition is of type self-transition, advance in time:
C*
```

```
            W=W*W1*W2R
C*          ---continue sampling---
            GO TO 999
C*
 10      CONTINUE
C*
         W=DBLE(NHF+NHFS+NHFN+NHFCM)/DBLE(NOH)
         print*,'percent of history failures: ',W*1D2
         CLOSE (7)
C*       ---end Monte Carlo simulation, return to MAINMC---
         RETURN
         END

C*3456789012345678901234567890123456789012345678901234567890123456789*C
C*                                                                   *C
C*       Subroutine NXTIME()                                         *C
C*                                                                   *C
C*       This subroutine samples the time to the next state          *C
C*       transition. Analog sampling is used if ANALOG=1, otherwise  *C
C*       the case splitting method is used [1].                      *C
C*                                                                   *C
C*       Input Parameters:                                           *C
C*         ETA ... Upper parameter for case splitting.               *C
C*         ZETA .. Lower parameter for case splitting.               *C
C*         ANALOG. Switch for analog/non-analog sampling.            *C
C*         RN .... Random number between 0 and 1.                    *C
C*         TL .... Simulation time left.                             *C
C*         GAM0 .. Current total state transition rate.              *C
C*       Output Parameters:                                          *C
C*         WT .... Trial weight correction for non-analog sampling.  *C
C*         DT .... The time to the next state transition.            *C
C*                                                                   *C
C* ----------------------------------------------------------------- *C

         SUBROUTINE NXTIME(ETA,ZETA,ANALOG,RN,TL,GAM0,WT,DT)

         INTEGER ANALOG
         DOUBLE PRECISION ETA,ZETA,RN,TL,GAM0,WT,DT,ENOT

C*       ENOT is the expected number of transitions in the remaining time.
C*
         ENOT=TL*GAM0
         IF ((ENOT .GT. ETA) .OR. (ANALOG .EQ. 1)) THEN
C*          ---use analog sampling---
            WT=1.0
            DT=-DLOG(RN)/GAM0
         ELSE IF (ENOT .LE. ZETA) THEN
C*          ---use rare event non-analog sampling---
            WT=ENOT
            DT=TL*RN
         ELSE
C*          ---use non-analog sampling---
            WT=1.0-DEXP(-ENOT)
```

```
          DT=-DLOG(1.0-WT*RN)/GAM0
      END IF
      RETURN
      END

C*34567890123456789012345678901234567890123456789012345678901234567890123456789*C
C*                                                                             *C
C*      Subroutine SETNFR()                                                    *C
C*                                                                             *C
C*      This subroutine computes intermediate near coincident                  *C
C*      fault rate values for each component group.  Subroutine                *C
C*      NCFRT then uses these intermediate values to update the                *C
C*      current near coincident fault rate for each component.                 *C
C*                                                                             *C
C*      Input parameters:                                                      *C
C*        NOCG .. Number of component groups.                                  *C
C*        INCG .. Initial no. of components in each group.                     *C
C*        NIG ... Array of NCF user-defined interfering groups.                *C
C*        ID .... Working dimension of array NIG.                              *C
C*        NOC ... Total number of system components.                           *C
C*        ISOIC.. The state of individual components (0 or 1).                 *C
C*        FR .... Constant failure rate of group components.                   *C
C*        ALPHA.. Weibull failure rate coefs. (0th-2nd derivatives).           *C
C*        RM .... Exp. power for Weibull rate (0th-2nd derivatives).           *C
C*        T0 .... Time at which each component became operational.             *C
C*        TIME .. Current model simulation time.                               *C
C*      Output parameter:                                                      *C
C*        SUMNFR. Sum of intermediate NCF rates for each group.                *C
C*                                              (0th-2nd derivatives)          *C
C* --------------------------------------------------------------------------- *C

      SUBROUTINE SETNFR(NOCG,INOC,NIG,ID,NOC,ISOIC,
     *                  FR,ALPHA,RM,T0,TIME,SUMNFR)

      INTEGER NOCG,INOC(NOCG),NIG(ID),ISOIC(NOC)

      DOUBLE PRECISION FRFUNC,FR,ALPHA,RM,T0,TIME,SUMNFR

      DIMENSION FR(NOCG),ALPHA(3,NOCG),RM(3,NOCG),
     *          SUMNFR(3,NOCG),T0(NOC)

      NSUM=0
      DO 40 N=1,NOCG
          NSTART=NOCG+NSUM+1
          NSTOP=NSTART+NIG(N)-1
          SUMNFR(1,N)=0D0
          SUMNFR(2,N)=0D0
          SUMNFR(3,N)=0D0
          J1=1
          K=0
          DO 30 I=NSTART,NSTOP
              J2=NIG(I)
              DO 10 J=J1,J2-1
```

```
                  K=K+INOC(J)
 10           CONTINUE
              DO 20 J=1,INOC(J2)
                  K=K+1
                  IF (ISOIC(K) .NE. O) THEN
C*                    ---0th,1st, and 2nd derivative sums---
                      SUMNFR(1,N)=SUMNFR(1,N)+FRFUNC(FR(J2),
     *                            ALPHA(1,J2),RM(1,J2),T0(K),TIME)
                      SUMNFR(2,N)=SUMNFR(2,N)+FRFUNC(0D0,
     *                            ALPHA(2,J2),RM(2,J2),T0(K),TIME)
                      SUMNFR(3,N)=SUMNFR(3,N)+FRFUNC(0D0,
     *                            ALPHA(3,J2),RM(3,J2),T0(K),TIME)
                  END IF
 20           CONTINUE
              J1=J2+1
 30       CONTINUE
          NSUM=NSUM+NIG(N)
 40   CONTINUE
      RETURN
      END

C*34567890123456789012345678901234567890123456789012345678901234567890123456789*C
C*                                                                        *C
C*    Subroutine NCFRT()                                                  *C
C*                                                                        *C
C*    This subroutine uses the sum totals computed by subroutine          *C
C*    SETNFR to quickly update the near coincident fault rate for         *C
C*    a component from group I.  The new fault rate value is used         *C
C*    to compute the Taylor series coefficients needed for                *C
C*    computing the state-dependent FEHM exit probabilities.              *C
C*                                                                        *C
C*    Input Parameters:                                                   *C
C*      FHMNAM. Fault/error-handling model name for group I.              *C
C*      NEAR .. Identifies the near coincident fault model.               *C
C*      INCLSV. Set to 1 (from 0) for self-interfering groups.            *C
C*      FRI ... Failure rate of components belonging to group I.          *C
C*      ALPHA.. Weibull failure rate coefs. (0th-2nd derivatives).        *C
C*      RM .... Exp. power for Weibull rate (0th-2nd derivatives).        *C
C*      I ..... The component group presently under consideration.       *C
C*      T0 .... Time a particular grp. I comp. became operational.        *C
C*      TIME .. Current model simulation time.                            *C
C*      TOTFR.. Sums computed by subroutine SETNFR.                       *C
C*    Output Parameters:                                                  *C
C*      NFRT1.. Coefficient of first moment to exit.                      *C
C*      NFRT2.. Coefficient of second moment to exit.                     *C
C*      NFRT3.. Coefficient of third moment to exit.                      *C
C*                                                                        *C
C* ---------------------------------------------------------------------- *C

      SUBROUTINE NCFRT(FHMNAM,NEAR,INCLSV,FRI,ALPHA,RM,I,
     *                 T0,TIME,TOTFR,NFRT1,NFRT2,NFRT3)

      CHARACTER*13 FHMNAM
```

```
      DOUBLE PRECISION FRI,ALPHA,RM,T0,TIME,TOTFR,GAMMA,
    *                  GAMMP,GAMPP,NFRT1,NFRT2,NFRT3,FRFUNC

      DIMENSION ALPHA(3,NOCG),RM(3,NOCG),TOTFR(3,NOCG)

C*    GAMMA,GAMMP,GAMMPP: 0th,1st & 2nd transition rate derivatives--

      IF ((FHMNAM .EQ. 'NONE') .OR. (NEAR .EQ. 4)) THEN
C*        ---no near coincident faults---
          GAMMA=0D0
          GAMMP=0D0
          GAMPP=0D0
      ELSE IF (INCLSV .EQ. 0) THEN
C*        ---no update is necessary---
          GAMMA=TOTFR(1,I)
          GAMMP=TOTFR(2,I)
          GAMPP=TOTFR(3,I)
      ELSE
C*        ---subtract component rate from the total for group I---
          GAMMA=TOTFR(1,I)-FRFUNC(FRI,ALPHA(1,I),RM(1,I),T0,TIME)
          GAMMP=TOTFR(2,I)-FRFUNC(0D0,ALPHA(2,I),RM(2,I),T0,TIME)
          GAMPP=TOTFR(3,I)-FRFUNC(0D0,ALPHA(3,I),RM(3,I),T0,TIME)
      END IF
      NFRT1=GAMMA
      NFRT2=GAMMA**2/2D0-GAMMP
      NFRT3=GAMMA*(GAMMA**2/6D0-GAMMP)+GAMPP/2D0
      RETURN
      END

C*3456789012345678901234567890123456789012345678901234567890123456789*C
C*                                                                   *C
C*    Function FRFUNC()                                              *C
C*                                                                   *C
C*    This function returns the value of a component failure rate    *C
C*    at the current time or returns the 1st or 2nd derivative of    *C
C*    the Weibull component failure rate at the current time.        *C
C*                                                                   *C
C*    Input Parameters:                                              *C
C*      LAM0 .. A constant component failure rate.                   *C
C*      ALPHA.. Coefficient for Weibull rate (0th,1st,or 2nd derv.)*C
C*      RM .... Exp. power for Weibull rate (0th,1st,or 2nd derv.).*C
C*      T0 .... Time when a component became operational.            *C
C*      TIME .. Current model simulation time.                       *C
C*                                                                   *C
C* ----------------------------------------------------------------- *C

      FUNCTION FRFUNC(LAM0,ALPHA,RM,T0,TIME)

      DOUBLE PRECISION FRFUNC,LAM0,ALPHA,RM,T0,TIME

      IF (ALPHA .EQ. 0D0) THEN
C*        ---constant component failure rate---
```

```
            FRFUNC=LAMO
        ELSE
C*          ---Weibull failure rate or 1st or 2nd derivative---
            FRFUNC=LAMO+ALPHA*(TIME-T0)**RM
        END IF
        RETURN
        END

C*3456789012345678901234567890123456789012345678901234567890123456789*C
C*                                                                    *C
C*      Function ISTATE()                                             *C
C*                                                                    *C
C*      This function compares the current system state with the      *C
C*      minimum cut sets to determine the state of the system:        *C
C*      ISTATE=0 (operational) or ISTATE=1 (failed).                  *C
C*                                                                    *C
C*      Input Parameters:                                             *C
C*        ISOIC.. The current state of individual components.         *C
C*        NOC ... The total number of system components.              *C
C*        MCSNUM. Number of singlets, doublets, ... , (LMCS)-lets.    *C
C*        LMCS .. No. of components in the largest minimum cut set.   *C
C*        MCSET.. Array containing the minimum cut sets.              *C
C*        IDIM .. Working dimension of array MCSET.                   *C
C*        NFC ... The total number of components currently failed.    *C
C*                                                                    *C
C* ------------------------------------------------------------------ *C

        FUNCTION ISTATE(ISOIC,NOC,MCSNUM,LMCS,MCSET,IDIM,NFC)

        DIMENSION MCSNUM(LMCS),MCSET(IDIM),ISOIC(NOC)
C*
        ISTATE=0
C*
        J=1
        N1=LMCS
        IF (NFC .LT. N1) N1=NFC
        DO 10 N=1,N1
              DO 20 I2=1,MCSNUM(N)
                 K=0
                 DO 30 I3=1,N
                    IF (ISOIC(MCSET(J)).EQ.0) K=K+1
                    J=J+1
 30              CONTINUE
                 IF (K.EQ.N) THEN
                    ISTATE=1
                    GO TO 99
                 END IF
 20           CONTINUE
 10     CCNTINUE
 99     RETURN
        END

C*3456789012345678901234567890123456789012345678901234567890123456789*C
```

```
C*                                                                      *C
C*      Subroutine DTOUT()                                              *C
C*                                                                      *C
C*      This subroutine modifies the unreliability tallies due to      *C
C*      hardware exhaustion, single point failure, near coincident     *C
C*      fault, and common mode failure for discrete time steps.        *C
C*      Data results for the total system unreliability U (plus or     *C
C*      minus standard deviation) as a function of time is written     *C
C*      to a file named OUTGR.DAT.                                      *C
C*                                                                      *C
C*      Input Parameters:                                               *C
C*        NOH ... Number of Monte Carlo histories.                      *C
C*        NOTI .. Number of time intervals for graphing.                *C
C*        DL .... The design life of the system model.                  *C
C*      Input/Output parameters:                                        *C
C*        TALCC.. Unreliability tally due to hardware exhaustion.       *C
C*        TALSP.. Unreliability tally due to single point failure.      *C
C*        TALNC.. Unreliability tally due to near coincident faults.    *C
C*        TALCM.. Unreliability tally due to common mode failure.       *C
C*                                                                      *C
C* ------------------------------------------------------------------- *C

      SUBROUTINE DTOUT(NOH,NOTI,DL,TALCC,TALSP,TALNC,TALCM)
C*
      DOUBLE PRECISION TALCC,TALSP,TALNC,TALCM,DL,DT,
     *                 U,SD,VAR,TALLY,TALY2,T,RNOH
C*
      DIMENSION TALCC(2,NOTI),TALSP(2,NOTI),
     *          TALNC(2,NOTI),TALCM(2,NOTI)
C*
      OPEN (3,FILE='OUTGR.DAT',STATUS='UNKNOWN')
      REWIND 3
C*
C*
      RNOH=DBLE(NOH)
      DT=DL/DBLE(NOTI)
      TALLY=0D0
      TALY2=0D0
      DO 10 I=1,NOTI
         TALLY=TALLY+TALCC(1,I)
         TALY2=TALY2+TALCC(2,I)
         TALCC(1,I)=TALLY
         TALCC(2,I)=TALY2
 10   CONTINUE
      TALLY=0D0
      TALY2=0D0
      DO 20 I=1,NOTI
         TALLY=TALLY+TALSP(1,I)
         TALY2=TALY2+TALSP(2,I)
         TALSP(1,I)=TALLY
         TALSP(2,I)=TALY2
 20   CONTINUE
      TALLY=0D0
```

```
      TALY2=0D0
      DO 30 I=1,NOTI
         TALLY=TALLY+TALNC(1,I)
         TALY2=TALY2+TALNC(2,I)
         TALNC(1,I)=TALLY
         TALNC(2,I)=TALY2
 30   CONTINUE
      TALLY=0D0
      TALY2=0D0
      DO 40 I=1,NOTI
         TALLY=TALLY+TALCM(1,I)
         TALY2=TALY2+TALCM(2,I)
         TALCM(1,I)=TALLY
         TALCM(2,I)=TALY2
 40   CONTINUE
      WRITE(3,200)
      WRITE(3,100) 0.,0.,0.,0.
      DO 60 I=1,NOTI
         U=(TALCC(1,I)+TALSP(1,I)+TALNC(1,I)+TALCM(1,I))/RNOH
         VAR=(TALCC(2,I)+TALSP(2,I)+TALNC(2,I)+TALCM(2,I))/RNOH-U*U
         SD=DSQRT(VAR/RNOH)
         T=I*DT
         WRITE(3,100) T,U,U+SD,U-SD
 60   CONTINUE
C*
 100  FORMAT (4(2X,E14.7))
 200  FORMAT (7X,'TIME',8X,'UNRELIABILITY',3X,'      +SD     ',
    * 3X,'     -SD     ',//)
C
      CLOSE(3)
      RETURN
      END

C*3456789012345678901234567890123456789012345678901234567890123456789*C
C*                                                                   *C
C*    Function RAN1()                                                *C
C*                                                                   *C
C*    This function returns a random number between 0 and 1.         *C
C*    The SUN FORTRAN random number generator DRAND is used.         *C
C*    The number of seconds since midnight is used to start the      *C
C*    random number generator.  From then on the seed is equal to    *C
C*    zero and the next random number in sequence is returned.       *C
C*                                                                   *C
C*    Input/Output Parameter:                                          *
C
C*      SEED.. The seed for the random number generator.             *C
C*                                                                   *C
C* --------------------------------------------------------------- *C

      FUNCTION RAN1(SEED)
C*
      INTEGER IARRY(3),SEED,SET
      DOUBLE PRECISION DRAND,RAN1
```

```
      DATA SET / 1 /
      SEED=0
      IF (SET .EQ. 1) THEN
C*       ---start with SUN FORTRAN time converted to seconds---
         CALL ITIME(IARRY)
         SEED=IARRY(1)*3600+IARRY(2)*60+IARRY(3)
         SET=0
      END IF
      RAN1=DRAND(SEED)
      RETURN
      END

C*3456789012345678901234567890123456789012345678901234567890123456789*C
C*                                                                    *C
C*      Subroutine INPUT()                                            *C
C*                                                                    *C
C*      This subroutine creates an input file for the Monte Carlo     *C
C*      unreliability calculation, or reads the input from            *C
C*      from a previous file (INPMC.DAT) or modifies this file.       *C
C*                                                                    *C
C*      Input Parameters:                                             *C
C*        MD .... Dimension constant for max. no. of comp. groups.    *C
C*        IMD ... Dimension constant for max. no. of components.      *C
C*      Output Parameters:                                            *C
C*        NOCG .. Number of component groups.                         *C
C*        NCIG .. Number of components in each group.                 *C
C*        NOC ... Total number of components in the system model.     *C
C*        FR .... Constant failure rate of group components.          *C
C*        RM .... Exp. power for Weibull rate (0th-2nd derivatives).  *C
C*        ALPHA.. Weibull failure rate coefs. (0th-2nd derivatives).  *C
C*        DL .... Design life for the system.                         *C
C*        NOH ... Number of Monte Carlo histories.                    *C
C*        NOTI .. Number of time intervals for graphing.              *C
C*        MCSNUM. Number of singlets, doublets, ... , (LMCS)-lets.    *C
C*        MCSET.. Array containing the minimum cut sets.              *C
C*        LMCS .. Number of components in largest minimum cut set.    *C
C*        IDIM .. Working dimension of array MCSET.                   *C
C*        NEAR .. Identifies the near coincident fault model.         *C
C*        NIG ... Array for NCF user-defined interfering groups.      *C
C*        ID .... Working dimension of array NIG.                     *C
C*        INCLSV. Set to 1 (from 0) for self-interfering groups.      *C
C*        FHMNAM. Fault/error-handling model name for each group.     *C
C*        ANSW .. Value for the "analog switch."                      *C
C*        X ..... Parameter for failure biasing.                      *C
C*        NCMF .. Number of specified common mode failure events.     *C
C*        NUMPV.. Number of next state possibilities for CMF events.  *C
C*        RTCMF.. Array of common mode failure rates.                 *C
C*        IC .... Working dimension of array PV.                      *C
C*        PV .... Array of next state probabilities for CMF events.   *C
C*        NXSTAT. Array specifying next states for CMF events.        *C
C*        GRPNAM. Name of each component group.                       *C
C*        ISPARO. Number of spare components for each group.          *C
C*                                                                    *C
```

```
C* ---------------------------------------------------------------- *C
      SUBROUTINE INPUT(MD,IMD,NOCG,NCIG,NOC,FR,RM,ALPHA,
     *                 DL,NOH,NOTI,MCSNUM,MCSET,LMCS,IDIM,
     *                 NEAR,NIG,ID,INCLSV,FHMNAM,ANSW,X,
     *                 NCMF,NUMPV,RTCMF,IC,PV,NXSTAT,
     *                 GRPNAM,ISPARO)
C*
      CHARACTER*13 FHMNAM(MD),GRPNAM(MD)
C*
      DOUBLE PRECISION FR,RM,ALPHA,DL,ANSW,X,RTCMF,PV,THETA,WM
C*
      DIMENSION NIG(IMD),FR(MD),RM(3,MD),INCLSV(MD),ISPARO(MD),
     *          ALPHA(3,MD),MCSNUM(MD),MCSET(3*IMD),NCIG(MD),
     *          NUMPV(MD),RTCMF(MD),PV(IMD),NXSTAT(IMD*MD)
C*
 1    PRINT*
      PRINT*,' THE MONTE CARLO INPUT FILE IS INPMC.DAT --'
      PRINT*,' DO YOU WANT TO:'
      PRINT*,' 1) INPUT A NEW SYSTEM MODEL;'
      PRINT*,' 2) EDIT THE OLD INPUT FILE;'
      PRINT*,' 3) USE THE INPUT FILE AS IS ?'
      READ*,NCHOSE
C*
      IF (NCHOSE .EQ. 1) THEN
C*
      CALL INPGRP(MD,IMD,NOCG,NCIG,NOC,ISPARO,GRPNAM,
     *            FR,ALPHA,RM,FHMNAM)
C*
      CALL INPMCS(MD,IMD,NOCG,LMCS,MCSNUM,MCSET)
C*
      CALL INPNCF(MD,IMD,NOCG,NEAR,ID,NIG,INCLSV)
C*
      CALL INPCMF(MD,IMD,NOCG,NCIG,FR,ALPHA,NCMF,RTCMF,NUMPV,
     *            IC,PV,NXSTAT)
C*
      PRINT*,' INPUT THE DESIGN LIFE FOR THIS SYSTEM:'
      READ*,DL
C*
      PRINT*,' INPUT NO. OF TIME INTERVALS FOR GRAPHING'
      READ*,NOTI
      IF (NOTI .LT. 1) NOTI=1
      IF (NOTI .GT. IMD) NOTI=IMD
C*
      PRINT*,' HOW MANY HISTORIES DO YOU WANT TO USE'
      PRINT*,' FOR THE MONTE CARLO SIMULATION ?'
      READ*,NOH
C*
      CALL DEFVAL(ANSW.X)
C*
      ELSE IF ((NCHOSE .EQ. 2) .OR. (NCHOSE .EQ. 3)) THEN
C*
C*    Read the input from the previous input file:
```

```
C*
        READ(1,*) NOCG
        NOC=0
        DO 260 J=1,NOCG
           READ (1,*) NCIG(J)
           NOC=NOC+NCIG(J)
           READ (1,*) ISPARO(J)
           READ (1,*) GRPNAM(J)
           READ (1,*) FR(J)
           READ (1,*) WM
           READ (1,*) THETA
C*         WM,THETA==> Weibull modulus and scale parameter.
           IF (THETA .EQ. 0D0) THEN
               RM(1,J)=0D0
               RM(2,J)=0D0
               RM(3,J)=0D0
               ALPHA(1,J)=0D0
               ALPHA(2,J)=0D0
               ALPHA(3,J)=0D0
           ELSE
               RM(1,J)=WM-1D0
               RM(2,J)=WM-2D0
               RM(3,J)=WM-3D0
               ALPHA(1,J)=WM/THETA**WM
               ALPHA(2,J)=ALPHA(1,J)*RM(1,J)
               ALPHA(3,J)=ALPHA(2,J)*RM(2,J)
           END IF
           READ(1,*) FHMNAM(J)
 260    CONTINUE
        READ(1,*) DL
        READ(1,*) NOTI
        READ(1,*) NOH
        READ(1,*) ANSW
        READ(1,*) X
        READ (1,*) LMCS
        IDIM=0
        DO 270 J=1,LMCS
           READ(1,*) MCSNUM(J)
           IDIM=IDIM+MCSNUM(J)*J
 270    CONTINUE
        N1=1
        N2=0
        DO 280 I=1,LMCS
           DO 275 J=1,MCSNUM(I)
              N2=N2+I
              READ(1,*) (MCSET(N),N=N1,N2)
              N1=N2+1
 275       CONTINUE
 280    CONTINUE
        READ(1,*) NEAR
        ID=NOCG
        DO 290 I=1,NOCG
           READ(1,*) NIG(I)
```

```
 290    CONTINUE
        DO 300 I=1,NOCG
           INCLSV(I)=0
           DO 295 J=1,NIG(I)
              ID=ID+1
              READ(1,*) NIG(ID)
              IF (NIG(ID) .EQ. I) INCLSV(I)=1
 295       CONTINUE
 300    CONTINUE
        IC=0
        READ(1,*) NCMF
        DO 320 I=1,NCMF
           READ(1,*) RTCMF(I)
           READ(1,*) NUMPV(I)
           DO 310 J=1,NUMPV(I)
              IC=IC+1
              N2=IC*NOCG
              N1=N2-NOCG+1
              READ(1,*) PV(IC)
              READ(1,*) (NXSTAT(KN), KN=N1,N2)
 310       CONTINUE
 320    CONTINUE
C*
        ELSE
           GO TO 1
        END IF
C*
        IF (NCHOSE .EQ. 2) THEN

 10     PRINT*,' SELECT AN EDITING OPTION:'
        PRINT*
        PRINT*,' 1) EDIT COMPONENT GROUP SPECIFICATIONS;'
        PRINT*,' 2) EDIT MINIMUM CUT SET SPECIFICATIONS;'
        PRINT*,' 3) EDIT THE NEAR COINCIDENT FAULT MODEL;'
        PRINT*,' 4) EDIT THE COMMON MODE FAILURE MODEL;'
        PRINT*,' 5) CHANGE THE DESIGN LIFE (MISSION) TIME;'
        PRINT*,' 6) CHANGE NO. OF TIME INTERVALS FOR GRAPHING;'
        PRINT*,' 7) CHANGE NUMBER OF MONTE CARLO HISTORIES;'
        PRINT*,' 8) CHANGE THE NON-ANALOG DEFAULT VALUES;'
        PRINT*,' 9) QUIT EDITING / RUN MONTE CARLO SIMULATION.'
        READ*,NUM
        IF (NUM .EQ. 1) THEN
           CALL INPGRP(MD,IMD,NOCG,NCIG,NOC,ISPAR0,GRPNAM,
     *                 FR,ALPHA,RM,FHMNAM)
        ELSE IF (NUM .EQ. 2) THEN
           CALL INPMCS(MD,IMD,NOCG,LMCS,MCSNUM,MCSET)
        ELSE IF (NUM .EQ. 3) THEN
           CALL INPNCF(MD,IMD,NOCG,NEAR,ID,NIG,INCLSV)
        ELSE IF (NUM .EQ. 4) THEN
           CALL INPCMF(MD,IMD,NOCG,NCIG,FR,ALPHA,NCMF,RTCMF,NUMPV,
     *                 IC,PV,NXSTAT)
        ELSE IF (NUM .EQ. 5) THEN
           PRINT*,' INPUT THE DESIGN LIFE FOR THIS SYSTEM:'
```

```
            READ*,DL
         ELSE IF (NUM .EQ. 6) THEN
            PRINT*,' INPUT NO. OF TIME INTERVALS FOR GRAPHING'
            READ*,NOTI
            IF (NOTI .LT. 1) NOTI=1
            IF (NOTI .GT. IMD) NOTI=IMD
         ELSE IF (NUM .EQ. 7) THEN
            PRINT*,' HOW MANY HISTORIES DO YOU WANT TO USE'
            PRINT*,' FOR THE MONTE CARLO SIMULATION ?'
            READ*,NOH
         ELSE IF (NUM .EQ. 8) THEN
            CALL DEFVAL(ANSW,X)
         END IF
         IF (NUM .NE. 9) GO TO 10
C*
         END IF

         IF (NCHOSE .NE. 3) THEN

C*       Rewrite the input file:
C*
         REWIND 1
         WRITE(1,*) NOCG
         DO 180 I=1,NOCG
            WRITE(1,*) NCIG(I)
            WRITE(1,*) ISPARO(I)
            WRITE(1,*) GRPNAM(I)
            WRITE(1,*) FR(I)
            IF (ALPHA(1,I) .EQ. 0D0) THEN
                 WM=0D0
                 THETA=0D0
                 WRITE(1,*) WM
                 WRITE(1,*) THETA
            ELSE
                 WM=RM(1,I)+1D0
                 WRITE(1,*) WM
                 THETA=(WM/ALPHA(1,I))**(1D0/WM)
                 WRITE(1,*) THETA
            END IF
            WRITE(1,*) FHMNAM(I)
 180     CONTINUE
         WRITE(1,*) DL
         WRITE(1,*) NOTI
         WRITE(1,*) NOH
         WRITE(1,*) ANSW
         WRITE(1,*) X
         WRITE(1,*) LMCS
         DO 185 I=1,LMCS
            WRITE(1,*) MCSNUM(I)
 185     CONTINUE
         N1=1
         N2=0
         DO 200 I=1,LMCS
```

```
            DO 190 J=1,MCSNUM(I)
               N2=N2+I
               WRITE(1,*) (MCSET(N),N=N1,N2)
               N1=N2+1
 190        CONTINUE
 200     CONTINUE
         WRITE (1,*) NEAR
         DO 210 I=1,ID
            WRITE (1,*) NIG(I)
 210     CONTINUE
         K=0
         WRITE(1,*) NCMF
         DO 240 I=1,NCMF
            WRITE(1,*) RTCMF(I)
            WRITE(1,*) NUMPV(I)
            DO 230 J=1,NUMPV(I)
               K=K+1
               N2=K*NOCG
               N1=N2-NOCG+1
               WRITE(1,*) PV(K)
               WRITE(1,*) (NXSTAT(KN),KN=N1,N2)
 230        CONTINUE
 240     CONTINUE
C*
         END IF

         RETURN
         END

C*3456789012345678901234567890123456789012345678901234567890123456789*C
C*                                                                   *C
C*       Subroutine INPGRP()                                         *C
C*                                                                   *C
C*       This subroutine asks the user to input:                     *C
C*         NOCG .. Number of component groups;                       *C
C*         NCIG .. Number of components in each group;               *C
C*         ISPARO. Number of spare components for each group;        *C
C*         GRPNAM. Name of each component group;                     *C
C*         FR .... Constant failure rates of group components;       *C
C*         WM .... Weibull modulus for each group;                   *C
C*         THETA.. Weibull scale parameter for each group;           *C
C*         FHMNAM. Fault/error-handling model name for each group.   *C
C*                                                                   *C
C*       For groups with constant component failure rates, the       *C
C*       Weibull modulus and scale parameter should be input as zero. *C
C*       ALPHA stores the component Weibull failure rate coefficients *C
C*       as well as the coefficients for the 1st and 2nd derivatives. *C
C*       RM stores the required exponential powers needed for the    *C
C*       Weibull failure rates and the 1st and 2nd derivatives.      *C
C*       NOC is a tally for the total number of system components.   *C
C*                                                                   *C
C* ----------------------------------------------------------------- *C
```

```
      SUBROUTINE INPGRP(MD,IMD,NOCG,NCIG,NOC,ISPARO,GRPNAM,FR,
     *                  ALPHA,RM,FHMNAM)
C*
      CHARACTER*13 FHMNAM(MD),GRPNAM(MD)
C*
      DOUBLE PRECISION FR,ALPHA,RM,THETA,WM
      DIMENSION NCIG(MD),ISPARO(MD),FR(MD),ALPHA(3,MD),RM(3,MD)
C*
      GO TO 10
 5    PRINT*,' NUMBER OF COMPONENT GROUPS SHOULD BE'
      PRINT*,' LESS THAN OR EQUAL TO',MD
 10   PRINT*,' HOW MANY COMPONENT GROUPS DOES YOUR SYSTEM HAVE?'
      READ*,NOCG
      IF (NOCG .GT. MD) GO TO 5
      K=0
      DO 20 I=1,NOCG
            PRINT 1000,I
            READ*,NCIG(I)
            K=K+NCIG(I)
            PRINT 1005,I
            READ *,ISPARO(I)
            PRINT 1010,I
            READ '(A)',GRPNAM(I)
            PRINT 1100,I
            READ *,FR(I)
            PRINT 1300,I
            PRINT*,' (INPUT ZERO FOR CONSTANT RATES)'
            READ *,WM
            PRINT 1500,I
            PRINT*,' (INPUT ZERO FOR CONSTANT RATES)'
            READ *, THETA
            IF (THETA .EQ. 0D0) THEN
               RM(1,I)=0D0
               RM(2,I)=0D0
               RM(3,I)=0D0
               ALPHA(1,I)=0D0
               ALPHA(2,I)=0D0
               ALPHA(3,I)=0D0
            ELSE
               RM(1,I)=WM-1D0
               RM(2,I)=WM-2D0
               RM(3,I)=WM-3D0
               ALPHA(1,I)=WM/THETA**WM
               ALPHA(2,I)=ALPHA(1,I)*RM(1,I)
               ALPHA(3,I)=ALPHA(2,I)*RM(2,I)
            END IF
            PRINT 1600,I
            READ '(A)',FHMNAM(I)
20    CONTINUE
      NOC=K
      IF (NOC .GT. IMD) THEN
         PRINT*,'MAXIMUM NUMBER OF COMPONENTS SHOULD BE',IMD
         GO TO 10
```

```
      END IF
 1000 FORMAT(' ENTER NUMBER OF COMPONENTS IN GROUP',I2)
 1005 FORMAT(' ENTER NUMBER OF SPARE COMPONENTS'/,
     *       ' AVAILABLE FOR COMPONENT GROUP',I2)
 1010 FORMAT(' ENTER NAME OF COMPONENT GROUP',I2)
 1100 FORMAT(' ENTER FAILURE RATE OF COMPONENT IN GROUP',I2)
 1300 FORMAT(' ENTER WEIBULL MODULUS FOR COMPONENT GROUP',I2)
 1500 FORMAT(' ENTER SCALE PARAMETER FOR COMPONENT GROUP',I2)
 1600 FORMAT(' ENTER FAULT HANDLING MODEL NAME FOR GROUP',I2,'--'/,
     * ' USE THE NAME YOU CHOSE FOR THE FEHM FILE FOR THIS',/,
     * ' GROUP OR ENTER "NONE" (MUST BE CAPITAL LETTERS)',/,
     * ' IF YOU WANT NO FAILURE HANDLING FOR THIS GROUP.')
 1800 FORMAT(A)
      RETURN
      END

C*34567890123456789012345678901234567890123456789012345678901234567890123456789*C
C*                                                                           *C
C*    Subroutine INPMCS()                                                    *C
C*                                                                           *C
C*    This subroutine asks the user to input the required minimum            *C
C*    cut sets for the system being modeled.                                 *C
C*                                                                           *C
C*    Input Parameters:                                                      *C
C*      MD .... Dimension constant for array MCSNUM.                         *C
C*      IMD ... (*3) Dimension constant for array MCSET.                     *C
C*      NOCG .. Number of component groups.                                  *C
C*    Output Parameters:                                                     *C
C*      LMCS .. Number of components in largest minimum cut set.             *C
C*      MCSNUM. Number of singlets, doublets, ... , (LMCS)-lets.             *C
C*      MCSET.. Array storing the minimum cut sets.                          *C
C*                                                                           *C
C* ------------------------------------------------------------------------- *C

      SUBROUTINE INPMCS(MD,IMD,NOCG,LMCS,MCSNUM,MCSET)

      DIMENSION MCSNUM(MD),MCSET(3*IMD)

 5    PRINT*,' NOW INPUT THE MINIMUM CUT SETS FOR THIS'
      PRINT*,' SYSTEM.  HOW MANY COMPONENTS ARE THERE '
      PRINT*,' IN THE LARGEST MINIMUM CUT SET ?       '
      READ*,LMCS
      IF (LMCS .GT. MD) THEN
         PRINT*,' LARGEST CUT SET SHOULD BE NO MORE THAN',MD
         GO TO 5
      END IF
      IDIM=0
      DO 10 I=1,LMCS
         PRINT*,' HOW MANY CUT SETS HAVE:',I,' COMPONENT(S)?'
         READ*,MCSNUM(I)
         IDIM=IDIM+MCSNUM(I)*I
 10   CONTINUE
      IF (IDIM .GT. 3*IMD) THEN
```

```
            PRINT*,' ***DIMENSION FOR ARRAY MCSET TO SMALL***'
            PRINT*,' EITHER STOP AND INCREASE THE DIMENSION CONSTANT'
            PRINT*,' OR OMIT SOME OF THE LARGER CUT SETS.'
            GO TO 5
         END IF
         PRINT*,' NUMBER THE SYSTEM COMPONENTS SEQUENTIALLY'
         PRINT*,' BEGINNING WITH COMPONENT NUMBER 1 IN GROUP 1'
         PRINT*,' THROUGH TO THE LAST COMPONENT IN GROUP',NOCG
         PRINT*
         PRINT*,' ENTER ONE CUT SET AT A TIME BY LISTING THE'
         PRINT*,' NUMBERS OF THE COMPONENTS IN THE SET SEPARATED'
         PRINT*,' BY COMMAS OR SPACES.  INPUT SINGLET SETS FIRST,'
         PRINT*,' THEN DOUBLETS, AND SO ON UP TO THE LARGEST SET.'
         PRINT*,' FOR EXAMPLE, A SYSTEM WITH NO SINGLETS, TWO'
         PRINT*,' DOUBLETS, AND ONE TRIPLET WOULD BE ENTERED AS:'
         PRINT*,' #,#                      # #'
         PRINT*,' #,#          (OR)        # #'
         PRINT*,' #,#,#                    # # #'
         PRINT*,' NOW BEGIN TO ENTER THE CUT SETS:'
         N1=1
         N2=0
         DO 30 I=1,LMCS
            DO 20 J=1,MCSNUM(I)
               N2=N2+I
               READ*, (MCSET(N),N=N1,N2)
               N1=N2+1
 20         CONTINUE
 30      CONTINUE
         RETURN
         END

C*3456789012345678901234567890123456789012345678901234567890123456789*C
C*                                                                   *C
C*      Subroutine INPNCF()                                          *C
C*                                                                   *C
C*      This subroutine asks the user to specify a near coincident   *C
C*      fault model.                                                 *C
C*                                                                   *C
C*      Input Parameters:                                            *C
C*        MD .... Dimension constant for array INCLSV.               *C
C*        IMD ... Dimension constant for array NIG.                  *C
C*        NOCG .. Number of component groups.                        *C
C*      Output Parameters:                                           *C
C*        NEAR .. Identifies the selected NCF model.                 *C
C*        ID .... Working dimension of array NIG.                    *C
C*        NIG(1:NOCG). Stores the total number of interfering groups *C
C*                for each of the component groups.                  *C
C*        NIG(NOCG+1:ID). Stores the group number(s) of all inter-   *C
C*                fering group(s) for each of the component groups.  *C
C*        INCLSV. Set to 1 (from 0) for self-interfering groups.     *C
C*                                                                   *C
C* ----------------------------------------------------------------- *C
```

```
      SUBROUTINE INPNCF(MD,IMD,NOCG,NEAR,ID,NIG,INCLSV)

      LOGICAL YES,NO
      CHARACTER*3 ANSR
      DIMENSION NIG(IMD),INCLSV(MD)

 5    PRINT*,' CHOSE A NEAR COINCIDENT FAULT MODEL:'
      PRINT*,' 1) ALL INCLUSIVE NCF''S'
      PRINT*,' 2) SAME COMPONENT NCF''S'
      PRINT*,' 3) USER DEFINED NCF''S'
      PRINT*,' 4) NO NCF''S ALLOWED'
      READ*, NEAR
C*
      K=NOCG
      IF (NEAR .EQ. 1) THEN
          DO 20 I=1,NOCG
              NIG(I)=NOCG
              DO 10 J=1,NOCG
                  K=K+1
                  NIG(K)=J
 10           CONTINUE
              INCLSV(I)=1
 20       CONTINUE
      ELSE IF (NEAR .EQ. 2) THEN
          DO 30 I=1,NOCG
              NIG(I)=1
              K=K+1
              NIG(K)=I
              INCLSV(I)=1
 30       CONTINUE
      ELSE IF (NEAR .EQ. 3) THEN
          PRINT*,' ***USER DEFINED NEAR COINCIDENT FAULT MODEL***'
          DO 50 I=1,NOCG
              NIG(I)=0
              INCLSV(I)=0
              PRINT*,' ARE NCF''S BETWEEN A COMPONENT FROM:'
              DO 40 J=1,NOCG
 35               PRINT 200,I,J
                  READ*,ANSR
                  YES=(ANSR(1:1).EQ.'Y').OR.(ANSR(1:1).EQ.'y')
                  NO=(ANSR(1:1).EQ.'N').OR.(ANSR(1:1).EQ.'n')
                  IF (YES) THEN
                      NIG(I)=NIG(I)+1
                      K=K+1
                      NIG(K)=J
                      IF (I .EQ. J) INCLSV(I)=1
                  ELSE
                       IF (.NOT.(NO)) GO TO 35
                  END IF
 40           CONTINUE
 50       CONTINUE
      ELSE IF (NEAR .EQ. 4) THEN
          DO 60 I=1,NOCG
```

```
                 NIG(I)=0
                 INCLSV(I)=0
 60           CONTINUE
        ELSE
            GO TO 5
        END IF
        ID=K
 200    FORMAT(' GRP.',I2,' AND THEN GRP.',I2,' FATAL (Y/N)?')
        RETURN
        END

C*3456789012345678901234567890123456789012345678901234567890123456789*C
C*                                                                   *C
C*      Subroutine INPCMF()                                          *C
C*                                                                   *C
C*      This subroutine allows the user to specify common mode       *C
C*      failure events which have constant rates.                    *C
C*                                                                   *C
C*      Input Parameters:                                            *C
C*        MD .... Dimension constant for array RTCMF and NUMPV.      *C
C*        IMD ... Dimension constant for array PV and (*MD) NXSTAT.  *C
C*        NOCG .. Number of component groups.                        *C
C*        NCIG .. Number of components in each group.                *C
C*        ALPHA.. Coefficients for Weibull component failure rates.  *C
C*      Output Parameters:                                           *C
C*        NCMF .. Number of specified common mode failure events.    *C
C*        RTCMF.. Common mode failure rate for each event.           *C
C*        NUMPV.. Number of next state possibilities for each event. *C
C*        IC .... Working dimension of array PV.                     *C
C*        PV .... Next state probability vector for each event.      *C
C*        NXSTAT. Stores next state possibilities for each event.    *C
C*                                                                   *C
C* ----------------------------------------------------------------- *C

        SUBROUTINE INPCMF(MD,IMD,NOCG,NCIG,FR,ALPHA,NCMF,RTCMF,NUMPV,
     *                    IC,PV,NXSTAT)
C
        DOUBLE PRECISION FR,ALPHA,RTCMF,PV,BETA,SUM
C
        DIMENSION NCIG(NOCG),FR(NOCG),ALPHA(3,NOCG),RTCMF(MD),
     *            NUMPV(MD),PV(IMD),NXSTAT(IMD*MD)
C
        PRINT*,' HOW MANY CMF EVENTS DO YOU WISH TO SPECIFY ?'
        READ*, NCMF
        K=0
        KN=0
        DO 70 I=1,NCMF
 10         PRINT*,' CHOOSE MODEL FOR CMF EVENT',I
            PRINT*,' 1) BETA-FACTOR       '
            PRINT*,' 2) RANDOM GENERATED '
            PRINT*,' 3) USER DEFINED      '
            PRINT*,' 4) SYSTEM FAILURE    '
            READ*, ICMF
```

```
C
            IF (ICMF .EQ. 1) THEN
 20            PRINT*,' BETA-FACTOR MODEL: SELECT COMP. GRP. NUMBER'
               READ*,NUM
               IF ((NUM .LT. 1) .OR. (NUM .GT. NOCG)) GO TO 20
               IF (ALPHA(1,NUM) .EQ. 0) THEN
                  PRINT*,' THE COMPONENT FAILURE RATE IS',FR(NUM)
 30               PRINT*,' WHAT FRACTION BETA IS DUE TO CMF ?'
                  READ*,BETA
                  IF ((BETA .LT. 0) .OR. (BETA .GT. 1D0)) GO TO 30
                  RTCMF(I)=BETA*FR(NUM)
                  FR(NUM)=FR(NUM)-RTCMF(I)
               ELSE
                  PRINT*,' IN ADDITION TO THE WEIBULL FAILURE RATE,'
                  PRINT*,' ESTIMATE A CONSTANT CMF RATE FOR THIS GROUP'
                  READ*,RTCMF(I)
               END IF
               NUMPV(I)=1
               K=K+1
               PV(K)=1D0
               DO 40 N=1,NOCG
                  KN=KN+1
C                 ---next state ==> all group NUM components fail---
                  IF (N .EQ. NUM) THEN
                     NXSTAT(KN)=NCIG(NUM)
                  ELSE
                     NXSTAT(KN)=0
                  END IF
 40            CONTINUE
C
            ELSE IF (ICMF .EQ. 2) THEN
               PRINT*,' INPUT THE CONSTANT CMF RATE FOR THIS EVENT'
               READ*, RTCMF(I)
               NUMPV(I)=1
               K=K+1
               PV(K)=1D0
               PRINT*,' DUE TO THIS EVENT, INPUT THE MAXIMUM NUMBER OF:'
               DO 50 N=1,NOCG
                  KN=KN+1
                  PRINT*,' GROUP',N,'  COMPONENTS WHICH FAIL'
                  READ*,NUM
C                 ---next state is randomly determined:
C                    if NUM > 0, between 1 and NUM grp. N comps. fail---
                  NXSTAT(KN)=-NUM
 50            CONTINUE
C
            ELSE IF (ICMF .EQ. 3) THEN
               PRINT*,' INPUT THE CONSTANT CMF RATE FOR THIS EVENT'
               READ*,RTCMF(I)
               PRINT*,' HOW MANY NEXT STATE POSSIBILITIES DO YOU WISH TO'
               PRINT*,' SPECIFY FOR THIS CMF EVENT ?'
               READ*,NUMPV(I)
               SUM=0
```

```
               K1=K+1
               DO 60 J=1,NUMPV(I)
                  K=K+1
                  PRINT*,' ENTER PROBABILITY FOR NEXT STATE',J
                  READ*,PV(K)
                  PRINT*,' IN TRANSITION TO THIS STATE---'
                  DO 55 N=1,NOCG
                     KN=KN+1
                     PRINT*,' HOW MANY GROUP',N,'  COMPONENTS FAIL ?'
                     READ*,NXSTAT(KN)
 55               CONTINUE
                  SUM=SUM+PV(K)
 60            CONTINUE
C              ---normalize probabilities to sum to one---
               DO 65 J=K1,K
                  PV(J)=PV(J)/SUM
 65            CONTINUE
C
            ELSE IF (ICMF .EQ. 4) THEN
               PRINT*,' INPUT THE CONSTANT CMF RATE FOR THIS EVENT'
               READ*,RTCMF(I)
               NUMPV(I)=1
               K=K+1
               PV(K)=1D0
C              ---next state==> all comps. fail==> system failure:
               DO 67 N=1,NOCG
                  KN=KN+1
                  NXSTAT(KN)=NCIG(N)
 67            CONTINUE
            ELSE
               GO TO 10
            END IF
 70      CONTINUE
         IC=K
         RETURN
         END

C*3456789012345678901234567890123456789012345678901234567890123456789*C
C*                                                                   *C
C*      Subroutine DEFVAL()                                          *C
C*                                                                   *C
C*      This subroutine sets the so-called analog switch ANSW and    *C
C*      the parameter X for failure biasing. The sampling of times   *C
C*      to the next state transition switches to analog exclusively  *C
C*      after ANSW-percent of the mission time has been simulated.   *C
C*      The default is ANSW=0.9 (90 percent).  Failure biasing only  *C
C*      is significant when time dependent rates are being used.     *C
C*      The default is X=0.5 which is likely to be sufficient for    *C
C*      all cases in which time dependent rates are used.            *C
C* --------------------------------------------------------------- *C

         SUBROUTINE DEFVAL(ANSW,X)
```

```
      DOUBLE PRECISION ANSW,X
      LOGICAL YES,NO
      CHARACTER*3 CHANGE

      ANSW=9D-1
      X=5D-1
 10   PRINT*,' CHANGE NON-ANALOG DEFAULT VALUES (Y/N) ?'
      READ*, CHANGE
      YES=(CHANGE(1:1).EQ.'Y').OR.(CHANGE(1:1).EQ.'y')
      NO=(CHANGE(1:1).EQ.'N').OR.(CHANGE(1:1).EQ.'n')
      IF (YES) THEN
 20      PRINT*,' ENTER VALUE FOR ANALOG SWITCH (DEFAULT=0.9)'
         READ*, ANSW
         IF ((ANSW .LT. 0) .OR. (ANSW .GT. 1)) THEN
            PRINT*,' CHOOSE A VALUE BETWEEN 0 AND 1'
            GO TO 20
         END IF
 30      PRINT*,' ENTER VALUE FOR FAILURE BIASING (DEFAULT=0.5)'
         READ*, X
         IF ((X .LT. 0.05) .OR. (X .GT. 0.95)) THEN
            PRINT*,' CHOOSE A VALUE BETWEEN 0.05 AND 0.95'
            GO TO 30
         END IF
      ELSE
         IF (.NOT.(NO)) GO TO 10
      END IF
      RETURN
      END

C*34567890123456789012345678901234567890123456789012345678901234567890*C
C*                                                                     *C
C*      Subroutine OUTPUT()                                            *C
C*                                                                     *C
C*      This subroutine writes the results of the Monte Carlo          *C
C*      unreliability calculation to file OUTMC.DAT.                   *C
C*                                                                     *C
C*      Input Parameters:                                              *C
C*        NOCG .. Number of component groups.                          *C
C*        INCG .. Number of components in each group (initially).      *C
C*        FR .... Constant failure rates of group components.          *C
C*        RM .... Exp. powers needed for Weibull rates.                *C
C*        ALPHA.. Coefficients for Weibull component failure rates.    *C
C*        RTCMF.. Common mode failure event rates.                     *C
C*        DL .... Design life for the system model.                    *C
C*        NOH ... Number of Monte Carlo histories used.                *C
C*        NCMF... Number of specified common mode failure events.      *C
C*        NEAR .. Identifies the near coincident fault model.          *C
C*        TALCC.. Unreliability tally due to hardware exhaustion.      *C
C*        TALSP.. Unreliability tally due to single point failure.     *C
C*        TALNC.. Unreliability tally due to near coincident faults.   *C
C*        TALCM.. Unreliability tally due to common mode failure.      *C
C*        TTAL .. Unreliability tally due to each component group.     *C
C*        TIME2.. CPU time for the unreliability calculation.          *C
```

```
C*        NOTI .. Number of time intervals for graphing.              *C
C*        ISPARO. Number of spare components for each group.          *C
C*        FHMNAM. Fault/error-handling model name for each group.     *C
C*        GRPNAM. The name specified for each component group.        *C
C*                                                                    *C
C* ------------------------------------------------------------------ *C

      SUBROUTINE OUTPUT(NOCG,INCG,FR,RM,ALPHA,RTCMF,DL,NOH,
     *                  NCMF,NEAR,TALCC,TALSP,TALNC,TALCM,TTAL,
     *                  TIME2,NOTI,ISPARO,FHMNAM,GRPNAM)
C*
      PARAMETER (MD=20)
C*
      CHARACTER*13 FHMNAM(NOCG),GRPNAM(NOCG),A*14
C*
      DOUBLE PRECISION FR,RM,ALPHA,DL,TIME,TALCC,
     *                 TALSP,TALNC,TALCM,TTAL,
     *                 TPH,TALLY,TALY2,RNOH,
     *                 U1,VAR1,S1,DELTA1,U2,VAR2,
     *                 S2,DELTA2,U3,VAR3,S3,DELTA3,
     *                 U4,VAR4,S4,DELTA4,RTCMF,
     *                 UT,VART,ST,DELTAT,U,VAR,
     *                 SD,DELTA,FOM,WM,THETA
C*
      DIMENSION INCG(NOCG),FR(NOCG),RM(3,NOCG),ALPHA(3,NOCG),
     *          TTAL(2,NOCG),UT(MD),VART(MD),TALLY(4),TALY2(4),
     *          ST(MD),DELTAT(MD),ISPARO(NOCG),RTCMF(NCMF),
     *          TALCC(2,NOTI),TALSP(2,NOTI),TALNC(2,NOTI),
     *          TALCM(2,NOTI)
C*
C*    Print header and system parameters:
C*
      WRITE (2,295)
      WRITE(2,1000) NOCG
      DO 10 I=1,NOCG
         WRITE(2,1005) GRPNAM(I),INCG(I)
         WRITE(2,1007) GRPNAM(I),ISPARO(I)
         WRITE(2,1010) GRPNAM(I),FR(I)
         IF (ALPHA(1,I) .EQ. 0D0) THEN
            WM=0D0
            THETA=0D0
            WRITE (2,1030) GRPNAM(I),WM
            WRITE (2,1050) GRPNAM(I),THETA
         ELSE
            WM=RM(1,I)+1D0
            WRITE (2,1030) GRPNAM(I),WM
            THETA=(WM/ALPHA(1,I))**(1D0/WM)
            WRITE (2,1050) GRPNAM(I),THETA
         END IF
         WRITE(2,1060) GRPNAM(I),FHMNAM(I)
 10   CONTINUE
      DO 15 J=1,NCMF
         WRITE(2,1070) J,RTCMF(J)
```

```
 15     CONTINUE
        WRITE(2,1120) DL,NOH,NEAR
C*
C*      Evaluate the unreliability tallies:
C*
        TIME=DBLE(TIME2)
        RNOH=DBLE(NOH)
        TPH=TIME/RNOH
        A='UNRELIABILITY'
C*
        DO 20 J=1,NOCG
           IF (TTAL(1,J) .GT. 0D0) THEN
              UT(J)=TTAL(1,J)/RNOH
              VART(J)=TTAL(2,J)/RNOH-UT(J)*UT(J)
              ST(J)=DSQRT(VART(J)/RNOH)
              DELTAT(J)=ST(J)/UT(J)
           END IF
 20     CONTINUE
C*
        CALL DTOUT(NOH,NOTI,DL,TALCC,TALSP,TALNC,TALCM)
C*
        TALLY(1)=TALCC(1,NOTI)
        TALY2(1)=TALCC(2,NOTI)
        IF (TALLY(1) .GT. 0D0) THEN
           U1=TALLY(1)/RNOH
           VAR1=TALY2(1)/RNOH-U1*U1
           S1=DSQRT(VAR1/RNOH)
           DELTA1=S1/U1
        END IF
C*
        TALLY(2)=TALSP(1,NOTI)
        TALY2(2)=TALSP(2,NOTI)
        IF (TALLY(2) .GT. 0D0) THEN
           U2=TALLY(2)/RNOH
           VAR2=TALY2(2)/RNOH-U2*U2
           S2=DSQRT(VAR2/RNOH)
           DELTA2=S2/U2
        END IF
C*
        TALLY(3)=TALNC(1,NOTI)
        TALY2(3)=TALNC(2,NOTI)
        IF (TALLY(3) .GT. 0D0) THEN
           U3=TALLY(3)/RNOH
           VAR3=TALY2(3)/RNOH-U3*U3
           S3=DSQRT(VAR3/RNOH)
           DELTA3=S3/U3
        END IF
C*
        TALLY(4)=TALCM(1,NOTI)
        TALY2(4)=TALCM(2,NOTI)
        IF (TALLY(4) .GT. 0D0) THEN
           U4=TALLY(4)/RNOH
           VAR4=TALY2(4)/RNOH-U4*U4
```

```
            S4=DSQRT(VAR4/RNOH)
            DELTA4=S4/U4
         END IF
C*
         U=U1+U2+U3+U4
         VAR=(TALY2(1)+TALY2(2)+TALY2(3)+TALY2(4))/RNOH-U*U
         SD=DSQRT(VAR/RNOH)
         IF (SD .LT. 1D-30) THEN
            FOM=0D0
         ELSE
            FOM=1D0/(VAR*TPH)
         END IF
         DELTA=SD/U
C*
C*       Write the Monte Carlo solution:
C*
         DO 30 K=1,NOCG
            WRITE (2,297) K,A,UT(K),ST(K),VART(K),DELTAT(K)
 30      CONTINUE
         WRITE (2,300) A,U1,S1,VAR1,DELTA1
         WRITE (2,301) A,U2,S2,VAR2,DELTA2
         WRITE (2,302) A,U3,S3,VAR3,DELTA3
         WRITE (2,303) A,U4,S4,VAR4,DELTA4
         WRITE (2,304) U,SD,VAR,DELTA,FOM,TPH
C*
C*************************** FORMATS *********************************C
C*
295      FORMAT (1X,/,
     * '========================================',/,
     * ' MONTE CARLO UNRELIABILITY CALCULATION',/,
     * '========================================',//)
C*
297      FORMAT (1X,/,
     * ' UNRELIABILITY DUE TO EXHAUSTION OF COMPONENT GROUP',I2,/,
     * ' ---------------------------------------------------------',/,
     * 1X,A14,' = ',D14.7,' +/- ',D14.7,/,
     * ' SAMPLE VARIANCE  =          ',D14.7,/,
     * ' COEFFICIENT OF VARIATION =',D14.7,//)
C*
300      FORMAT (1X,/,
     * ' OVERALL UNRELIABILITY DUE TO EXHAUSTION OF HARDWARE',/,
     * ' ---------------------------------------------------------',/,
     * 1X,A14,' = ',D14.7,' +/- ',D14.7,/,
     * ' SAMPLE VARIANCE  =          ',D14.7,/,
     * ' COEFFICIENT OF VARIATION =',D14.7,//)
C*
301      FORMAT (1X,/,
     * ' UNRELIABILITY DUE TO SINGLE POINT FAILURE',/,
     * ' -------------------------------------------',//,
     * 1X,A14,' = ',D14.7,' +/- ',D14.7,/,
     * ' SAMPLE VARIANCE  =          ',D14.7,/,
     * ' COEFFICIENT OF VARIATION =',D14.7,//)
C*
```

```
302     FORMAT (1X,/,
     * ' UNRELIABILITY DUE TO NEAR COINCIDENT FAULT',/,
     * ' ------------------------------------------',//,
     * 1X,A14,' = ',D14.7,' +/- ',D14.7,/,
     * ' SAMPLE VARIANCE  =         ',D14.7,/,
     * ' COEFFICIENT OF VARIATION =',D14.7,//)
C*
303      FORMAT (1X,/,
     * ' UNRELIABILITY DUE TO COMMON MODE FAILURE',/,
     * ' ------------------------------------------',//,
     * 1X,A14,' = ',D14.7,' +/- ',D14.7,/,
     * ' SAMPLE VARIANCE  =         ',D14.7,/,
     * ' COEFFICIENT OF VARIATION =',D14.7,//)
C*
304      FORMAT (1X,/,
     * ' OVERALL SYSTEM CALCULATION:',/,
     * ' ===========================',//,
     * ' ****************************************************',/,
     * ' * UNRELIABILITY  = ',D14.7,' +/-',D14.7,'*',/,
     * ' * SAMPLE VARIANCE  =       ',D14.7,9X,' *',/,
     * ' * COEFFICIENT OF VARIATION=',D14.7,9X,' *',/,
     * ' * FIGURE OF MERIT  =       ',D14.7,9X,' *',/,
     * ' * TIME PER HISTORY =       ',D14.7,9X,' *',/,
     * ' ****************************************************')
C*
 1000    FORMAT (' NUMBER OF COMPONENT GROUPS: ',I2,/)
 1005    FORMAT (' NUMBER OF COMPONENTS IN GROUP ',A,': ',I2)
 1007    FORMAT (' NUMBER OF SPARES FOR GROUP ',A,'   : ',I2)
 1010    FORMAT (' FAILURE RATE FOR COMPONENT ',A,'   : ',D11.4)
 1030    FORMAT (' WEIBULL MODULUS FOR COMPONENT ',A,': ',D11.4)
 1050    FORMAT (' SCALE PARAMETER FOR COMPONENT ',A,': ',D11.4)
 1060    FORMAT (' FAILURE HANDLING MODEL FOR GROUP ',A,': ',A13,/)
 1070    FORMAT (' TRANSITION RATE FOR CMF EVENT',I2,':      ',D18.4)
 1120    FORMAT (' MISSION TIME FOR THIS MODEL:                    ',G11.4,/,
     *    ' NUMBER OF MONTE CARLO HISTORIES:               ',I6,/,
     *    ' NEAR COINCIDENT FAULT MODEL:                   ',I2,/)
C*
        RETURN
        END
```

Appendix D, [2]

MONTE CARLO SIMULATION OF COMPLEX SYSTEM MISSION RELIABILITY

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ABSTRACT

A Monte Carlo methodology for the reliability simulation of highly redundant systems is presented. Two forms of importance sampling, forced transitions and failure biasing, allow large sets of continuous-time Markov equations to be simulated effectively and the results to be plotted as continuous functions of time. A modification of the sampling technique also allows the simulation of both nonhomogeneous Markov processes and of nonMarkovian processes involving the replacement of worn parts. A number of benchmark problems are examined. For problems with large numbers of components, Monte Carlo is found to result in decreases in computing times by as much as a factor of twenty from the Runge-Kutta Markov solver employed in the NASA code HARP.

1. INTRODUCTION

There is an increasing need to predict mission unreliability and related parameters for systems exhibiting very low rates of failure. Typically, such systems are designed in configurations with many component redundancies and are organized in such a manner that there are component dependencies in the forms of standby subsystems, shared-load components, and shared repair or fault handling faculties. The utility of probabilistic analysis based on combinatorial techniques may be extremely limited. In contrast, such systems may often be modeled as continuous-time Markov processes, particularly if the models are generalizable to include nonhomogeneous Markov processes.

While Markov processes may be an excellent modeling tool, difficulties arise in carrying out computations, particularly in models that are too large or complex to treat by conventional analytical means. As n, the number of components, increase the 2^n explosion of states means that very large systems of coupled differential equations must be solved. Moreover, these equations tend to be very stiff since the time constants involved may range from fault occurrences that are rare events even over weeks or months to fault handling mechanisms that take place in small fractions of a second. As a result, the number of distinct components that can be treated is severely restricted if deterministic methods are employed. If the time constants fall into two widely separated time domains, behavioral decomposition (Bavuso, et al., 1987) may be employed to treat the short time constant events as instantaneous changes of state. But difficulties may then arise when there is inadequate separation in the magnitudes of the time constants.

We have found that Monte Carlo methods may be an effective tool for treating the simulation of systems having highly redundant configurations of components (Lewis and Boehm, 1984; Lewis and Tu, 1986; Boehm, et al., 1988). Regardless of whether component dependencies are present, modeling the system as a continuous-time Markov process allows the average number of event samplings required per trial to be reduced to only slightly more than one. More important, however, is the use of a form of importance sampling that we refer to as forced transitions, to ensure that a substantial fraction of the independent trials will contribute to the tally of the system unreliability. Monte Carlo analysis may be further refined with a second form of importance sampling, referred to as failure biasing, that has the potential for eliminating the approximations inherent in behavioral decomposition. Finally, Monte Carlo tallies may be constructed to yield more than the traditional single answer results; tallies of reliability or other quantities of interest may be generated as continuous functions of time to provide more physical insight into the meaning of the results.

2. MONTE CARLO FORMULATION

For purposes of the Monte Carlo simulation the nonhomogeneous Markov equations are converted to semi-Markov equations. If $p_k(t)$ represents the probability that the system is in state k at time t, then

$$\frac{\partial}{\partial t} p_k(t) = -\gamma_k p_k(t) + \sum_{k'} q(k|k',t)\gamma_{k'} p_{k'}(t) ,$$

where the initial conditions are given by

$$p_k(0) = \delta_{k0} .$$

If $\lambda_{jk}(t)$ is the transition rate from state k to state j, then the net transition rate out of state k is

$$\gamma_k = \sum_j \lambda_{jk}(t) ,$$

and the quantity

$$q(k|k',t) = \frac{\lambda_{kk'}(t)}{\gamma_{k'}}$$

is the conditional probability of arrival in state k, given a transition out of state k' at t.

In a Markov process the self-transition rates λ_{kk} vanish. However since effective Monte Carlo sampling requires the values of γ_k appearing in the Markov equation to be independent of time, we treat nonhomogeneous Markov processes by forcing the transition rates γ_k to have positive value that are independent of time This is accomplished by defining a fictitious self-transition rate

$$\lambda_{kk}(t) = \gamma_k - \sum_{j \neq k} \lambda_{jk}(t) ,$$

where γ_k is taken to be sufficiently large that $\lambda_{kk}(t)$ will remain nonnegative. In cases where the transition rates either remain constant or increase with time this may be achieved by letting

$$\gamma_k = \sum_{j \neq k} \lambda_{jk}(T) ,$$

where T is the mission time.

2.1. Analog Monte Carlo

Analog Monte Carlo trials are performed as indicated in Figure 1. The times to the successive transitions are determined by setting the cumulative distribution function

$$F(t|t',k') = 1 - e^{-\gamma_k(t-t')}$$

equal to a uniformly distributed random number ξ and solving for t,

$$t = t' - \frac{1}{\gamma_k}\ln(1-\xi)\,.$$

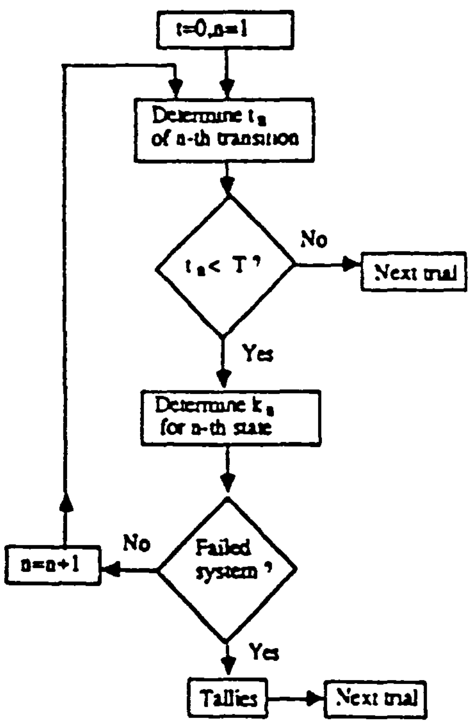

Figure 1: Monte Carlo Trial Procedure for a Design Life T

The new system state is determined by generating a second uniformly distributed random number ζ and choosing the state for which

$$\frac{\lambda_{kk'}(t)}{\gamma_{k'}} \leq \zeta \leq \frac{\lambda_{k+1,k'}(t)}{\gamma_{k'}}\,.$$

This procedure is repeated until the mission time is exceeded or the system reaches an absorbing (i.e., failed) state. At any given time the unreliability is just the fraction of trials that have reached failed states.

2.2. Forced Transitions

In highly reliable systems the foregoing algorithm will in most cases require only one sampling per history since the first state transition is not likely to occur until t > T. This also means that only a very small fraction of the histories will contribute to the tally, and as a result the variance in the result will tend to be large. To circumvent this difficulty we may modify the distribution of the time to the next transition to force additional transitions within the time interval $0 < t < T$ while modifying the tally such that the results are unbiased. The modified cumulative distribution is

$$\tilde{F}(t|t',k') = \frac{1 - e^{-\gamma_{k'}(t-t')}}{1 - e^{-\gamma_{k'}(T-t')}}\quad,\quad t' < t < T$$

With the uniformly distributed random number ξ, the time of the next transition is then determined from

$$t = t' - \frac{1}{\gamma_{k'}}\ln\left\{1 - \xi\left[1 - e^{-\gamma_{k'}(T-t')}\right]\right\}.$$

To obtain an unbiased result a weight w_i is attached to each trial and initialized at $w_i = 1$. Each time that forced transition sampling is performed the weight is modified by

$$w_i \rightarrow w_i\left[1 - e^{-\gamma_k(T-t')}\right].$$

The tally for the unreliability is then

$$u_T = \frac{1}{N}\sum_{t_i \leq T} w_i\,,$$

with a sampling variance given by

$$S^2(u_r) = \frac{1}{N-1}\sum_{n=1}^{N}\left[w_n - u_r\right]^2\,.$$

2.3. Failure Biasing

Forced transitions assure that faults will occur in a substantial fraction of the Monte Carlo trials. However in some situations the sampling may remain poor. In mechanical systems, for example, repair rates typically are orders of magnitude larger than component failure rates. Likewise, in avionic systems electronic fault handling systems result in state transition rates that are much faster than the rates at which failures are induced into the system To further enhance the effectiveness of the Monte Carlo simulation the fraction of smaller probability failure transitions may be increased by the use of a second variance reduction technique which we refer to as failure biasing

In failure biasing the transition probabilities q(k|k') are modified to increase the ratio of failures to other events such as successful fault handlings. We first divide the transitions out of state k' into to sets; Λ includes those resulting from component failures and R those resulting from successful repair or fault handling. We may then write

$$\gamma_k = \sum_{j \in \Lambda_k} \lambda_{jk}(t) + \sum_{j \in R_k} \mu_{jk} \ .$$

We require that some fraction x of the transitions come from the set L. The biased transition probabilities are then

$$\tilde{q}(k|k') = \frac{q(k|k')}{\sum_{k'' \in \Lambda} q(k''|k')} x \,, \qquad k \in \Lambda \ ,$$

and

$$\tilde{q}(k|k') = \frac{q(k|k')}{\sum_{k'' \in R} q(k''|k')} (1 - x), \qquad k \in R \ .$$

To maintain unbiased results the trial weight is modified by

$$w_1 \rightarrow w_1 \frac{1}{x} \sum_{k'' \in \Lambda} q(k''|k')$$

for component failures and

$$w_1 \rightarrow w_1 \frac{1}{(1 - x)} \sum_{k'' \in R} q(k''|k')$$

for repair. In using failure biasing we typically choose x to be between 0.5 and 0.6; studies of model problems have indicated that values as high as 0.75 may be used before one begins to observe the increases in the sample variance that arise from improbable but very high weight histories (Kirsch, 1988).

3. APPLICATIONS

Two classes of problems are considered in order to examine the accuracy and efficiency of Monte Carlo methods The first consists of simple hybrid redundant systems for which we have also obtained analytical solutions. By varying the ratio of failure to fault handling rate the ability of the variance reduction methods to provide accurate simulations can be determined for systems with very small failure probabilities. In the second class of problems are included two benchmark configurations for which computing times and deterministic solutions have been obtained using the NASA Hybrid Automated Reliability Predictor (HARP) (Bavuso, et al., 1987a, 1987b).

Behavioral composition is employed in the HARP code to separate fault/error-handling models from the fault occurrence models. The code includes the capability for treating a variety of error handling models, while fault occurrence is modeled as an nonhomogeneous continuous-time Markov process. The imperfect coverage fault/error handling models are reduced to a set of transition probabilities, allowing the entire system to be treated with nonhomogeneous Markov equations in which only the longer time constants of fault occurrence appear. The HARP code solves the Markov equations by the Runge-Kutta method.

3.1. Hybrid Model Problem

We consider a simple hybrid (Lewis and Tu, 1986; Bavuso, et al., 1987) system for which we have obtained analytical solutions elsewhere (Kirsch, 1988). It consists of three units in a majority vote configuration with one spare. Each of the units including the spare has a constant failure rate l, where it is assumed that the spare can not fail until it is switched in. Coverage of the fault by switching in the spare takes place with a constant rate u. The ten hour mission system failure probability is shown in Table 1 over a large range of parameters, with λ and υ given in hrs^{-1}. The ability of Monte Carlo simulation with variance reduction to provide accurate estimates of very small failure probabilities is clearly illustrated.

Table 1. Model Problem Comparison of Analytical and Monte Carlo Unreliability with N = 1000

λ	υ/λ	exact solution	Monte-Carlo solution	COV	relative error
10^{-2}	10^{5}	0 2464 10^{-2}	0 2507 10^{-2}	0 08827	0 01745
10^{-3}	10^{6}	0 2999 10^{-5}	0 3073 10^{-5}	0 09123	0 02471
10^{-4}	10^{7}	0 3592 10^{-8}	0 3667 10^{-8}	0 07626	0 02088
10^{-5}	10^{8}	0 8997 10^{-11}	0 9136 10^{-11}	0 02628	0 01545
10^{-5}	10^{9}	0 6299 10^{-13}	0 6371 10^{-13}	0 01476	0 01143

3.2. Three-Processor Two-Memory One-Buss System

The detailed problem specification for the 3-processor, 2-memory 1-buss system is given elsewhere (Bavuso, et al., 1987). Briefly, the system is modeled by the Markov diagram shown in Figure 2, where λ, υ and σ represent the processor, memory and buss failure rates. The three numbers associated with each Markov state are the number of operational processors, memory units and buses, respectively, and F1 through F3 are states of system failure. Not shown are the direct transitions from each of the states to system failure that result from near-coincidence and single point failures. The relative frequencies of such failures are determined from the AIRES fault/error handling model (Bavuso, et al., 1987) and appear in the Markov equations as modifications of the state transition probabilities.

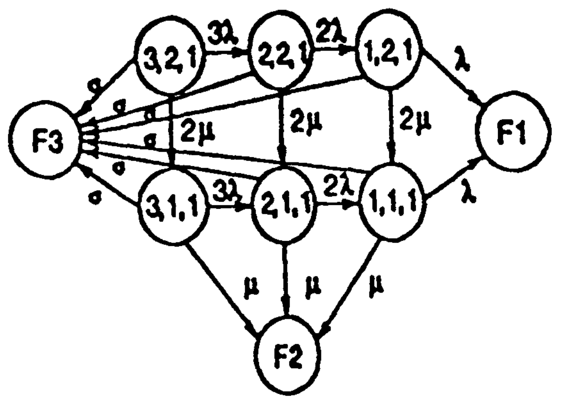

Figure 2: Markov Representation of the 3-Processor, 2-Memory, 1-Buss System

Figure 3 shows Monte Carlo results for the system unreliability over a mission time of ten hours. The data, given in Bavuso, et al., 1987, is for time-independent fault occurrence rates. The three lines correspond to the point estimate and the 68% confidence interval. The Monte Carlo results shown in Fig 4 are for the same system, but with Weibull distributions for fault occurrence rates; these have moduli of m = 2.5 In both cases the Monte Carlo simulations consisted of 10,000 trials.

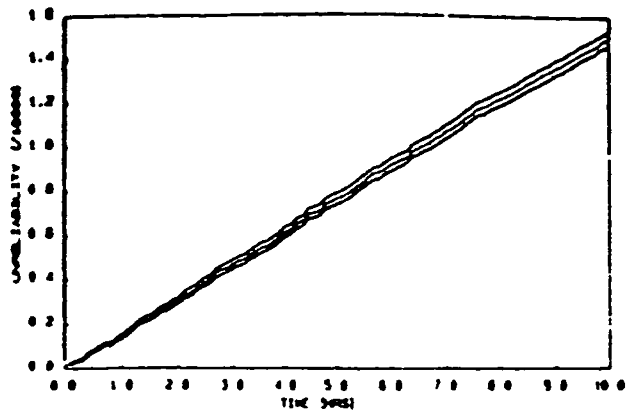

Figure 3. Unreliability vs. Time for the 3-Processor, 2-Memory, 1-Buss System with Constant Failure Rates

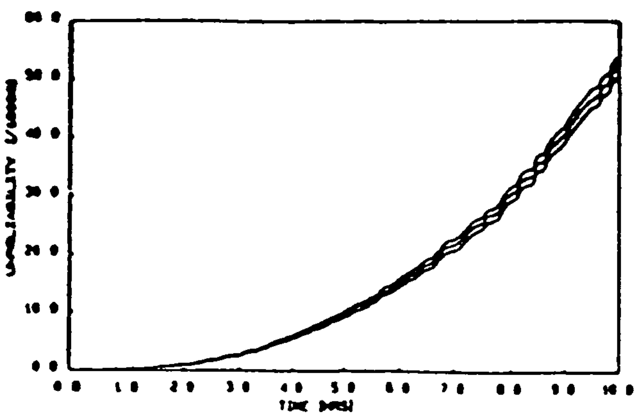

Figure 4: Unreliability vs. Time for the 3-Processor, 2-Memory, 1-Bass System with Incresing Failure Rates

Table 2 indicates that the results from the Monte Carlo and HARP calculations are in excellent agreement; all CPU times are on a VAX 11/785. The Monte Carlo simulations also provide reasonable estimates of the smaller probabilities corresponding to particular failure modes As an extreme example, the near-coincidence failure probability given as 2.79 10^{-11} by HARP is estimated as 1 27 (± 1.26) 10^{-11}. Since this few-component problem can be reduced to a set of only six nonabsorbing Markov states, it is not surprising that the Monte Carlo simulations are longer running. It is instructive to note, however, that even for small problems the running times are comparable when Weibull distributions are employed.

Table 2: Ten Hour Mission Unreliability for a 3-Processor 2-Memory 1-Buss System

Constant Failure Rates	Monte Carlo	HARP
Unreliability	1.498 (±0.034)10^{-4}	1.521 10^{-4}
CPU sec.	56	~6
Weibull Failures	Monte Carlo	HARP
Unreliability	4.789(±0.158) 10^{-3}	4.783 10^{-3}
CPU sec.	582	796

3.3. Jet Engine Control System

The jet engine controller problem, specified in detail elsewhere (Bavuso, et al., 1987), provides a basis for comparing the Monte Carlo and HARP codes for a system with a larger number of components. The CARE II model (Bavuso, et al., 1987) is used for error/fault-handling. The 20 component system has 171 minimum cut sets and is highly redundant as indicated by the fault tree representation shown in Figure 5. The Monte Carlo results for a 10 hour mission are shown in Figure 6 The Monte Carlo unreliability estimate of 1.073 (±0.087) 10^{-5} compares well with the HARP result of 1 112 10^{-5}.

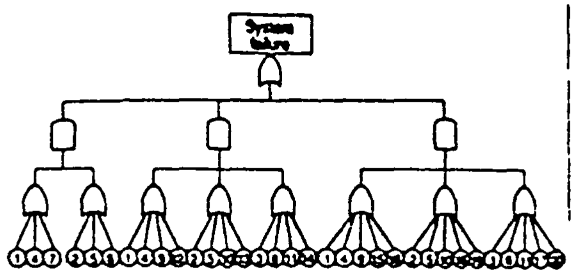

Figure 5: Fault Tree Representation of the Jet Engine Control System

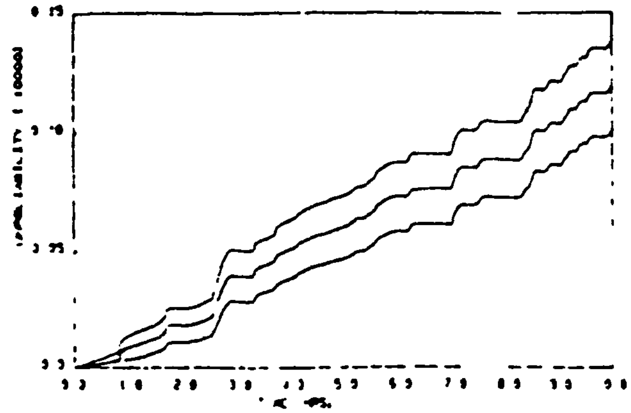

Figure 6: Unreliability vs. Time for the Jet Engine Control System

The time advantages of Monte Carlo simulation become apparent for problems with many Markov states. While the 10,000 history simulation from which the above results were obtained required 20 minutes on the VAX 11/785 the time that would be requred by HARP on the same machine is estimated to be of the order of 10 hours. To examine the effect of time-dependent failure rates on the Monte Carlo simulation times the power supply failure rates in the jet engine control were replaced with Weibull distributions with modulus two (Kelkhoff, 1989). This results in less than a 50% increase in the computing time needed to obtain comparable confidence intervals on the unreliability. The Monte Carlo model has also been generalized to allow nonMarkovian as-good-as-new parts replacement on the power supply components. Such modeling increased the computing time by roughly a factor of three over the constant failure rate model but allows problems to be simulated by Monte Carlo that cannot be treated with HARP.

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REFERENCES

Bavuso, S. J., Dugan, J. B., Trivedi, K. S., Rothmann, E. M. and Smith, W. E. (1987). Analysis of fault tolerant architectures using HARP. *IEEE Transactions Reliability R-36*, 187-193.

Bavuso, S. J., Dugan, J. B., Trivedi, K. S., Smotherman, B. and Boyd, M. (1987). Applications of the hybrid automated reliability predictor. NASA Technical Paper 2760.

Boehm, F., Hald, U. P., and Lewis, E. E. (1988). Parts renewal in continuous-time Monte Carlo reliability simulation. *Proceedings of 1988 Reliability and Maintainability Symposium*, Los Angeles, California, 345-349.

Kelkhoff, B. P. (1989). Incorporation of preventive maintenance into Monte Carlo reliability analysis. Unpublished project report, Mechanical Engineering Department, Northwestern University, Evanston, Illinois.

Kirsch, C. (1988). Fault/error-handling model incorporation into Markov Monte-Carlo reliability analysis. Unpublished project report, Mechanical Engineering Department, Northwestern University, Evanston, Illinois.

Lewis, E E and Boehm, F (1984). Monte Carlo simulation of Markov unreliability models *Nuclear Engineering and Design* 77, 49-62.

Lewis, E. E. and Tu, Z. (1986). Monte Carlo modeling by inhomogeneous Markov processes. *Reliability Engineering* 16, 277-296.

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A Monte Carlo Fortran computer program was developed that uses two varience reduction techniques for computing system reliability applicable to solving very large highly reliable fault-tolerant systems The program is consistent with the Hybrid Automated Reliability predictor (HARP) code which employes behavioral decomposition and complex fault-error handling models This new capability is called MC-HARP which efficiently solves reliability models with non-constant failures rates (Weibull) Common mode failure modeling is also a specialty

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