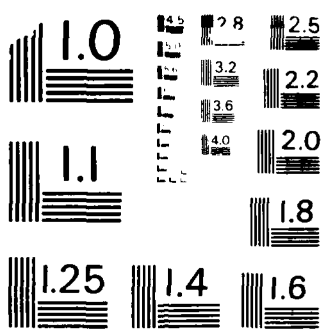
AD-A189 972 MONTE CARLO RELIABILITY ANALYSIS(U) NORTHWESTERN UNIV EVANSTON IL E E LEWIS 01 OCT 87 AFOSR-84-0340 1/1

UNCLASSIFIED F/G 12/1 NL



MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

AD-A189 972

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

(2)

DTIC FILE COPY

DTIC ELECTE JAN 14 1988 S D

1a. REPORT SECURITY CLASSIFICATION

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
Approved for public release; distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S)
AFOSR-TR- 87-1963

6a. NAME OF PERFORMING ORGANIZATION
Northwestern University

6b. OFFICE SYMBOL (If applicable)

7a. NAME OF MONITORING ORGANIZATION
AFOSR/NM

6c. ADDRESS (City, State, and ZIP Code)
619 Clark Street
Evanston, IL 60201

7b. ADDRESS (City, State, and ZIP Code)
AFOSR/NM
Bldg 410
Bolling AFB DC 20332-6448

8a. NAME OF FUNDING / SPONSORING ORGANIZATION
AFOSR

8b. OFFICE SYMBOL (If applicable)
NM

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
AFOSR-84-0340

8c. ADDRESS (City, State, and ZIP Code)
AFOSR/NM
Bldg 410
Bolling AFB DC 20332-6448

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO	WORK UNIT ACCESSION NO
61102F	2304	A5	

11. TITLE (Include Security Classification)
Monte Carlo Reliability Analysis (Unclassified)

12. PERSONAL AUTHOR(S)
Professor E.E. Lewis

13a. TYPE OF REPORT: Annual

13b. TIME COVERED: FROM 9/1/86 TO 8/31/87

14. DATE OF REPORT (Year, Month, Day): 10/1/87

15. PAGE COUNT: 9

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The work carried out during the 1986/87 contract year is summarized: The Monte Carlo simulation methods are generalized to treat nonMarkovian systems and applied to problems with time and batch replacement maintenance policies. Trimodular redundant systems with reconfigurable spares are also simulated. A new graphical technique is developed for the presentation of Monte Carlo results. Finally, an investigation of the reliability behavior of brittle solids is initiated.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION

22a. NAME OF RESPONSIBLE INDIVIDUAL
Maj. Woodruff

22b. TELEPHONE (Include Area Code)
(202)767-5027

22c. OFFICE SYMBOL
NM

DD Form 1473, JUN 86 — Previous editions are obsolete. — SECURITY CLASSIFICATION OF THIS PAGE

INSTRUCTIONS FOR PREPARATION OF REPORT DOCUMENTATION PAGE

GENERAL INFORMATION

The accuracy and completeness of all information provided in the DD Form 1473, especially classification and distribution limitation markings, are the responsibility of the authoring or monitoring DoD activity.

Because the data input on this form will be what others will retrieve from DTIC's bibliographic data base or may determine how the document can be accessed by future users, care should be taken to have the form completed by knowledgeable personnel. For better communication and to facilitate more complete and accurate input from the originators of the form to those processing the data, space has been provided in Block 22 for the name, telephone number, and office symbol of the DoD person responsible for the input cited on the form.

All information on the DD Form 1473 should be typed.

Only information appearing on or in the report, or applying specifically to the report in hand, should be reported. If there is any doubt, the block should be left blank.

Some of the information on the forms (e.g., title, abstract) will be machine indexed. The terminology used should describe the content of the report or identify it as precisely as possible for future identification and retrieval.

NOTE: **Unclassified abstracts and titles describing classified documents may appear separately from the documents in an unclassified context, e.g., in DTIC announcement bulletins and bibliographies. This must be considered in the preparation and marking of unclassified abstracts and titles.**

The Defense Technical Information Center (DTIC) is ready to offer assistance to anyone who needs and requests it. Call Data Base Input Division, Autovon 284-7044 or Commercial (202) 274-7044.

SECURITY CLASSIFICATION OF THE FORM

In accordance with DoD 5200.1-R, Information Security Program Regulation, Chapter IV Section 2, paragraph 4-200, classification markings are to be stamped, printed, or written at the top and bottom of the form in capital letters that are larger than those used in the text of the document. See also DoD 5220.22-M, Industrial Security Manual for Safeguarding Classified Information, Section II, paragraph 11a(2). This form should be unclassified, if possible.

SPECIFIC BLOCKS

Block 1a Report Security Classification: Designate the highest security classification of the report. (See DoD 5220.1-R, Chapters I, IV, VII, XI, Appendix A.)

Block 1b Restricted Marking. Enter the restricted marking or warning notice of the report (e.g., CNWDI, RD, NATO).

Block 2a Security Classification Authority: Enter the commonly used markings in accordance with DoD 5200.1-R, Chapter IV, Section 4, paragraph 4-400 and 4-402. Indicate classification authority.

Block 2b Declassification / Downgrading Schedule: Indicate specific date or event for declassification or the notation, "Originating Agency Determination Required" or "OADR." Also insert (when applicable) downgrade to ______________ on ______________ (e.g., Downgrade to Confidential on 6 July 1983). (See also DoD 5220.22-M, Industrial Security Manual for Safeguarding Classified Information, Appendix II.)

NOTE: **Entry must be made in Blocks 2a and 2b except when the original report is unclassified and has never been upgraded.**

Block 3 Distribution/Availability Statement of Report: Insert the statement as it appears on the report. If a limited distribution statement is used, the reason must be one of those given by DoD Directive 5200.20, Distribution Statements on Technical Documents, as supplemented by the 18 OCT 1983 SECDEF Memo, "Control of Unclassified Technology with Military Application." The Distribution Statement should provide for the broadest distribution possible within limits of security and controlling office limitations.

Block 4 Performing Organization Report Number(s). Enter the unique alphanumeric report number(s) assigned by the organization originating or generating the report from its research and whose name appears in Block 6. These numbers should be in accordance with ANSI STD 239.23-74, "American National Standard Technical Report Number." If the Performing Organization is also the Monitoring Agency, enter the report number in Block 4.

Block 5 Monitoring Organization Report Number(s): Enter the unique alphanumeric report number(s) assigned by the Monitoring Agency. This should be a number assigned by a DoD or other government agency and should be in accordance with ANSI STD 239.23-74. If the Monitoring Agency is the same as the Performing Organization, enter the report number in Block 4 and leave Block 5 blank.

Block 6a Name of Performing Organization. For in-house reports, enter the name of the performing activity. For reports prepared under contract or grant, enter the contractor or the grantee who generated the report and identify the appropriate corporate division, school, laboratory, etc., of the author.

Block 6b Office Symbol: Enter the office symbol of the Performing Organization.

Block 6c Address. Enter the address of the Performing Organization. List city, state, and ZIP code.

Block 7a Name of Monitoring Organization: This is the agency responsible for administering or monitoring a project, contract, or grant. If the monitor is also the Performing Organization, leave Block 7a blank. In the case of joint sponsorship, the Monitoring Organization is determined by advance agreement. It can be either an office, a group, or a committee representing more than one activity, service, or agency.

Block 7b Address. Enter the address of the Monitoring Organization. Include city, state, and ZIP code.

Block 8a Name of Funding/Sponsoring Organization. Enter the full official name of the organization under whose immediate funding the document was generated, whether the work was done in-house or by contract. If the Monitoring Organization is the same as the Funding Organization, leave 8a blank.

Block 8b Office Symbol. Enter the office symbol of the Funding/Sponsoring Organization.

Block 8c Address. Enter the address of the Funding/Sponsoring Organization. Include city, state and ZIP code.

Block 9. Procurement Instrument Identification Number: For a contractor grantee report, enter the complete contract or grant number(s) under which the work was accomplished. Leave this block blank for in-house reports.

Block 10. Source of Funding (Program Element, Project, Task Area, and Work Unit Number(s): These four data elements relate to the DoD budget structure and provide program and/or administrative identification of the source of support for the work being carried on. Enter the program element, project, task area, work unit accession number, or their equivalents which identify the principal source of funding for the work required. These codes may be obtained from the applicable DoD forms such as the DD Form 1498 (Research and Technology Work Unit Summary) or from the fund citation of the funding instrument. If this information is not available to the authoring activity, these blocks should be filled in by the responsible DoD Official designated in Block 22. If the report is funded from multiple sources, identify only the Program Element and the Project, Task Area, and Work Unit Numbers of the principal contributor.

Block 11. Title: Enter the title in Block 11 ir :nitial capital letters exactly as it appears on the report. Titles on all classified reports, whether classified or unclassified, must be immediately followed by the security classification of the title enclosed in parentheses. A report with a classified title should be provided with an unclassified version if it is possible to do so without changing the meaning or obscuring the contents of the report. Use specific, meaningful words that describe the content of the report so that when the title is machine-indexed, the words will contribute useful retrieval terms.

If the report is in a foreign language and the title is given in both English and a foreign language, list the foreign language title first, followed by the English title enclosed in parentheses. If part of the text is in English, list the English title first followed by the foreign language title enclosed in parentheses. If the title is given in more than one foreign language, use a title that reflects the language of the text. If both the text and titles are in a foreign language, the title should be translated, if possible, unless the title is also the name of a foreign periodical. Transliterations of often used foreign alphabets (see Appendix A of MIL-STD-847B) are available from DTIC in document AD-A080 800.

Block 12. Personal Author(s): Give the complete name(s) of the author(s) in this order: last name, first name, and middle name. In addition, list the affiliation of the authors if it differs from that of the performing organization.

List all authors. If the document is a compilation of papers, it may be more useful to list the authors with the titles of their papers as a contents note in the abstract in Block 19. If appropriate, the names of editors and compilers may be entered in this block.

Block 13a Type of Report: Indicate whether the report is summary, final, annual, progress, interim, etc.

Block 13b Time Covered: Enter the inclusive dates (*year, month, day*) of the period covered, such as the life of a contract in a final contractor report

Block 14 Date of Report: Enter the year, month, and day, or the year and the month the report was issued as shown on the cover

Block 15 Page Count: Enter the total number of pages in the report that contain information, including cover, preface, table of contents, distribution lists, partial pages, etc A chart in the body of the report is counted even if it is unnumbered

Block 16 Supplementary Notation: Enter useful information about the report in hand, such as: "Prepared in cooperation with ," "Translation at (or by) ," "Symposium ," If there are report numbers for the report which are not noted elsewhere on the form (such as internal series numbers or participating organization report numbers) enter in this block

Block 17. COSATI Codes: This block provides the subject coverage of the report for announcement and distribution purposes. The categories are to be taken from the "COSATI Subject Category List" (DoD Modified), Oct 65, AD-624 000. A copy is available on request to any organization generating reports for DoD. At least one entry is required as follows:

Field - to indicate subject coverage of report.

Group - to indicate greater subject specificity of information in the report.

Sub-Group - if specificity greater than that shown by Group is required, use further designation as the numbers after the period (.) in the Group breakdown. Use <u>only</u> the designation provided by AD-624 000.

Example: The subject "Solid Rocket Motors" is Field 21, Group 08, Subgroup 2 (page 32, AD-624 000)

Block 18. Subject Terms: These may be descriptors, keywords, posting terms, identifiers, open-ended terms, subject headings, acronyms, code words, or any words or phrases that identify the principal subjects covered in the report, and that conform to standard terminology and are exact enough to be used as subject index entries. Certain acronyms or "buzz words" may be used if they are recognized by specialists in the field and have a potential for becoming accepted terms "Laser" and "Reverse Osmosis" were once such terms.

If possible, this set of terms should be selected so that the terms individually and as a group will remain UNCLASSIFIED without losing meaning. However, priority must be given to specifying proper subject terms rather than making the set of terms appear "UNCLASSIFIED " Each term on classified reports must be immediately followed by its security classification, enclosed in parentheses.

For reference on standard terminology the "DTIC Retrieval and Indexing Terminology" DRIT-1979, AD-A068 500, and the DoD "Thesaurus of Engineering and Scientific Terms (TEST) 1968, AD-672 000, may be useful

Block 19 Abstract: The abstract should be a pithy, brief (preferably not to exceed 300 words), factual summary of the most significant information contained in the report. However, since the abstract may be machine-searched, all specific and meaningful words and phrases which express the subject content of the report should be included, even if the word limit is exceeded.

If possible, the abstract of a classified report should be unclassified and consist of publicly releasable information (Unlimited), but in no instance should the report content description be sacrificed for the security classification.

NOTE: **An unclassified abstract describing a classified document may appear separately from the document in an unclassified context e.g., in DTIC announcement or bibliographic products. This must be considered in the preparation and marking of unclassified abstracts.**

For further information on preparing abstracts, employing scientific symbols, verbalizing, etc., see paragraphs 2.1(n) and 2.3(b) in MIL-STD-847B

Block 20. Distribution / Availability of Abstract: This block must be completed for all reports Check the applicable statement: "unclassified / unlimited," "same as report," or, if the report is available to DTIC registered users "DTIC users."

Block 21. Abstract Security Classification: To ensure proper safeguarding of information, this block must be completed for all reports to designate the classification level of the entire abstract For CLASSIFIED abstracts, each paragraph must be preceded by its security classification code in parentheses

Block 22a,b,c. Name, Telephone and Office Symbol of Responsible Individual: Give name, telephone number, and office symbol of DoD person responsible for the accuracy of the completion of this form

☆ U.S. Government Printing Office 1986—490-962/51424

AFOSR-TR- 87-1963

Accomplishments: During the project year ending August 31, 1987 there were three areas in which work was carried out and results obtained. These relate to nonMarkovian extensions of the Markov Monte Carlo simulation methods, graphical presentations of Monte Carlo results, and prediction of time to failure distributions of brittle components.

We have completed the implementation of the generalization of our earlier inhomogeneous Markov Monte Carlo code to treat parts replacement problems for which the Markov property is lost. The resulting method retains the use of the self-transition sampling[1] to model time-dependent failure rates and is fully compatible with our variance reduction techniques.

The effectiveness of the new techniques have been demonstrated by applying them to two classes of problems. In the first, comparisons are made between batch replacement and time replacement policies on redundant configurations of components. This work was recently presented at an international topical meeting on probabilistic risk assessment; a reprint is included as an appendix.[2] In addition, we have used our code to make reliability simulations of a widely used redundant configuration for flight-critical avionics systems: the trimodular redundant (TMR) system with reconfigurable spares. This work[3] will be reported at the Annual Reliability and Maintainability Symposium to be held in January, 1988.

The second area was unanticipated at the time the proposal was written. It is the development of an effective means for the graphical presentation of Monte Carlo results. An argument in favor of analytical or deterministic numerical methods for the analysis of Markov processes has been that from them one obtains results in the form of time-dependent curves, while Monte Carlo Simulation yields only a single result at a specified time. Since a great deal of insight into the nature of the solution is lost, Monte Carlo is often relegated to a method of last resort for otherwise intractable problems. We have circumvented this problem by treating the Monte Carlo simulation as a set of grouped life-test data and employing nonparametric methods to generate curves of reliability or availability vs time. The resulting techniques increase the computation times over those required for a result at a specified time by only a few percent. They were employed to generate the curves shown in the appendix and will be reported in a short paper.[4]

The third area involves the development of methods to generate the time-dependent failure rate curves needed to estimate wear or aging effects in Monte Carlo or deterministic treatments of reliability problems. We are focusing our efforts on the mathematical representation of fatigue failures of brittle mechanical components. We have tentatively constructed a model in which finite element results can be represented as probability density functons of stress which in turn can be incorporated into Monte Carlo reliability simulations.

Personnel: In addition to the principal investigator, the contract continued to support a graduate student, Franz Boehm, who is seeking the PhD in mechanical engineering. In addition, the research was assisted by an MS student, Mr. Uve Hald, who received no support from the AFOSR contract.

Travel: During the year the principal investigator made a one day visit to the Rome Air Development Center to confer with personnel in the Reliability and Maintainability Section, and he attended the Annual Reliability and Maintainability Symposium. These visits were instrumental in bringing about the work on the TMR system described above. In addition, part of the principal investigator's summer appointment at the University of Stuttgart was spent conferring with Dr. Lauf and others in developing the third area listed above.

References

1. E. E. Lewis and Z. Tu, "Monte Carlo Reliability Modeling by Inhomogeneous Markov Processes," Reliability Engr. 16, 277-296 (1986).

2. E. E. Lewis, F. Boehm, U. P. Hald, and Z. Tu, "Generalization of Markov Monte Carlo Reliability Analysis to Include Non Markovian Maintenance Strategies," Trans. Int. Topical Conf. on Probabilistic Safety Assessment and Risk Management, Zurich, Aug. 30-Sept. 4, 1987.

3. Franz Boehm, Uve P. Hald and E. E. Lewis, "Parts Removal in Continuous Time Monte Carlo Reliability Simulation," Ann. Reliab. & Maint. Symp., 1988 (awaiting publication).

4. E. E. Lewis, Z. Tu, U. P. Hald and F. Boehm, "Explicit Time Dependent Analysis in Monte Carlo Reliability Simulation," Trans. Am. Nucl. Soc. (awaiting publication).

APPENDIX A

From Proc. Probabilistic Safety Assessment and Risk Management, I, TÜV, Rheinland 1987.

GENERALIZATION OF MARKOV MONTE CARLO RELIABILITY ANALYSIS TO INCLUDE NONMARKOVIAN MAINTENANCE STRATEGIES

F. Boehm, U. P. Hald, E. E. Lewis and Z. Tu
[Department of Mechanical Engineering
Northwestern University, Evanston, IL 60201, USA]

ABSTRACT

The Lagrangian approach to Markov Monte Carlo methods for systems reliability analysis is generalized to include nonMarkovian phenomena in which system components are replaced. The method is then employed to analyze the unreliability and unavailability of a number of redundant systems in which maintenance is carried out by batch or time replacement of aging components.

INTRODUCTION

The Lagrangian approach to Markov Monte Carlo methods has been shown to be very effective for estimating reliability and availability of complex systems. The ability to treat general component dependencies in multicomponent systems, coupled with the use of variance reduction techniques to greatly increase sampling efficiency, results in highly efficient algorithms, capable of treating Markov models that would be intractable by deterministic computational methods.[1,2] More recently, the Monte Carlo formulation has been generalized through a nonanalog sampling technique called self-transitions to treat time-inhomogeneous Markov processes.[3] This has allowed the replacement of constant failure rates with more realistic "bathtub" curves thereby permitting the simulation of component wear and periodic preventive maintenance.

In a variety of problems, some critical to reactor safety, departures from Markov models are required. For, if as-good-as-new repair or parts replacement are permitted following revealed failures, the Markov property[4] is lost. This is illustrated by the failure rate curves in Fig. 1. The solid line (curve c) represents the failure rate (with preventive maintenance) in a time-inhomogeneous Markov calculation. Curve (c) is a reasonable approximation to the as-good-as-old repair (curve b) since the time between failure and repair ($t_r - t_f$) normally is small. However, for as-good-as-new repair (curve a) faithful modeling requires that the failure rate curve be reinitialized at t_r. Moreover, if age (as opposed to batch) replacement policies are to be studied, the times at which preventive replacement is carried out then also depend on the time of the last component failure.

In this paper earlier work in applying Monte Carlo techniques to the evaluation of Markov reliability models[1-3] is generalized to systems in which the Markov property must be violated in order to retain the age of each replaceable component in the simulation. For only in this way can classes of reliability problems that combine component wear, preventive maintenance, and parts replacement be treated. Such analysis is required, for example, to determine the effects of alternative maintenance policies on the reliability and availability of highly redundant nuclear safety systems.

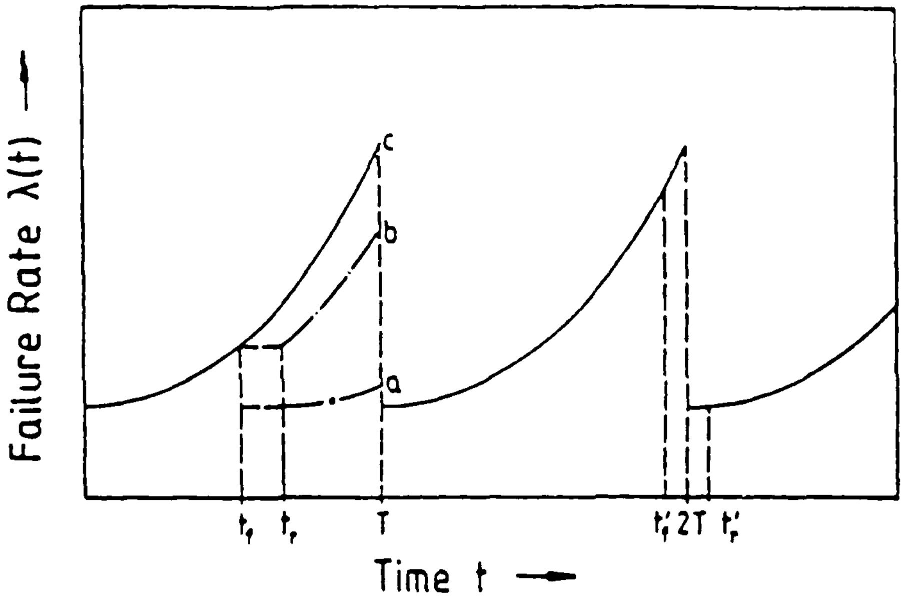


Figure 1: Failure rate curves showing three models for repair of revealed failures: (a) as-good-as new; (b) as-good-as old; (c) continuous wear.

THEORY

The generalization of the Monte Carlo formalism to treat nonMarkovian renewal processes can be most compactly summarized by retaining the framework used in simulating reliability problems represented as continuous-time, inhomogeneous Markov processes. Let $p_k(t)$ be the probability that a system is in state k at time t, where each of the 2^n states for an n-component system constitutes a unique combination of operating and failed components. The equations to be simulated are then

$$\frac{d}{dt} p_k(t) = -\gamma_k(t)p_k(t) + \sum_{k'} q(k,k',t)\gamma_{k'}(t)p_{k'}(t) \quad , \tag{1}$$

with initial conditions $p_k(0) = \delta_{k0}$. The transition rate $\gamma_k(t)$ out of state k is given by

$$\gamma_k(t) = \sum_{\ell \epsilon O_k} \lambda_{\ell k}(t) + \sum_{\ell \epsilon F_k} \mu_{\ell k} , \tag{2}$$

where $\lambda_{\ell k}(t)$ and $\mu_{\ell k}$ are the failure and repair rates of component ℓ, while in state k and O_k and F_k are the sets of operational and failed components, respectively, in state k. The quantity $q(k,k',t)$ is the conditional probability that given a transition out of state k' at time t, the new state will be k; it may be written as

$$q(k|k',t) = \gamma_{kk'}(t)/\gamma_{k'}(t), \tag{3}$$

where $\gamma_{kk'}(t)$ is the component failure or repair rate that corresponds to the $k' \to k$ transition.

In Markov Monte Carlo each of the N trials consists of following the state transitions through some finite period of time, say the design life of the system, T. From time t' and state k', the time of the next transition is sampled from the cumulative probability distribution

$$F(t|t',k') = 1 - \exp\{- \int_{t'}^{t} \gamma_{k'}(t'')dt''\}. \tag{4}$$

In analog Monte Carlo simulation of homogeneous Markov processes, in which the failure rates are constant, the time can be sampled using a uniformly distributed random number in the direct inverse method. The sampling is modified by the use of self transitions if it is necessary to treat the time-dependent failure rates that appear with wear or early failures[3]. For computational efficiency nonanalog variance reduction normally is employed. In this, the sampling distribution of Eq. (4) is modified to force more transitions, and each trial then caries a weight which is appropriately altered to maintain unbiased estimates of the system unreliability or unavailability. After each transition a second random number is generated to sample Eq. (3) and determine the new system, state k. Once again, nonanalog variance reduction is employed to enhance the number of failures and suppress the number of repairs. The resulting biasing of the state transition matrix is compensated once again by a change in the trial weight to maintain an unbiased reliability or availability estimate[1].

To determine when system failure has resulted from state transition, a fault tree describing the component configuration is evaluated qualitatively either by bottom up evaluation or by using cut sets. The tally for the unreliability is

$$\hat{U}_r = \frac{1}{N} \sum_{t_n<T} w_n \tag{5}$$

where w_n is the weight of the nth trial at the time of system failure, if system failure for that trial occurs at $t_n<T$. The corresponding mission availability estimator is

$$\hat{U}_a = \frac{1}{TN} \sum_{n=1}^{N} w_n \Delta_n \tag{6}$$

where w_n is the history weight at the time of the first system failure. Since in our algorithms the calculation reverts to analog Monte Carlo after the first system failure in a trial, the weight at the time, t_n, of the first failure is multiplied by Δ_n the total down time for the duration of the trial. For both unreliability and unavailability the sampe variance is tallied along with Eqs. (5) or (6), and the central limit theorem is used to estimate 68% confidence intervals for the results.

Component replacement of renewal is incorporated into the above formalism by replacing t with a vector $\underline{\tau}$ in the transition rates and probabilities appearing in the Markov equations. The ith component of the vector $\underline{\tau}$ is just the time since the ith component in the system was replaced, or underwent as-good-as-new maintenance. Equation (2) for the kth state transition rate is thus replaced by

$$\gamma_k(\underline{\tau}) = \sum_{\ell < O_k} \lambda_{\ell k}(\tau_\ell) + \sum_{\ell \epsilon F_k} \mu_{\ell k} \qquad (7)$$

where τ_ℓ is the age of the ℓth component. Likewise, the transition probability is now given by

$$q(k|k',\underline{\tau}) = \gamma_{\underline{kk}}(t)/\gamma_{k'}(\underline{\tau}) .$$

The ability to track Monte Carlo trials in which the age of each component must be incorporated into the transition probabilities has been incorporated into our Monte Carlo simulations. Moreover, this generalization placed no limitations on the use of presently-used importance sampling techniques or on the use of the self-transition technique for treating time dependent failure rates.

RESULTS

To demonstrate the use of the component renewal feature of Monte Carlo reliability analysis simulations have been made for a number of redundant configurations in which component wear is present, and/or in which either time or batch replacement is used as maintenance policies. Recall that in time replacement a component is replaced at failure or after it has been in operation for a predetermined length of time, whichever occurs first; in batch replacement the component is replaced at failure or during predetermined maintenance times that do not depend on how long the component has been in operation.

In Tables I and II the unreliability and unavailability results for four different systems, namely a single component and (1/2), (1/3) and (2/3) active parallel systems. The components are taken to be identical; their failure rates are represented by Weibull distributions, i.e.

$$\lambda(t) = \lambda_0 + \frac{m}{\theta}(t/\theta)^{m-1},$$

with the parameters λ_0 = 0.013/yr, m = 2.5 and θ = 7.5 yr. The repair rate is given as μ = 10/yr. The design life of the systems is 5 yr. The time of the first maintenance for the single component is t = 1 yr. For the multicomponent systems, maintenance is performed on a staggered basis, i.e., for the two component system the time of the first maintenance of compoment 1 is t = 1 yr and t = 2 yr for component 2. For the three component system the time of the first maintenance is t = 0.667 yr for component 1, t = 1.333 yr for component 2 and t = 2 yr for component 3. The maintenance intervals in case of batch replacement and the age of the component in case of time replacement are taken to be Δt = 2 yr for all calculations.

TABLE I: Unreliabilities for example problems.

System	Model[1]	Without maintenance	With maintenance
1/1	1	$(0.3428\pm0.0027)*10^{0}$	$(0.1350\pm0.0008)*10^{0}$
	2	$(0.3428\pm0.0027)*10^{0}$	$(0.1350\pm0.0008)*10^{0}$
	3	$(0.3428\pm0.0027)*10^{0}$	$(0.1350\pm0.0008)*10^{0}$
1/2	1	$(0.9259\pm0.0175)*10^{-2}$	$(0.7582\pm0.0066)*10^{-3}$
	2	$(0.6886\pm0.0131)*10^{-2}$	$(0.7457\pm0.0066)*10^{-3}$
	3	$(0.6886\pm0.0131)*10^{-2}$	$(0.7578\pm0.0067)*10^{-3}$
1/3	1	$(0.1816\pm0.0086)*10^{-3}$	$(0.2990\pm0.0039)*10^{-5}$
	2	$(0.1114\pm0.0044)*10^{-3}$	$(0.2899\pm0.0039)*10^{-5}$
	3	$(0.1114\pm0.0044)*10^{-3}$	$(0.3008\pm0.0041)*10^{-5}$
2/3	1	$(0.2747\pm0.0085)*10^{-1}$	$(0.2268\pm0.0016)*10^{-2}$
	2	$(0.2080\pm0.0068)*10^{-1}$	$(0.2227\pm0.0016)*10^{-2}$
	3	$(0.2080\pm0.0068)*10^{-1}$	$(0.2257\pm0.0016)*10^{-2}$

Table II: Interval unavailabilities for example problems.

System	Model[1]	Without Maintenance	With Maintenance
1/1	1	$(0.1200\pm0.0008)*10^{-0}$	$(0.2756\pm0.0045)*10^{-2}$
	2	$(0.7229\pm0.0094)*10^{-2}$	$(0.2714\pm0.0038)*10^{-2}$
	3	$(0.7229\pm0.0094)*10^{-2}$	$(0.2780\pm0.0039)*10^{-2}$
1/2	1	$(0.9397\pm0.0174)*10^{-4}$	$(0.7721\pm0.0169)*10^{-5}$
	2	$(0.7022\pm0.0152)*10^{-4}$	$(0.7520\pm0.0166)*10^{-5}$
	3	$(0.7022\pm0.0152)*10^{-4}$	$(0.7665\pm0.0170)*10^{-5}$
1/3	1	$(0.1255\pm0.0041)*10^{-5}$	$(0.2053\pm0.0073)*10^{-7}$
	2	$(0.7354\pm0.0299)*10^{-6}$	$(0.1981\pm0.0072)*10^{-7}$
	3	$(0.7354\pm0.0299)*10^{-6}$	$(0.2030\pm0.0074)*10^{-7}$
2/3	1	$(0.2728\pm0.0054)*10^{-3}$	$(0.2292\pm0.0045)*10^{-4}$
	2	$(0.2023\pm0.0044)*10^{-3}$	$(0.2241\pm0.0045)*10^{-4}$
	3	$(0.2023\pm0.0044)*10^{-3}$	$(0.2300\pm0.0046)*10^{-4}$

[1] Model 1 ... continuous aging with batch replacement,
Model 2 ... as good as new repair with batch replacement, with maintenance
Model 3 ... as good as new repair with time replacement.

The data in Tables I and II are indicative of the increases in reliability and availability through component maintenance and replacement. Equally valuable is the ability to examine the time dependence of the reliability and/or availability. To this end, algorithms have been developed which will allow the generation of the time dependent quantities along with the corresponding confidence interval. This is done while adding less than 10% to the computing time of a Monte Carlo Simulation[6].

In Figures 2 and 3 are shown the unreliability and interval unavailability vs time for the 1/2 active parallel systems. Each run is for 1000 trials. Three sets of curves are shown, each with three lines corresponding to the estimator and the 68% confidence interval.

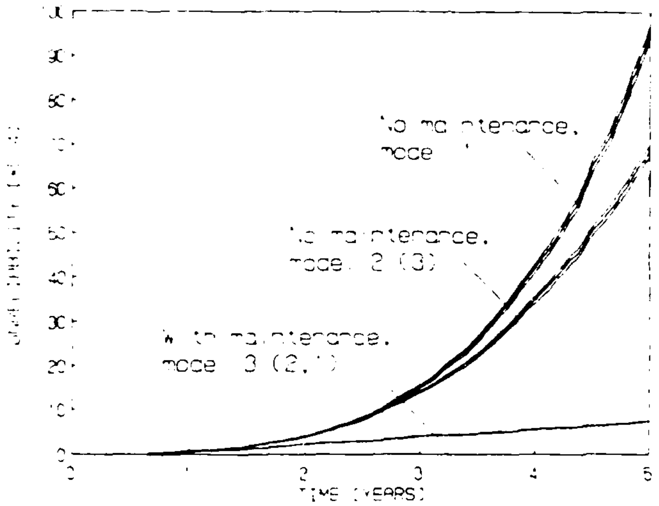


Figure 2: Unreliability versus time.

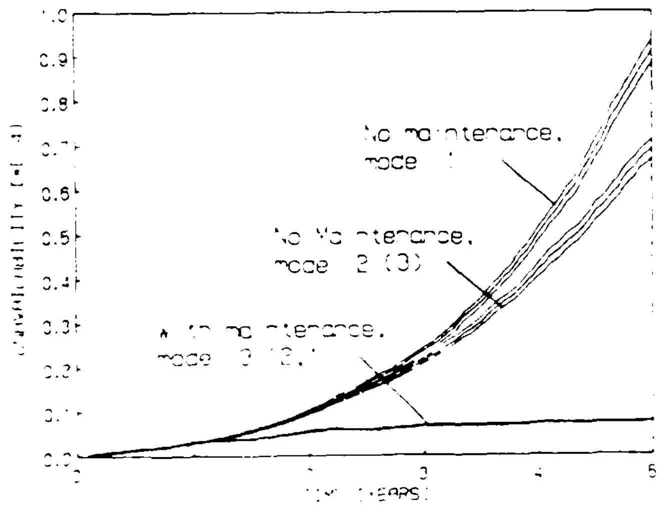


Figure 3: Interval unavailability versus time.

The highest unreliability and unavailability are for model (1) with no maintenance. The results for model 2 and model 3 with no maintenance are nearly indistinguishable and are hence shown as one set of curves. Finally the smallest unreliabilities and maintainabilities shown in Figs. 2 and 3 are for the maintained systems. Here the differences between the three models are nearly indistinguishable. As could be expected, the curves for the unmaintained systems are concave up and demonstrating the marked effects of component aging. Where maintenance is present the unreliability uses in a more linear manner while the unavailability levels off toward an asymptotic value.

Similar results are obtained for standby configurations and for multi-component systems with more complex redundant configurations. Brevity requires that they not be presented here.

References

(1) E. E. Lewis and F. Boehm, "Monte Carlo Simulation of Markov Unreliability Models, Nucl. Eng. Res. 77, 49-62 (1984).

(2) Z. Tu and E. E. Lewis, "Component Models in Markov Monte Carlo Simulation," Reliab. Engr. 13, 45-61 (1985).

(3) E. E. Lewis and Z. Tu, "Monte Carlo Reliability Modeling by Inhomogeneous Markov Processes, Reliab. Engr. 16, 277-296 (1986).

(4) E. Cinlar, Introduction to Stochastic Processes, Prentice-Hall, Englewood Cliffs, NJ, 1975.

(5) R. E. Barlow and F. Proscham, Statistical Theory of Reliability and Life Testing, Holt, Rinehart & Winston, NY, 1981.

(6) E. E. Lewis, Z. Tu, U. P. Hald and F. Boehm, "Explicit Time-Dependent Analysis in Monte Carlo Reliability Simulations," in preparation.

END

DATE

FILMED

APRIL

1988

DTIC