# An International Research Conference on

# Reliability

## May 17-19, 1988
## UNIVERSITY OF MISSOURI
## Columbia, Missouri

# *Program & Abstracts*



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U.S. Air Force Office of Scientific Research,
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American Statistical Association

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INTERNATIONAL RESEARCH CONFERENCE ON RELIABILITY
UNIVERSITY OF MISSOURI-COLUMBIA
MAY 17-19, 1988

AFOSR-88-0144

PROGRAM

AFOSR-TR 89-0377

MONDAY, MAY 16, 1988
P.M.

| | | |
|---|---|---|
| 7:30 - 9:30 | REGISTRATION AND MIXER | Rodeway Inn |

TUESDAY, MAY 17, 1988
A.M.

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|---|---|---|
| 8:00 - 10:00 | REGISTRATION | Memorial Union<br>2nd Floor Foyer |
| 8:30 | **WELCOME**<br>Milton Glick<br>Dean, College of Arts & Science<br>University of Missouri-Columbia | Memorial Union<br>Auditorium |
| | **SESSION I**<br><br>**ARTIFICIAL INTELLIGENCE AND EXPERT SYSTEMS IN RELIABILITY**<br><br>Chair: M. Tortorella<br>AT&T Bell Laboratories | Memorial Union<br>Auditorium |
| 8:45 | **An Application of Expert Systems to the Statistical Analysis of Reliability Data**<br>Sarah Brooks<br>IIT Research Institute | |
| 9:10 | **Unified Diagnosis for Reliability Enhancement in Real-Time Systems**<br>Roy A Maxion<br>Carnegie Mellon University | |
| 9:35 | **Artificial Intelligence and Reliability**<br>S. J. Amster<br>AT&T Bell Laboratories | |
| 10:05-10:30 | **COFFEE** | Memorial Union<br>2nd Floor Foyer |

A-1

**SESSION II** — Memorial Union Auditorium

**SOFTWARE RELIABILITY**

Chair: John Musa
AT&T Bell Laboratories

| | | |
|---|---|---|
| 10:30 | **The Effect of Test Strategy on Software Reliability Measurement**<br>Willa K. Ehrlich, Thomas J. Emerson and John Musa<br>AT&T Bell Laboratories | |
| 11:00 | **Quality Improvement Resulting from Cleanroom Software Engineering**<br>M. Dyer<br>IBM Federal Systems Division | |
| 11:30 | **On Software Reliability Modeling**<br>B. Bergman<br>Linköping Institute of Technology, Sweden | |
| P.M.<br>12:00-1:30 | **LUNCH** | Memorial Union<br>Room N201/202 |

**SESSION III** — Memorial Union Auditorium

**RELIABILITY AND QUALITY MANAGEMENT**

Chair: R. Chadda
Bell Communications Research

| | | |
|---|---|---|
| 1:30 | **AMC Life Cycle Cost Versus System Reliability Study Findings**<br>P. Ellner<br>U.S. Army Material System Analysis Activity | |
| 1:55 | **Lessons Learned from Challenger - A Reliability/Risk/Statistical Perspective**<br>B. Hoadley<br>Bell Communications Research | |
| 2:30-3:00 | **COFFEE** | Memorial Union<br>2nd Floor Foyer |

**SESSION IV** — Memorial Union Auditorium

**RELIABILITY GROWTH**

Chair: Steve Rigdon
Southern Illinois University

| | | |
|---|---|---|
| 3:00 | **Reliability Growth Concepts and Modeling**<br>Larry Crow<br>AT&T Bell Laboratories | |
| 3:25 | **Analyzing and Modeling the Behavior of Process Failures**<br>C. Benski<br>Merlin Gerin, France | |
| 3:50 | **Some Comments on Reliability Analysis**<br>L. N. Harris<br>British Aerospace, U.K. | |
| 4:15 | **Discrete Reliability Growth Models**<br>R. A. Johnson<br>University of Wisconsin, Madison | |
| 4:40 | **Estimation In A Discrete Time Reliability Growth Model**<br>J. K. Ghosh and G. K. Bhattacharyya<br>Indian Statistical Institute, Calcutta, India and University of Wisconsin, Madison | |
| 8:00-10:30 | **WELCOME PARTY AND POSTER SESSION** | Rodeway Inn |

<u>**WEDNESDAY, MAY 18, 1988**</u>

A.M.

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|---|---|---|
| 8:00-10:00 | **REGISTRATION** | Memorial Union 2nd Floor Foyer |

**SESSION V** — Memorial Union Auditorium

**STATISTICAL MODELS FOR AUTOMATIC DIAGNOSTICS OF COMPLEX SYSTEMS**

Chair: R. Kowalski
ARINC Research Corporation

8:30 **Experiences with an Information Theoretic Testability Analysis Tool**
H. S. Balaban
ARINC Research Corporation

9:00 **Design of Fault Tolerant Subsystems to Reduce the Hazard Risk of a Weapon System**
D. R. Allen
Northrop Corporation

9:30 **Testability Research: Where We Are, What We Need**
J. Klion
Rome Air Development Center, New York

10:00-10:25 **COFFEE** — Memorial Union, 2nd Floor Foyer

**SESSION VI** — Memorial Union Auditorium

**SYSTEM RELIABILITY**

Chair: B. Woodruff
Air Force Office of Scientific Research

10:25 **The Superconducting Super Collider: Availability and Reliability Analysis**
R. E. Barlow
University of California, Berkeley

10:50 **Some Recent Results on Information Based Minimal Repair of a System of Components**
B. Natvig
University of Oslo, Norway

11:15 **System Based Component Test Plans and Operating Characteristics**
M. Mazumdar
University of Pittsburgh and
R. G. Easterling, F. W. Spencer and
K. V. Kiegert, Sandia National

11:40 **Estimating System and Component Reliabilities Under Partial Information on Cause of Failure**
Frank Guess
University of South Carolina

P.M.
12:00-1:30 **LUNCH** — Memorial Union, Room N201/202

## SESSION VII

Memorial Union Auditorium

### COMPLEX SYSTEM AND ACCELERATED TESTS

Chair: Sam Kotz
University of Maryland

| | | |
|---|---|---|
| 1:30 | **Probabilistic Control Methods of the PWR Reactor Control Rod Guide Tubes Steel Pins**<br>L. Piepszownik<br>ISPRA, Italy | |
| 1:50 | **Some Exact Algebraic Expressions For the Reliability of Multipath Switching Networks**<br>G. A. Whitmore<br>McGill University, Canada | |
| 2:10 | **Design of Accelerated Tests--Materials Engineering Considerations**<br>S. G. Sundaresan<br>Copeland Corporation | |
| 2:25 | **Monte Carlo Reliability Estimates for Highly Redundant Systems**<br>E. E. Lewis, F. Boehm and C. Kirsch<br>Northwestern University | |
| 2:45 | **Reliability Analysis of a Deteriorating System**<br>M. Abdel Hameed<br>Kuwait University, Kuwait | |
| 3:00 | **GROUP PICTURE**<br>Gather in front of the Memorial Union for a group picture. | |
| 3:10 | **COFFEE** | Memorial Union 2nd Floor Foyer |

## SESSION VIII

Memorial Union Auditorium

### BAYESIAN RELIABILITY

Chair: B. Launer
Army Research Office

| | |
|---|---|
| 3:25 | **Pre-posterior Analysis in Software Testing**<br>N. Singpurwalla<br>George Washington University |

| | | |
|---|---|---|
| 3:50 | **Failure Data Analysis in Reliability Practice - From Sampling Theory to Stochastic Filtering**<br>C. A. Clarotti and W. Runggaldier<br>ENEA, Italy | |
| 4:10 | **Bayesian Approach to Life Testing and Reliability Estimation Using Asymmetric Loss Function**<br>A. P. Basu and N. Ebrahimi<br>University of Missouri-Columbia and Northern Illinois University | |
| 4:30 | **Bayes Optimal Burn-In Time**<br>F. Spizzichino and C. A. Clarotti<br>University "La Sapienza", Rome and ENEA, Italy | |
| 4:50 | **On the Stochastic Modeling of Fatigue Crack Propagation**<br>P. K. Goel and P. N. Palattas<br>Ohio State University | |
| 6:30 | **CASH BAR** | Alumni Center |
| 7:00 | **BANQUET** | Alumni Center |
| | **Speaker:**<br>Bob Hogg, University of Iowa and President, American Statistical Association | |

<u>THURSDAY, MAY 19, 1988</u>
A.M.

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|---|---|---|
| | **SESSION IX** | Memorial Union Auditorium |

**MODELS AND INFERENCE I**

Chair: Y. Mittal
National Science Foundation

| | |
|---|---|
| 8:30 | **Nonparametric Methods for Reliability Models**<br>M. Hollander<br>Florida State University |
| 8:55 | **Generation of Distributions of Dependent Lifetimes: A Review**<br>M. Shaked and J. George Shanthikumar<br>University of Arizona and University of California, Berkeley |

| | | |
|---|---|---|
| 9:20 | **Active Redundancy Allocation in Coherent Systems**<br>P. J. Boland, E. El-Neweihi and F. Proschan<br>University College, Dublin, Ireland,<br>University of Illinois, and<br>Florida State University | |
| 9:45 | **Peakedness in Multivariate Distribution**<br>Ingram Olkin, Stanford University and<br>Y. L. Tong, Georgia Institute of Technology | |
| 10:10-10:30 | **COFFEE** | Memorial Union<br>2nd Floor Foyer |
| | **SESSION X** | Memorial Union<br>Auditorium |

**MODELS AND INFERENCE II**

Chair: W. A. Thompson
University of Missouri-Columbia

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|---|---|---|
| 10:30 | **The Impact of Reliability and Life Length Analysis On Statistical Research**<br>B. Epstein<br>Israel Institute of Technology<br>Haifa, Israel | |
| 11:00 | **Multivariate Distributions Generated From Polya-Eggenbeger Urn Models**<br>A. W. Marshall and I. Olkin,<br>University of British Columbia, Canada and<br>Stanford University | |
| 11:30 | **Applications of Ranking and Selections to Reliability Problems**<br>M. Sobel and J. V. Deshpande<br>University of California, Santa Barbara | |
| P.M.<br>12:00-1:30 | **LUNCH** | Memorial Union<br>Room N201/202 |
| | **SESSION XI** | Memorial Union<br>Auditorium |

**MODELS AND INFERENCE III**

Chair: Paul Shaman
University of Pennsylvania

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|---|---|---|
| 1:30 | **Applications of Proportional Hazards Modeling to Hardware and Software Reliability**<br>Tony Bendell and D. Wightman<br>Trent Polytechnic, UK | |
| 1:55 | **Drawing Inferences From a Shared Dynamic Multidisciplinary Database**<br>N. Flournoy<br>National Science Foundation | |
| 2:20 | **TTT-Plotting - A Tool for Both Theoretical and Practical Problems**<br>B. Klefsjo<br>University of Luleå, Sweden | |
| 2:45 | **A Model for Critical Crack Size Estimation in Fatigue Failure of Gun Barrels**<br>W. J. Padgett and S. D. Durham<br>University of South Carolina | |
| 3:10-3:30 | **COFFEE** | Memorial Union<br>2nd Floor Foyer |
| 3:30-5:00 | **SESSION XII** | Memorial Union<br>Auditorium |

**OPEN FORUM AND CLOSING REMARKS**

Chair: Nancy Mann
UCLA

Bill Golomski
Golomski & Associates

Nancy Flournoy
National Science Foundation

Nozer Singpurwalla
George Washington University

Ingram Olkin
Stanford University

## CONTRIBUTED PAPERS FOR POSTER SESSION AND OTHER PARTICIPANTS

| | | |
|---|---|---|
| 1. | Gyorgy Barta | Budapest, Hungary |
| 2. | G. P. Butsan and I. I. Ejov | Ukrainian Academy of Sciences, Kiev, U.S.S.R. |
| 3. | Wang Dinghua | Northwest Textile Institute, China |
| 4. | Jerzy Filus | Illinois Institute of Technology |
| 5. | J. M. Jobe | Miami University |
| 6. | K. Joag-Dev | University of Illinois |
| 7. | S. Kotz | University of Maryland |
| 8. | K. B. Kulasekera & L. Saxena | University of Nebraska |
| 9. | H. Kunitz (2) | GRS, W. Germany |
| 10. | Larry Lee & George Finelli | Old Dominion University |
| 11. | Mei-Ling Tine Lee | Boston University |
| 12. | Sameeh Ahmed Mahmoud | Zigazig University, Egypt |
| 13. | Xie Min | Linköping University, Sweden |
| 14. | S. P. Mukherjee & A. Chatterjee | Calcutta University, India |
| 15. | Alan G. Munford | University of Exeter, U.K. |
| 16. | T. Nayak | George Washington University |
| 17. | Dong Ho Park & P. Lahiri | University of Nebraska |
| 18. | S. H. Park | Seoul National University, Korea |
| 19. | A. Sengupta (2) | Indian Statistical Institute, India |
| 20. | J. L. Shau & Wu Feng | Air Force Telecommunication Engineering Institute, China |
| 21. | W. A. Thompson, Jr. | University of Missouri-Columbia |
| 22. | Hassan Zahedi | Florida International University |
| 23. | Yan Kun Zhou | Utah State University and East China Normal University |

# RELIABILITY ANALYSIS OF A DETERIORATING SYSTEM

Mohamed Abdel-Hameed
Kuwait University

A system is subject to deterioration. The deterioration is assumed to be an increasing pure-jump Markov process. The system has a threshold and it fails once the deterioration exceeds the threshold. Upon failure the system is replaced by a new system. The system can be also replaced before failure, at a cost rate that depends on the deterioration level. We examine life distribution properties of such system; furthermore, we determine the optimal replacement policies that minimizes the infinite horizon discounted cost, and the long-run average cost.

# DESIGN OF FAULT TOLERANT SUBSYSTEMS TO REDUCE THE HAZARD RISK OF A WEAPON SYSTEM

D. R. Allen
Northrop Corporation

A hazard risk index which is based on both the reliabilities and the criticalities of major subsystems of a weapon system has been defined. The accompanying figure illustrates the principle. The reliability, expressed in terms of frequency of failure occurrences, is one component of the hazard index, and the criticality of the subsystem is the other. The subsystems with the lowest index have the greatest risk. The starting point is assumed to be a weapon system which has no fault tolerance in the form of added redundancy. Critical subsystems with high failure rates may require design changes, and adding redundancy is one alternative to reduce the overall hazard risk of the total weapon system. The figure shows a possible line of demarkation; that is, those subsystems above the line require redesign and those below do not.

If redundancy is added to those critical subsystems whose index lies below a given line of demarkation, the effective reliability of the total system has been increased and the probability of mission success has increased. It is understood that there are cost weight, volume and power penalties associated with adding redundancy, but in safety critical subsystems particularly, the added burdens, if limited, are justified.

The addition of redundancy requires major improvements in the quality of on-board diagnostic systems relative to the diagnostic capabilities of present weapon systems. The testability of the diagnostic systems within subsystems can be defined in terms of two parameters: the fault coverage (fraction of faults detectable and isolatable within redundant elements to the total fault population) and the false alarm probability (probability of a fault indication being false). Ideally, the coverage should be one and the false alarm probability (FAP) should be zero. Since this cannot be achieved practically, we must consider the impact of less than perfect testability on redundant systems. Whereas, adding redundancy increases the effective reliability, the impact of added Built-in Test hardware and software, less-than-100% fault coverage, and a high FAP all decrease the effective reliability. It is necessary to determine quantitative measures of their impacts on effective reliability for testability parameters.

This paper describes procedures for subsystems which lie above the demarkation line in the hazard index figure to determine what level of redundancy needs to be added to bring the index higher than the critical value and the quality of the testability necessary to make sure that redundant elements achieve the required improved reliability.

# HAZARD RISK INDEX

| FREQUENCY / CRITICALITY | FREQUENTLY | PROBABLE | OCCASIONAL | REMOTE | IMPROBABLE |
|---|---|---|---|---|---|
| CATASTROPHIC | 1 | 2 | 4 | 8 | 12 |
| CRITICAL | 3 | 5 | 6 | 10 | 15 |
| MARGINAL | 7 | 9 | 11 | 14 | 17 |
| NEGLIGIBLE | 13 | 16 | 18 | 19 | 20 |

1 - 5 UNACCEPTABLE, DESIGN MUST CHANGE (HIGH)
6 - 9 UNACCEPTABLE (MEDIUM)
10 - 14 ACCEPTABLE (LOW)
15 - 20 ACCEPTABLE (VERY LOW)

# ARTIFICIAL INTELLIGENCE AND RELIABILITY

S. J. Amster
AT&T Bell Laboratories
Holmdel, NJ

This talk explores various applications of artificial intelligency techniques in the field of reliability. Some of their advantages and disadvantages are examined in a fairly general context and by specific examples. An attempt at predicting the future directions of this potential AI application is made as a "straw proposal" to invite contrary viewpoints and general discussion of the issues. Emphasis is placed on the questions to be asked rather than the answers.

The talk is divided into two parts, one discussing tools for experts, and the other discussing tools for less experienced analysts. Some of the topics we mention include finding weak links, reliability optimization and budgeting, and choosing an appropriate reliability model.

## THE SUPERCONDUCTING SUPER COLLIDER: AVAILABILITY AND RELIABILITY ANALYSIS

R. E. Barlow
University of California-Berkeley

The Superconducting Super Collider (SSC) is a proposed proton accelerator which will be capable of energizing protons up to 20 TEV ($10^{12}$ electron volts). The magnet subsystem consisting of 10,000 superconducting magnets in series constitutes the most critical part of the system from an availability and reliability point of view. We review the general principles of a system reliability analysis and discuss the particular approach and problems encountered relative to the SSC. In particular we describe how we used data and information from a much smaller system, the Tevatron at Fermi lab, to construct fault trees and analyze the SSC.

Bayesian Approach to Life Testing and Reliability Estimation

Using Asymmetric Loss Function

by

A.P. Basu* and Nader Ebrahimi

University of Missouri–Columbia and University of Northern Illinois

Abstract

In this paper the problem of estimating mean lifetime and reliability function has been considered using asymmetric loss functions. Exponential distribution has been considered as a model. A number of prior distributions have been considered and Bayesian estimates have been compared with corresponding estimates with squared error loss function.

*Research sponsored by the Air Force Office of scientific Research, Air Force Systems Command, USAF, under grant number AFOSR–87–0139. The US Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation thereon.

# APPLICATIONS OF PROPORTIONAL HAZARDS MODELLING TO HARDWARE AND SOFTWARE RELIABILITY

Professor Tony Bendell and Dr. David Wightman
Trent Polytechnic, U.K.

The paper describes work at Trent Polytechnic in extending the use of Proportional Hazards Modelling within both hardware and software applications. Developments in diagnostic aids to investigate model structure are described, as well as the adaption to diverse reliability data structures. Illustrative applications are described in railway engineering, computer hardware, weapon systems, electricity supply, electronic components and computer software.

# ANALYZING AND MODELING THE BEHAVIOR OF PROCESS FAILURES

Claudio Benski
Merlin Gerin, France

## 1. Introduction

We consider the case of a single repairable system whose failure times can be considered a stochastic point process and whose repair times are negligible compared to the times between successive failures. Many practical systems correspond to this description and there is a large amount of literature devoted to this subject {1}. In this context there are three questions that must usually be answered:

1. Can the times between failures be considered as being a random sample from a Homogeneous Poisson Process (HPP) If this hypothesis is (statistically) rejected one can often model the point process as a non HPP (NHPP) in which case the second question is:

2. Can one model the intensity of the NHPP by a particular simple functional expression, say a power law? If the answer to this question is yes, we have question number three:

3. Using the times between system failures, can one estimate the parameters belonging to the model, eventually obtain confidence intervals and use these to predict future system behavior?

The mathematical techniques to answer these questions have been developed in the recent past. But they have relied on a number of tables {2,3}. Now, the system we are going to describe is a diskless data acquisition and control one for which tables make a poor substitute for a more compact formula type approach. We intend to present here a procedure which is totally self-contained. It thus allows the user to apply this approach to the case of a computer controlled driven system in which the computer itself can use the results of the above tests to modify certain parameters of the process it controls. Naturally, here the point process does not mean "system failures" involving the computer but process related events like a spark in a high voltage installation, a broken unit in a mass production system and so on. The repair aspect of the process is taken care of by the computer modifying the process parameters right after each of these events, presumably with the purpose of decreasing the intensity of the point process. Or it can simply reset the degraded process for another run. In terms suggested by Ascher {1} and if these events were really failures, this intensity would be called "Rate of Occurrence of Failures" or ROCOF.

One surprising and useful feature of the procedure that will be proposed below is that a pocket computer is shown to be enough for the above tasks. The usefulness comes about when it is realized that it is not just the small size that helps under some experimental conditions. Instead, because these computers and some of the data acquisition instruments are battery operated, the whole process and its failures are decoupled from line voltage perturbations.

## 2. Procedure

We will first discuss the aspects of the procedure specifically related to the three questions invoked in the introduction. The computational details of the statistical distribution functions that are needed will be left to Section 4.

In order to answer the question of whether the sequence of times between failures can be considered a HPP, as opposed to a NHPP, Cox and Lewis (4) and Lawless (5) give a simple answer by means of a U-statistic which follows approximately a normal distribution. The U-statistic is very easily calculated in terms of the times to failure.

Let x1,x2,...xn be the sequence of times between failures. Then t1=x1,t2=x1+x2,...tj=x1+x2+...+xj are the times to failure. If the process is observed until a time To, greater than or equal to tn, the U-statistic takes the form:

$$U = \frac{\sum_{i=1} t_i - \frac{mT_0}{2}}{T_0 \sqrt{\frac{m}{12}}}$$

For a process that is observed until the time of the nth. failure that is To=tn, the formula uses m=n-1. For a process observed until a fixed time To>tn, m=n must be used in the formula for U. Large values of U constitute evidence for rejecting the HPP hypothesis. In case of rejection, a positive U means that the intensity of the NHPP is increasing. That is, if the events are failures, the process is deteriorating. The converse is, of course, true for a negative U.

Assuming now that the absolute value of U has been found to be significant, question number 2 must be answered. The AMSAA model (2) is a simple reliability growth approach in which the intensity of the NHPP is supposed to vary as a simple power of time. Since the functional form of the intensity resembles Weibull's law, this model has sometimes been called a Weibull process (3,6). The reader will find a discussion of why this terminology is misleading in reference 6. Now, if one assumes the AMSAA model, the NHPP intensity can be written as:

$$\rho(t) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1}$$

A Cramer-von Mises (CM) goodness of fit test of this model can be done using the unbiased estimate of B, B {2} in:

$$CM^2 = \frac{1}{12m} + \sum_{i=1}^{m}\left[\left(\frac{t_i}{T_0}\right)^{\bar{\beta}} - \frac{2i-1}{2m}\right]^2$$

with:

$$\bar{\beta} = \frac{m-1}{m}\hat{\beta}$$

where B is the maximum likelihood estimate (MLE) of B and m takes the same meaning as before. To compute the MLE of both parameters of the AMSAA model is straightforward. The following formulas are valid for time and failure terminated testing:

$$\hat{\beta} = \frac{n}{\sum_{i=1}^{m} \ln\left(\frac{T_0}{t_i}\right)} \quad ; \quad \hat{\alpha} = \frac{T_0}{n^{1/\hat{\beta}}}$$

where the symbol  is used to denote MLE estimates. However, the significance points of the Cramer-von Mises test as given in MIL-HDBK 189 are in table form (Table C-11, p. 144) and this does not lend itself well to our purpose. Fortunately, a look at this table shows that for m greater than, say, 6 the critical values do not change by more than 10 percent at any significance level. Since, in this table, the significance levels go from .20 to .01 and this is enough for any practical purpose (confidence levels from 80 to 99 percent), it was very tempting to try and find a single simple function, valid for any m, that would give an approximately significance level as a function of the CM statistic. This has been done and, for the range of the table, the following expression gives a reasonable approximation of the probability values: p=1-exp[1-87*CM 2)/6].

to a HPP:

$$W = 2\sum_{i=1}^{n-1} \ln\left(\frac{T_0}{t_i}\right)$$

Since W is Chi squared distributed {1,2,5} with 2 (n-1) degrees of freedom, it is a simple matter to add this check to the procedure and thus complete the answer to question 2. This can be done using the statistical distribution algorithms described in Section 4.

This last test has the advantage of being optimum for testing HPP against a monotonously varying intensity of a NHPP {7}.

Question three is already partially answered since we have the MLE of the parameters. The MLE of the mean time to next failure after time To is just the reciprocal of the MLE of the intensity function. In order to compete this answer it is necessary to obtain confidence limits for this. Depending on whether one has a failure or time terminated situation, references 2 and 3 give tables to compute confidence intervals at levels 0.8, 0.9, 0.95 and 0.98 for sample sizes up to 100. Contrary to the CM table these ones are strongly dependent on the sample size. It was decided that a fixed confidence level such as 0.9 would give satisfactory results and so the following simple formulas were obtained. They give factors to multiply the MLE of the mean time to next failure for confidence intervals at the 90 percent level, also for sizes under 100:

$$\rho_1 = 0.811 - \frac{3}{n} + \frac{8.546}{n^2} \quad ; \quad \rho_2 = 1.3 + \frac{10.512}{n} + \frac{49.833}{n^2}$$

$$\Pi_1 = \frac{\rho_1}{1 + \frac{2.5}{n}} \quad ; \quad \Pi_2 = \frac{\rho_2}{1 + \frac{0.95}{n}}$$

where the factors on the first line are for failure terminated tests and those on the second line are for time terminated tests. For bigger samples there is an asymptotic approximation {3}, which has been incorporated into the procedure. If Zp is the normal deviate corresponding to p then:

$$\rho_1 = \left[ 1 + \sqrt{\frac{2}{n}}\, Z_{\frac{\alpha}{2}} \right]^{-1} \quad ; \quad \rho_2 = \left[ 1 - \sqrt{\frac{2}{n}}\, Z_{\frac{\alpha}{2}} \right]^{-1}$$

$$\Pi_1 = \frac{n^2}{\delta_1} \quad ; \quad \Pi_2 = \frac{n^2}{\delta_2}$$

$$\delta_1 = \left[ n + \frac{Z^2_{\alpha/2}}{4} + \sqrt{\frac{Z^2_{\alpha/2}}{2} n + \frac{Z^2_{\alpha/2}}{8}} \right]^2 \qquad \delta_2 = \left[ n + \frac{Z^2_{\alpha/2}}{4} - \sqrt{\frac{Z^2_{\alpha/2}}{4} n} - \sqrt{\frac{Z^2_{\alpha/2}}{2} n + \frac{Z^2_{\alpha/2}}{8}} \right]^2$$

These asymptotic expressions are important because when, as in our case, the point process is not related to system failures but to an event such as those mentioned in the introduction, sample sizes can quickly grow to large values. But this is in fact an advantage from the statistical point of view. For example, Blanks and Tordon {8} have shown that for B=2, there is still a 7 percent probability of not detecting this trend when using the U-statistic at the 10 percent level with a sample of 20 failures. Other probabilities for sample sizes under 20 and for several levels of the U-test for B varying between 1 and 3 can be found in reference 8.

Table 1 contains the results of the computer output obtained with the data used in reference 1 (20.2.1.4, pp. 135-136) for a time truncated test. The point estimates and the CM statistic are, of course, identical. The confidence interval values are [9.9 - 26.1] in MIL-HDBK 189 and [10.1 - 26.3] with this procedure. The agreement is very adequate. Thus question 3 is answered.

## 3. Application

As stated in the introduction the main goal was to have an autonomous system which could be battery operated in a diskless computer configuration. The process would have several parameters which could be modified whenever a certain event, call it "process failure" without loss of generality, takes place. This was made possible by programming the above procedure in a HP 71 pocket computer. This computer can address half a megabyte of core memory and its operating system is memory based. It allows for multiple programs coexisting in a non-hierarchical manner: any program can call any routine, even itself, passing parameters by value or reference. The value of this computer for statistical calculations has already been pointed out in {9}.

In this case, we have used its interfacing capabilities to measure the instants of arcing of a high voltage condenser. The experiment operated under higher than nominal voltage to accelerate failure. At some point in time arcing occurred inside the condenser. This constituted our point process. During the arcing, pressure and voltage across the condenser were recorded by a fast transient analyzer. In some runs the HV was lowered after each failure or the temperature modified. Then the experiment was started again until the next failure. Eventually the condenser would fail completely and the test was stopped.

The procedure described in Section 2 allowed the determination of an increasing intensity of the failure process which was ascribed to the higher number of pitts in the internal parts of the condenser. These pits were created by the electrical arcing. The more pits the condenser has, the more likely it is that the next arcing will occur soon.

## 4. Statistical Functions

For many practical purposes, such as this procedure or the one described in {9}, it was deemed desirable to have a single file which would contain the Normal, Student's t, Chi squared and Fisher's F distributions as well as their inverses. Although accuracy was a main concern, speed was also essential since the idea was to use the HP 71 to make statistically valid decisions while measurements were in progress. The following approaches gave excellent results.

For the Normal distribution we use formula 26.2.17 of reference {10}. This is still a fast and accurate formula since it gives an error smaller than 0.1 ppm. The inverse of the Normal distribution, that is the value of the normal deviate corresponding to a given probability value was calculated using algorithm AS 111 of {11}.

Student's t distribution is calculated using its relation to Fisher's distribution: for n degrees of freedom, Student`s t is just half the square of the abscissa for the Fisher distribution with 1 and n degrees of freedom. For Student's inverse with one and two degrees of freedom, exact expressions exist as can be shown using its series expansion, formulas 26.7.3 and 26.7.4 in {10}. For degrees of freedom higher than 2 we use an algorithm similar to that of reference {12}.

Fisher's distribution function is computed using its series expansion, formulas 26.6.4 and 26.6.5 in {10}, for degrees of freedom under 200. If both degrees of freedom are greater than 200 the normal approximation is used. If only one of them is greater than 200 then the Chi squared distribution approximation is used. The inverse of Fisher's distribution is known analytically if both degrees of freedom are equal to 1 or if one of them is equal to 2. If only one of the two degrees of freedom is equal to 1, we use the relationship to the inverse student distribution. If none of these conditions are met we use formula 26.6.16 in {10}.

For the Chi squared distribution we use its series expansion given by formulas 26.4.4 and 26.4.5 in {10}. For its inverse weuse algorithm AS 91 from {11}.

Most of these algorithms call one or several of the others so the whole must be kept self-consistent. This again was made possible by the flexible operating system and its inherent accuracy. It was also helped by its dynamic computational range: exponents of +499 with a 12 significant digit mantissa are used while implementing the IEEE 854 floating point standard. Although the author is aware of some better performing algorithms, their use led to slower calculating speed without significant increase in accuracy. For our purposes, the forms used were satisfactory. Yet, should a real improvement be available, the structured nature of these routines would make the change very simple to implement.

## 5. Conclusions

We have shown how to integrate some of the recent techniques to analyze and model a repairable system and adapted them to a process failure monitoring system. This has been made possible by the sophisticated nature of a small albeit very powerful calculating device and by approximating some of the published tables with suitable simple algorithms. The procedure has been applied to the prediction of failure of high voltage condensers under failure induced stress.

Example: MIL-HDBK-189 20.2.1.4

Stopping time To = 300
27 times between successive failures

| | |
|---|---|
| t1 = 2.6 | t15 = 2.6 |
| t2 = 13.9 | t16 = 3 |
| t3 = 0 | t17 = 30.9 |
| t4 = .5 | t18 = 10.2 |
| t5 = 4.4 | t19 = 5.5 |
| t6 = 7.7 | t20 = 1,3 |
| t7 = 4.2 | t21 = 18.2 |
| t8 = 23.2 | t22 = 23.5 |
| t9 = 6.6 | t23 = 2.3 |
| t10 = 7.5 | t24 = 5.7 |
| t11 = 2.4 | t25 = 53.2 |
| t12 = 4.7 | t26 = 30.6 |
| t13 = 16.2 | t27 = 3.6 |
| t14 = 1.6 | |

Probability of a trend: 97.955% (Decreasing intensity).

Probability to reject the hypothesis of AMSAA model: < 80%

Assuming AMSAA model the parameters are:
BETA = .716339 ALPHA = 3.0127

Probability of having BETA<1: 98.128%

Therefore INTENSITY = 3.251E-1*t 0.2837

MLE of time to next failure: 15.51
Approximate 90% confidence interval: [10.1 - 26.34]

Table 1: Summary of computer output for procedure in Section 2.

# ON SOFTWARE RELIABILITY MODELLING

Bo Bergman
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In this expository paper we review some of the most common assumptions leading to the usual software reliability models. These assumptions are discussed and some more general assumptions are suggested. Some possible models based on these assumptions are discussed.

# ESTIMATION IN A DISCRETE TIME RELIABILITY GROWTH MODEL

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and

J. K. Ghosh
Indian Statistical Institute, India

A non-homogeneous Poisson process $N(t)$ with Weibull intensity $u(t) = u\ Bt^{B-1}$ has been used to model reliability growth or repairable systems. In this problem there is a unique MLE which can be explicitly written down and can be shown to have a limiting normal distribution. In analogy with the continuous time case, reliability growth in the discrete case has been modelled in the literature by a sequence of Bernoulli variables $X_1, X_2, \ldots X_i, \ldots$ with $q_i = P\{X_1 = 0\} = u\ (i^B - (i-1)^B)$. In this case we show the limiting (joint) distribution of the MLE exists and is identical with the limiting bivariate distribution of what are called continuous time analogue estimates.

# ACTIVE REDUNDANCY ALLOCATION IN COHERENT SYSTEMS

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E. El-Neweihi
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University College, Dublin, Ireland
University of Illinois and
Florida State University

We introduce a new measure of component importance in coherent systems which is called redundancy importance. It is a measure of importance for the situation in which an active redundancy is to be made in a coherent system. This measure of component importance is compared with both the (Birnbaum) reliability importance and the structural importance of a component in a coherent system. Various models of component redundancy are studied, with particular reference to **k** out of **n** systems, parallel--series systems and series--parallel systems.

# AN APPLICATION OF EXPERT SYSTEMS TO THE STATISTICAL ANALYSIS OF RELIABILITY DATA

Sarah Brown
IIT Research Institute

This talk describes the development of an Expert System in Statistical Analysis using the M-1 shell.

The expert system called "SEER" (Statistical Expert Expedity Reporter) asks leading questions of the user to determine the nature of the data and the purpose of the study for which the data was collected. It then selects the appropriate technique to perform the statistical analysis and reports the results.

The methods of developing this system are described in detail. Real data such as a time-to-failure distribution is analyzed to illustrate the operation of the system.

# SOME FUNCTIONALS FOR QUEUEING SYSTEMS OF G/G/1 TYPE

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The main aim of this article is to disperse the pessimism of L. Kleinrock (ref. 1*, part IV) about the impossibility of G/G/1 systems' functional investigations.

We consider the discrete systems with discrete time and unlimited queue; we are going to succeed by using our method for investigating systems with continuous time, the limited queue, entering streams being described by the semimarkov process.

To find the distribution of some functionals from the system we build first of all the suitable Marcov chain and in terms of generating functions from its functionals we write the functional equations for the generation functions of unknown functionals of our system. Then by the straight probabilistic methods we find the factorization components of the functional coefficients and in its terms we describe the solutions of these equations.

This abstract deals with the realization of above idea for finding the distributions of the queueing length and busy period of G/G/1 system in terms of their generating functions.

**FAILURE DATA ANALYSIS IN RELIABILITY PRACTICE.**
**FROM SAMPLING THEORY TO STOCHASTIC FILTERING**

C. A. Clarotti
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ENEA, Italy

Why are stochastic filtering techniques needed in statistical reliability practice?

The above question is answered in the paper. Surprisingly stochastic filtering techniques will turn out to be more useful as "numerical tools" than they are as "inference tools". The use of stochastic filtering methods have been introduced in reliability statistics for solving the problem of failure data contaminated by maintenance (1), but their potential has been fully experienced only at the moment of numerically processing the recursive equations related to that problem.

In the paper it is shown how approximating the non-linear filtering problems of interest in case of contaminated data can lead to important simplifications in numerically estimating the reliability of components which are exchangeable with the observed ones.

# RELIABILITY GROWTH CONCEPTS AND MODELLING

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Complex systems with new technology will usually require system level testing to verify the performance, safety, reliability and other major considerations. It is not a viable, cost effective approach for development testing to be used simply for a pass/fail decision. Rather, information from development testing is generally used to determine what must be done to make the system acceptable to the customer. Reliability growth during development testing is achieved through an iterative process of testing to find reliability problems, incorporating design changes to correct these problems and retesting to verify the corrective action and to uncover additional problem areas. Reliability Growth is an in-line engineering design tool and has become widely accepted for development programs in both government and industry. This paper will illustrate the use of reliability growth testing during development and describe a practical framework for reliability assessments. Within this framework a useful and widely accepted statistical model for assessments is developed and illustrated by numerical examples.

# A PRACTICAL METHOD FOR INTERVAL ESTIMATION OF FAILURE RATE OF EXPONENTIAL SERIES SYSTEMS

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The document [1] of IEC, widely used in many countries, stipulates the standard method for testing the failure rate of components whose life obeys the exponential distribution. The failure rate value tested by using this method is not suitable for calculating the reliability of system. The articles [3]-[5] discussed this problem, but it is not suitable for calculating the real engineering problem.

A new algorithm is developed in this paper, which is suitable to any dimension problem and varied failure rate tests, need not to look up any table, and is more accurate and simple. With this practical method the engineers and technicians will be able to accurately analyze and evaluate the interval estimate value of the reliability of the exponential-life products.

It is pointed out in this paper that under the 50% degree of confidence the random variable $\sqrt{2\chi^2}$ asymptotically obeys the normal distribution $N(\sqrt{2n-4/3},1)$.

At last, the author suggested that in the rule of document [1] the 60% and 90% degree of confidence in the increasing or determining ranks tests should be improved to 50%.

# QUALITY IMPROVEMENT RESULTING FROM CLEANROOM SOFTWARE ENGINEERING

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The Cleanroom process for software development introduces formal methods for product design and testing that significantly improve the quality of the delivered software. Formal software design ideas bring new levels of error prevention with a rigorous design process for decomposing product requirements, systematically verifying the correctness of each decomposition and having requirements integrity throughout the process. This design process has been effectively applied to software of significant size and complexity.

Methodology for software design is important since the majority of software errors (40% - 60%) are introduced at that point and the cost of their removal can be 100 times more expensive than other types of errors. The use of formal methods can result in fewer total errors than currently realized (in the 0 - 20 range) and in their early detection and removal (90% prior to code execution).

The Cleanroom methodology also avoids the traditional dichotomy of opinion on the use of software testing versus formal verification in software development by combining both ideas into an effective development process. The mathematics based design methods support the production of software with sufficient quality to forego unit or structural testing. Statistical test ideas are introduced which define objective and formal strategies for product or functional testing with reliable extension to end-user operating capability.

The Cleanroom model recognizes that human fallibility inhibits the creation of perfect software and that formal design methods do not check for all operating characteristics. While typical structural testing is replaced by formal verification, functional testing is still performed but with an extended scope. This testing is still used to insure that product requirements have been satisfied but takes on an added responsibility for projecting field reliability. Statistical methods are introduced to select test samples that are representative of planned operating environments but with inputs randomly chosen to create a stochastic process.

The sampling approach has been effectively applied to significant commercial, realtime, interactive and similar complex applications. The concern on requirements coverage with random test selection has not materialized with statistical samples providing upwards of 90% coverage of product requirements. Testing driven by end-user distributions has been particularly effective in quickly finding residual errors that would cause product failures since the chance would trigger the failure. Reliability growth has been seen in the test process and the released software has had exceptionally good operating characteristics. In terms of current measures, products are experiencing post-delivery error rates of less than one error per thousand lines of delivered code.

# SYSTEM BASED COMPONENT TEST PLANS AND OPERATING CHARACTERISTICS

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Component test plans are often designed by allocating system reliability among the system components, then choosing individual component plans suitable for achieving system reliability goals. This approach does not consider how much information relating to the system reliability goal is provided by the ensemble of the component tests. We propose and develop the notion of system reliability O.C. curves, based on the component tests, and illustrate their use in designing and evaluating an overall test program. By specifying the O.C. values (akin to producers' and consumers' risk), optimum system oriented component test plans can be derived. These ideas are illustrated for a series system.

# AMC LIFE CYCLE COST VERSUS SYSTEM RELIABILITY STUDY FINDINGS

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In establishing the reliability requirement of a weapon system, Army policy dictates that the following factors be taken into account: (a) the level of reliability required by tne system's mission and (b) the reliability impact on the system's life cycle cost. The life cycle costs include research and development costs, investment costs, and operating and support costs. Increasing the system's reliability above the level required by the mission typically impacts each of these life cycle cost elements. Thus, early in a weapon's acquisition program, it is of interest to conduct a cost-reliability trade-off analysis to explore the feasibility of achieving a significant life cycle cost savings by specifying a system reliability value above the mission need level.

The Army Material Command (AMC) formed a task force consisting of selected AMC agencies and chaired by the U. S. Army Material Systems Analysis Activity (AMSAA) to identify useful cost-reliability trade-off methodology. In this paper we present the principal findings of the Task Force. We also discuss a number of difficulties identified by the Task Force that must be overcome to relate system reliability to life cycle costs.

# THE IMPACT OF RELIABILITY AND LIFE LENGTH ANALYSIS ON STATISTICAL RESEARCH

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Reliability and life length analysis give rise to a wide class of interesting problems. This has had a strong impact on statistical research and has resulted in a substantial body of theory and application. Particular emphasis is placed in this talk on those intrinsic features of reliability and life length data, which provide the empirical basis and motivation for the theory.

<u>A Graph Approach to the Marshall, Olkin Model for Multiple Failures</u>

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Abstract

Consider a model of a system that consists of a pair of graphs with the same set of nodes.

The nodes are to be components of a system with a coherent reliability structure.

The first graph of the model is the well known graph that represents the systems reliability structure.

The second one describes the mechanism of occurence of multiple failures in the system.

Suppose $e_1, e_2, \ldots, e_n$ are components of the system (nodes of the graphs) and suppose a component $e_i (i=1,2,\ldots,n)$ has failed at a certain moment.

Then there is an arc from the node $e_i$ to a node $e_j$ ($e_i \xrightarrow{p_{ij}} e_j$) if and only if the failure of $e_i$ causes an instantaneous failure of $e_j$ with probability $p_{ij} > 0$.

In turn the failure of the component $e_j$ can cause such failures for components $e_{j_1}, e_{j_2}, \ldots, e_{j_k}$ ; $k \leq n - 2$ ; $j_1, j_2, \ldots j_k \neq i,j$ with positive probabilities $p_{jj_1}, p_{jj_2}, \ldots p_{jj_k}$ and so on. The second graph

with the probabilities $p_{kl}$ $(k,l = 1,2,\ldots,n)$ on its arcs is a network.

The main goal is to determine the reliability of such a system.

In addition we discuss some very interesting maintainance aspects of the problem.

# DRAWING INFERENCES FROM A SHARED DYNAMIC MULTIDISCIPLINARY DATABASE

Nancy Flournoy
National Science Foundation

An environment was created at the Fred Hutchinson Cancer Research Center in which the medical disciplines (such as Virology, Microbiology, Hematology, Nutrition, Oral Medicine, and Immunology) contributed longitudinal laboratory results to a single database, augmenting a core set of demographic data, protocol information, and outcome measures on each patient. Twenty years of accumulated data invites a proliferation of retrospective analysis, motivated by desires to explore new hypotheses, draw inferences, and accelerate publication rates. The uses and abuses of this data system will be described. The need for statistical methods and standards for such systems will be discussed.

# ON THE STOCHASTIC MODELING OF FATIGUE CRACK PROPAGATION

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An accurate assessment of Fatigue Crack Propagation (FCP) is important to the structural design of fracture critical aerospace components. Traditionally, the Paris-Erdogan model is devoted to modeling the variability in N(a) or the crack growth rate dN/da for fixed crack length a. Some stochastic models for FCP based on embedded Markov chains have also been developed. A review of the important concepts is presented.

An important problem in the modeling of FCP phenomena is to predict the number of load cycles N(a) required for the crack to grow to a specified length a. Two predictive models for FCP are examined in our work. The first is a simple predictive model based on Time Transformation (T T) ideas. Since individual specimen's crack growth curve and the mean curve can be considered to be from the same family of curves, the idea of T T has turned out to be an excellent way of predicting N(a). The second model is based on Gamma Processes, in which N(a) is represented as a sum of a countable number of jumps of random height at a countable number of random points. A Pareto family of priors for the jump points, is suggested by the Paris-Erdogan model. Hierarchical Bayes is used to update the model parameters.

# ESTIMATING SYSTEM AND COMPONENT RELIABILITIES UNDER PARTIAL INFORMATION ON CAUSE OF FAILURE

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Estimating component reliabilities along with the system reliability frequently requires using lifetimes from the system level. Due to cost and time constraints, however, the exact cause of system failure may be unknown. Instead, it may only be ascertained that the cause of failure is due to one component in a subset of components, e.g., the subset forms a subsystem. Confronted with such data, this article discusses how to exploit fully the available information using a maximum likelihood approach. We extend and clarify the useful work of Kiyakawa (1984). A small Monte Carlo study indicates the helpfulness of this approach.

KEY WORDS: Reliability estimation; Partially masked cause of failure; Incomplete data; Maximum likelihood estimation; Reliability data bases.

# SOME COMMENTS ON RELIABILITY ANALYSIS

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In his "The General Theory of Employment, Interest and Money" John Maynard Keynes wrote:

"The ideas of economists and political philosophers are more powerful than is commonly understood. Indeed the world is ruled by little else. Practical men who believe themselves to be quite exempt from intellectual influence are usually slaves of some defunct economist."

Whilst these remarks were addressed to people in government, they have an all too familiar ring when we survey the current activities we call "reliability analysis".

It is not that any of the analytical techniques of the past are necessarily wrong; it is that their domain of applicability, in relative terms, has shrunk. In the absence of alternatives, traditional techniques are being used often in grotesquely distorted form for applications for which they were never designed and for which there is little evidence that they will work.

The response of the research community to that area of technology that does not succumb to traditional techniques of analysis, is to offer to the engineering community contraptions which they call models. Inspection shows many of these are merely technical affectations, because they lack the rigor that makes them useful. I do not confine the term rigor to mathematics, as the level of mathematical rigor is often high. My comment addresses philosophical, logical, scientific, and engineering rigor, which have to combine for models to be useful.

The explanation of this is forthcoming when we consider the nature of our assertions. All assertions that are in the nature of statistical estimates, particularly predictions, are to some extent philosophical statements. They are inductions, and the justification and logic of induction is philosophical, and not as is often assumed mathematical or scientific. Further, in reliability studies the method by which estimates and predictions are derived may be based directly on philosophical principles (e.g., "simple enumeration" as in the case of reliability sampling, and "the principle of insufficient reason" as is the case of parts count and software reliability predictions).

We should note that in mathematics what has been proved correct, in the absence of detected errors of proof is considered to remain correct. Thus mathematics is cumulative. However, philosophical logic, like science, is constantly undergoing revision and reformulation. What was considered meaningful say

50 years ago, may now be regarded as naive or even misleading.

Now statistics is closely connected to philosophy. In fact many of the pioneers of mathematical statistics saw their endeavors as logic-mathematical interpretations of particular philosophical tenets. For example Karl Pearson was committed to the philosophical system known as "phenomenalism", a system that also influenced R. A. Fisher. Harold Jefferys was to adopt a modified version of phenomenalism called "subjective idealism". On the other hand Jezzy Neyman was influenced by "Pragmatism". A further example is that of Bruno De Finetti who regarded his own work as a straightforward logic-mathematical interpretation of David Hume's ideas. This identifies his work as being closely connected to mainstream "British empiricism". It follows that if statistics is to a large extent a mathematical interpretation of philosophical systems, as such systems are revised, reformulated or even discarded, so must the statistical techniques based upon them.

For the statistician it must be refreshing to observe that the ideas underpinning the Bayesian approach to statistics are having a large effect on modern philosophy. For example the idea of subjective probability is a central tenet of "mathematical measurement theory", and "decision theory". Equally the concept of inverse probability plays a central role in "knowledge engineering". In my assessment Bayesian ideas are having more impact outside of the statistical profession than they are having within it.

Perhaps more important in the operational sense is the realization that assertions that are in the nature of statistical or causal descriptions and explanations, measurements, hypothesis, theoretical deductions, are required to articulate in a consistent manner with empirical, mathematical and probabilistic logic. Also assertions that purport to be based on an objective assessment of real world behavior are first and foremost scientific. Last but by no means least is that all assertions that are product, equipment or engineered system dependent are engineering assertions. It is only when philosophy, logic, mathematics, science, and engineering articulate well together that we can regard our research as having practical importance. To think otherwise is to give a charter for anarchy.

Whilst it would be useful to survey how these things fully articulate together, such a task is well beyond the bounds of this paper. However, what will be presented is a list and short discussion on what I believe are the most frequent and significant errors made on the part of the research community as a consequence of their failure to realize the importance of this articulation. f Namely:

1. The distinction between local and global inference.

2. The importance of logical types.

3. The distinction between statistical, logical and causal correlation.

4. The relevance of statistical curve fitting to scientific inference and prediction.

5. The distinction between a statistical and a scientific hypothesis. (The conjunctive hypothesis).

6. Glymore's Bootstrap test: And the relevance of case studies to inference.

7. Real, Nominal, Explication, Fuzzy, and Open textured definitions.

8. Measurement systems and statistical models.

Whilst these points are general, their discussion will be specific to software reliability and reliability growth, as these are currently large research activities, and it is within these areas that the gravest errors occur.

# LESSONS LEARNED FROM CHALLENGER - A RELIABILITY/RISK/STATISTICAL PERSPECTIVE

Bruce Hoadley
Bellcore

The Report of the Presidential Commission on the Space Shuttle Challenger Accident contains historical information on the events and decisions that preceded the accident. In this talk I examine this historical information from a reliability management and quantitative risk assessment point of view. To illustrate the ideas, I present a probabilistic risk assessment of the pre-challenger field joints (i.e., the O-rings that failed). This assessment uses modern statistical techniques and is based on data published in the Commission's Report.

# NONPARAMETRIC METHODS FOR RELIABILITY MODELS

Myles Hollander
The Florida State University

Some recently proposed nonparametric methods for analyzing reliability data are surveyed. Various nonparametric classes of life distributions are considered. Tests, estimators, and confidence bands for the reliability function are presented.

# ESTIMATION AND DISCRIMINATION PROCEDURES FOR A NEW MEASURE OF MAINTAINABILITY/RELIABILITY

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A new maintainability/reliability measure discussed in this paper is referred to as MTUT. It corresponds to the average number of maintenance hours required per operating hour. This measure integrates maintenance and repair time expenditures of all types from three levels of maintenance. Other measures discussed in the literature commonly reflect just one of the following: operational readiness (availability), logistics and support burden, or system maintainability. MTUT logically incorporates the information from these three sources into a single coherent figure of merit. This article presents motivational aspects of this new measure as well as estimation and discrimation procedures for MTUT under various assumptions.

# DISCRETE RELIABILITY GROWTH MODELS

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After reviewing some key concepts underlying reliability growth models, we investigate various discrete time versions of Crow's continuous time reliability growth model. Our study reveals that the estimates, analogous to the continuous time maximum likelihood estimators, have quite different sampling properties than their continuous time counterparts. Other estimates, based directly on the discrete time models are also discussed. Monte Carlo studies support the large sample theory.

# TTT-PLOTTING - A TOOL FOR BOTH THEORETICAL AND PRACTICAL PROBLEMS

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During the last ten years the scaled total time on test (TTT-) transform and its empirical counterpart, the TTT-plot, have proven to be very useful in different applications in reliability (e.g. model identifications, replacement theory and burn-in problems). Some of these applications will be touched in the presentation. Furthermore, it will be indicated how the TTT-concept can be used as a source of inspiration in some research situations.

# REPAIRABLE PHASED MISSION SYSTEMS - COMPARISON OF MARKOV AND FAULT TREE APPROACHES FOR QUANTITATIVE RELIABILITY ANALYSIS

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F.R.G.

Reliability evaluation of a multiphase system, composed of repairable components, is mainly performed on the basis of Markov or Fault Tree approaches.

In nuclear science, the widespread use of the fault tree technique derives from the fact that the considered systems are very complex. As this fact reflects on the number of differential equations to be solved the exact solution to the problem using the Markov analytical method is restricted to relative small systems. The price paid in order to be able to treat large systems is that fault tree technique only results in an upper bound on mission reliability.

The purpose of this paper is to work out that the integrated use of the two approaches is a need in reliability analysis not only for risk assessment or licensing procedures of nuclear power plants.

A comparison of the both above mentioned approaches basing on the experience gained from one computer code for each technique is presented. Some ideas are applied to a repairable phased mission system, i.e. to an emergency core cooling system of a boiling water reactor during a hypothetical loss of coolant accident.

**REPRESENTATION AND IDENTIFICATION OF DISTRIBUTIONS WITH BATHTUB-SHAPED HAZARD RATES**

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In reliability situations we often deal with a class of life distributions that are constructed by assuming a hazard rate initially decreasing during the so-called "infant mortality" phase, next constant during the "useful life" phase, and finally increasing during the "wear-out" phase. This concept of "bathtub" distributions gave rise to the proposal of several parametric families of life distributions as appropriate probability models.

A critical note is made on well known "bathtub"-distributions from a theoretical and a practical point of view which results in introducing a class of "bathtub"-distributions that is extremal in the context of power investigations. Use has been made of these distributions in a Monte Carlo power investigation of test statistics derived for testing the hypothesis of exponentiality (constant hazard rate) with unknown scale parameter against "bathtub"-distributions.

The presentation is done on the basis of the total time on test concept that has proven to be a fundamental tool in reliability investigations.

# A TRANSFORMATION FOR TESTING GOODNESS-OF FIT OF AN EXPONENTIAL ORDER STATISTICS MODEL

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ABSTRACT

Consider a system which is subject to testing to remove defects and improve reliability. One model for this process, sometimes called the Jelinski-Moranda model, assumes that the times between failures are independent and exponentially distributed with failure rate $(\nu - i + 1)\phi$, $i = 1,2,\ldots,\nu$ where $\nu$, a parameter, is the initial number of defects in the system. Using the conditional probability integral transformation (CPIT) procedure of O'Reilly and Quesenberry (1973), a transformation is given which changes the problem of testing exponentiality into one of testing uniformity. Applications to censored and time-truncated sampling as well as to a related Poisson model are discussed.

Key words: exponential distribution, conditional probability integral transformation, censored and time-truncated sampling, goodness-of-fit.

# PROPERTIES OF CONDITIONALLY INDEPENDENT GENERALIZED GAMMA DISTRIBUTIONS

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Conditionally independent lifetime distributions arise naturally in many real life situations. In this paper, models of life time observations that have conditionally independent generalized gamma distributions are investigated. The dependence relationships among the unconditional marginals are discussed. Moment inequalities are obtained. Conditional hazard rate and mean residual life functions are also discussed. Two applications are considered: (a) testing the equality of relapse distributions; (b) bounds on system reliability.

# MONTE CARLO RELIABILITY ESTIMATES FOR HIGHLY REDUNDANT SYSTEMS

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Monte Carlo methods are presented for the solution of continuous-time Markov and related models encountered in the analysis of highly reliable systems. The reliabilities of highly redundant systems with too many states to be treated by deterministic means are computed by combining Markov Monte Carlo with two importance sampling methods. In addition, self-transition sampling allows inhomogeneous and nonMarkovian generalizations to treat wear phenomena, preventive maintenance and parts replacement. The use of nonparametric statistical methods results in convenient presentation of the results as curves of system reliability and/or availability as a function of time. The Monte Carlo methods are used to treat a variety of problems including ultrareliable fault tolerant control systems.

# MULTIVARIATE DISTRIBUTIONS GENERATED FROM POLYA-EGGENBEGER URN MODELS

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The Polya-Eggenberger urn model was created in order to model contagion. From this distribution, a number of well-known distributions (such as the negative binomial distribution) can be obtained as limits. There is no unique extension of the urn model to the bivariate case, and we obtain several bivariate urn models. These in turn are used to obtain limiting bivariate distributions, among which are the bivariate Poisson, negative binomial, and exponential distributions.

*Presenter

# UNIFIED DIAGNOSIS FOR RELIABILITY ENHANCEMENT IN REAL-TIME SYSTEMS

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The intuitive sense of reliability is availability. To most users, if a system is available for its specified purpose, at the moment the user (or other process) wishes to use it, then the system is perceived as being reliable. Hence high availability can be used to enhance the perception of high reliability. When a system fails, then, it is important to restore service, or availability, as quickly as possible.

Diagnosis is an important response to system failure. In critical applications which demand high reliability, such as process control systems or hospital patient-monitoring systems, a swift and accurate failure diagnosis and subsequent prescription for remediation can provide the operating margin necessary for maintaining operational reliability. Diagnosis, usually a retrospective technique, can also be employed predictively to avoid certain classes of failure.

This paper presents an architecture which supports an empirical testbed for a unified theory of diagnostic reasoning. The testbed supports theoretical modeling as well as practical applications; the underlying diagnostic engine can be fine tuned, and the practical performance results can be subsequently observed. The testbed has been migrated to a real-world environment -- the 5,000 station nonhomogeneous campus computing network at Carnegie Mellon University -- and used in real-time detection and diagnosis of network failures. Examples and explanations of problems discovered and diagnosed by the system will be presented.

# ON SOME DOMINANCE RELATIONS AMONG LIFE DISTRIBUTIONS

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Partial (and pre-) orderings among life distributions (particularly ordering against the exponential distributions) and their implications in terms of ageing properties have been studied by several authors in recent years. Properties of stochastic dominance (including pth order stochastic dominance) and likelihood ratio dominance have been used in the study of many inference problems. In the present paper, the authors define failure rate dominance, average failure rate dominance and mean residual life dominance.

Inter-relations among these different types of dominance have been examined - proving relevant theorems in some cases and citing counter-examples in others. Conditions under which one type of dominance implies some other type of dominance have been investigated in a few particular cases. Implications of some types of dominance in terms of relations between distributions of life and of residual life have also been examined.

# Using Median Run Lengths in the Assessment of Cumulative Score Type Process Control Schemes

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Process control schemes are usually assessed in terms of their Average Run Length (ARL) function, which is the expected time time taken to take corrective action at a given quality level. The ARL is usually required to be suitably large at some prescribed acceptable quality level, and yet be as small as possible at some other prescribed unacceptable quality level. The difficulty in computing the ARL function for the highly efficient cumulative sum process control scheme has motivated the study of simpler schemes based on scoring procedures, whereby samples are assigned integer valued scores and stopping rules are based on cumulative sums of these scores. Examples of these schemes are the CuScore scheme (Munford), the modified CuScore scheme (Ncube and Woodall), and the gauged CuScore scheme (Chung and Reynolds).

Run length random variables can usually be regarded as first passage times in some associated stochastic process, and as such tend to be heavy tailed and highly skewed. In this case the average run length is an inflated measure of central tendency, and higher moments provide no useful measure of dispersion.

In this paper we illustrate how the median run length (MRL) can be used to assess the CuScore process control scheme, for which the exact run length distribution is known. Comparison of the MRL with the ARL for schemes designed on the basis of their ARL functions reveal that the MRL is considerably smaller than the ARL, particularly when the process is in control. Consequently the ARL may often provide a distorted measure of a process control scheme's performance.

## SOME RECENT RESULTS ON INFORMATION BASED MINIMAL REPAIR OF A SYSTEM OF COMPONENTS

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In the first part of this talk we question the fruitfulness of the F-minimal repair concept of Arjas and Norros (1987). For instance it is indicated that for a system of components this does not incorporate a minimal repair based on information on the component level. For the case of independent components, some results are also presented comparing "black box" minimal repair of a system with the wanted minimal repair based on information on the component level. In the second part we consider the reduction in remaining system lifetime due to the failure of a specific module. This reduction also equals the increase in remaining system lifetime due to a minimal repair of the module at its time of failure. The expected value of this reduction/increase is proportional to the so called Natvig measure of the importance of the module. Min (1987) considers this measure and treats without reflection this minimal repair of the module as a "black box" minimal repair. Here we argue, as implicit in our earlier papers on this subject, that this minimal repair often more reasonably should be based on information on the module's components. This leads to results different to the ones derived by Min (1987).

# BAYES AND EMPIRICAL BAYES ESTIMATORS OF MEAN RESIDUAL LIFE AT AGE t.

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Given that a unit is of age t (> 0), the residual life at time t is random. Let F be a life distribution with a finite first moment. The mean residual life is defined as $m(t) = \int_t^\infty \bar{F}(x)dx/\bar{F}(t)$, where $\bar{F} = 1-F$. One natural estimator of m(t) is obtained by replacing F by the empirical distribution based on a complete data $X_1, \ldots, X_n$.

In this paper we first derive a Bayes estimator of mean residual life at age t and develop an empirical Bayes estimator using Dirichlet process prior under squared error loss. We assume that we are at the math stage of the sampling experiment and information is available not only for the current stage, but also for the previous (m-1) stages. We also assume that at each stage there are at least one observations exceeding t.

The proposed empirical Bayes estimators are found to be asymptotically optimal in the sense of Robbins' definition. For small sample study, Monte Carlo simulations are undertaken to compare the Bayes risks of the proposed empirical Bayes estimators with those of the estimators based on the empirical distribution. It is shown that the empirical Bayes estimators perform better under some situations.

# PEAKEDNESS IN MULTIVARIATE DISTRIBUTIONS

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Peakedness provides one of the principal descriptive indices of a distribution. A definition for the univariate case was developed by Birnbaum (1948) and generalized to the multivariate case by Sherman (1955). Of course, other multivariate definitions can be developed. In this paper we study and extend some closure properties of peakedness. In particular, two multivariate generalizations are given of a majorization inequality of Proschan (1965). The results are shown to apply to the family of elliptically contoured distributions, and to have implications in estimation and for tests of hypotheses.

# A MODEL FOR CRITICAL CRACK SIZE ESTIMATION IN FATIGUE FAILURE OF GUN BARRELS

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With repeated firing, fatigue cracks are produced in a gun barrel, and the barrel is no longer useful when a crack reaches a critical size. The initial crack size and the critical crack size, as well as the number of firings producing the critical crack size, may be considered as random variables. Assuming a proportional damage model for crack growth, a method for estimating the critical crack size distribution is presented. From these results, an estimate of the barrel life, or the residual barrel life once a crack of a given size is measured, can be obtained.

# QUALITY CONTROL AND PRODUCTIVITY ACTIVITIES IN KOREA AND THEIR PRACTICES IN MANUFACTURING COMPANIES

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This article deals with statistics-related activities for total quality control (TQC) and productivity in manufacturing companies in Korea. First of all, the history and current status of TQC in Korea is briefly introduced. Some important characteristics of Korean TQC are presented. Secondly, the most often used statistical methods for productivity, reliability and quality control, and the way of implementation of these methods in Korean manufacturing companies are reviewed. Thirdly, a typical system for statistical process control (SPC) activity is introduced. A real practice of SPC is provided with real examples which the author consulted with in a semiconductor company in Korea. Finally, future desirable directions to improve the productivity, reliability and quality control are suggested.

# IMPROVED ESTIMATION AND OPTIMAL TESTING FOR THE PARAMETER, $\theta$, OF AN EXPONENTIAL DISTRIBUTION IN THE TYPE I CENSORING CASE

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Noting the difficulties with the MLE, alternative estimators e.g. Bayes estimator, emperical Bayes estimator and a class of admissible estimators for $\theta$ are derived. Inadmissibility of the MLE is also established for some cases. Our underlying population is identified as a member of the curved exponential family (CEF) and hence the application of the general approach of obtaining the best equivariant estimator in a CEF to our population is discussed. Based on an encouraging value of the statistical curvature for our population, the LMP test for $\theta$ is proposed. It is shown to have superior power performance compared to all previously proposed tests for $\theta$.

# OPTIMAL TEST FOR THE INTRACLASS CORRELATION COEFFICIENT IN SYMMETRIC MULTIVARIATE NORMAL MIXTURES WITH APPLICATIONS TO RELIABILITY

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The intraclass correlation coefficient, $\rho$ , and the symmetric multivariate normal mixtures have found wide applications in reliability. We obtain LMP similar tests for $\rho$, cut-off points for which are already available. We establish the asymptotic normality of the test statistics under both the null and alternative hypotheses and the consistency of the tests. We also demonstrate the monotonicity of the power functions and hence the global unbiasedness of the tests.

# GENERATION OF DISTRIBUTIONS OF DEPENDENT LIFETIMES: A REVIEW

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Let F be a distribution function of the vector of lifetimes $(T_1, T_2, \ldots, T_n)$. Several methods of generating a random vector $(T_1, T_2, \ldots, T_n)$ which has the distribution function F will be described. The generating methods have various practical and theoretical uses. Among the practical applications are the numerical generation of copies of $(T_1, T_2, \ldots, T_n)$ for simulation purposes. Among the theoretical applications are the use of the generation methods in the establishment of stochastic comparison results involving two possible distributions $F_1$ and $F_2$ of $(T_1, T_2, \ldots, T_n)$.

# BAYES OPTIMAL BURN-IN TIME

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A firm belief of reliability analysts is that weak items are present in a lot of components and these must be eliminated. To this end the lot is put on test to burn them. To the best of authors' knowledge, the duration of the burn-in period is a matter of engineering judgement.

In this paper, the burn-in procedure is obtained as the solution of a suitable decision problem. Two cases are examined:

i) Component failure-times are independent in the subjective sense.

ii. Component failure-times are exchangeable. The two decision problems differ in that problem ii) is a sequential decision problem. For case i) solutions are available in terms of equations on the failure rate value at the optimal burn-in time.

In case ii) these equations generalize into equations in terms of conditional failure rate value.

Some interesting suggestions are also obtained for the characterization of components which have "subjectively" DFR Life distributions (see [1]) and which need a burn-in period.

[1] R. E. Barlow, A Bayesian Explanation of an Apparent Failure-rate Paradox, ORC 83-13, October 1983.

# DESIGN OF ACCELERATED TESTS--
# MATERIALS ENGINEERING CONSIDERATIONS

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The primary interest in the design of accelerated tests is to considerably decrease the test duration. Sample size is second in line for attention in terms of trade-offs between costs and statistical significance. This paper focuses attention on the broad aspects of material behavior that must be incorporated into the design of accelerated tests. The failure mechanisms of interest such as fracture, fatigue, corrosion, or wear and, in greater detail, the failure-governing properties unique to the materials under consideration must be thoroughly understood. The validity of accelerated tests is the key issue in most cases. This paper reviews the validity requirements from a Materials Engineering point of view. Discussions include, but are not limited to, thermodynamics and kinetics of mechanisms, various test parameters such as temperature, strain rate, and concentration of chemicals, and statistical considerations of process variability. This paper will illustrate these principles with several examples of prior work that has been done in electrical insulation materials.

# SOME EXACT ALGEBRAIC EXPRESSIONS FOR THE RELIABILITY OF MULTIPATH SWITCHING NETWORKS

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Several of the new submerged cable communication systems employing optical fiber technology have multipath switching designs that do not lend themselves to reliability evaluation using conventional methods for series and parallel components. Whitmore, Pullum and Chown (1987) and Pullum, Chown and Whitmore (1988) present efficient and exact numerical procedures for reliability evaluation of such multipath systems based on Markov multipath systems carrying multiple signal streams, i.e., systems with n paths that must carry m ( , n) distinct signals. In a forthcoming book, Chown, Pullum and Whitmore give a detailed account of the methodology, with an emphasis on practical issues and cases, as well as a general discussion of reliability issues in communications technology.

Exact algebraic expressions for reliabilities of general multipath switching systems are mathematically intractable, except possibly by means of computerized symbol manipulation. In the course of research on the numerical methodology, however, algebraic expressions have been developed for the reliabilities of several of the simplest multipath systems. These expressions are useful in their own right but also are useful for the theoretical insight that they provide. In spite of the difficulty posed by their initial derivation, once discovered, the expressions have a surprising simplicity. The method of derivation of these expressions is also of theoretical and practical interest because it may provide the basis for further development of the reliability algebra. The derivation is based on an eigensystem representation of the probability matrices involved in the reliability evaluation. The paper describes the method of derivation and presents some of the resulting expressions.

# ON A GENERAL MEASURE OF COMPONENT IMPORTANCE

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In this paper a general measure of the importance of system components is studied. The measure is obtained by ordering the reduction of the expected yield due to the variation of the lifetime distribution of the components. Some results useful in comparison of the importance of components are obtained and some bounds are also derived. Some interesting properties of the importance of modules are also studied.

Keywords: importance measure, coherent system, bounds on the importance, importance of modules, parallel redundancy.

# ON APPROXIMATED TOLERANCE LIMITS AND LOWER CONFIDENCE LIMITS OF SURVIVOR ON WEIBULL MODEL

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The two-parameter Weibull model is an important one in which is widely employed in various science and engineering areas such as life tests, industrial reliability, biology and medical studies, etc. In its inference, an interesting problem is to estimate lower confidence limits (LCL) of reliability and tolerance limits. Although much ink has been split over it in the literatures, there is still room for more work on it. In this paper we deal mainly with an available technique to calculate the approximated LCL of them. It was used only the tables of percentiles of Weibull parameters without expensive simulations technique to R(t). The estimated formulas is simple and they can be conveniently programmed, and be used by statisticians and engineers.

For $R(t)=\exp(-\frac{t}{\alpha})^{\beta}$, if $\hat{\alpha}$, $\hat{\beta}$ and $\hat{\nu}(t)$ are MLE's of $\alpha$, $\beta$ and $\nu(t)=(\frac{t}{\alpha})^{\beta}$ respectively, then $\nu(t)^{\hat{\beta}/\beta}/\hat{\nu}(t)$ is a pivotal quantily, and its percentiles can be calculated from that of $\hat{\beta}\log(\hat{\alpha}/\alpha)$. Denote $l_{\gamma}$ and $h_{\gamma}$ as the upper percentiles of $u=\hat{\beta}/\beta$ and $\nu(t)^{u}/\hat{\nu}(t)$, respectively, then

$$R_L(t)=\begin{cases} e^{-(h_{\gamma/2}*\hat{\nu}(t))^{1/l_{\gamma/2}}} & \text{if } R(t)>e^{-1} \\ e^{-(h_{\gamma/2}*\hat{\nu}(t))^{1/l_{1-\gamma/2}}} & \text{if } R(t)<e^{-1} \end{cases}$$

It will satisfy $P(R(t)>R_L)>1-\gamma$. The estimation $t^*_{R^*}$ of tolerance limits is

$$t^*_{R^*}=\hat{\alpha}\left(\frac{(-\log R^*)^{l_{\gamma/2}}}{h_{\gamma/2}}\right)^{1/\hat{\beta}} \qquad \text{if } R(t)>e^{-1}$$

though $R_L$ is an underestimation of LCL of survivor, but it will be improve to close to exact limits if we employ percentiles of pooled estimates, which was discussed by W. Park, to calculate that of $\hat{\beta}/\beta$ and $\hat{\beta}\log(\hat{\alpha}/\alpha)$.(see IEEE on R. Vol.R-32,No.1,91-95).

Example: Lieblein and Zelen provided the following sample of size n=23 to illustrate the use of a Weibull model. For the endurance, in millions of revolutions, for deep-groove, The data are below:

23 ball bearings

| | | | | | |
|---|---|---|---|---|---|
| 17.58, | 28.92, | 33.00, | 41.52, | 42.12, | 45.60, |
| 48.48, | 51.84, | 51.96, | 54.12, | 55.56, | 67.80, |
| 68.64, | 68.64, | 68.68, | 84.12, | 93.12, | 98.64, |
| 105.12, | 105.84, | 127.92, | 128.04, | 173.40. | |

we have the point estimations:

$\hat{\alpha}=81.99$; $\hat{\beta}=2.012$; $\hat{R}(40)=.8016$.

The exact tolerance limits and LCL of R(40) which were calculated by Thoman et al's method (see 1969 Technometrics):

$R_L(40)=.694$, $t^*_{.1,\gamma}=18.75$, $\gamma=.1$

If we take the table of percentiles of pooled estimate, and m as number of pooled data groups present method will make out LCL of survivor as following:

| m | 1 | 2 | 3 | 4 | 5 | 7 |
|---|---|---|---|---|---|---|
| R (40) | .6372 | .6665 | .6779 | .6860 | .6904 | .6978 |
| $1-\gamma'$ | .9896 | .9410 | .9237 | .9114 | .9047 | .8935 |

here $\gamma'$ is actual confidence degree corrsponding to $R_L(40)$, so it is suitable to take m=3--5.

For confidence degree $\gamma=.1$, the tolerance limits under reliability requirement 90% is $t^*_{.1,\gamma}=19.84$ (m=5).

A computer program used desk computer have been made that cover point and confidence estimations of parameters, tolerance limits and LCL of survivor with present method, it was proved that we are able to save a lot time and space of computer than existing other methods.

# "Proportional Mean Remaining Life Model"
## A Preliminary Report

by

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ABSTRACT

The regression models proposed for lifetime data, generally involved the assumption of the "proportional hazard rate function" In this paper, parallel to Cox(1972)'s Proportional Hazard (PH) model we propose a new model involving the assumption of "proportional mean remaining life function". The concept of the Proportional Mean Remaining Life (PMRL) model is based on the intuitive concept of mean. In this report after developing the model we establish its relationship with the Cox's PH model. Some possible estimation procedures, and extensions of the model for multivariate lifetime data are briefly discussed.

## ISLAMIC MEAN

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In a preceding study the islamic mean of some values can be calculated by computing the mean of every two neighboured values after being ordered and then repeating this step until obtaining the final mean which is the islamic mean of these values. for example, the islamic mean of $x_{(1)}$ and $x_{(2)}$ is

$$\bar{x}_1^{(1)} = \frac{x_{(1)} + x_{(2)}}{2} \qquad \text{where } x_{(1)} < x_{(2)}.$$

and the islamic mean of $x_{(1)}$ , $x_{(2)}$ and $x_{(3)}$ is $\bar{x}_1^{(2)}$ which can be obtained as follows:

| Values | Means (Ist step) | Final Mean |
|---|---|---|
| $x_{(1)}$ | | |
| | $\bar{x}_1^{(1)}$ | |
| $x_{(2)}$ | | $\bar{x}_1^{(2)}$ |
| | $\bar{x}_2^{(1)}$ | |
| $x_{(3)}$ | | |

Where:

$$x_{(1)} < x_{(2)} < x_{(3)}.$$

$$\bar{x}_1^{(1)} = \frac{x_{(1)} + x_{(2)}}{2} \; ; \quad \bar{x}_2^{(1)} = \frac{x_{(2)} + x_{(3)}}{2}$$

$$\bar{x}_1^{(2)} = \frac{\bar{x}_1^{(1)} + \bar{x}_2^{(1)}}{2} = \frac{x_{(1)} + 2\,x_{(2)} + x_{(3)}}{2^2} ,$$

$$= \frac{\binom{2}{0} x_{(1)} + \binom{2}{1} x_{(2)} + \binom{2}{2} x_{(3)}}{2^2}$$

$$, \binom{n}{i} = \frac{n!}{i!\,(n-i)!}$$

$$; \; n! = n\,(n-1)\,(n-2) \ldots\ldots\ldots \times 3 \times 2 \times 1 .$$

Similarly , the islamic mean of :

$x_{(1)}$ , $x_{(2)}$ , $x_{(3)}$ and $x_{(4)}$, ( $x_{(1)} < x_{(2)} < x_{(3)} < x_{(4)}$ )

can be defined as follows :

| Values | Means (Ist step) | Means (2nd step) | Final Mean |
|---|---|---|---|
| $x_{(1)}$ | | | |
| | $\bar{x}_1^{(1)}$ | | |
| $x_{(2)}$ | | $\bar{x}_1^{(2)}$ | |
| | $\bar{x}_2^{(1)}$ | | $\bar{x}_1^{(3)}$ |
| $x_{(3)}$ | | $\bar{x}_2^{(2)}$ | |
| | $\bar{x}_3^{(1)}$ | | |
| $x_{(4)}$ | | | |

Then :

$$\bar{x}_1^{(3)} = \frac{\bar{x}_1^{(2)} + \bar{x}_2^{(2)}}{2} = \frac{x_{(1)} + 3x_{(2)} + 3x_{(3)} + x_{(4)}}{2^3}$$

$$= \frac{\binom{3}{0} x_{(1)} + \binom{3}{1} x_{(2)} + \binom{3}{2} + \binom{3}{3} x_{(4)}}{2^3}$$

By the same method the islamic mean of $x_{(1)}, x_{(2)}, x_{(3)}, x_{(4)}$ and $x_{(5)}$ $(x_{(1)} < x_{(2)} < x_{(3)} < x_{(4)} < x_{(5)})$ can be shown as :

$$\bar{x}_1^{(4)} = \frac{\binom{4}{0} x_{(1)} + \binom{4}{1} x_{(2)} + \binom{4}{2} x_{(3)} + \binom{4}{3} x_{(4)} + \binom{4}{4} x_{(5)}}{2^4}$$

In general , the islamic mean of the values $x_{(1)}, x_{(2)}, x_{(3)}, \ldots\ldots\ldots, x_{(n)}$, $(x_{(1)} < x_{(2)} < x_{(3)} \cdots < x_{(n)})$ is :

$$\bar{x}_1^{(n-1)} = \frac{\binom{n-1}{0} x_{(1)} + \binom{n-1}{1} x_{(2)} + \binom{n-1}{2} x_{(3)} + \cdots + \binom{n-1}{n-1} x_{(n)}}{2^{n-1}}$$

$$= \frac{\sum_{i=0}^{n-1} \binom{n-1}{i} x_{(i+1)}}{2^{n-1}}$$

Lest us denote to the islamic mean by :

$$\bar{x}_a = \frac{\sum_{i=o}^{n-1} \binom{n-1}{i} x_{(i+1)}}{2^{n-1}}$$

Hence, the islamic mean $\bar{x}_a$ of the values 5, 20, 30 , 40, 50 , 60 , 70 , 80 , 90, 200 is equal to 55.2 while the usual mean of these values $\bar{x}$ equals 64.5.

If we considered the value 500 instead of the value 200 in this example then :

$$\bar{x}_a = 55.8 \quad ; \quad \bar{x} = 94.5$$

So ,it is clear that the very large and also very small values has no action on the islamic mean $\bar{x}_a$ , while it has an acute action on the usual mean $\bar{x}$. Hence, the islamic mean represents the true mean.

EXPERIENCES WITH AN INFORMATION-THEORETIC
TESTABILITY ANALYSIS TOOL

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ABSTRACT

Testability is an engineering design characteristic that is related to the confidence and efficiency with which system faults can be identified. Research was performed to develop a method that employs dependency modeling to assess the design testability of a system and provide information useful to improve the design. Additionally, an information-theoretic approach is used to develop efficient, fault-diagnostic strategies.

The information-theoretic approach used is adaptive and inferential. First, a graph-closure approach is used to obtain all higher system dependencies, based on the topology of test points and components. We then seek to develop a sequence of tests so that the size of the set of candidate failed components is reduced to one in an optimal manner (e.g., minimum number of tests or minimum test costs). This is done through a stage-by-stage decision process similar to a dynamic programming algorithm. The next test in the test sequence is one that maximizes the expected weighted information where the weight is based on the optimization criteria (e.g., time or cost). The information measure for a given test changes as testing progresses because of the changing structure of the knowledge base.

This paper will review the approach used in STAMP (System Testability and Maintenance Program) to perform these analyses, as well as summarize a number of applications to military and commercial systems.

# Testability Research: Where We Are, What We Need

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BACKGROUND: It was approximately ten years ago that the need for better testability became suddenly evident. We were faced with providing guidance in an area that, to that time, had been virtually ignored. The content of this summary will outline how the Rome Air Development Center (RADC) initially attached this problem; the immediate products which were provided; the technology products provided; and the long-term solutions needed and planned.

INTRODUCTION: The RADC is charged with the development of techniques for predicting, demonstrating and improving reliability and maintainability in electronic systems. In 1977, the Center was in the midst of a program to modernize the maintainability engineering discipline and discovered the greatest needs in maintainability engineering were techniques for the specification, design, and measurement of fault detection and isolation parameters. These techniques can be considered a subset of maintainability techniques, but are important enough in their own right to deserve the specific title of Testability Engineering Techniques. Thus, the RADC Testability Program was born.

Figure 1 shows the general plan of attach and the interfaces associated with the Program. While effort continues to develop the fundamentals and tools necessary to establish and maintain a testability engineering discipline, products are developed through distillation of existing information (from various sources) coupled with initial findings from on-going research efforts. Concurrently, as such products are being produced, the results are continually evolved to develop final versions of these and other testability engineering tools and documentation. Throughout this development process, close contacts and coordination with other organizations and groups involved in testability are maintained through memberships on committees, working groups and personal contacts.

The testability products developed fall into two general categories:

- ° Technical Management Tools
- ° Design/Evaluation Tools
  - ° Prediction
  - ° Analysis/Design
  - ° Demonstration

  — Design Guides, Specification Guides, Testability Analysis/Evaluation, Computer-Aided Design Tools/Standards & Handbooks, Smart BIT Procedures

Addressing the area of Design, Evaluation Tools Subcategory by Subcategory:

In the area of testability prediction we have rudimentary tools available to:

1) Predict testability qualitatively (using check lists) to determine the degree of testability inherent to a printed circuit board (PCB) design, however:

   - The check lists are not up-to-date and require revision to take new technology into account and they are qualitative in nature.

   - No means are available to equate PCB testability to the testability of a system comprised of PCB's.

2) Predict system level fault isolation and false alarm characteristics (based on regression results), however:

   - Results can be considered only a first cut at the problem

   - Uncertainty exists that the rudimentary Figures of Merit that are evaluated are the right ones.

In the area of design analysis we have tools such as LAZAR, STAMP, LOGMod to assess fraction of faults detectable, to evaluate overall testability design strategy and they serve their purpose very well.

There are, however, areas of design analyses which have not sufficiently matured:

- Accounting for the impacts of testability, failure rates and failure modes of diagnostic and recovery systems associated with fault tolerance.

- Failure modes and effects analyses and their use and integration with test program set generation.

- Providing visibility into the effect of R,M,T decisions on logistics, support and ATE needs.

- Development of testability allocation procedures.

- Total testability optimization procedures - bottom up and top down.

- Testability growth.

In the area of testability demonstration we have methods based on sampling procedures which may be used for verification purposes. These, however, will not be adequate for tomorrows systems designs. Problems exist with respect to:

- Failure simulation/emulation strategies and techniques
  - Device, Printed Board, Module
- Failure mode identification and handling
- Complexities introduced by systems which comprise large quantities of VLSI design

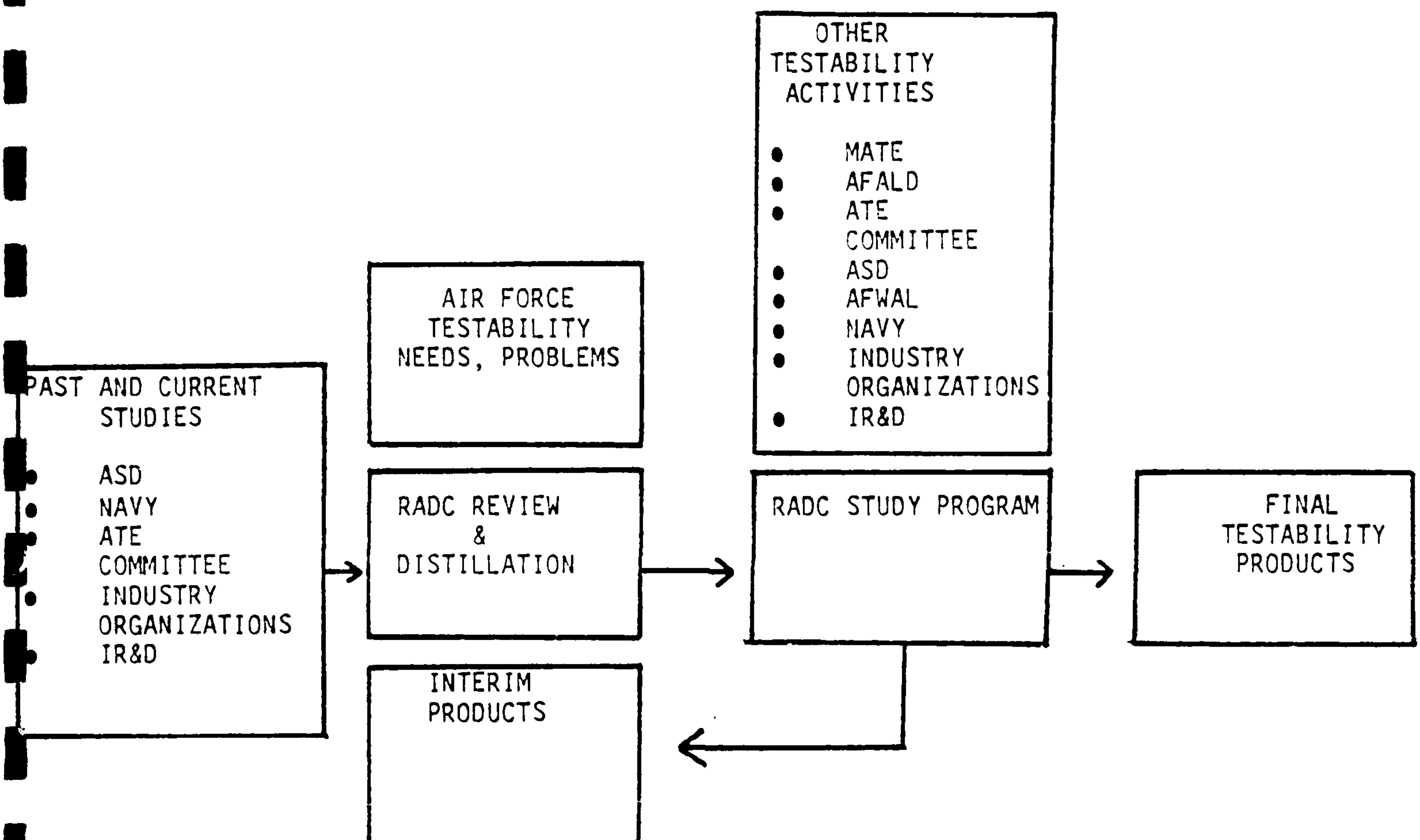


FIGURE 1 - General Plan of Attack