Accelerated Testing

Statistical Models, Test Plans, and Data Analyses

WAYNE NELSON
Consultant, Schenectady, NY

WILEY-INTERSCIENCE

A JOHN WILEY & SONS, INC., PUBLICATION

This Page Intentionally Left Blank

Accelerated Testing

This Page Intentionally Left Blank

Accelerated Testing

Statistical Models, Test Plans, and Data Analyses

WAYNE NELSON
Consultant, Schenectady, NY

WILEY-INTERSCIENCE

A JOHN WILEY & SONS, INC., PUBLICATION

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
Published simultaneously in Canada.

Library of Congress Cataloging-in-Publication is available.

ISBN 0-471-69736-2

Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1

This book is gratefully dedicated to the many clients whose fruitful collaboration and challenging applications stimulated my interest and developments in accelerated testing, and to the many colleagues who kindly provided me with examples, references, suggestions, and encouragement.

This Page Intentionally Left Blank

Contents

Preface to the Paperback Edition

First published in 1990, this book remains the most comprehensive presentation of statistical models and methods for accelerated test data. It is gratifying that it has been widely used and praised by practitioners and researchers in statistics and engineering. This paperback edition is available at a bargain price thanks to the fine work of Mr. Steve Quigley, Ms. Susanne Steitz, and the Wiley staff.

For subsequent advances in accelerated testing, the reader may wish to consult:

- Meeker, W.Q. and Escobar, L.A. (1998), *Statistical Methods for Reliability Data,* Wiley, New York, www.wiley.com. In particular, their degradation models and corresponding statistical methods and Chapter 11 of this book overlap little and together comprise a basic introduction to accelerated degradation.
- Nelson, Wayne (2004), "A Bibliography of Accelerated Test Plans," over 100 references, available from the author, WNconsult@aol.com.

Since 1990, commercial software for analysis of accelerated test data has continued to advance. To reflect these advances, Table 1.1 of Chapter 5 and corresponding text have been updated. Note that confidence limits using a normal approximation to the sampling distribution of a maximum likelihood estimator and its asymptotic standard error are not current best practice. Instead, one should use software that calculates confidence limits using the likelihood ratio, as described in Section 5.8 of Chapter 5, as these intervals are now known to be a better approximation in virtually all applications.

WAYNE B. NELSON
Consulting and Training
WNconsult@aol.com

Schenectady, New York
June 2004

Preface

Product reliability contributes much to quality and competitiveness. Many manufacturers yearly spend millions of dollars on product reliability. Much management and engineering effort goes into evaluating reliability, assessing new designs and design and manufacturing changes, identifying causes of failure, and comparing designs, vendors, materials, manufacturing methods, and the like. Major decisions are based on life test data, often from a few units. Moreover, many products last so long that life testing at design conditions is impractical. Many products can be life tested at high stress conditions to yield failures quickly. Analyses of data from such an accelerated test yield needed information on product life at design conditions (low stress). Such testing saves much time and money. This book presents practical, modern statistical methods for accelerated testing. Up-to-date, it provides accelerated test models, data analyses, and test plans. In recent years, much useful methodology has been developed, and this book makes it available to practitioners. This book will contribute to more efficient accelerated testing and to valid and more accurate information.

This book is written for practicing engineers, statisticians, and others who use accelerated testing in design, development, testing, manufacturing, quality control, and procurement. It will aid workers in other fields concerned with regression models for survival, for example, in medicine, biology, and actuarial science. Also, this book is a useful supplement for statistics and engineering courses, as it presents many stimulating real examples, emphasizes practical data analysis (employing graphical methods and computer programs), and shows how to use versatile maximum likelihood methods for censored data.

This book is organized to serve practitioners. The simplest and most useful material appears first. The book starts with basic models and graphical data analyses, and it progresses through advanced maximum likelihood methods. Available computer programs are used. Each topic is self-contained for easy reference, although this results in some repetition. Thus this book serves as a reference or textbook. Derivations are generally omitted unless they provide insight. Such derivations appear in advanced sections for those seeking deeper understanding or developing new statistical models, data analyses, and computer programs. Ample references to the literature will aid those seeking mathematical proofs.

Readers of this book need a previous statistics course for Chapter 4 and beyond. Chapters 1, 2, and 3 do not require a previous course. For advanced material, readers need facility in calculus through partial differentiation and the basics of matrix algebra.

There is a vast and growing literature on statistical methods for accelerated testing. However, this book has been limited to the most basic and widely used methods, as I did not wish to complete it posthumously. Topics not given in detail in this book are referenced. While I included my previously unpublished methods developed for clients, there are gaps in methodology, which are noted to encourage others to fill them. For advanced innovations and complex applications beyond the basics in this book, one can consult the literature and experts.

Chapter 1 introduces accelerated testing – basic ideas, terminology, and practical engineering considerations. Chapter 2 presents models for accelerated testing – basic life distributions and life-stress relationships for products. Chapter 3 explains simple graphical analyses to estimate product life. Requiring little statistical background, these data plots are easy and very informative. Chapter 4 covers least squares estimates and confidence limits for product life from complete data (all test specimens run to failure). Chapter 5 shows how to use maximum likelihood estimates and confidence limits for product life from censored data (some specimens not run to failure). Chapter 6 shows how to choose a test plan, that is, the stress levels and corresponding numbers of specimens. Chapter 7 treats data with competing failure modes – models, graphical analyses, and maximum likelihood analyses. Chapters 8 and 9 present comparisons (hypothesis tests) with least squares and maximum likelihood methods. Chapter 10 treats step-stress testing and cumulative damage models. Chapter 11 introduces aging-degradation testing and models.

The real data in all examples come mostly from my consulting for General Electric and other companies. Many data sets are not textbook examples; they are messy – not fully understood and full of pimples and warts. Proprietary data are protected by generically naming the product and multiplying the data by a factor. I am grateful to the many clients and colleagues who kindly provided their data for examples.

I am most grateful to people who contributed to this book. Dr. Gerald J. Hahn, above all others, encouraged my work on accelerated testing and is a valued, knowledgeable, and stimulating co-worker. Moreover, he helped me obtain support for this book from the General Electric Co. I am deeply indebted for support from my management at General Electric Co. Corporate Research and Development – Dr. Roland Schmitt (now President of Rensselaer Polytechnic Inst.), Dr. Walter Robb, Dr. Mike Jefferies, Dr. Art

Chen, Dr. Jim Comly, and Dr. Gerry Hahn. Professor Josef Schmee, when Director of the Graduate Management Institute of Union College, kindly provided an office where I worked on this book. He also gave me an opportunity to teach a course from the book manuscript and thereby improve the book.

Friends generously read the manuscript and offered their suggestions. I am particularly grateful for major contributions from Prof. Bill Meeker, Dr. Necip Doganaksoy, Dr. Ralph A. Evans, Mr. D. Stewart Peck, Dr. Agnes Zaludova, Mr. Don Erdman, Mr. John McCool, Mr. Walter Young, Mr. Dev Raheja, and Prof. Tom Boardman. My interest in and contributions to accelerated testing owe much to the stimulating applications of and many collaborations with Mr. Del Crawford, Mr. Don Erdman, Mr. Joe Kuzawinski, and Dr. Niko Gjaja, among others. Many experts on engineering topics and statistics provided key references and other contributions.

The illustrations are the superb work of Mr. James Wyanski (Scotia, NY) and Mr. Dave Miller. The manuscript benefited much from the skillful word processing of Mr. John Stuart (Desktop Works, Schenectady, NY) and Ms. Rita Wojnar.

Authors who wish to use examples, data, and other material from this book in journal publications may do so to the extent permitted by copyright law with suitable acknowledgement of the source. *Any* other use of such material requires the written permission of the publisher: Permissions Dept., John Wiley & Sons, 605 Third Ave., New York, NY 10158-0012.

I would welcome correspondence on suggestions on key references and improvements for the book.

WAYNE NELSON

Schenectady, New York, August 1989

About the Author

Dr. Wayne Nelson is a leading expert on statistical analysis of reliability and accelerated test data. He currently privately consults with companies on diverse engineering and scientific applications of statistics and develops new statistical methods and computer programs. He presents courses and seminars for companies, universities, and professional societies. He also works as an expert witness. An employee of General Electric Corp. Research & Development for 25 years, he consulted across GE on applications.

For his contributions to reliability, accelerated testing, and reliability education, he was elected a Fellow of the American Statistical Association (1973), the American Society for Quality (1983), and the Inst. for Electrical and Electronics Engineers (1988). GE Corp. R&D presented him the 1981 Dushman Award for outstanding developments and applications of statistical methods for product reliability and accelerated test data. The American Society for Quality awarded him the 2003 Shewhart Medal for outstanding technical leadership and innovative developments.

He has authored over 120 literature publications on statistical methods, mostly for engineering applications. For publications, he was awarded the 1969 Brumbaugh Award, the 1970 Youden Prize, and the 1972 Wilcoxon Prize, all of the American Society for Quality. The ASA has awarded him eight Outstanding Presentation Awards for papers at the national Joint Statistical Meetings.

In 1990, he was awarded the first NIST/ASA/NSF Senior Research Fellowship at the National Inst. of Standards and Technology to collaborate on modeling electromigration failure of microelectronics. On a Fulbright Award in 2001, he did research and lecturing on reliability data analysis in Argentina.

Dr. Nelson authored the book *Applied Life Data Analysis*, published by Wiley in 1982; it was translated into Japanese in 1988 by the Japanese Union of Scientists and Engineers. In 1990, Wiley published his landmark book *Accelerated Testing: Statistical Models, Test Plans, and Data Analyses*. In 2003, ASA-SIAM published his book *Recurrent Events Data Analysis for Product Repairs, Disease Episodes, and Other Applications*. He has authored various book chapters and tutorial booklets, and he contributed to standards of engineering societies.

Further details of his work appear at www.members.aol.com/WNconsult. He can be reached at WNconsult@aol.com, 739 Huntingdon Dr., Schenectady, NY 12309.

1

Introduction and Background

HOW TO USE THIS BOOK

This section describes this book's contents, organization, and how to use this book. This book presents statistical models, test plans, and data analyses for estimating product reliability from accelerated tests.

Chapter overview. This chapter presents an introduction to accelerated testing methods. Section 1 surveys common applications of accelerated testing and sources of information. Section 2 describes types of accelerated test data. Section 3 describes types of acceleration and types of stress loading. Section 4 discusses engineering considerations in planning and running an accelerated test. Section 5 describes common accelerated tests. Section 6 outlines the statistical steps and considerations in data collection and analysis. This chapter is background for the rest of this book. To profit from this chapter, readers need only a general engineering background. Of course, previous acquaintance with accelerated testing helps. Those lacking such acquaintance may benefit from reading Chapters 2 and 3 before Chapter 1.

Book overview. Chapter 1 gives an overview of the book and presents needed background. Chapter 2 describes accelerated life test models, consisting of a life distribution and a life-stress relationship. Chapter 3 presents simple probability and relationship plots for analyzing complete and censored data. Briefly stated, when all specimens have run to failure, the data are **complete**. When some specimens are unfailed at the time of the data analysis, the data are **censored.** The plots yield estimates for model parameters, product life (distribution percentiles, reliabilities, failure rates), and other quantities. Chapter 4 presents least-squares analyses of complete data; these analyses yield such estimates and corresponding confidence limits. Chapter 5 gives maximum likelihood methods for censored data; these methods yield estimates and confidence limits. Chapter 6 presents test plans. Chapter 7 presents models and graphical and maximum likelihood analyses for data with a mix of failure modes. Chapters 8 and 9 present comparisons (hypothesis tests) for complete and censored data. Chapter 10 treats step-stress testing, cumulative damage models, and data analyses. Chapter 11

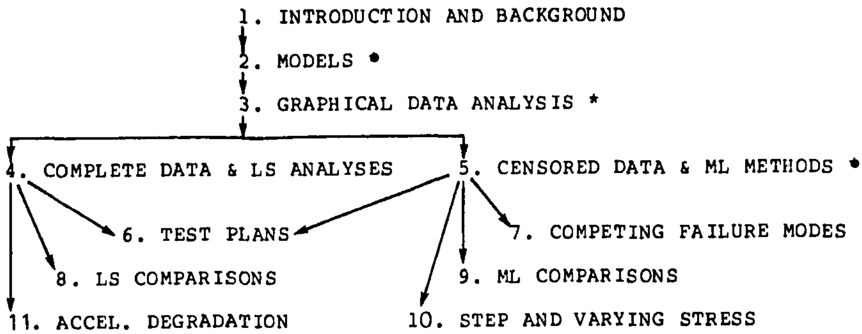

Figure 1.1. Book organization (* basic chapter).

introduces accelerated degradation testing, models, and data analyses. Nelson (1990) briefly covers the most basic applied essentials of these topics.

Organization. Figure 1.1 shows this book's chapters. They are organized by type of data (complete, censored, and competing failure modes) and by statistical method (graphical, least squares, and maximum likelihood). The chapters are in order of difficulty. The arrows in Figure 1.1 show which chapters are background for later chapters. Also, each chapter introduction refers to needed background and describes the level of the chapter. The first three chapters are simple and basic reading for all. Chapter 2 on models is background for all else. Chapter 3 on graphical data analysis is most useful. The more advanced Chapters 4 through 6 are in order of difficulty. Chapter 6 (test plans) follows Chapter 5 (maximum likelihood analysis of censored data) in the logical development of the subject, but it can profitably be read after Chapter 2. Many readers who plan to use a particular model can selectively read just the material on data analysis with that model, skipping other material in data analysis chapters. Maximum likelihood methods (Chapter 5) are essential. They are versatile and apply to most models and types of data. Also, they have good statistical properties. If time is limited, read key Chapters 2, 3, and 5 for basics to solve most problems. Chapters 7 through 11 treat special topics and may be read in any order.

Numbering. The book numbers sections, equations, figures, and tables as follows. Within each chapter, the sections are numbered simply 1, 2, 3, etc.; subsections are numbered 4.1, 4.2, etc. Equation numbers give the (sub)section number and equation number; for example, (2.3) is the third numbered equation in Section 2. Figure and table numbers include the section number; Figure 2.3 is the third figure in Section 2. Such numbers do not include the chapter number. Unless another chapter is stated, any referenced equation, figure, or table is in the same chapter.

Problems. There are two types of problems at the end of a chapter. One type involves an analysis of data with the methods in that chapter; the other involves extending the results of the chapter to other problems. An asterisk (*) marks more laborious or difficult problems.

Citations. The book cites references by means of the Harvard system. A citation includes the author's name, year of publication, and his publications in that year. For example, "Nelson (1972b)" refers to Nelson's second referenced publication in 1972. All references are listed near the end of the book. Coauthored references follow all singly authored references by the first named coauthor. For example, Nelson and Hahn (1972) follows all references authored solely by Nelson.

Tables. Basic statistical tables are in Appendix A near the end of the book. Other tables must be obtained from the literature and are referenced.

Index. The index of the book is detailed. It will be an aid to those who wish to use the book as a reference for selected methods. Also, to aid users, some sections are self-contained, thus repeating some material.

Derivations. The book omits most derivations. Reasons for this are: (1) readers can properly apply most methods, knowing assumptions but not knowing derivations, (2) many derivations are easy for a reader or instructor to supply, and (3) more time can be spent on methods useful in practice. Many derivations appear in Mann, Schafer, and Singpurwalla (1974), Bain (1978), and particularly Lawless (1982) and Viertl (1988).

Terminology. This book uses common *statistical* terminology, whose meaning often differs from engineering and everyday meanings. Terms such as "normal," "independent," "dependent," and "confidence" are examples. Moreover, there are many instances of a single concept with several names. For example, independent, explanatory, and predictor variables are equivalent terms. Thus those not familiar with statistical terminology need to pay special attention to words in italics, boldface, and quotation marks. *Caveat lector.*

1. SURVEY OF METHODOLOGY AND APPLICATIONS

Overview. This section briefly surveys statistical and engineering methodology and the vast literature for accelerated testing. Also, this section briefly describes applications to indicate the wide use of accelerated testing. No doubt important references are lacking.

1.1. Methodology

Accelerated testing. Briefly stated, accelerated testing consists of a variety of test methods for shortening the life of products or hastening the degradation of their performance. The aim of such testing is to quickly obtain data which, properly modeled and analyzed, yield desired information on product life or performance under normal use. Such testing saves much time and money. The aim of this book is to provide practitioners with basic, practical statistical models, test plans, and data analyses for accelerated tests.

Statistical methodology. In recent years statisticians have developed much statistical methodology for accelerated testing applications. Indeed they solved most of the statistical problems listed by Yurkowski, Schafer, and Finkelstein (1967). For example, statisticians solved the big bugaboo of accelerated testing, namely, proper analysis of data with a mix of failure modes (Chapter 7). Recent books with chapters on statistical methodology for accelerated tests include Lawless (1982), Mann, Schafer, and Singpurwalla (1974), Jensen and Petersen (1982), Lipson and Sheth (1973), Tobias and Trindade (1986), Kalbfleisch and Prentice (1980), Cox and Oakes (1984), and Little and Jebe (1975). Viertl (1988) surveys statistical theory for accelerated testing. Nelson (1990) briefly presents the most basic essentials of applied statistical methods and models for accelerated testing. The present book provides applied statistical models and methods for accelerated testing. Statistical methodology is improving rapidly. Thus books over 5 years old lack important developments, and books over 10 years old are seriously out of date. This book is no exception.

Surveys of the statistical literature on accelerated testing include Viertl (1988), Nelson (1974), Ahmad and Sheikh (1983), Meeker's (1980) bibliography, Singpurwalla (1975), and Yurkowski, Schafer, and Finkelstein (1967). Peck and Trapp (1978) present simple graphical methods for semiconductor data. Peck and Zierdt (1974) survey semiconductor applications.

Journals. Journals with articles on accelerated testing may be found in the **References** at the back of this book. Journals with statistical methodology for accelerated testing include:

- *American Soc. for Quality Control Annual Quality Congress Transactions*
- *Annals of Reliability and Maintainability*
- *Applied Statistics*
- *IEEE Transactions on Reliability*
- *J. of Quality Technology*
- *J. of the American Statistical Assoc.*
- *J. of the Operations Research Soc. of America*
- *J. of Statistical Planning and Inference*
- *Naval Research Logistics Quarterly*
- *Proceedings of the Annual Reliability and Maintainability Symposium*
- *The Q R Journal – Theory and Practice, Methods and Management*
- *Quality and Reliability Engineering International*
- *Reliability Review* of the American Soc. for Quality Control
- *Technometrics*

Engineering methodology. Engineers have long used accelerated testing for diverse products. Governments and professional societies publish lists of standards and handbooks for testing methodology and data analysis. The engineering literature contains many papers on accelerated testing theory and applications. The bibliographies on accelerated testing of Meeker (1980) and Yurkowski and others (1967) with 524 older references show the scope of this literature. Also, various engineering books devote some space to this topic. A sample of references appears in the applications below.

Data banks/handbooks. This book covers **statistical methods** for collection and analysis of accelerated test data. It lacks data banks and handbooks for specific materials and products. The following brief list of sources may serve as a starting point in a search for such data. The US Department of Defense (DoD) (1981,1985) maintains Information Analysis Centers (IACs):

- Concrete Technology IAC, (601) 634-3269.
- DoD Nuclear IAC, (805) 963-6400.
- Infrared IAC, (313) 994-1200 ext. 214.
- Metals and Ceramics IC, (614) 424-5000. See the publication list of Metals and Ceramics IAC (1984)
- Metal Matrix Composites IAC, (805) 963-6452.
- Plastics Technical Evaluation Center, (201) 724-3189.
- Pavement and Soils Trafficability IAC, (601) 634-2209.
- Reliability AC, (315) 330-4151.
- Thermophysical and Electronic Properties IAC, (317) 494-6300.

Other sources of information include:

- Standards in many fields, American National Standards Inst. Catalog, 1430 Broadway, New York, NY 10018.
- National Nuclear Data Center, (516) 282-2103.
- Computerized references and data bases, STN International (Chemical Abstracts Service), PO Box 3012, Colombus, OH 43210-9989.
- Index to IEEE Publications (1988), (201)981-1393. Also, *Quick Reference to IEEE Standards.*
- *Ulrich's International Periodicals Directory*, R.R. Bowker Co., New York.
- *Science Citation Index* for locating more recent papers citing known papers on a topic.
- GIDEP, Government-Industry Data Exchange Program, for failure rates of electronic and mechanical components, (714)736-4677.
- CINDAS – Center for Information and Numerical Data Analysis and Synthesis, Purdue Univ., Dr. C. Y. Ho, (317)494-6300. Maintains data bases on dielectrics and other materials.

Omissions. This book omits various engineering aspects of accelerated testing. Omissions include:

- *Failure analysis.* Sources of information include the International Symposium for Testing and Failure Analysis, the Symposium on Mechanical Properties, Performance, and Failure Modes of Coatings (NBS/NIST), the Failure Analysis Special Interest Group of the Society of Plastics Engineers, and Chapter 13 of Ireson and Coombs (1988).
- *Test equipment and labs.* Sources of information include *Quality Progress*

(1988), *Evaluation Engineering* magazine (813) 966-9521, the Amer. Assoc. for Laboratory Accreditation, P.O. Box 200, Farifax Station, VA 22039, and various standards of professional societies.

- *Measurements/metrology and test methods.* Standards of engineering societies treat this in detail. Meetings include the Instrumentation and Measurement Technology Conference (IEEE). References include Heymen (1988).

Applications. For convenience, the following applications appear under three headings: (1) Materials, (2) Products, and (3) Degradation Mechanisms. These brief discussions are intended only to suggest the widespread use of accelerated testing. Those acquainted with a particular application will find the discussion rudimentary. Each discussion briefly describes applications, typical products, accelerating stresses, professional societies, journals, and meetings. Some references are included. Applications appear in the accelerated testing bibliographies of Meeker (1980) and Carey (1988), and older applications appear in the survey of Yurkowski and others (1967). Most applications involve time – either as time to failure or as time over which a performance property of a product degrades.

1.2. Materials

The following paragraphs briefly survey accelerated testing of materials. These include metals, plastics, dielectrics and insulations, ceramics, adhesives, rubber and elastics, food and drugs, lubricants, protective coatings and paints, concrete and cement, building materials, and nuclear reactor materials.

Metals. Accelerated testing is used with metals, including test coupons and actual parts, as well as composites, welds, brazements, bonds, and other joints. Performance includes fatigue life, creep, creep-rupture, crack initiation and propagation, wear, corrosion, oxidation, and rusting. Accelerating stresses include mechanical stress, temperature, specimen geometry and surface finish. Chemical acceleration factors include humidity, salt, corrosives, and acids. Societies include the American Society for Testing and Materials (ASTM), the American Society for Mechanical Engineers (ASME), American Powder Metallurgy Institute, ASM International (formerly the American Society for Metals), Institute of Metals, Society of Automotive Engineers (SAE), and the Society for Experimental Mechanics (SEM). References include ASTM STP 91-A, 744, and E739-80, Little and Jebe (1975), Graham (1968), Dieter (1961), Shelton (1982), Metals and Ceramics Information Center (1984), SAE Handbook AE-4 (1968), and Carter (1985).

Plastics. Accelerated testing is used with many plastics including building materials, insulation (electrical and thermal), mechanical components, and coatings. Materials include polymers, polyvinyl chloride (PVC), urethane foams, and polyesters. Performance includes fatigue life, wear, mechanical properties, and color fastness. Accelerating stresses include mechanical load (including vibration and shock), temperature (including cycling and shock), and weathering (ultraviolet radiation and humidity). Societies include the Plastics Institute of America, Plastics and Rubber Institute (PRI), and Society of Plastics Engineers (particularly its Failure Analysis Special Interest Group). Meetings include the International Conference on Fatigue in Polymers. Publications include *Polymer Engineering and Science* and *J. of Applied Polymer Science*. References include Mark (1985), Brostow and Corneliussen (1986), Hawkins (1984,1971), Underwriter Labs (1975), and Clark and Slater (1969).

Dielectrics and insulations. Accelerated testing is used with many dielectrics and electrical insulations including solids (polyethylene, epoxy), liquids (transformer oil), gases, and composites (oil-paper, epoxy-mica). Products include capacitors, cables, transformers, motors, generators, and other electrical apparatus. Performance includes time to failure and other properties (breakdown voltage, elongation, ultimate mechanical strength). Accelerating stresses include temperature, voltage stress, thermal and electrical cycling and shock, vibration, mechanical stress, radiation, and moisture. Societies include the Institute of Electrical and Electronics Engineers (IEEE), American Society for Testing and Materials (ASTM), and International Electrotechnical Commission (IEC). Publications include the *IEEE Trans. on Electrical Insulation* and *IEEE Electrical Insulation Magazine*. Meetings include the IEEE Annual Conference on Electrical Insulation and Dielectric Phenomena, IEEE Biannual International Symposium on Electrical Insulation, and Electrical/Electronics Insulation Conference. References include Sillars (1973), IEEE Standard 101 (1986), IEEE Standard 930 (1987), Goba (1969), IEEE Index (1988), Vincent (1987), Simoni (1974,1983), Vlkova and Rychtera (1978), and Bartnikas (1987, Chap. 5).

Ceramics. Applications are concerned with fatigue life, wear, and degradation of mechanical and electrical properties. References include Metals and Ceramics Information Center (1984). Societies include the United States Advanced Ceramics Association and American Ceramics Society. Publications include the *J. of the American Ceramics Soc.* Meetings include the World Materials Congress (ASM) and CERAMTEC Conference and Exposition (ASM/ESD). See Frieman (1980) and references for Metals.

Adhesives. Accelerated testing is used with adhesive and bonding materials such as epoxies. Performance includes life and strength. Accelerating stresses include mechanical stress, cycling rate, mode of loading, humidity, and temperature. References include Beckwith (1979,1980), Ballado-Perez (1986,1987), Millet (1975), Gillespie (1965), and Rivers and others (1981).

Rubber and elastics. Accelerated testing is used with rubbers and elastic materials (e.g., polymers). Products include tires and industrial belts. Performance includes fatigue life and wear. Accelerating stresses include mechanical load, temperature, pavement texture, and weathering (solar radiation, humidity, and ozone). Societies include the Plastics and Rubber Institute (PRI). References include Winspear's (1968) *Vanderbilt Rubber Handbook* and Morton (1987).

Foods and drugs. Accelerated testing is used with foods (e.g., browning of white wines), drugs, pharmaceuticals, and many other chemicals. Performance is usually shelf (or storage) life, usually in terms of amount of an active ingredient that degrades. Performance variables include taste, pH, moisture loss or gain, microbial growth, color, and specific chemical reactions. Accelerating variables include temperature, humidity, chemicals, pH, oxygen, and solar radiation. Societies include the American Society of Test Methods, US Pharmacopoeia, and Pharmaceutical Manufacturers Association. Major meetings include the Annual Meeting of Interplex. Kulshreshtha (1976) gives 462 references on storage of pharmaceuticals. References include Carstensen (1972), Connors et al. (1979), Bentley (1970), US FDA Center for Drugs and Biologics (1987), Young (1988), Labuza (1982), Beal and Sheiner (1985), and Grimm (1987).

Lubricants. Accelerated testing is used with solid (graphite, molybdenum disulphide, and teflon), oil, grease, and other lubricants. Performance includes oxidation, evaporation, and contamination. Accelerating stresses include speed, temperature, and contaminants (water, copper, steel, and dirt). Societies include the Society of Tribologists and Lubrication Engineers, STLE (formerly the American Society of Lubrication Engineers, ASLE). National Lubricating Grease Institute (NLGI), American Society for Testing and Materials (ASTM), and Society for Automotive Engineers (SAE). Elsevier Sequoia, S.A. (Switzerland) publishes *WEAR*, an international journal on the science and technology of friction, lubrication, and wear.

Protective coatings and paints. Accelerated testing is used for weathering of paints (liquid and powder), polymers, antioxidants, anodized aluminum, and electroplating. Performance includes color, gloss, and physical integrity (e.g., wear, cracking, and blistering). Accelerating stresses include weathering variables – temperature, humidity, solar radiation (wavelength and intensity) – and mechanical load. Societies include the American Electroplaters and Surface Finishers Society. Meetings include the World Materials Congress (ASM), and the Symposium on Mechanical Properties, Performance, and Failure Modes of Coatings (NBS/NIST).

Concrete and cement. Accelerated testing is used with concrete and cement to predict performance – the strength after 28 days of curing. The accelerating stress is high temperature applied for a few hours. Meetings include the Cement Industry Technical Conference.

Building materials. Accelerated testing is used with wood, particle board, plastics, composites, glass, and other building materials. Performance includes abrasion resistance, color fastness, strength, and other mechanical properties. Accelerating stresses include load and weathering (solar radiation, temperature, humidity). References include Clark and Slater (1969).

Nuclear reactor materials. Accelerated testing is used with nuclear reactor materials, for example, fuel rod cladding. Performance includes strength, creep, and creep-rupture. Accelerating stresses include temperature, mechanical stress, contaminants, and nuclear radiation (type, energy, and flux). Societies include the Institute of Environmental Sciences (1988) and American Nuclear Society. Journals include the *IEEE Trans. on Nuclear Science* and *Radiation Research.* DePaul (1957) surveys such work.

1.3. Products

The following paragraphs describe accelerated testing of certain products. Such products range from simple components through complex assemblies.

Semiconductors and microelectronics. Accelerated testing is used for many types of semiconductor devices including transistors such as gallium arsenide field emission transistors (GaAs FETs), insulated gate field emission transistors (IGFETs), Gunn and light emitting diodes (LEDs), MOS and CMOS devices, random access memories (RAMs), and their bonds, connections, and plastic encapsulants. They are tested singly and in assemblies such as circuit boards, integrated circuits (LSI and VLSI), and microcircuits. Performance is life and certain operating characteristics. Accelerating variables include temperature (constant, cycled, and shock), current, voltage (bias), power, vibration and mechanical shock, humidity, pressure, and nuclear radiation. Societies include the Institute for Electrical and Electronics Engineers (IEEE), American Electronics Association (AEA), Society for the Advancement of Material and Process Engineering (PO Box 2459, Covina, CA 91722). Major professional meetings include the International Reliability Physics Symposium, Annual Reliability and Maintainability (RAM) Symposium, International Symposium for Testing and Failure Analysis, Electronic Materials and Processing Congress (ASM), Annual Conference on Electronic Packaging and Corrosion in Microelectronics, and Gallium Arsinide Integrated Circuits Symposium (IEEE). References include Peck and Trapp (1978), Peck and Zierdt (1974), Reynolds (1977), IEEE Index (1988), and Howes and Morgan (1981). Publications include proceedings of the symposia above, *Microelectronics and Reliability, IEEE Trans. on Reliability, IEEE Journal of Solid-State Circuits, IEEE Trans. on Consumer Electronics, IEEE Circuits and Devices Magazine, IEEE Trans. on Circuits and Systems, IEEE Trans. on Electron Devices, IEEE Trans. on Power Electronics, Proceedings of the International SAMPE Electronics Materials Conference, IEEE J. of Quantum Electronics,* and *IEE Proceedings* (England).

Capacitors. Accelerated testing is used with most types of capacitors, including electrolytic, polypropylene, thin film, and tantalum capacitors. Performance is usually life. Accelerating variables include temperature, voltage, and vibration. Professional societies that publish standards and journal articles on accelerated test methods and applications include the Institute of Electrical and Electronics Engineers (IEEE) and the American Electronics Association (AEA). Also, see resources for semiconductor applications.

Resistors. Accelerated testing is used with thin and thick film, metal oxide, pyrolytic, and carbon film resistors. Performance is life. Accelerating variables include temperature, current, voltage, power, vibration, electrochemical attack (humidity), and nuclear radiation. References include Krause (1974). Also, see resources for semiconductor applications.

Other electronics. Accelerated testing is used with other electronic components such as optoelectronics (opto couplers and photo conductive cells), lasers, liquid crystal displays, and electric bonds and connections. The performance, accelerating stresses, professional societies, and references are much the same as those for semiconductors. Publications include *IEE Proceedings* (England), *IEEE Trans. on Power Electronics, IEEE Journal of Electronic Materials*, and *IEEE Trans. on Electron Devices*. Meetings include the Electronic Components Conference (IEEE) and International Electron Devices Meeting (IEEE).

Electrical contacts. Accelerated testing is used for electrical contacts in switches, circuit breakers, and relays. Performance includes corrosion and life. Metal fatigue, rupture, and welding are common failure mechanisms. Accelerating stresses include high cycling rate, temperature, contaminants (humidity), and current. References include the IEEE Index (1988). Meetings include the Holm Conference on Electrical Contacts (IEEE).

Cells and batteries. Accelerated testing is used with rechargable, nonrechargable, and solar cells. Performance includes life, self discharge, current, and depth of discharge. Accelerating variables include temperature, current density, and rate of charge and discharge. Societies include the Electrochemical Society (609) 737-1902. Publications include the *Journal of the Electrochemical Society, Solar Cells* (Switzerland), and *Proceedings of the Symposium on Lithium Batteries.* References include Sidik and others (1980), McCallum and others (1973), Linden (1984), and Gobano (1983). Meetings include the Battery Workshop (NASA), Annual Battery Conference on Applications and Advances (IEEE and California State University), and International Power Sources Symposium.

Lamps. Accelerated testing is used with incandescent (filament), fluorescent (including ballasts), mercury vapor, and flash lamps. Performance includes life, efficiency, and light output. Accelerating variables include voltage, temperature, vibration, and mechanical and electrical shock. Societies include the International Electrotechnical Commission (IEC). References include EG&G Electro-Optics (1984), IEC Publ. 64 (1973), and IEC Publ. 82 (1980).

Electrical devices. Accelerated testing is used with various electrical devices including motors, heating elements, and thermoelectric converters. References include the IEEE Index (1988). Motor and generator failures are almost always due to insulation or bearing failure. Thus their life distribution is inferred from that of their insulation and bearings (Chapter 7).

Bearings. Accelerated testing is used with roller, ball, and sliding (oil film) bearings. Performance includes life and wear (weight loss). Materials include steels and silicon nitride for rolling bearings and porous (sintered) metals, bronzes, babbitt, aluminum alloys, and plastics for sliding bearings. Accelerating stresses include overspeed, mechanical load, and contaminants. Societies include the Anti-Friction Bearing Manufacturers Association (AFBMA), International Standards Organization (ISO), American Society for Testing and Materials (ASTM), Society of Automotive Engineers (SAE), and ASM International (formerly the American Society for Metals). References include Harris (1984), SKF (1981), and Lieblein and Zelen (1956).

Mechanical components. Accelerated testing is used with mechanical components and assemblies such as automobile parts, hydraulic components, tools, and gears. Performance includes life and wear. Accelerating stresses include mechanical load, vibration, temperature and other environmental factors, and combinations of such stresses. Societies include the American Society for Testing and Materials (ASTM), Society for Automotive Engineers (SAE), and American Society for Mechanical Engineers (ASME). Meetings include the International Machinery Monitoring and Diagnostic Conference (sponsored by Union College, Schenectady, NY). References include Collins (1981), Zalud (1971), and Boothroyd (1975). See resources for Metals.

1.4. Degradation Mechanisms

The following paragraphs describe common mechanisms for degradation of product *performance*. Such mechanisms are utilized or studied in accelerated tests. For more detail, refer back to discussions of materials and products. Meetings include the International Machinery Monitoring and Diagnostic Conference (sponsored by Union College, Schenectady, NY).

Fatigue. Materials eventually fail by fatigue if subjected to repeated mechanical loading and unloading, including vibration. Well studied are the fatigue of metals, plastics, glass, ceramics, and other structural and mechanical materials (see references on these). Fatigue is a major failure mechanism of mechanical parts including bearings and electrical contacts. The usual accelerating stress is load. Other stresses are temperature and chemicals (water, hydrogen, oxygen, etc.). References include Tustin and Mercado (1984), ASTM STP 648 (1978), ASTM STP 744 (1981), ASTM STP 748 (1981), ASTM STP 738 (1981), Frieman (1980), and Skelton (1982).

Creep. Creep, the slow plastic deformation of materials under constant mechanical load, may interfere with product function or cause rupture or fracture. Accelerating variables are typically temperature and mechanical load, load cycling, and chemical contaminants (for example, water, hydrogen, and fluorine). References include Goldhoff and Hahn (1968), Hahn (1979), and Skelton (1982). See resources for Metals and Plastics.

Cracking. Metals, plastics, glass, ceramics, and other materials crack. People study crack initiation and growth. Accelerating stresses include mechanical stress, temperature, and chemicals (humidity, hydrogen, alkalis, and acids). See resources for Metals and Plastics.

Wear. In applications, many materials are subjected to friction that removes the material. For example, rubber tires lose tread, house paints wash off, gears, bearings, and machine tools wear away. Accelerating stresses include speed, load (magnitude and type), temperature, lubrication, and chemicals (humidity). References include Rabinowicz (1988) and Peterson and Winer (1980). DePaul (1957) surveys nuclear applications. Boothroyd (1975) treats machine tool wear. Elsevier Sequoia, S.A. (Switzerland) publishes *WEAR*, an international journal on the science and technology of friction, lubrication, and wear.

Corrosion/oxidation. Most metals and many foods, pharmaceuticals, etc., deteriorate by chemically reacting with oxygen (oxidation and rusting), fluorine, chlorine, sulphur, acids, alkalis, salt, hydrogen peroxide, and water. Accelerating stresses include concentration of the chemical, activators, temperature, voltage, and mechanical load (stress-corrosion). Meetings include the Annual Conference on Electronic Packaging and Corrosion in Microelectronics. Professional societies include the National Assoc. of Corrosion Engineers (NACE). The publications list of the Metals and Ceramics Information Center (1984) includes work on corrosion. References include DePaul (1957) on nuclear applications, Rychtera (1985), and Uhlig and Revie (1985).

Weathering. This concerns the effects of weather on materials in outdoor applications. Such materials include metals, protective coatings (paint, electroplating, and anodizing), plastics, and rubbers. Accelerating stresses include solar radiation (wavelength and intensity) and chemicals (humidity, salt, sulphur, and ozone). The degradation generally involves corrosion, oxidation (rust), tarnishing, or other chemical reaction. Professional societies include Institute of Environmental Sciences (1988). Publications include the *Journal of Environmental Sciences.*

2. TYPES OF DATA

This section presents background on accelerated test data. Accelerated test data can be divided into two types. Namely, the product characteristic of interest is 1) **life** or is 2) some other measure of **performance**, such as tensile strength or ductility. Such data are described below. This background is essential for the rest of this book.

Performance data. One may be interested in how product performance degrades with age. In such performance testing, specimens are aged under high stress, and their performance measured at different ages. Such performance data are analyzed by fitting a degradation model to the data to estimate the relationship between performance, age, and stress. Chapter 11 discusses such data in detail and presents such models and data analyses. Such a degradation test has been used, for example, for temperature aging of electrical insulation and pharmaceuticals. Goba (1969) references such testing of electrical insulation.

Life data. The proper analysis of life data depends on the type of data. The following paragraphs describe the common types of life data from a single test or design condition.

Complete. Complete data consist of the *exact* life (failure age) of each sample unit. Figure 2.1A depicts a complete sample from a single test condition. There the length of a line corresponds to the length of life of a test unit. Chapters 3, 4, and 8 treat such data. Much life data are incomplete. That is, the exact failure times of some units are unknown, and there is only partial information on their failure times. Examples follow.

Censored. Often when life data are analyzed, some units are unfailed, and their failure times are known only to be beyond their present running times. Such data are said to be **censored on the right.** In older literature, such data or tests are called **truncated.** Unfailed units are called run-outs, survivors, removals, and suspensions. Such censored data arise when some units are (1) removed from test or service before they fail, (2) still running at the time of the data analysis, or (3) removed from test or service because they failed from an extraneous cause such as test equipment failure. Similarly, a failure time known only to be before a certain time is said to be **censored on the left.** If all unfailed units have a common running time and all failure times are earlier, the data are said to be **singly censored** on the right. Singly censored data arise when units are started together at a test condition and the data are analyzed before all units fail. Such data are singly **time censored** if the censoring time is fixed; then the number of failures in that fixed time is random. Figure 2.1B depicts such a sample. There the line for an unfailed unit shows how long it ran without failure, and the arrow pointing to the right indicates that the unit's failure time is later. Time censored data are also called **Type I censored.** Data are singly **failure censored** if the test is stopped when a specified number of failures occurs. The time to that fixed number of failures is random. Figure 2.1C depicts such a sample. Time censoring is more common in practice. Failure censoring is more common in the theoretical literature, as it is mathematically more tractable. Chapters 3 and 5 present analyses for singly censored data.

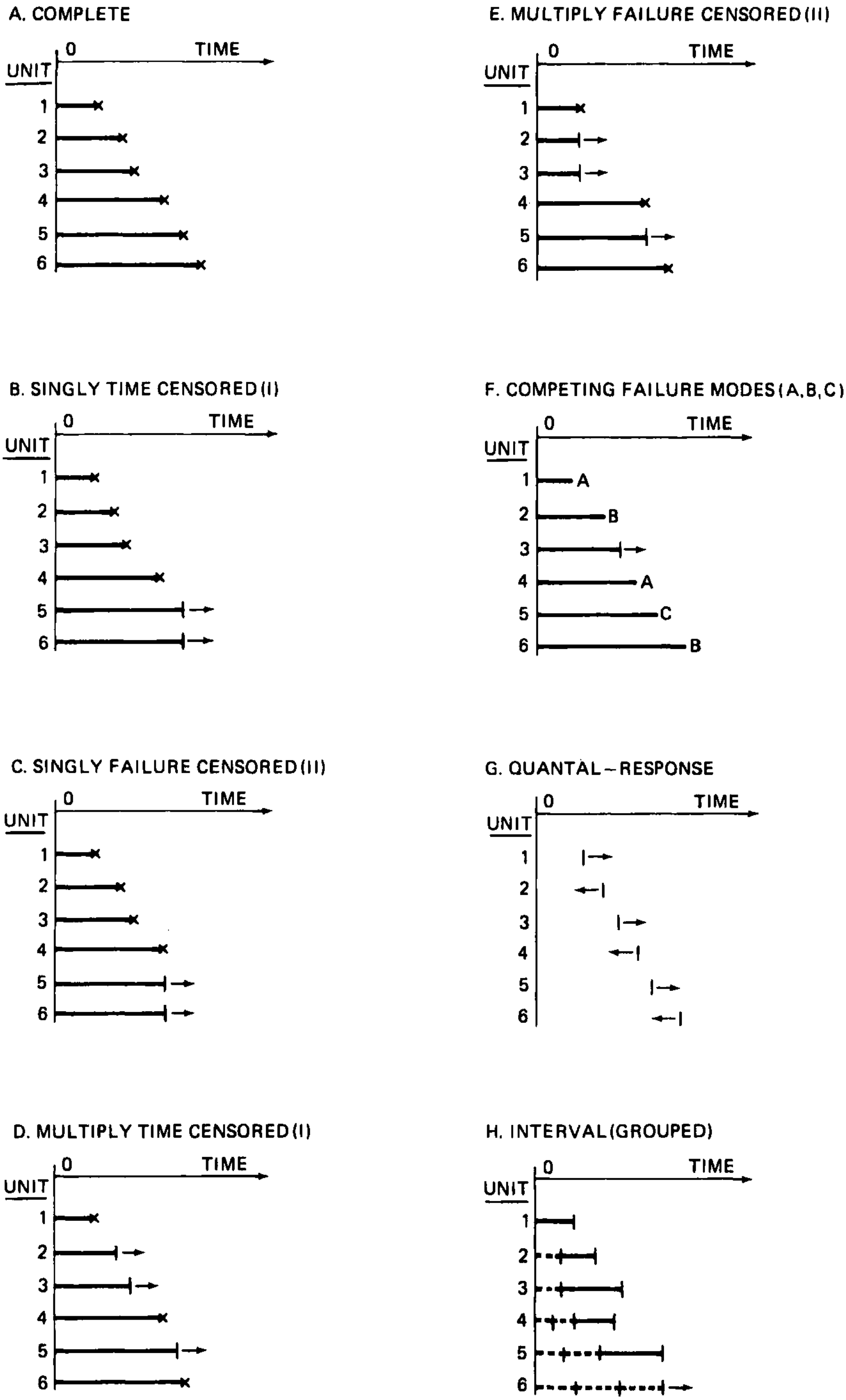

Figure 2.1. Types of data (failure time ×, running time ⊢→, failure occurred earlier ←⊣).