IOE562/Stat535 – Reliability
Fall 2007
Instructor: Vijay Nair
Preliminaries

- **Class Syllabus and Topics (Handout #1)**

- **Text and Other References (Handout #2)**

- **Grading (Handout #2)**

- **Student Background (Handout #3)**

- **Homework policy (Handout #4)**

- **Homework #1**

VNN Info

- **Class web page: Ctools course site**

- **Office:**   **453 West Hall (central campus)**
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Handout #1
IOE 562/Stat 535: RELIABILITY
Fall 2007
Instructor: Vijay Nair

<u>COURSE DESCRIPTION</u>: This course will cover important reliability concepts and methodology that arise in modeling, assessing and improving product reliability and in analyzing field and warranty data.

Topics will be selected from the following:
- Basic Concepts in Reliability
- Component and System Reliability
  - Aging
  - Hazard
  - Component Reliability
  - Common Models for Component Reliability

- Types of Censoring Schemes
- Analysis of Time-to-Failure Data
  - Nonparametric Techniques
  - Graphical and Formal Goodness-of-Fit Tests for Model Selection
  - Parametric Techniques
- Reliability, Availability, and Maintainability for Repairable Systems
  - System Structures
  - Common Models for System Reliability
  - Analysis of Time-Between-Failure Data
  - Maintenance and Availability
- Accelerated Stress Testing for Reliability Assessment
- Reliability Improvement Through Experimental Design
- Special Topics: Warranty Data Analysis, Stress-Strength Models, etc.

TEXT: ``*Statistical Methods for Reliability Data"* by Meeker and Escobar (1998), Wiley.
This will be supplemented by selected material from engineering text books in reliability.

Handout #2
IOE 562/Stat 535: RELIABILITY
Fall 2007
Vijay Nair

REFERENCES

1. Meeker. W. Q. and Escobar L. (1998) *Statistical Methods for Reliability Data*, New York: Wiley
2. Nelson, W. (1990), *Accelerated Testing: Statistical Models, Test Plans and Data Analyses*, New York: Wiley.
3. Ascher, H. and Fiengold H. (1984), *Repairable Systems Reliability*, New York: Marcell Dekker, Inc.
4. O'Connor, P. D. T. (1985), Practical Reliability Engineering, New York: Wiley.
5. Ebeling, C. E. (1997), *Reliability and Maintainability Engineering,* New York: McGraw Hill.
6. Billinton, R. (1992), *Reliability Evaluation of Engineering Systems: Concepts and Techniques*, Plenum Pr. NY.
7. Lewis, E. E. (1996) *Introduction to Reliability Engineering*, New York: Wiley.
8. Jardine, A. K. S. (1973), *Maintenance, Replacement and Reliability*, New York: Wiley
9. Ditlevson, O. and Madsen, H. O. (1996) *Structural Reliability Methods*, New York: Wiley.

GRADING SCHEME
Homework 25%
Midterm 25%
Class Project 15%
Final Exam 25%
Class Participation 10%

Name:

Dept & Program: (eg. IOE/Stat etc., Master's/Ph.D. etc):

Stat/Prob classes taken and level:

Other relevant information: (eg. practical experience)

Reading Assignment and HW #1
(See Ctools course site in the future)

Reading Assignment:

Meeker and Escobar –

Chapter 1 – browse through whole chapter;

Chapter 2 – Sections 2.1-2.2

Chapter 4 – Sections 4.1-4.11

Chapter 5 – Sections 5.1, 5.2, 5.6, 5.7, 5.10

HW #1: *(due Mon 9/17)*

Meeker and Escobar:

Problems 1.5, 1.6, 1.7, 1.8 (choose 3 of the applications), and 1.9

Course Background

- Focus on methods for collecting and analyzing reliability data for making engineering decisions

- Breadth vs Depth (variety of topics)

- Not covered -- very applied, engineering and economic aspects of reliability (life cycle costs, FMEA, FTA, maintenance, …)

Review:

- Distributions (Important distributions, properties – quantiles, moments, …)

- Multivariate normal distributions (mean, covariance/correlation matrices)

- Likelihood – MLEs, Fisher information, etc.

Summary of Chapter 1 – M&E
Reliability Concepts and Reliability Data Objectives

- Explain the importance of reliability

- List some reasons for collecting reliability data

- Describe the distinguishing features of reliability data

- Provide examples of reliability data and describe the motivation for the collection of the data.

- Outline a general strategy that can be used for data analysis, modeling, and inference from reliability data.

Motivation

Recent directions:

- Intense global competition → improve Q&R, reduce product development cycle time, reduce product life-cycle costs

- Increasing customer expectations → lot more functionality, high quality, AND low cost

- Rapid advances in technology → more sophisticated products → increase in product complexity → more reliance on data

Emphasis on Quality and Reliability

→ Increasing pressure on manufacturers to produce products with high quality and reliability

Reliability:

- "Ho" topic (like Q&P and quality management in 1980's)
- Lots of $$ at stake – product warranty now std but costs in billions of $ -- Ford/Firestone eg.
- Safety issues: Aircraft, Nuclear, Space, …
- Software vs Hardware Reliability
- Parts/Components vs System Reliability

What is the difference between quality and reliability?

Intuitive meaning of reliability?

Other terms – durability, …

Definitions of Reliability

- **Informal:** "Reliability is quality over time" (Condra 1993)

- **Technical:** Reliability is the probability that a system, vehicle, machine, device, and so on, will perform its intended function under encountered operating conditions, for a specified period of time.

T = "time"-to-failure   R(100) = P(T > 100)

More generally: Reliability function: R(t) = P(T > t)

T is random: why?

Probability distribution – where does it come from? →

"Time" → surrogate for …

Some Issues in Modeling Reliability Data

- Causes of failure?

- Degradation and environmental effects on reliability

- Catastrophic vs "soft" failures

- Homogeneous vs heterogeneous population?

- Definition of time scale

- Definitions of time origin and time of failure

Reliability Applications

1. Assessing characteristics of materials (strength, failure modes, …)
2. Assessing the effect of a proposed design change
3. Comparing several different manufacturers, suppliers, designs, …
4. Predict product reliability in design stage
5. Assess product reliability in field
6. Checking the veracity of an advertising claim -- (related to 3)
7. Predict product warranty costs
8. Risk assessment for safety-critical systems
9. Determine maintenance/repair/replacement schedules

Other Names for Reliability Data

- Life data

- Failure data

- Time-to-failure (TTF) data → "time"

- Time-between-failure data

- Survival data

- Event-time data

Degradation data (somewhat different) → measure how device state or performance changes over time

Distinguishing Features of Reliability Data

- Models for positive random variables (e.g., exponential, log-normal, Weibull, gamma). Normal distribution not common.

- Model parameters *not* of primary interest (instead, hazard rates, quantiles, probabilities of failure, …)

- Extrapolation often required (e.g., want proportion failing by 900 hours but test runs for only 400 hours).

- Data are typically censored (bounds on observations)
  – different types of censoring (examples to follow)

Repairable Systems and Nonrepairable Devices

- Failure data on <u>components</u> or nonrepairable devices
  - Laboratory tests on materials or components
  - Failure data of components in field
  - Time to <u>first</u> failure of a system.

- Failure data on <u>repairable systems</u>
  - -- time-between-failures
  - -- how do failure patterns change over time?
  - -- repair → as good as new?

Example: Ball Bearing Data

Fatigue endurance tests for deep-groove ball bearings from **four** major bearing companies (Lawless 1982) → several stress levels

Data: Millions of revolutions to failure for each of $n = 23$ bearings until fatigue failure →

Main objective of the study: Determine relationship between lifetime and stress load (<u>best</u> values of the parameters in equation relating fatigue to load)

Motivation:
- Fatigue affects service life of ball bearings.
- Disagreement in the industry on the appropriate model to describe relationship

Ball Bearing Failure Data
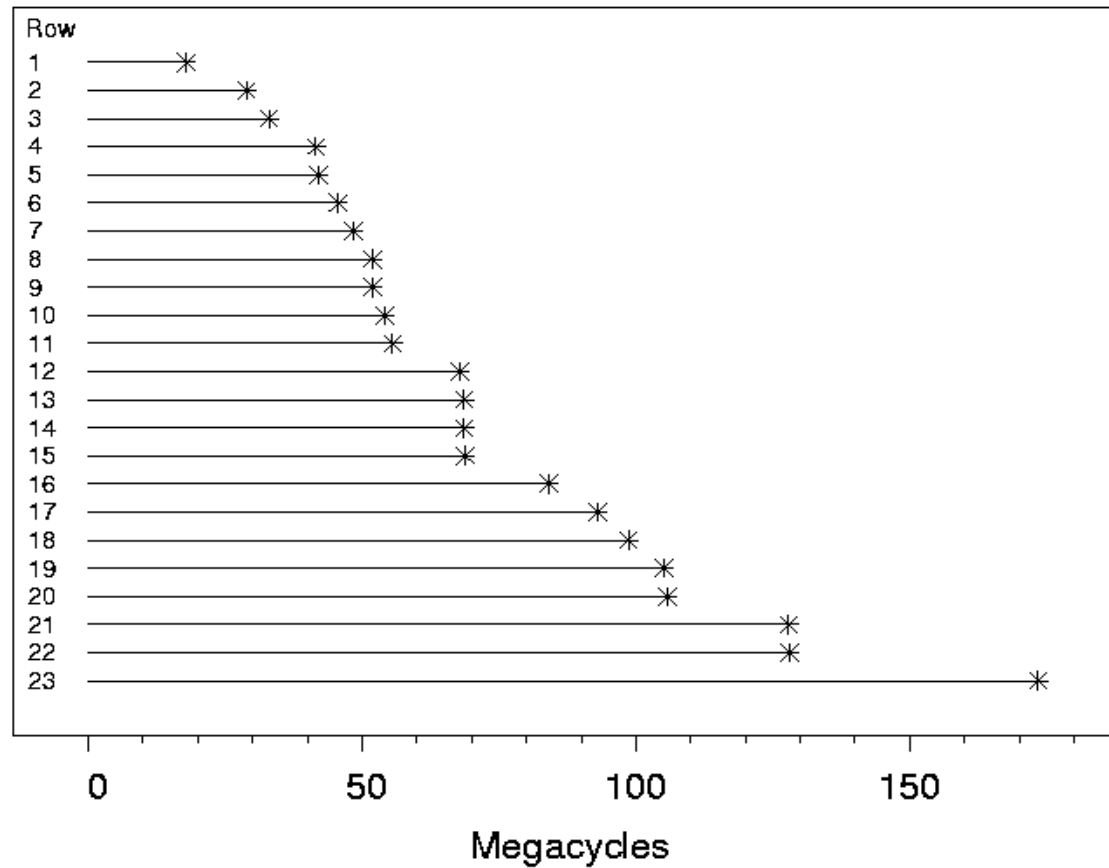(Lieblein and Zelen 1956. Data from Lawless 1982)

F(80)?
Proportion failing
by 80 million cycles?
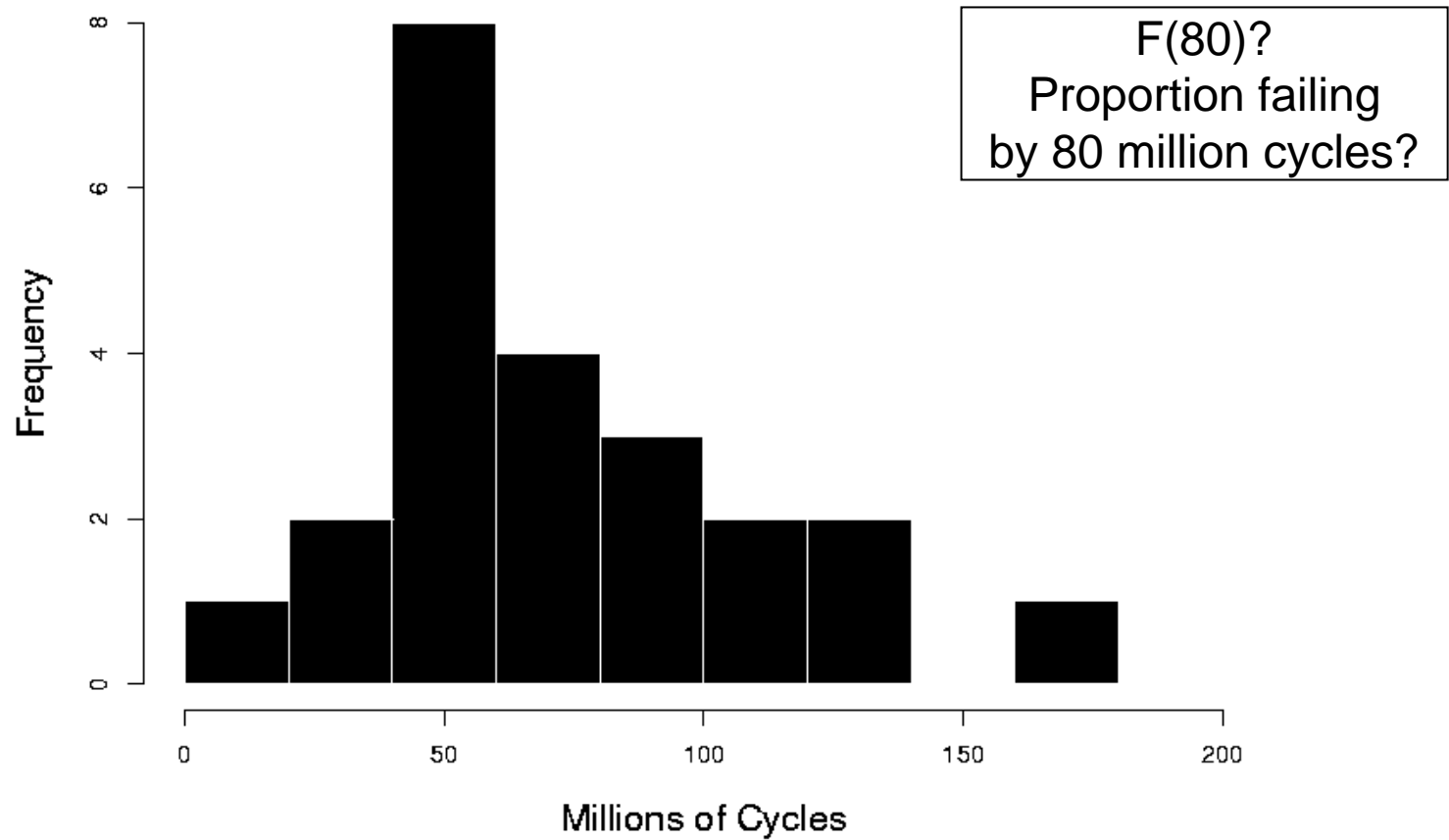
Ball Bearing Failure Data
(Lawless 1982)

Lieblein and Zelen Ball Bearing Failure Data

All units failed in this study → not very common

F(80)?

Example: IC Data (Meeker, 1987)

Integrated circuit failure times in hours – stress test

Test ended at 1,370 hours – 26 failed; 4,128 units were still running at end of test – (right) censored →

|					
.10	.10	.15	.60	.80	.80
1.20	2.5	3.0	4.0	4.0	6.0
10.0	10.0	12.5	20.	20.	43.
43.	48.	48.	54.	74.	84.
94.	168.	263.	593.		

Any interesting features in the data?

Questions:

- Probability of failing before *100* hours?
- Hazard function at *100* hours
- Proportion of units that will fail in 10^5 hours?
- Extrapolation – in time and stress

Failure Pattern of the Integrated Circuit Life Test Data Where 28 Out of 4156 Units Failed in the 1370 Hour Test at $80°C$ and 80% RH (Meeker 1987)

Integrated Circuit Failure Data After 1370 Hours
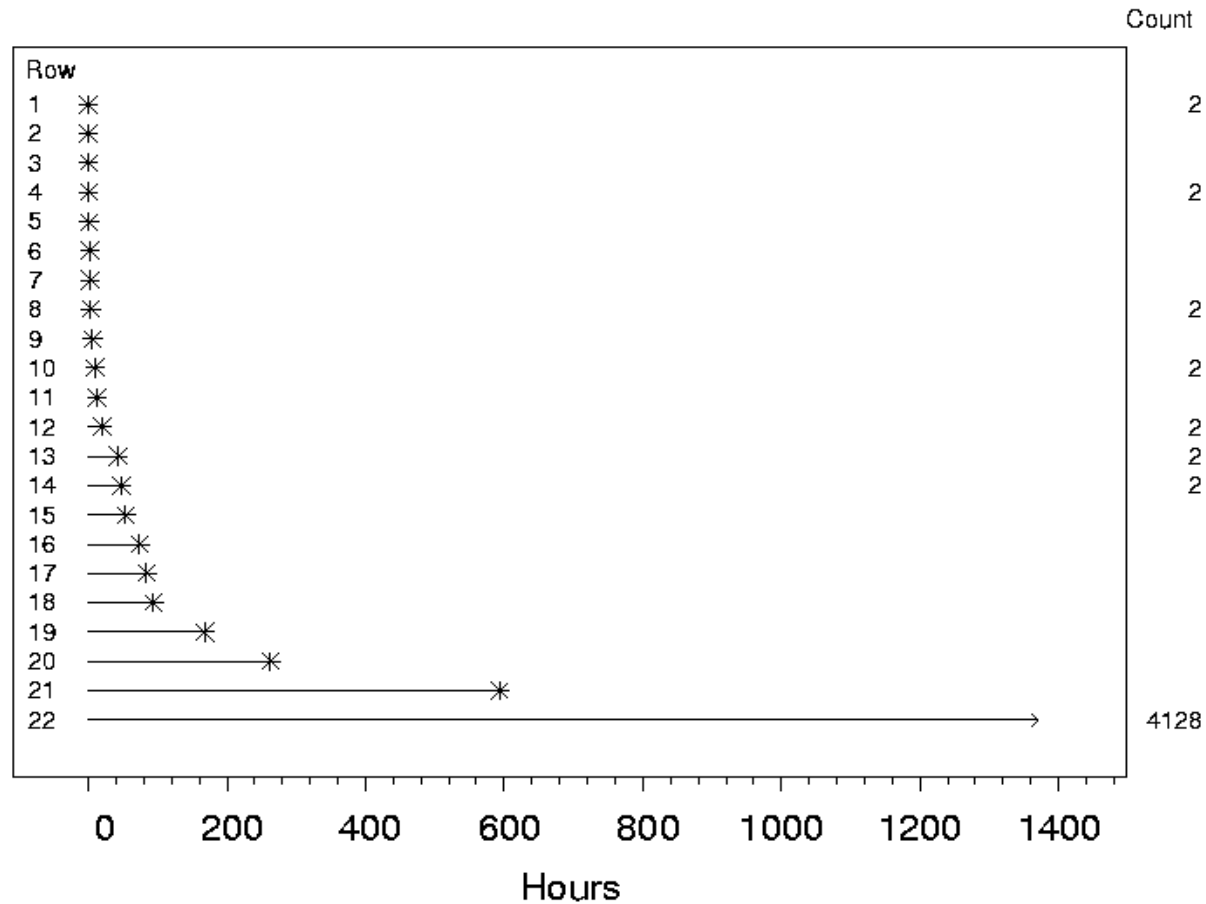
Example: Fan Failure Data

Hours to fan failure on 12 diesel generators and running times on 58 generators without fan failure, n = 70 (Nelson 1982).
-- example of different censoring times for different units

Some <u>important</u> questions of interest:

- Estimate percentage failing under warranty.

- Would the problem get better or worse as the remaining fans age?

In reliability terminology: does hazard function increase or decrease with age?

Shock Absorber Failure Data
(O'Conner, 1985)

- Failure times of vehicle shock absorbers (in kilometers of vehicle use) →

- Two failure modes, denoted M1 and M2

- Interest is on failure-time distributions of mode M1, mode M2, and overall part

- Example of "competing risks" and random right censoring

Failure Pattern in the Shock Absorber Data
(O'Connor 1985)

Shock Absorber Data (Two Failure Modes)
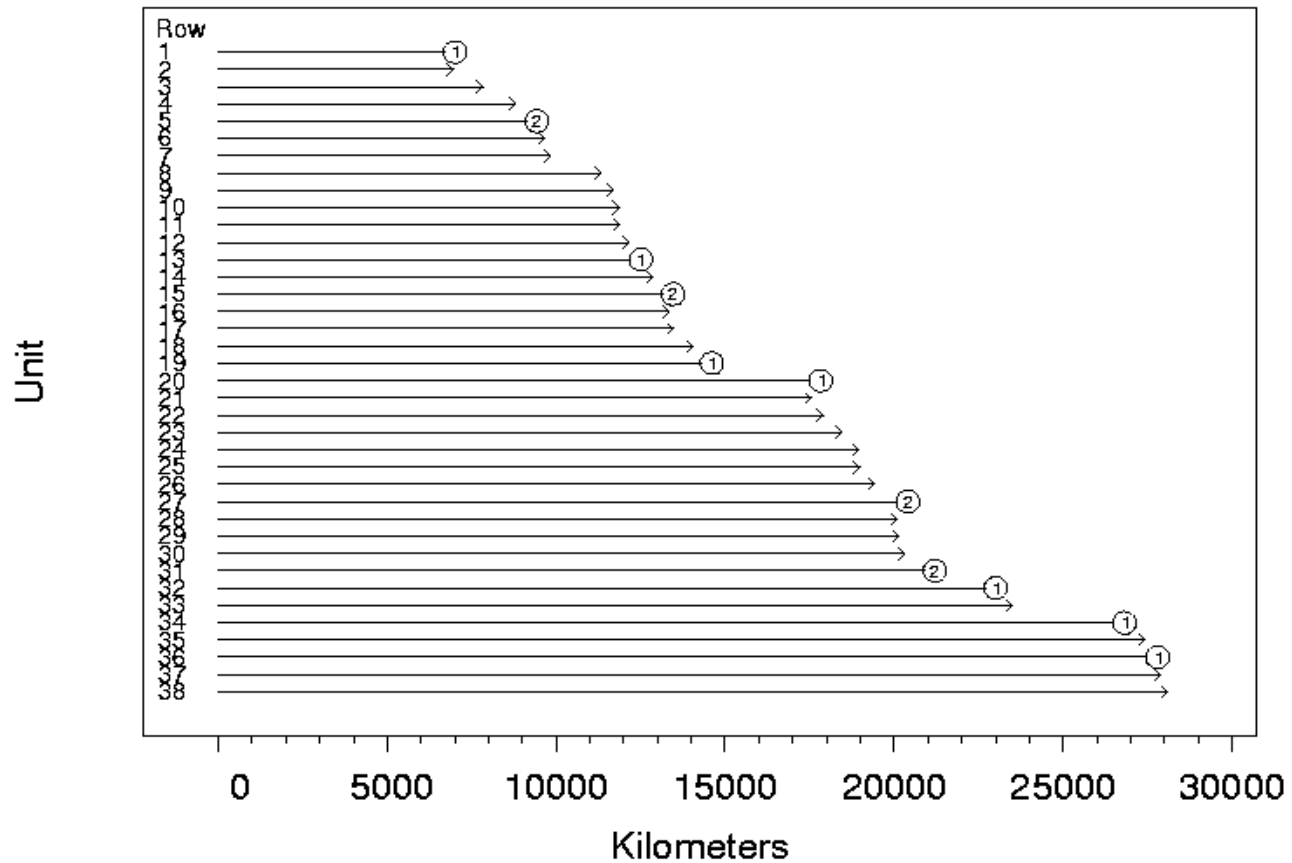
Example: Heat Exchanger Crack Data

Data from heat exchangers for power plants.

- 100 tubes in each exchanger.

- Each tube inspected at the end of each year for cracks.

- Data from *3* plants with same design. Each plant entered into service at different dates.

Cracked tubes at the end of each year,

Exchanger	Year 1	Year 2	Year 3
1	1	2	2
2	2	3	no insp.
3	1	no insp.	no insp.

Heat Exchanger Tube Crack Inspection Data in Real Time

Heat Exchanger Tube Crack Inspection Data in Operating Time

| | Year 1 | Year 2 | Year 3 |
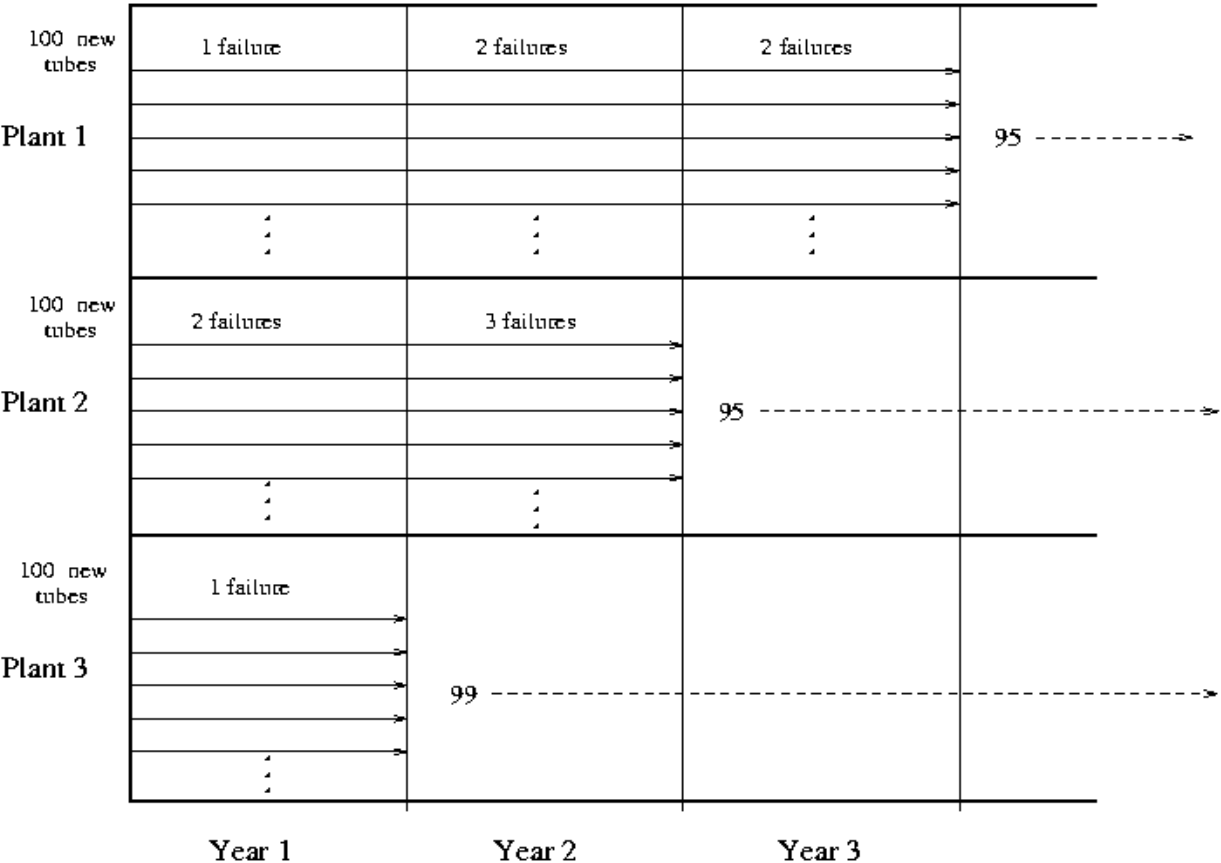
Example: Turbine Wheel Data

Each of n = 432 wheels was inspected once to determine if it had started to crack or not. Wheels had different ages at inspection (Nelson 1982) →

Some <u>important</u> objectives were:
* Need to schedule regular inspections.

* Estimate the distribution of time to crack.

* Is the reliability of the wheels getting worse as the wheels age?

An increasing hazard function would require replacement of the wheels by some age when the risk of cracking gets too high.

Example: Turbine Wheel Data
Summary at Time of Study (Nelson 1982)

100-hours of Exposure	# Cracked Left Censored	# Not Cracked Right Censored
4	0	39
10	4	49
14	2	31
18	7	66
22	5	25
26	9	30
30	9	33
34	6	7
38	22	12
42	21	19
46	21	15

Cross-sectional study

Turbine Wheel Inspection Data (Nelson 1982)
Summary at Time of Study

Turbine Wheel Crack Initiation Data

Count

Row		Count
1		39
2	?	4
3		49
4	?	2
5		31
6	?	7
7		66
8	?	5
9		25
10	?	9
11		30
12	?	9
13		33
14	?	6
15		7
16	?	22
17		12
18	?	21
19		19
20	?	21
21		15

0   10   20   30   40   50

Hundreds of Hours
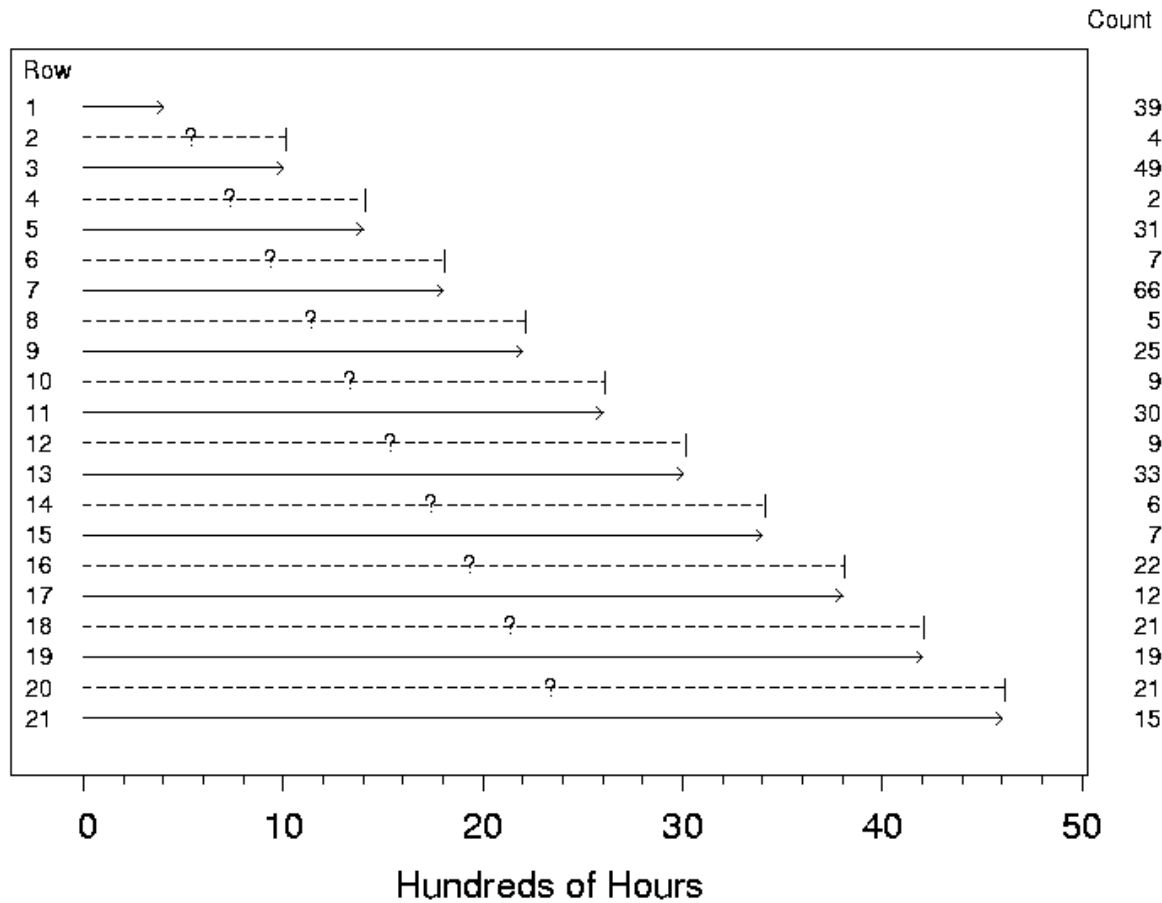
Scatter Plot of Low-Cycle Fatigue Life Versus Pseudo-Stress for Specimens of a Nickel-Base Superalloy (Nelson 1990)

Homogeneous vs Heterogeneous Population
Failure time varies with stress

Fatigue Crack Size as a Function of Number of Cycle
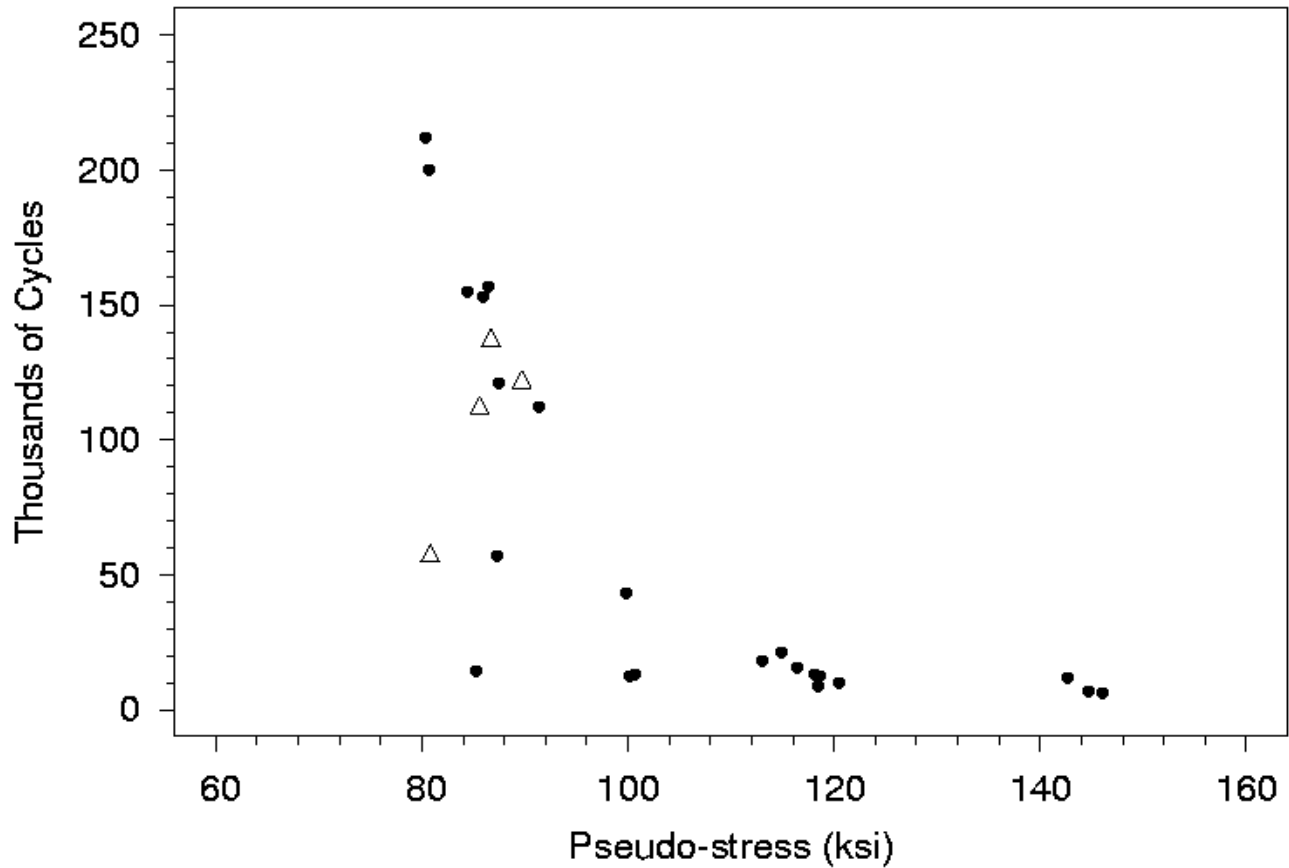
Degradation Data

Degradation Data

- Provides information on progression toward failure.

- Becoming more common in certain areas of component reliability where few or no failures expected in life tests.

- Important connections with physical mechanisms of failure and time-to-failure reliability models.

- Special methods of analysis needed (Chapters 13,21,22).

Biomedical Data

- Biomedical studies can yield data with censored structures similar to the ones observed in reliability.

- Similarly, some of the degradation data from biomedical studies resembles degradation data from reliability studies.

- Though some of the reliability methodology can be applied to biological studies, one can not blindly apply it ignoring the distinct nature of the problem handled in these two areas.

Example: DMBA Data

Number of days until the appearance of a carcinoma in *19* rats papinted with carcinogen DMBA.

Days	Status	Days	Status
143	dead	216	censored
188	dead	220	dead
188	dead	227	dead
190	dead	230	dead
192	dead	234	dead
206	dead	244	censored
209	dead	246	dead
213	dead	265	dead
216	dead	304	dead

Data from Pike (1966). See Lawless (1982).

Strategy for Data Analysis, Modeling, and Inference

- Model-free graphical analysis of data based on nonparametric methods

- Model fitting (parametric, including possible use of prior information).

- Inference: estimation or prediction (e.g., statistical intervals to reflect uncertainty/variability).

- Graphical and analytical diagnostics, assessment of model assumptions

- Sensitivity analysis

- Reliability conclusions
    → not in this order

Plan

- Discuss reliability concepts and how to answer engineering questions if we know the underlying distributions

  In practice – reliability distributions unknown
  $\rightarrow$

- How to estimate the distributions based on reliability data and then answer engineering questions of interest?

Computer Software
Analysis of Reliability Data with Censoring

Some capabilities in:

- Minitab
- S-PLUS
- SAS
- WeibullSMITH
- BMDP
- StatGraphics

Illustrative Applications
CASE 1: REDUNDANCY

In a large electronics company that manufactures small electrical parts such as resistors, capacitors, transistors, and inductors, a new component is experiencing a high failure rate. In order to meet government contract specifications, the function being performed by this component must have a 90 percent or better reliability over a 4-hour mission in a high-stress environment. Because of the cost and time required to redesign the component, design engineers are considering adding redundancy to achieve the desired reliability.

In order to determine the reliability, 75 units were placed on test in a high-stress environment. The test was terminated at the 50th failure. The following failure times (in hours) were recorded:

0.4	0.8	0.8	1.9	2.0	2.2	2.4	2.7
3.1	3.2						
3.6	3.9	4.0	4.0	4.3	5.7	6.0	6.3
6.5	6.8						
8.3	10.1	11.1	11.4	11.5	11.7	11.8	12.4
12.7	13.1						
15.0	15.4	17.6	17.8	18.3	18.7	18.9	19.4
19.6	19.8						
21.0	21.5	21.6	22.2	22.8	24.1	25.1	25.6
25.8	26.0						

What should the company do?

CASE 2: BURN-IN TESTING

A new fuel pump is experiencing manufacturing problems resulting in high infant mortality. The company has a 25-operating-hour warranty program that, because of the high infant mortality rate, is costing the company a considerable amount of money. Each failure under the warranty program costs the company approximately $1200 in replacement costs, administrative costs, and an estimated cost for the loss of goodwill. The company would like to implement a burn-in program in order to eliminate marginal pumps before they are sold under warranty. However, it is not certain whether a burn-in program will be effective and, if so, how many hours of testing would be necessary to implement the program. To answer these questions, the company first needed to establish an appropriate reliability model.

Twenty-five fuel pumps selected randomly from the production line were placed on test. The test ran for 500 operating hours (Type 1 test). The following failure times were obtained:

| 0.005 | 0.0 | 0.2 | 1.0 | 1.0 | 2.3 | 9.3 | 10.1 |
| 14.2 | 16.4 | 29.7 | 155.2 | 172.6 | 393.1 | 442.8 | 445.0 |

Should burn-in be used? If so, what is the optimal burn-in period?

CASE 3: PREVENTIVE MAINTENANCE ANALYSIS

A new turbine steam generator requires a 0.98 reliability over a 1000-cycle period. A cycle occurs whenever the superheated steam reaches a temperature in excess of 700oC. The first 40 generators had failures occurring at the following times (cycles).

347	396	433	513	624	673	1008
1035	1055	1066	1162	1266	1298	1361
1367	1549	1561	1576	1708	1834	1840
2497	2554	2656	2666	2686	3261	3278
3281	3338	3421	4238	4242	4481	4845
5022	5744	6013	6238	13446		

A preventive maintenance program is being considered, if necessary, to achieve the reliability objective. Preventive maintenance will replace the turbine, thus restoring the generator to as good as new condition.

Will a preventive maintenance program be effective? If so, what is the appropriate maintenance cycle?

CASE 4: RELIABILITY ALLOCATION

A high-frequency radio receiver consists of the serially related components shown in the figure below. A reliability testing program conducted during initial development tested each component independently, with the following results. The test was concluded after 8,000 operating hours (accelerated life testing).

If you are the design engineer, how would you use the test data below to determine the design configuration (optimal number of redundant components of each type) that achieves a 95 percent reliability at 1,000 operating hours at minimum cost?

	Power Supply	Tuner	Receiver
Unit cost ($)	175	250	525
Number on test	30	20	15
Failure times	4779	588.0	82.8
	5051	3682.6	820.2
	5633	3819.0	858.3
	6317	4999.5	1201.9
	7491	5048.3	1412.3
	7573	5688.1	1989.1
	7637	7480.7	2042.7
	7953	4641.6	3113.9
			3176.6
			3706.7
			3790.3
			4057.0
			4488.0

CASE 5: REPAIRABLE SYSTEM ANALYSIS

The Notso Reliable Manufacturing Company has been experiencing a high number of failures with its five-year-old industrial robot used for arc welding. Once the unit fails, it is often down for what is considered to be an excessive length of time for repair. Downtime costs the company $750 an hour in lost production and repair costs. A replacement unit will cost $21,000. The company wishes to determine whether it is economical to replace the unit. The unit was advertised as having a 10-year design life. The unit operates 8 hours per day for 240 days out of the year (1920 total operating hours per year).

From the time the robot was first installed, the company has recorded the following failure times, in operating hours, of the unit:

1339	1857	2307	3329	3792	3891
5541	5646	5726	5806	6530	6736
6771	6826	7056	7065	7097	7771
7779	7942	8045	8088	8558	8642
8764 8765	8958	9034 9104		9318	9523

For the last 16 failures it has also maintained a log of the following repair times, in hours:

36.2	47.7	81	7.2	36.1	2.7	4.5	27.6
5.2	7.2	16.7	26.8	7.7	12.6	8.4	10.8

What would you conclude?