Achieving Product Reliability: How Statistics Fits In

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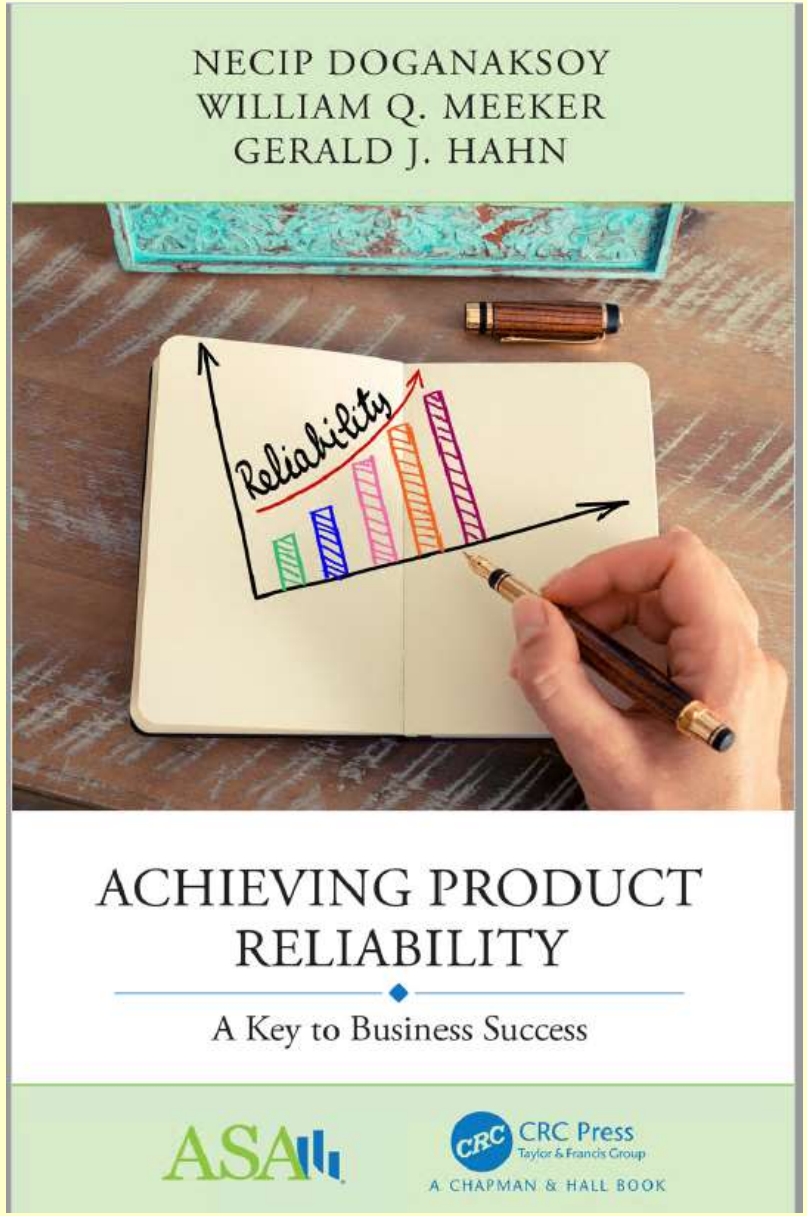
Based on the new book by Necip Doganaksoy, William Meeker, and Gerald Hahn.


NECIP DOGANAKSOY
WILLIAM Q. MEEKER
GERALD J. HAHN
Reliability
ACHIEVING PRODUCT RELIABILITY
A Key to Business Success
ASA
CRC Press
Taylor & Francis Group
A CHAPMAN & HALL BOOK

Overview

- Reliability definition
- Reliability disasters
- Basic concepts of reliability, reliability processes and system reliability
- Where do component reliability values come from?
  - Accelerated testing
  - Field data
  - Degradation data
- Bayesian methods in reliability
- Concluding remarks

Reliability

- ***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 (Meeker, Escobar, and Pascual 2021)
- Quality over time (Condra 1993)
- Failure avoidance
- A highly quantitative engineering discipline, often requiring complicated statistical and probabilistic analyses

Today's customers expect high reliability

Chilling Tale

This is the kind of thing we are trying to avoid

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Chilling Tale

GE Refrigerator Woes Illustrate the Hazards In Changing a Product

Firm Pushed Development Of Compressor Too Fast, Failed to Test Adequately

Missing: the 'Magical Balance'

By Thomas F. O'Boyle

GE Refrigerator Compressor Problem

- Early 1980s, GE was losing market share to competitors—Jack Welch was unhappy
- 1983-1986 GE designed, tested, and began to produce a new higher efficiency, lower cost, ***rotary compressor***
- Stopped accelerated testing after one year and no failures
- One million + in service by 1987
- First failure after 1.5 years
- Virtually all would have eventually failed prematurely
- GE replaced all compressors in refrigerators that it could find. Total cost was more than $450 Million
- What went wrong?

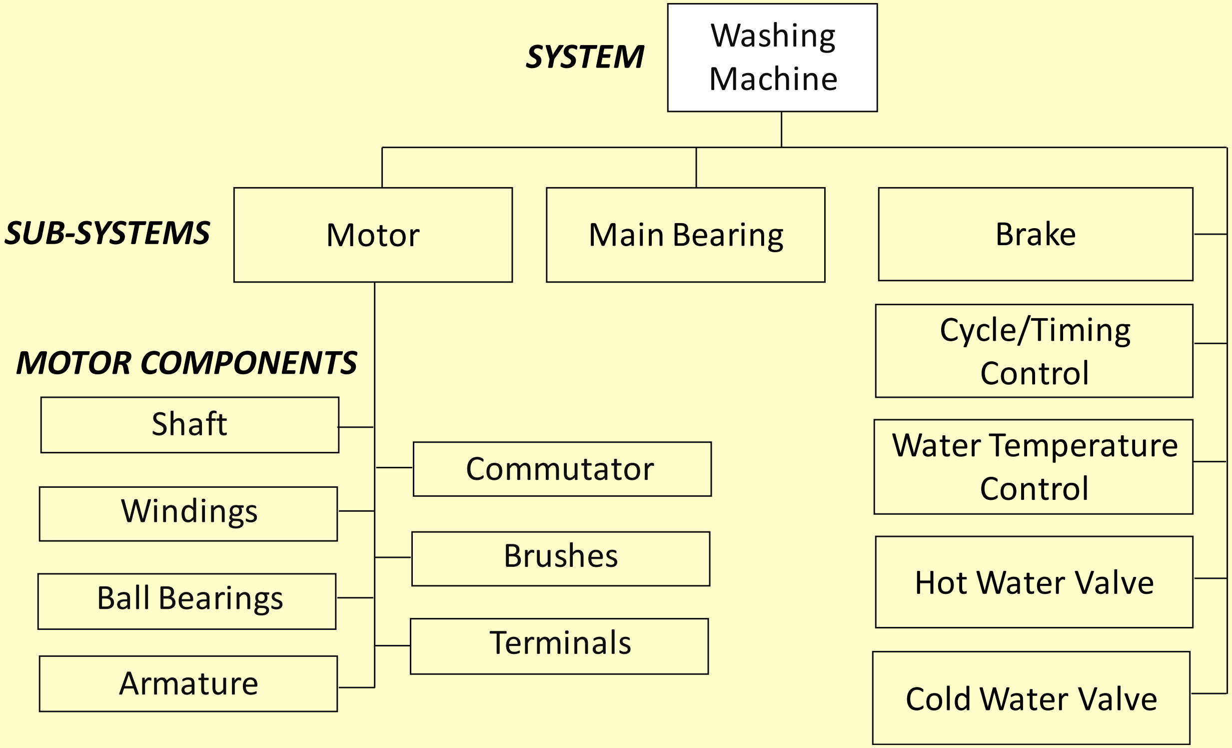
Reliability Processes

- Historically, reliability got focus when
  - It was obviously necessary (e.g., aerospace)
  - A serious problem arose in the field
- Reliability is not at the core of engineering education
- Engineers are expected to design and manufacture things that "work"
- Now, many companies recognize high reliability provides competitive advantage
  - Reliability by Design
  - Design for Reliability

Basic Concepts of System Reliability

- A system is made up of subsystems
- A subsystem is made up of components
- System reliability depends on
  - System structure
  - Reliability of the system's components
- A system reliability model uses **basic probability concepts**

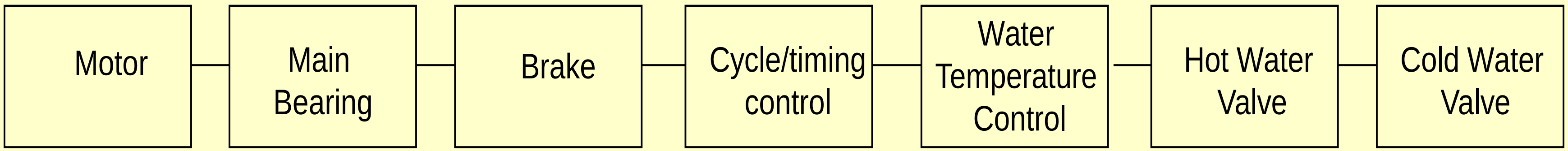
Subsystems of a Washing Machine Components of the Motor Subsystem



Reliability goal: 90% of all washing machines operate with no failures for 10 years

Washing Machine Reliability Block Diagram

(Series system with seven components)



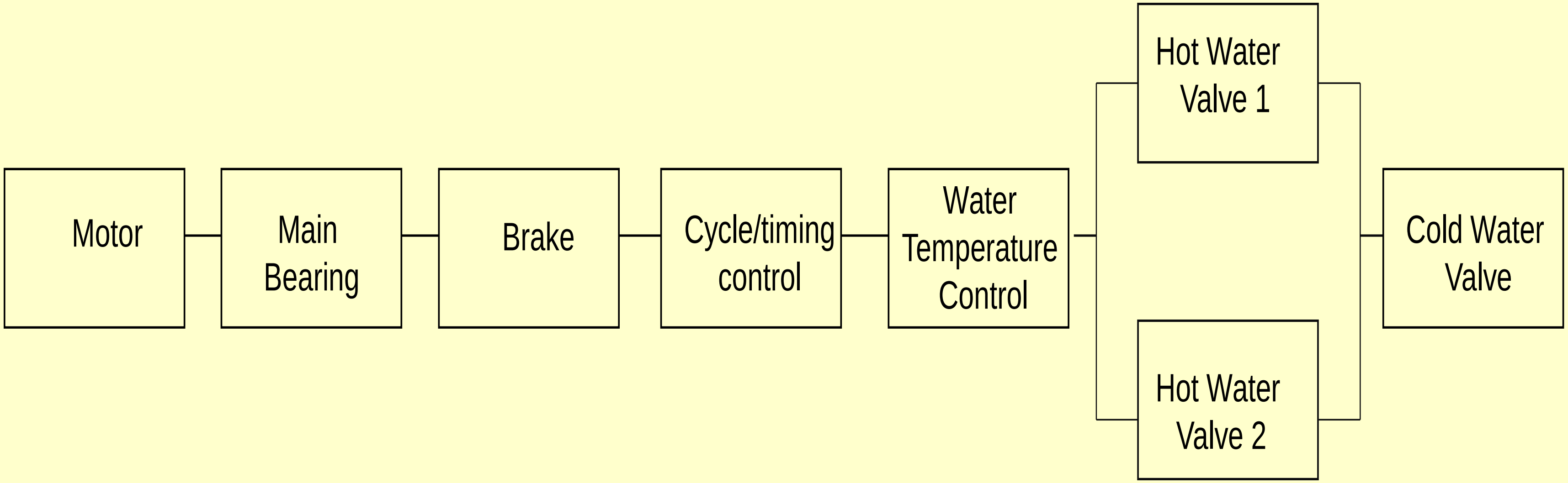
Computation of 10-year reliability

$$R_{system} = R_M \times R_{MB} \times R_B \times R_{CTC} \times R_{WTC} \times R_{HWV} \times R_{CWV}.$$

$$R_{system} = 0.970 \times 0.990 \times 0.990 \times 0.985 \times 0.985 \times 0.950 \times 0.995 = 0.872.$$

The hot water valve is the “weak link.”

Washing Machine Reliability Block Diagram With Redundant Hot Water Valves



Adding hot water valve redundancy changes R_{HWV} from 0.950 to

.

$$(1-(1-0.950)^2)=0.9975$$

This improves 10-year system reliability from 0.872 to 0.915

Where Do Component Reliability Values Come From?

- Information from vendors
- Knowledge of physics of failure and computer simulation
- Engineering judgement and simple tests
- **Laboratory accelerated tests**
- **Previous experience with the same component in another product (field data)**

Motor Accelerated Life Test

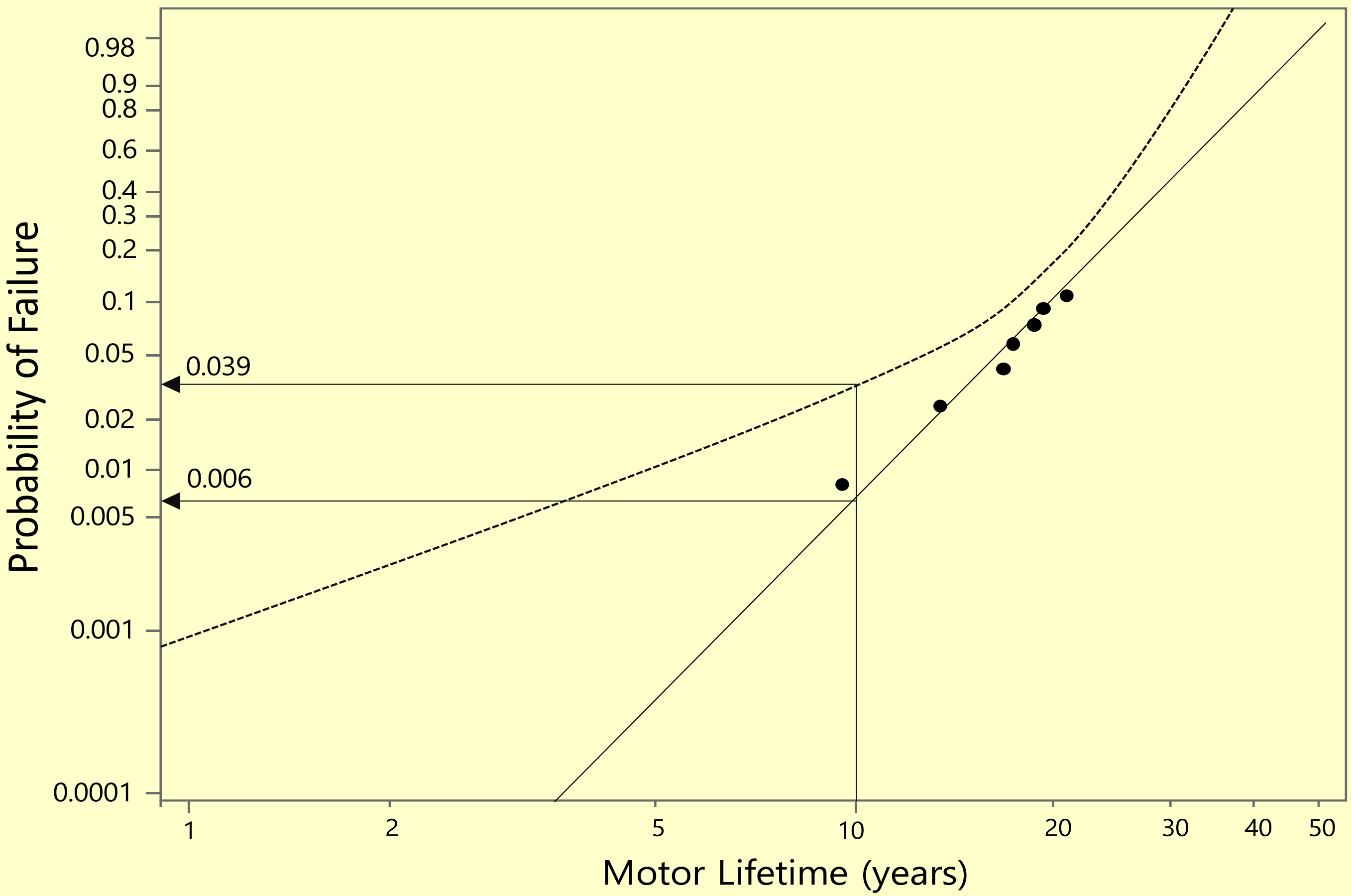
- 6 months of testing with 66 motors
- Each month of nearly continuous testing equivalent to 3.5 years
- 14 failures in 10.7 (simulated) years of testing
- Plastic part failures were unanticipated but this failure mode could be easily eliminated

Disposition	Number of Motors	Failure Times (years)*
Plastic part failures	7	4.5, 6.7, 7.5, 10.6, 10.7, 17.8, 19.7
Bearing failures	7	9.6, 13.5, 16.8, 17.4, 18.7, 19.3, 20.9
Unfailed	52	21+

Probability Plots
An Important Reliability Tool

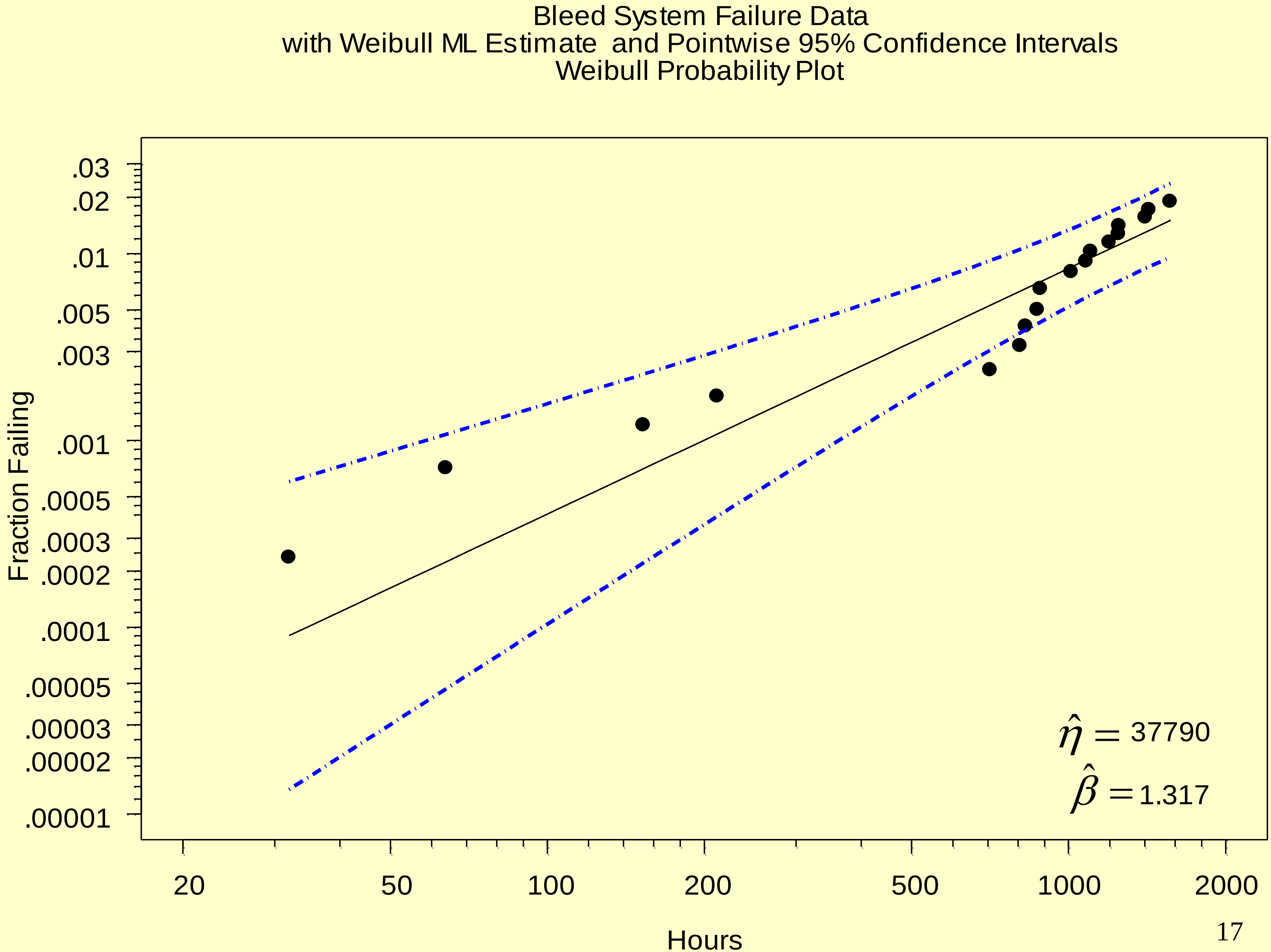
- Probability plots are the most widely used reliability data analysis tool
- Plot a “nonparametric” estimate on a distribution-specific scale
- Assess whether the nonparametric estimate points are approximately linear
- Can see evidence of different failure modes, if the modes behave differently

Weibull Motor Reliability Assessment (focus on the life-limiting bearing failures)



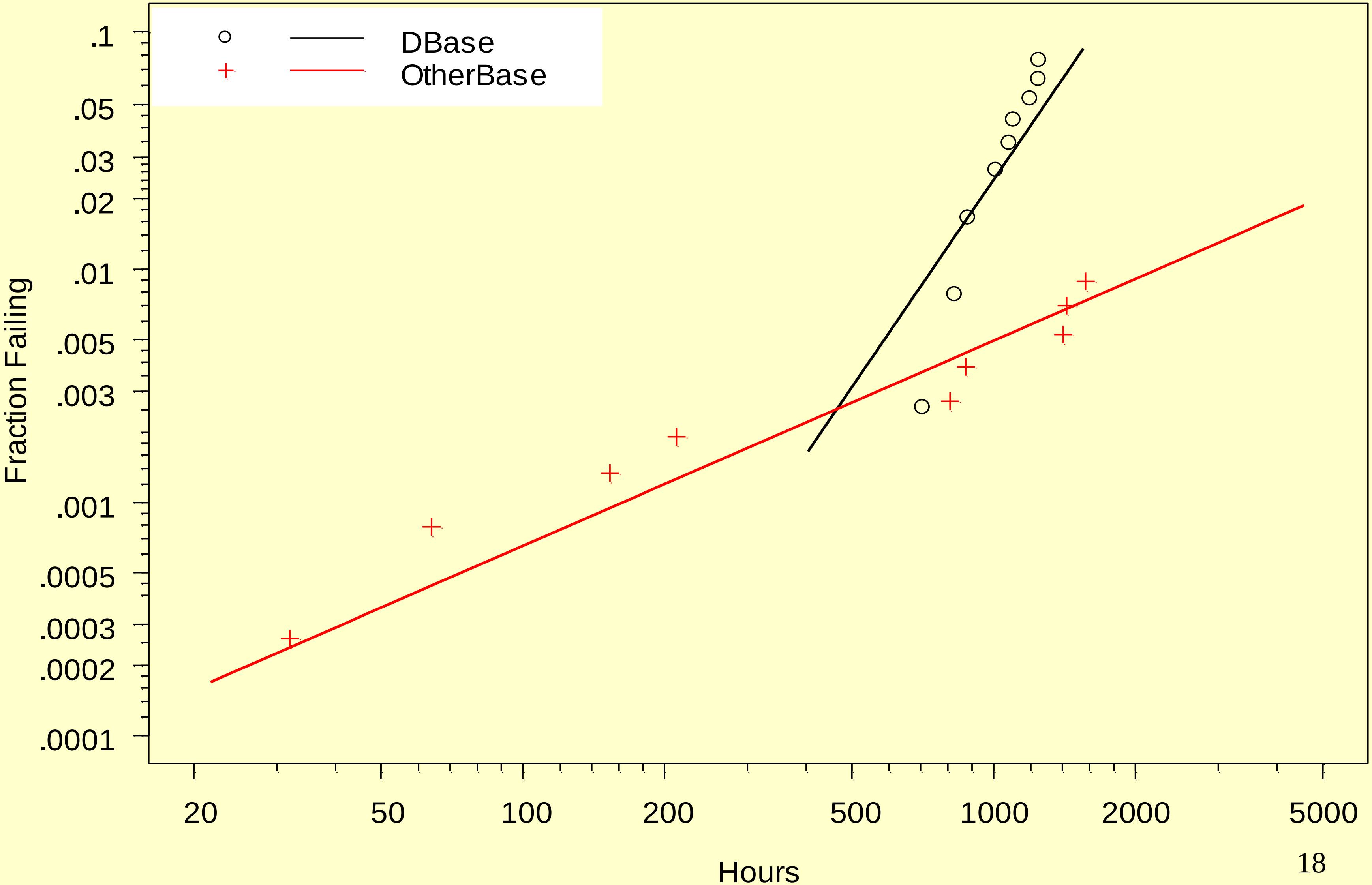
Jet Engine Bleed System Field Failures

- Field data from 2256 aircraft engines in the field; staggered entry--multiple censoring
- Unexpected failures
- What is going on??



Bleed System Failure Data
with Weibull ML Estimate and Pointwise 95% Confidence Intervals
Weibull Probability Plot
Fraction Failing
.03
.02
.01
.005
.003
.001
.0005
.0003
.0002
.0001
.00005
.00003
.00002
.00001
20
50
100
200
500
1000
2000
Hours
$\hat{\eta} =$ 37790
$\hat{\beta} =$ 1.317

Bleed System Failure Data
With Individual Weibull Distribution ML Estimates
Weibull Probability Plot



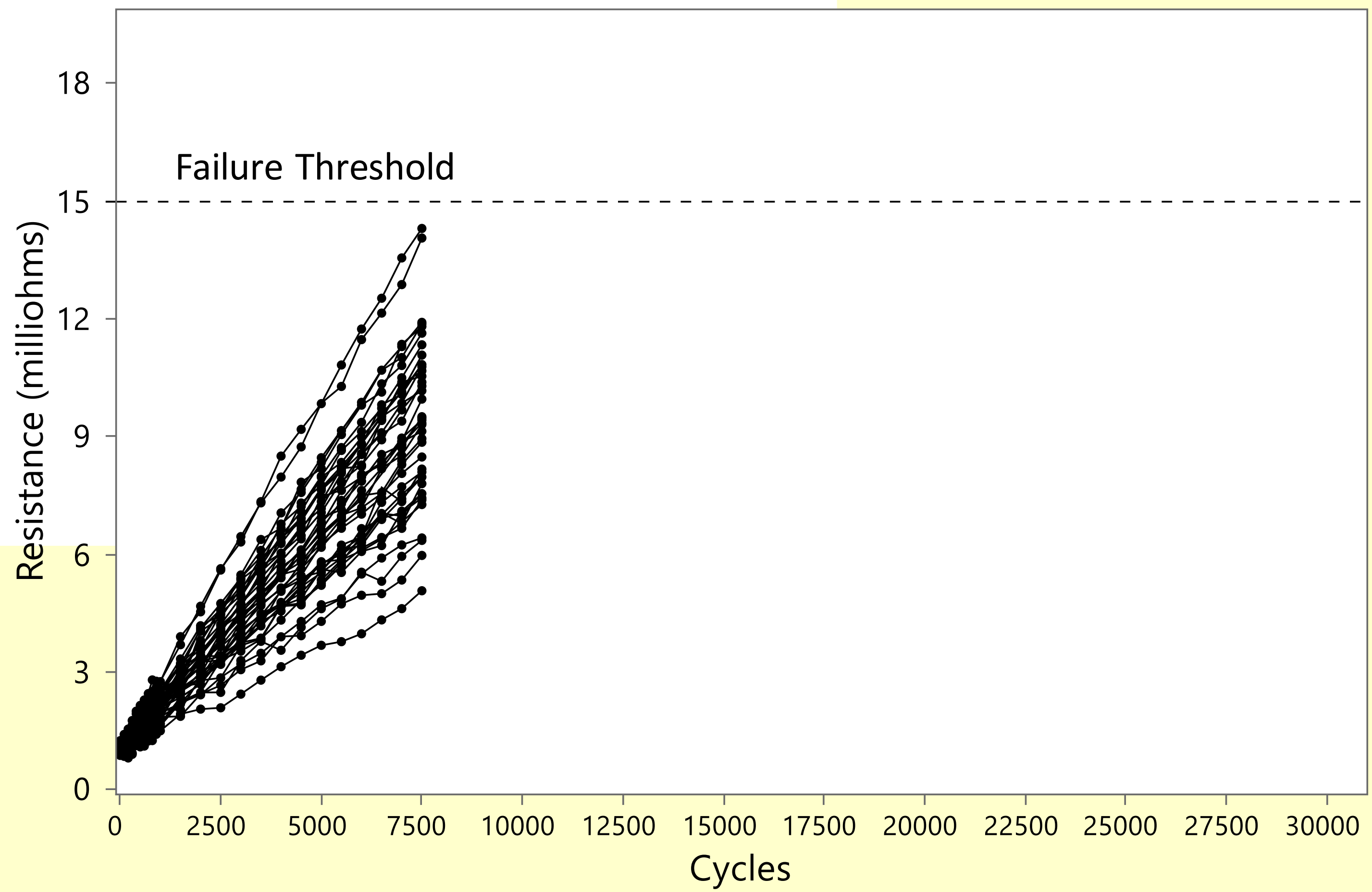
Lessons Learned

- A shift in slope of a probability plot often indicates a different failure mode
- Look for explanatory variables to help better understand data sources

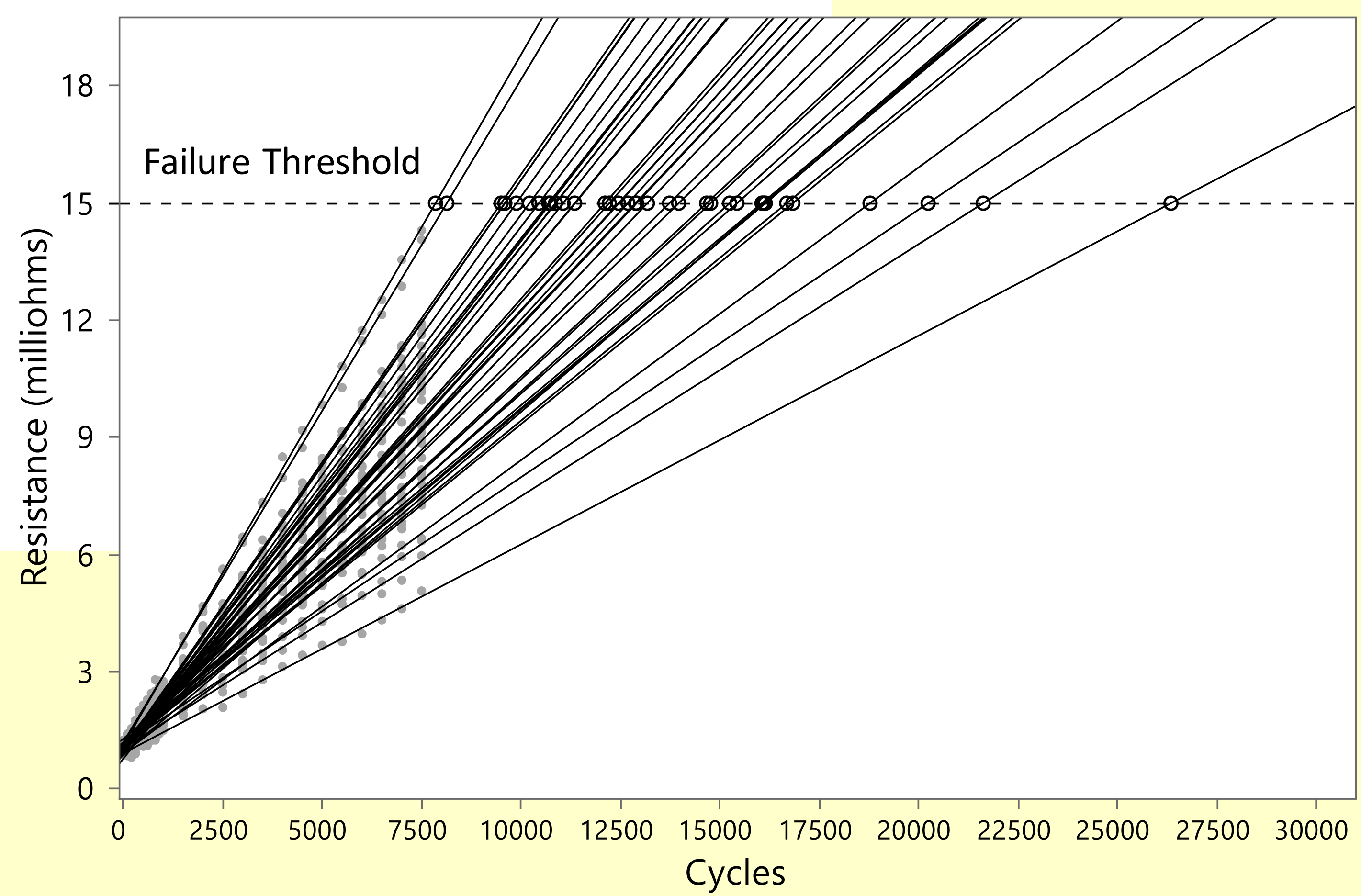
Accelerated Test to Evaluate the Lifetime of a Battery---**Degradation Data**

- Newly designed battery for a non interruptible power supply.
- Time is number of charge-discharge cycles.
- Test 40 batteries for 7,500 cycles (the design life).
- A new battery has a resistance of 1 milliohm.
- Failure is defined when resistance reaches 15 milliohm.
- Exploratory graphical analysis showed that resistance increased linearly in time.
- What is the probability of surviving 7,500 cycles (i.e., battery reliability)?

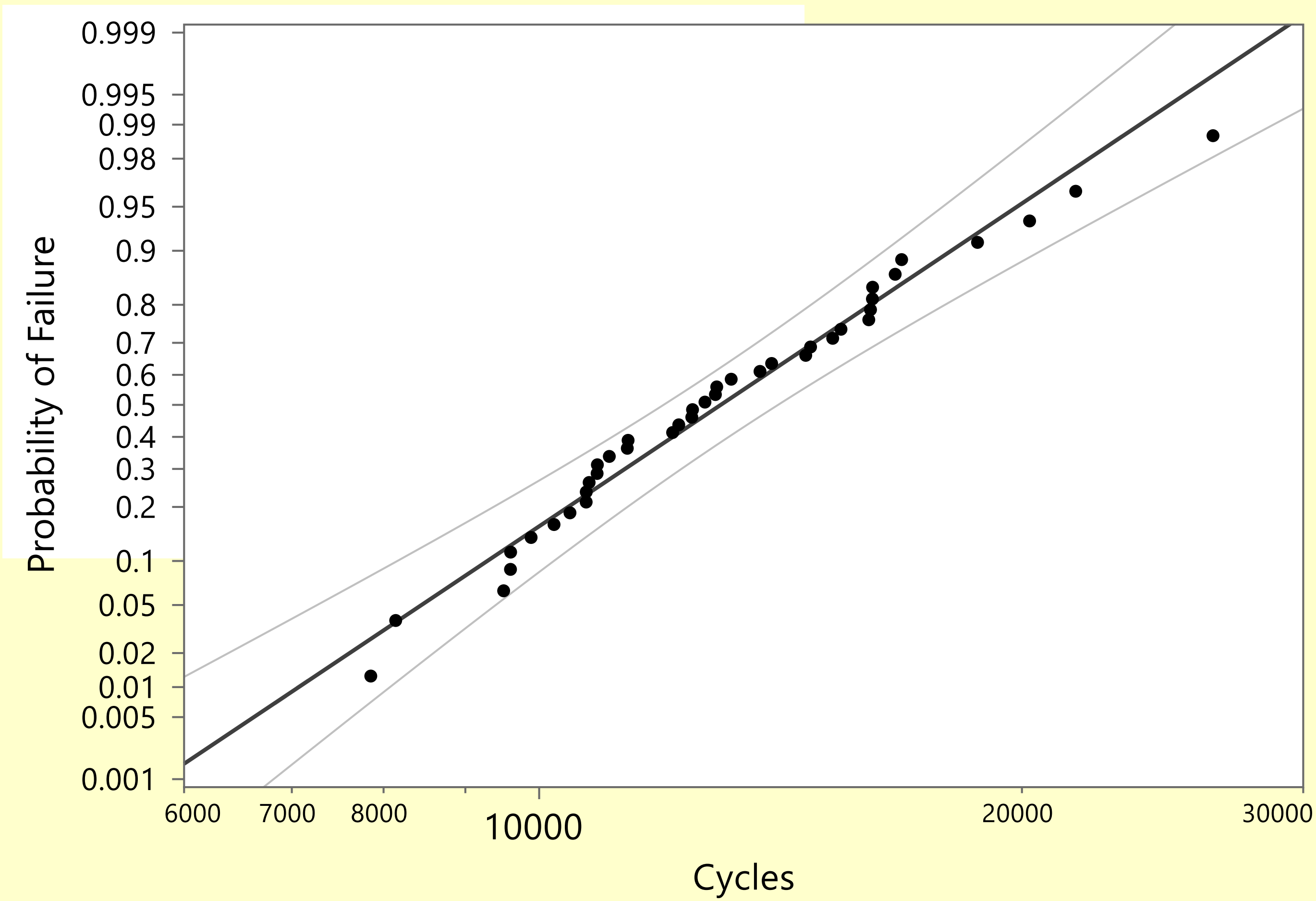
Battery Accelerated Test Degradation Data



Resistance Paths at 7,500 Cycles Extrapolated to Failure



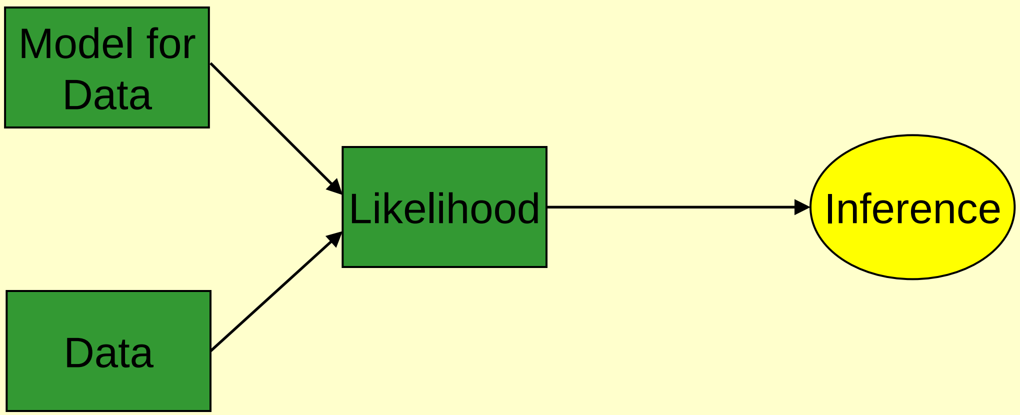
Lognormal Probability Plot for 40 Battery Pseudo-Lifetimes



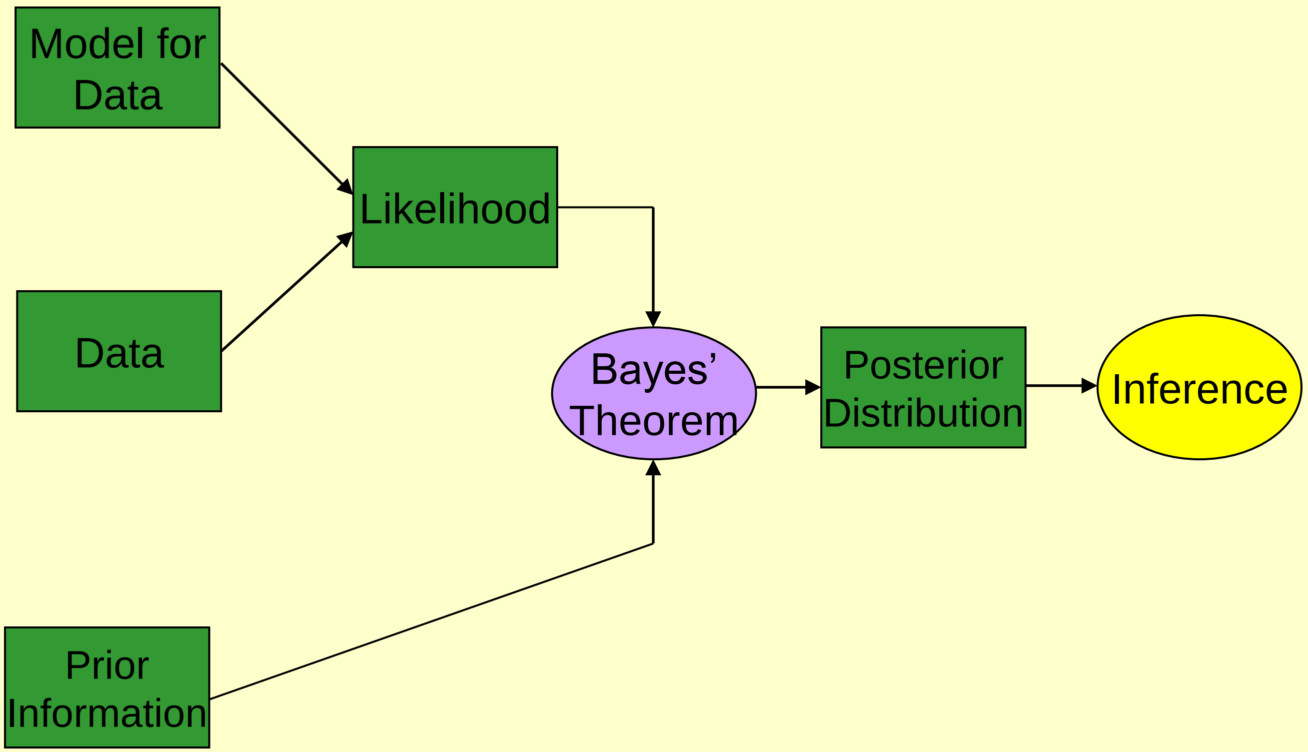
Lessons Learned

- Even with no failures, degradation data are useful to estimate reliability
- A purposeful choice of a failure definition links the degradation model to the failure-time model
- With modern software the degradation analysis is straightforward

Likelihood Inference



Bayesian Inference



Importance of a Good Parameterization

- One needs to think carefully about how to define **parameters** in a model
- Use of interpretable parameters generally leads to
  - More sure and faster convergence of estimation algorithms
  - Quantities for which it **is easier to elicit prior information**

Sources of Prior Information

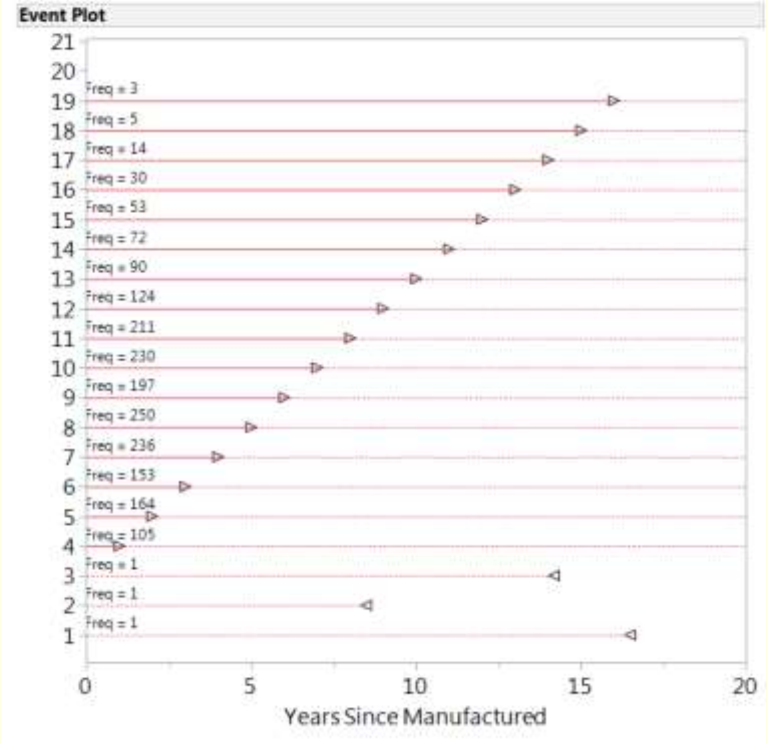
- Most reliability applications have **informative** prior information for **just one parameter**.
- Usually there is a need to specify noninformative or weakly-informative prior distributions for other parameters
- Sources for informative prior distributions:
  - Previous experience with the same failure mechanism and test or environment
  - Knowledge from physics of failure
  - Expert opinion
- **Beware of wishful thinking masquerading as prior information**

Rocket-Motor Lifetime Data

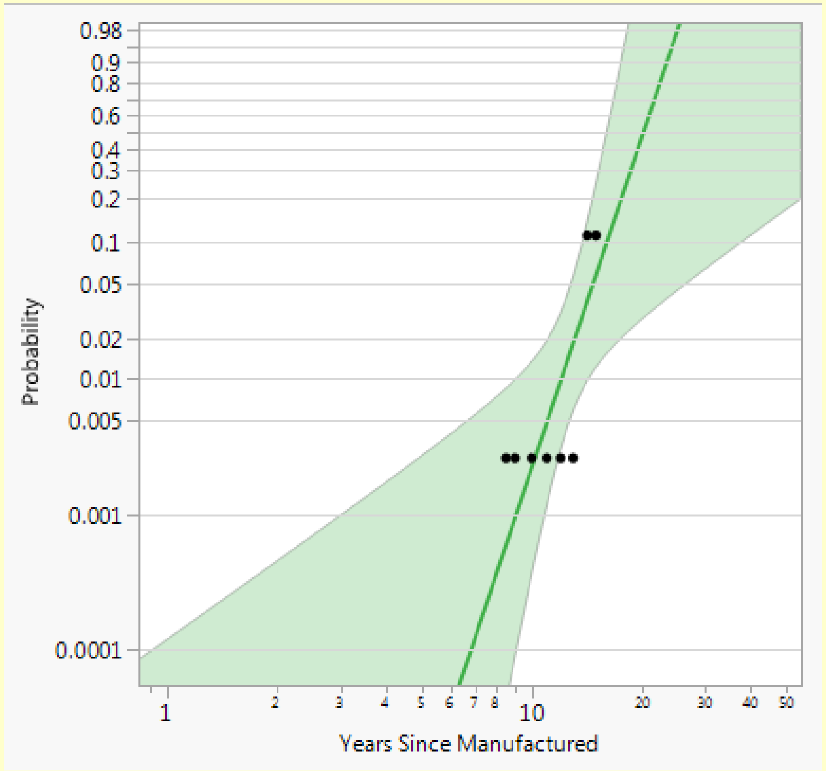
Years	Number of Motors	Years	Number of Motors	Years	Number of Motors
> 1	105	> 8	211	> 14	14
> 2	164	> 9	124	> 15	5
> 3	153	> 10	90	> 16	3
> 4	236	> 11	72	< 8.5	1
> 5	250	> 12	53	< 14.2	1
> 6	197	> 13	30	< 16.5	1
> 7	230				

Rocket Motor Life Data Analysis

Event Plot



Weibull Probability Plot

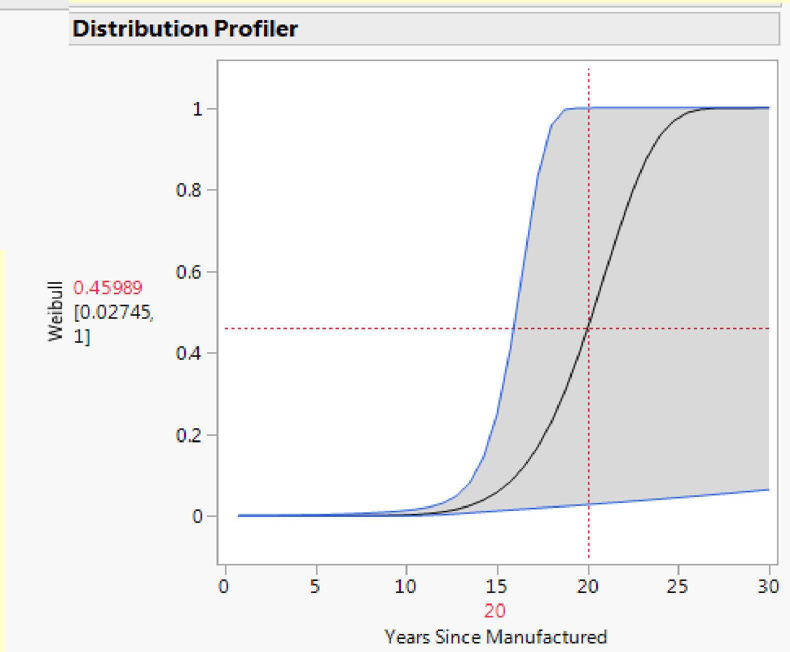


Rocket Motor Weibull ML Analysis

Parametric Estimate - Weibull

Parameter	Estimate	Std Error	Lower 95%	Upper 95%
location	3.055358	0.2162706	2.631476	3.479241
scale	0.123058	0.0480368	0.028908	0.217209
Weibull α	21.228791	4.5911625	13.894260	32.435089
Weibull β	8.126236	3.1721454	4.603869	34.592771
Mean	20.007199	3.9737989	13.555700	29.529128

Criterion	
-2*LogLikelihood	31.508244
AICc	35.514439
BIC	46.649130

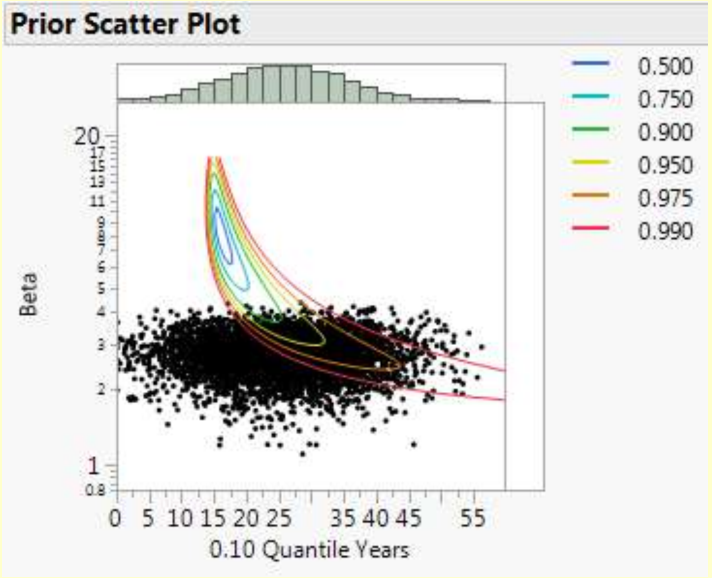


Weibull shape parameter estimate was 8.1
(unexpectedly large)

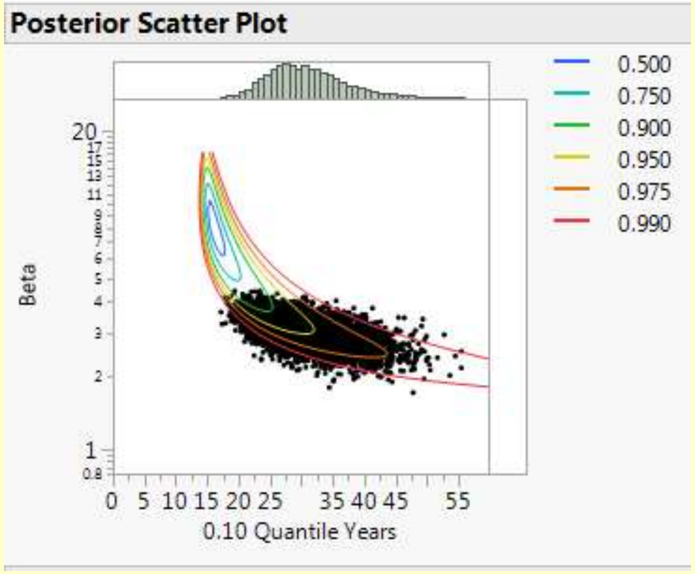
Rocket Motor Bayesian Weibull Analysis

- The ML estimate of beta=8.1 was much larger than expected and was physically unreasonable.
- ML estimate of fraction failing at 20 years was 0.46
- LR Confidence Interval=(0.023, 0.9999); not useful
- Prior distributions (99% intervals):
  - **Informative:** $\beta \sim TNORM<1, 5>$
  - Weakly informative: $B10 \sim TNORM<5, 400>$
- 10,000 MCMC draws obtained from the joint posterior distribution

Rocket Motor Comparison of the Likelihood Contours and Samples from the Prior and Posterior Distributions Using Prior Information on β



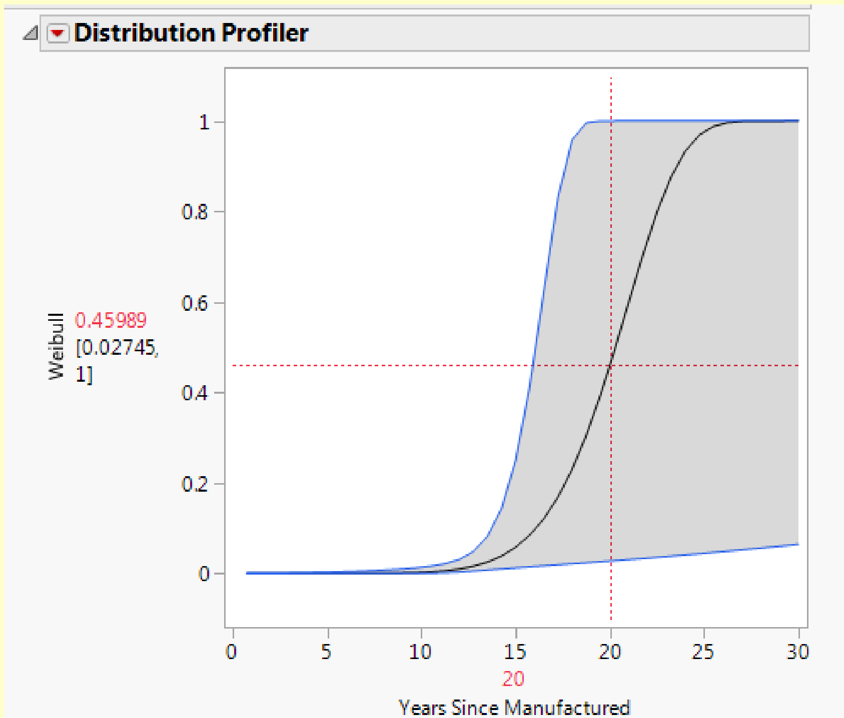
Prior Sample



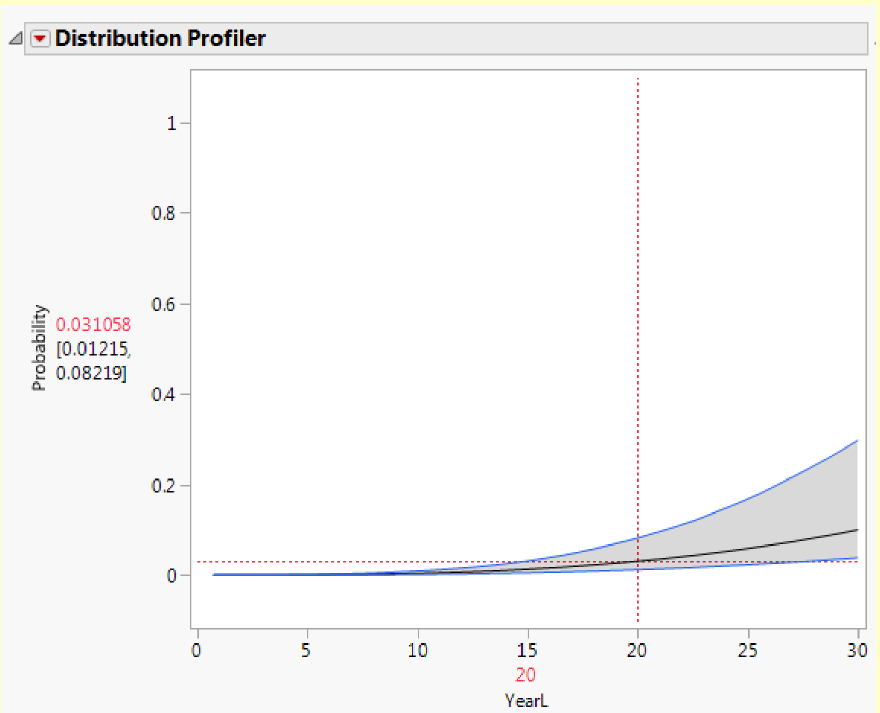
Posterior Sample

Rocket Motor Comparison of ML Estimates and Bayesian Estimates Using Prior Information on β

Maximum Likelihood



Bayesian Informative for β



Lessons Learned

- Even when no actual failure times, there is still reliability information in the data.
- With very few failures, there is little information in the data
- The limited information can be supplemented by using knowledge about the failure mode and other engineering information
- Modern computing tools make Bayesian analyses easy.

Summary: Statistics in Reliability

- Up-front consideration of reliability is important in engineering design processes
- Statistics plays an important role in proactive product reliability assessment and improvement
- Statistical methods in reliability are often different from those typically taught in introductory courses
- Specialized software like JMP makes it easy to properly analyze reliability data

Thanks for Watching?