Introduction to Reliability Fundamentals

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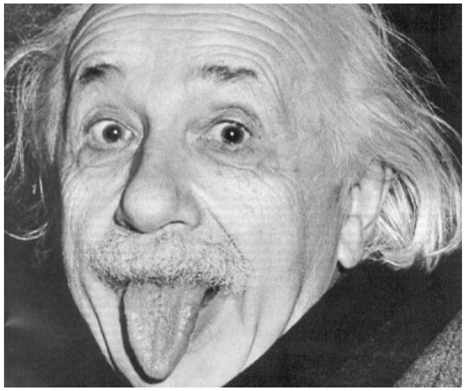


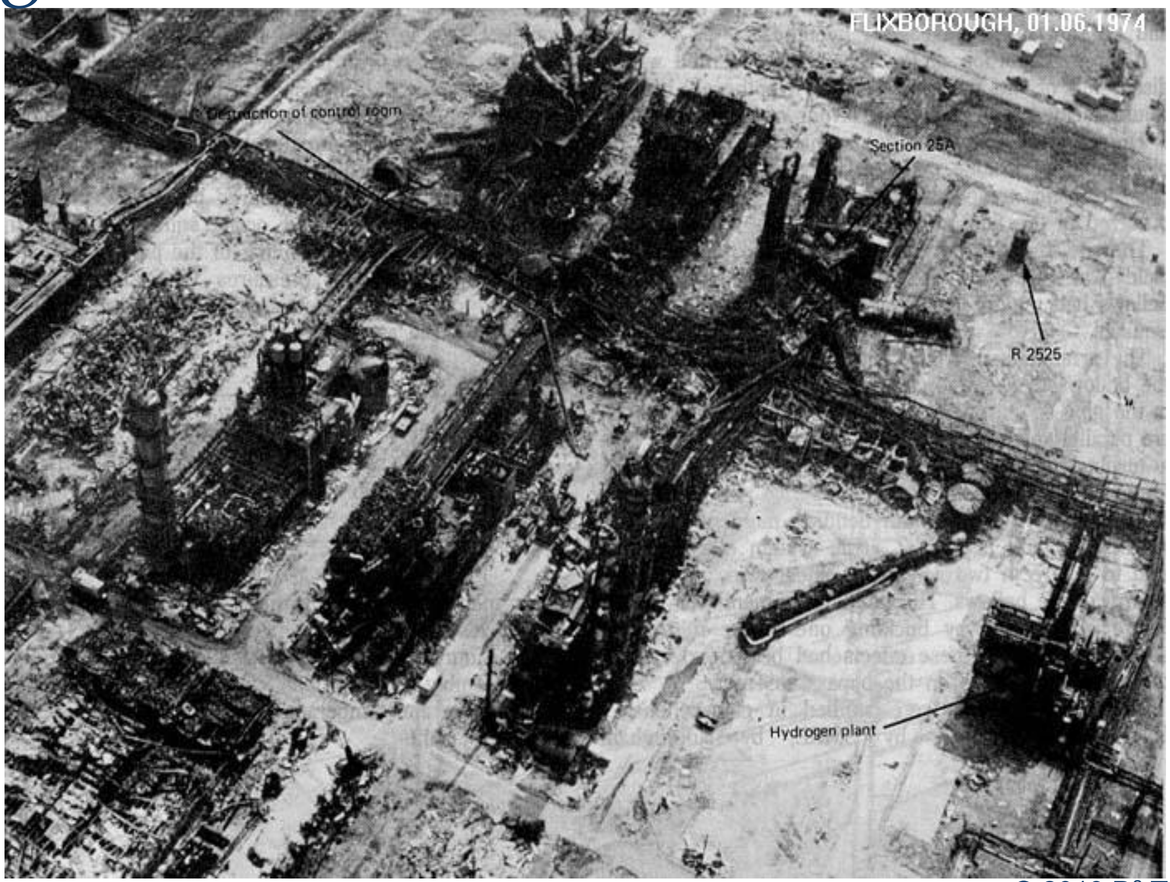
Reliability Fundamentals Overview

- Why Reliability
- The Problem
- Reliability = Safety
- The Process from 50K
- Weibull History
- Reliability Definitions
- Weibull Analysis
- Dirty Data
- Data Inconsistencies
- Inspection Interval Data and Course Data
- WEIBAYES
- Crow – AMSAA Reliability Growth Model
- Data Set Issues
- Example Analysis
- SAP/Meridium Methods
  - How to Rearrange a Historical Multiyear Work Order (SAP/Meridium)

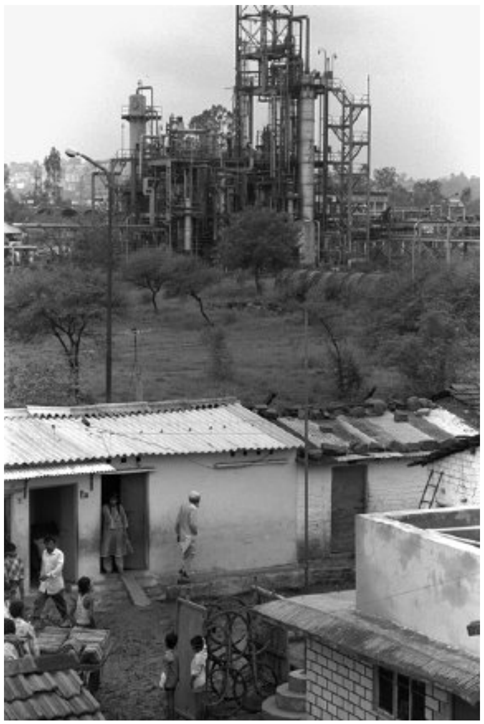
Why Should I be Concerned with Reliability?

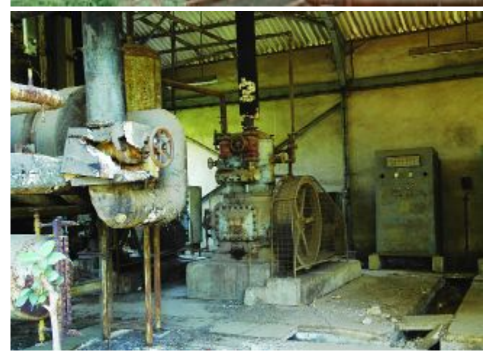
Filxborough - 1974

Filxborough - 1974



Bhopal - 1984





Piper Alpha - 1988

Henderson, Nevada – 1988

Milford Haven, UK – 1994

Milford Haven, UK – 1994

Toulouse, France - 2001

Toulouse, France - 2001

Texas City - 2005

Texas City - 2005

Texas City - 2005

Puerto Rico - 2009

Puerto Rico - 2009

Puerto Rico - 2009

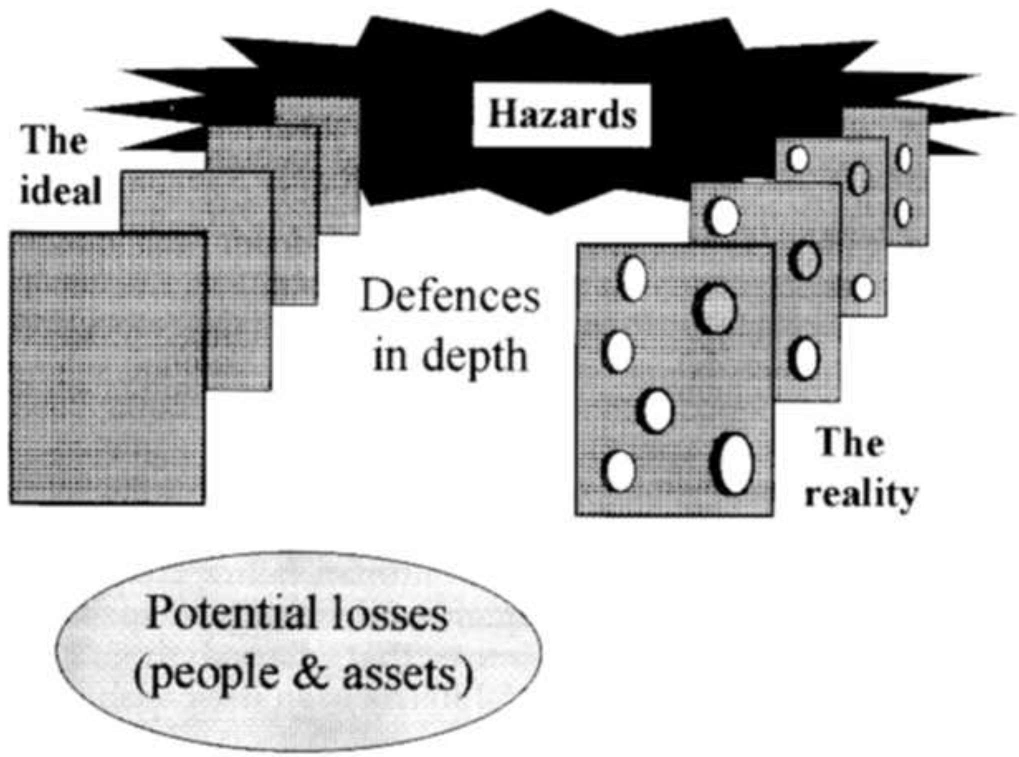
Torrance, CA - 2015

Crosby, TX - 2017

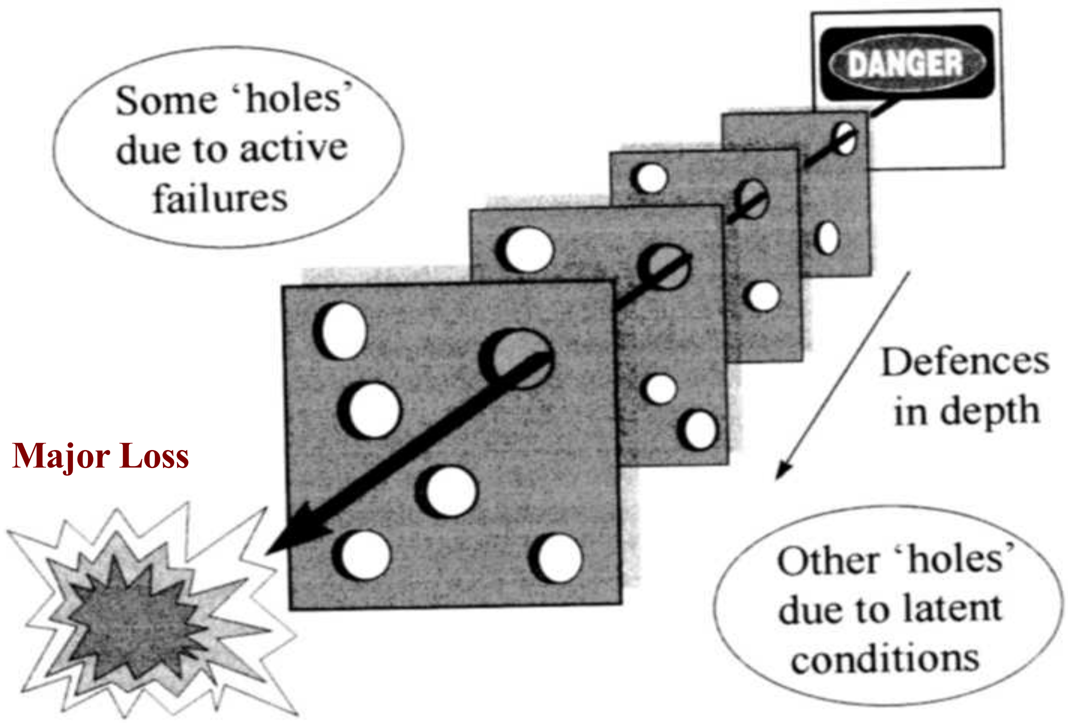
Superior, WI - 2018

The Problem

The "Swiss Cheese" Theory of Risk



Accident Trajectory



The Problem

- Management measured by KPI's
  - One numerical indicators budgets
  - Maintenance, engineering and reliability programs
- Invoke budget cuts by arbitrary percentages
  - Without due consideration to the effects
  - Without reflecting on impact of cost cutting
- Significant Compensation Component
  - Bonus & Stock Options
- Growing Experience/Knowledge GAP
- Management never directly request cuts on safety!
- Unfortunate few grasps reliability tied safety

The Problem

- Few accidents occur when things run smoothly and the equipment has a high level of reliability.
- Accidents occur in reactive maintenance realm
  - Where assets fail unexpectedly
  - There is a rush to get the process running
- Manufacturing plants are asset-intensive
  - Reliability increases so do safety.
  - When assets become more reliable
  - End-users service them less
  - Workforce is exposed to hazards less

Reliability = Safety

Reliability = Safety

- Three maintenance environments

- Reactive Maintenance - all behavior is reactive
  - Reliability is nonexistent
  - No planned maintenance or failure mode activities
  - All activities are reactive or breakdown maintenance
  - Safety is instinctive

Reliability = Safety

- Three maintenance environments

- Planned Maintenance - behavior is guided through the planning and scheduling process
  - Safety procedures are embedded in maintenance plan and thus enforced
  - Reliability is scheduled, scheduled maintenance activities can support reliability initiatives.
  - Focusing maintenance activities on failure modes

Reliability = Safety

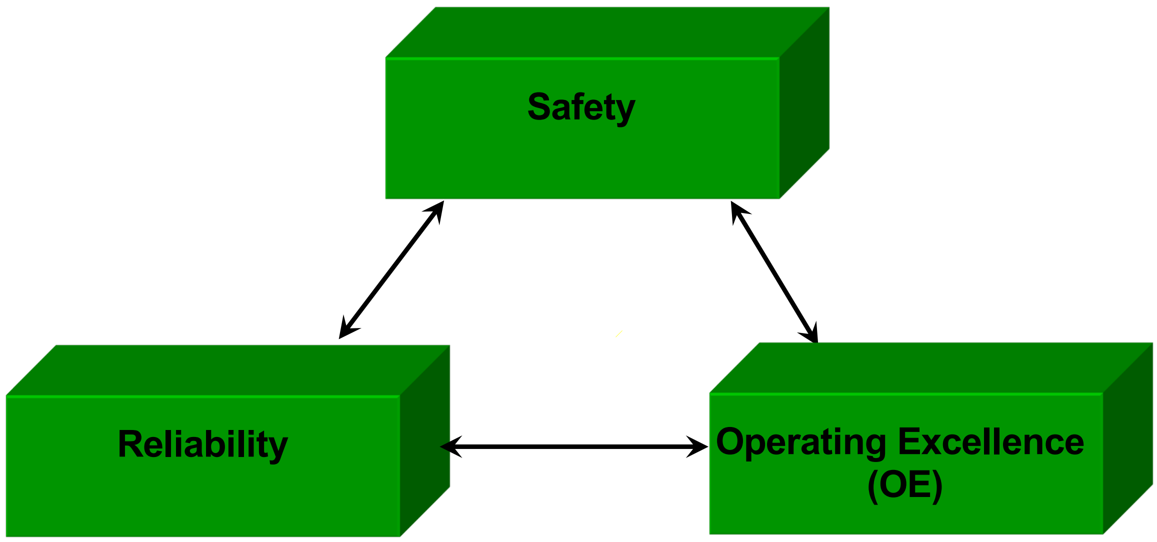
- Three maintenance environments
- Pro-active Maintenance - behaviors are a self-disciplined
  - Focus on continuous reliability improvement
  - Embedded safety all aspects maintenance/production
  - Maintenance focus on how they can be improved
  - Strong focus on condition monitoring
    - Only intervening when failure mode trends up
  - Reliability & Safety are embedded & pro-active
    - Second nature where responsibility is everyone's role
    - Viewed value add to the business

Reliability = Safety

- Studies on Maintenance-related major accidents
  - 30-40 percent determined maintenance was a factor
    - Includes preparation and performance of maintenance
    - Contains incidents caused by lack of proper maintenance
  - 76% occurred during the maintenance activity
  - 24% occurred during site preparation or transition to or from production activities
  - Maintenance activities expose workers to higher risks

Studies by Okoh & Haugen, "Maintenance-related major accidents: Classification of causes and case study"

Three Legs to the Stool

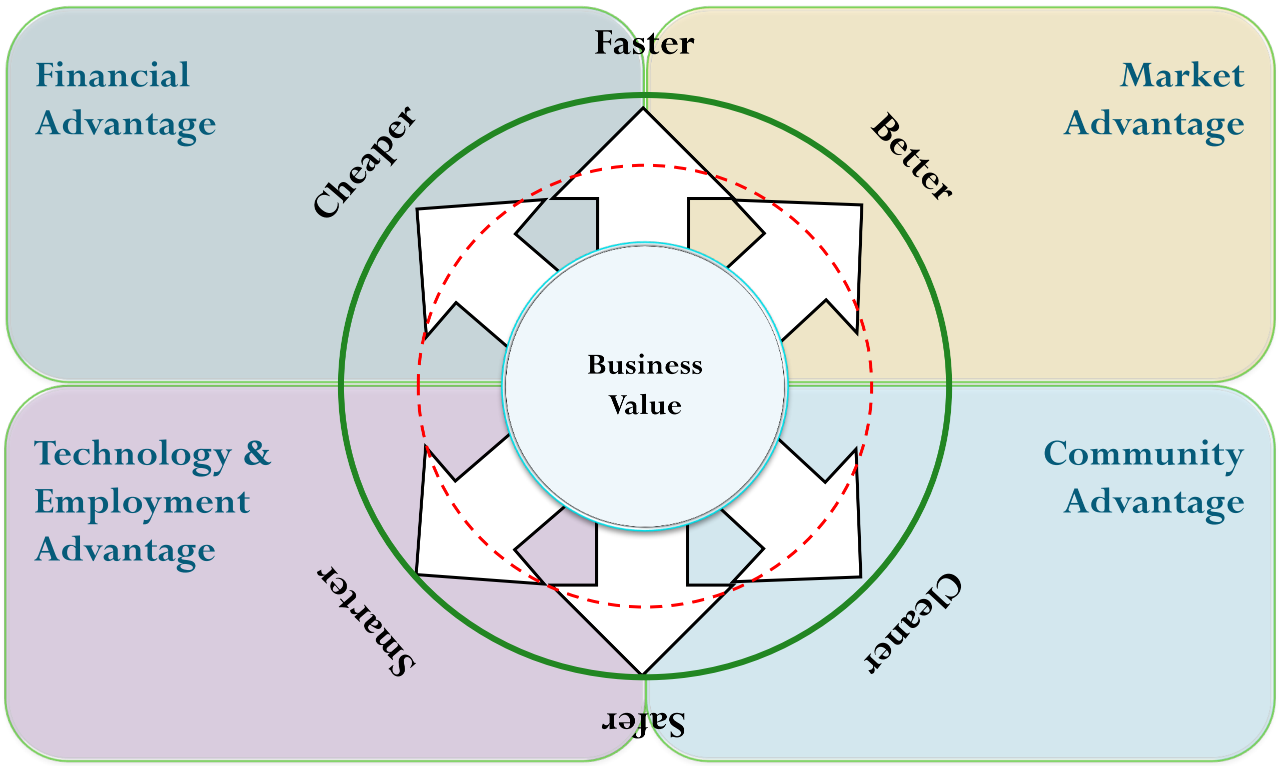


Reliability = Safety

The Process from 50K

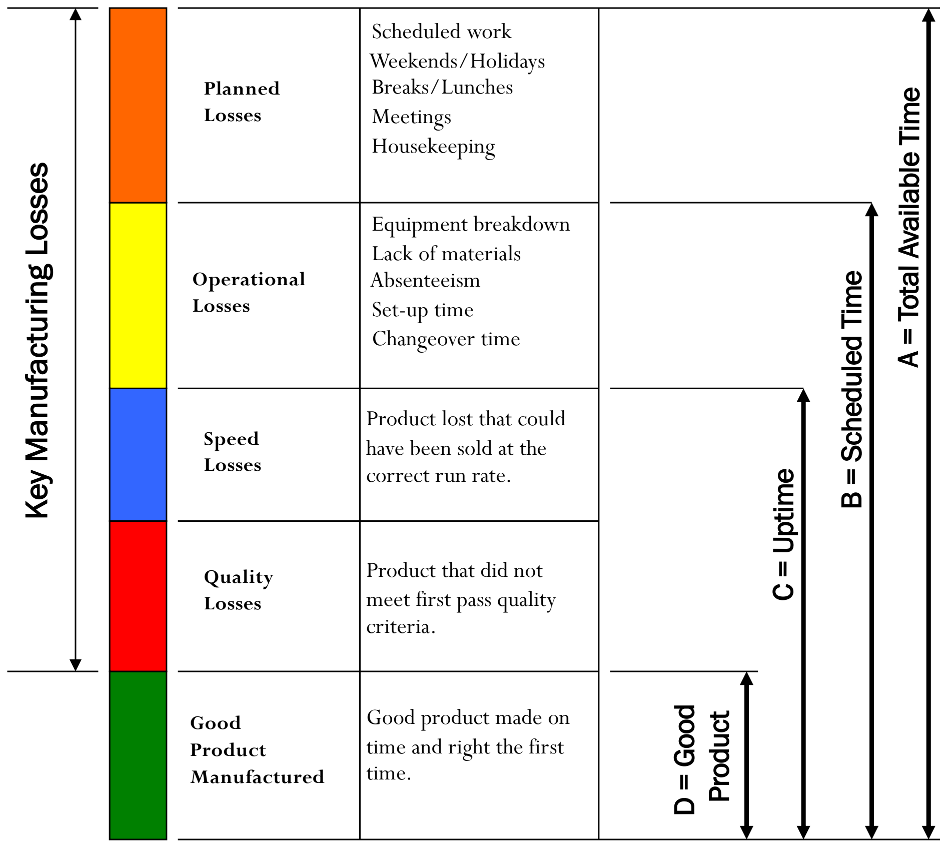
Reliability Management Program

Excellence in **Asset Management** Drives Competitive Edge



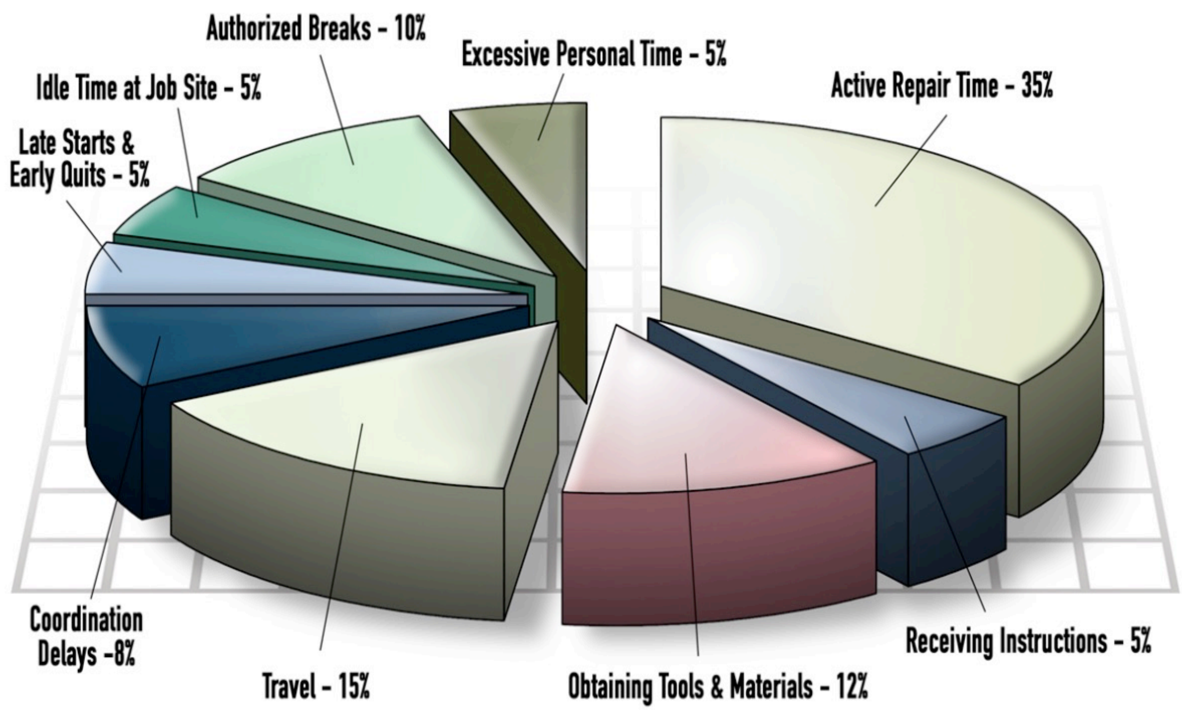
Overall Equipment Effectiveness (OEE)

- Uptime
- Throughput
- First-pass Yield



Maintenance Inefficiencies:

North American Average Wrench Time = 25%



World Class -- Key Performance Indicators

Manufacturing:

OEE/Asset Utilization		85/95%
On-time Deliveries	99%	
Customer Complaints		0.01%
Process Quality - Cpk		>2
OSHA Injuries per 200k hrs		
Recordables		<0.5
Lost Time		<0.05

Human Resources:

Overtime	<5%	
Skills Training	($/yr)	$2-3K
	(hrs/yr)	>40

Maintenance:

Mtce Costs, % ARV*	<1-3%
Unplanned Downtime Loss	<1-2%
Planned Maintenance	>90%
Reactive Maintenance	<10%
$ARV per Mtce Tech	>$6-8M
% Maintenance Rework	<1%

Stores:

Parts Stock out Rate	<1%
Parts Inventory Turns	>2
Value as a % of ARV	<0.5%

*ARV= Plant Asset Replacement Value

How does your plant compare to these?

Metrics – Leading & Lagging

Behavioral Metrics (Recommended Target)	Results Metrics

Behavioral Metrics (Recommended Target)

- % Labor-Hours PM (15%)
- PM Coverage % (+95%)
- **PM Route Compliance (+95%)**
- **PM Route Adherence (+90%)**
- % Labor-Hours PdM (15%)
- Mean Time to Implement (<45 days)
- PdM Coverage % (Top 2nd Quartile)
- PdM Route Compliance (+95%)
- Labor Utilization (+95%)
- Ready Backlog (>2 Crew Weeks)
- Total Backlog (<6 Crew Weeks)
- Schedule % (100%)
- **Schedule Compliance % (+95%)**
- **Proactive Work % (40%)**
- **Planned Work % (+90%)**
- Overdue Work Order % (<10%)
- % Rework (<5%)

Results Metrics

- Asset Health % (+90)
- Overall Equipment Effectiveness (OEE)
- Maintenance Availability
- Wrench Time 45-55%
- Mean Time To Repair (MTTR)
- MTBF
- Reliability %
- Maintenance Costs/Unit Shipped

Criticality

- Purpose
  - Develop relative ranking of equipment for use during:
    - Equipment Maintenance Plan (EMP) creation
    - Input for corrective work planning and execution
    - Prioritization of assets to review/create bill of materials (BOMs)
    - Input for critical spare identification yielding data for stock versus non-stock parts and service level agreements (SLAs)

Criticality

- Ranking items to determine which items get preferential treatment with respect to resource allocation
- Items are generally assets and the resources are labor, materials and schedule priority
- Criticality analysis be performed at:
  - System
  - Asset
  - Failure Mode
- Level of effort increase, with the system level requiring least amount of time.

Criticality Analysis – Biggest Opportunity

- Opportunities to reduce criticality
  - Install redundant asset
  - Complete BoMs
  - Adjust part plan or establish SLAs

- When to periodically review?
  - New Equipment
  - About every 3 years
  - Change in Operating Context Change
  - Change in failure probability
    - Successful RCA and RCM projects

Defining Asset Reliability

Asset Reliability – the probability that an asset will perform without failure within a given period of time, under known conditions.

Asset Performance – the state of asset operation that adds value to the organization.

Asset Accountability – the responsibility of an organization for asset performance.

Source: ISO PC 251 – ISO 55000 Asset Management

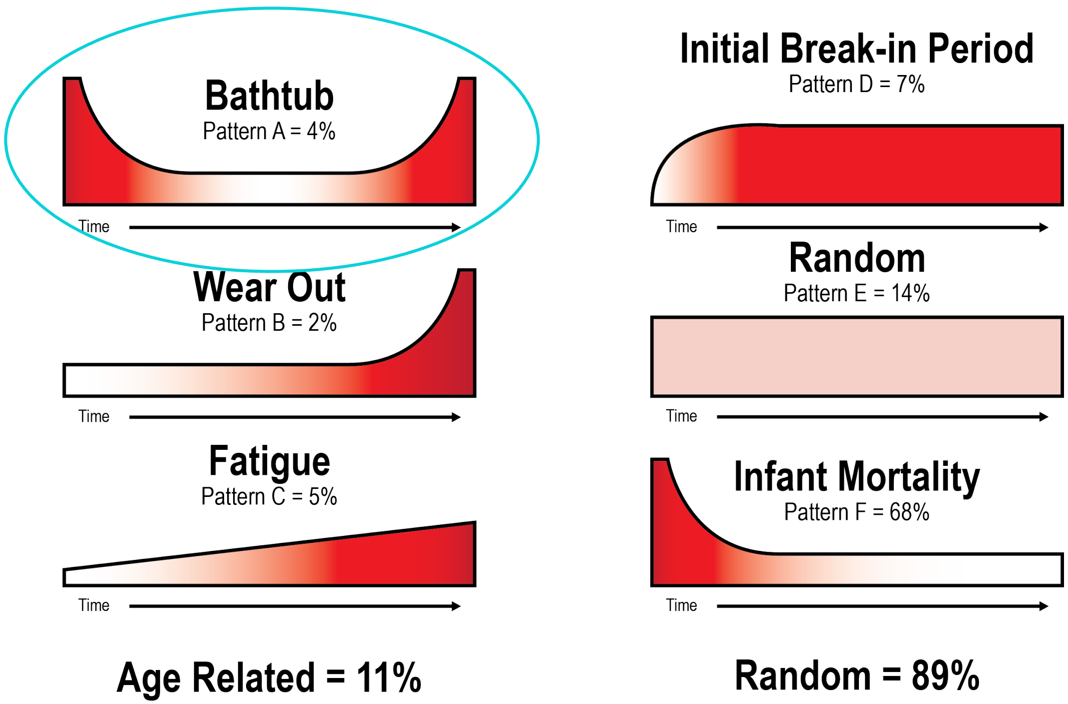
What Causes the Defects?

23% Production	• Operating above/below design parameters • Improper operating procedures • Operator errors
22% Engineering	• Undefined/unclear specifications • Improper design • Undocumented changes
17% Maintenance	• Poorly designed maintenance strategies • Improper maintenance procedures • Craft errors
12% Procurement	• Providing out-of-specification materials • Improper storage and handling procedures • Material degradation in Stores

15% as a result of Sales/Customer expectations exceeding Production capabilities.
11% as a result of current Management philosophies (i.e. postponing capital replacement).

Source: A.T. Kearney study of U.S. Manufacturing. Originally published by *Newsweek* in 1999.
Corroborated by studies performed by Keith Mobley and the Plant Performance Group.

Failure Patterns and PM Tasks



Equipment Maintenance Strategy:

- 89% of failures are random in nature
- 11% are a function of time

Source: John Moubray, Nowlan & Heap

What is a Failure Mode? Why Important?

- As defined by Stan Nowlan and Howard Heap, a Failure Mode is the specific manner of failure; the circumstances or sequence of events which leads to functional failure.
- Understanding failure modes is the only way to design a complete maintenance strategy that will ensure the inherent designed reliability of your equipment.
- A failure modes based strategy is focused on dealing with causes instead of effects!

Failure Modes Analysis

- Understanding the failure modes present in each piece of equipment, and how to identify those failure modes, should dictate your Design, PM and PdM activities
- If a task is being performed that:
  - Doesn't have the ability to identify a failure mode
  - Isn't a regulatory or statutory requirement
  - Doesn't prevent a failure mode
- Then…we are simply wasting our valuable craft time!

Failure Mode - Definition

- Part
  - Bearing
  - Breaker
  - Shaft
- Defect
  - Fatigued
- Reason
  - Misalignment

Defect

- Not just the Mode
  - Worn
  - Not descriptive enough

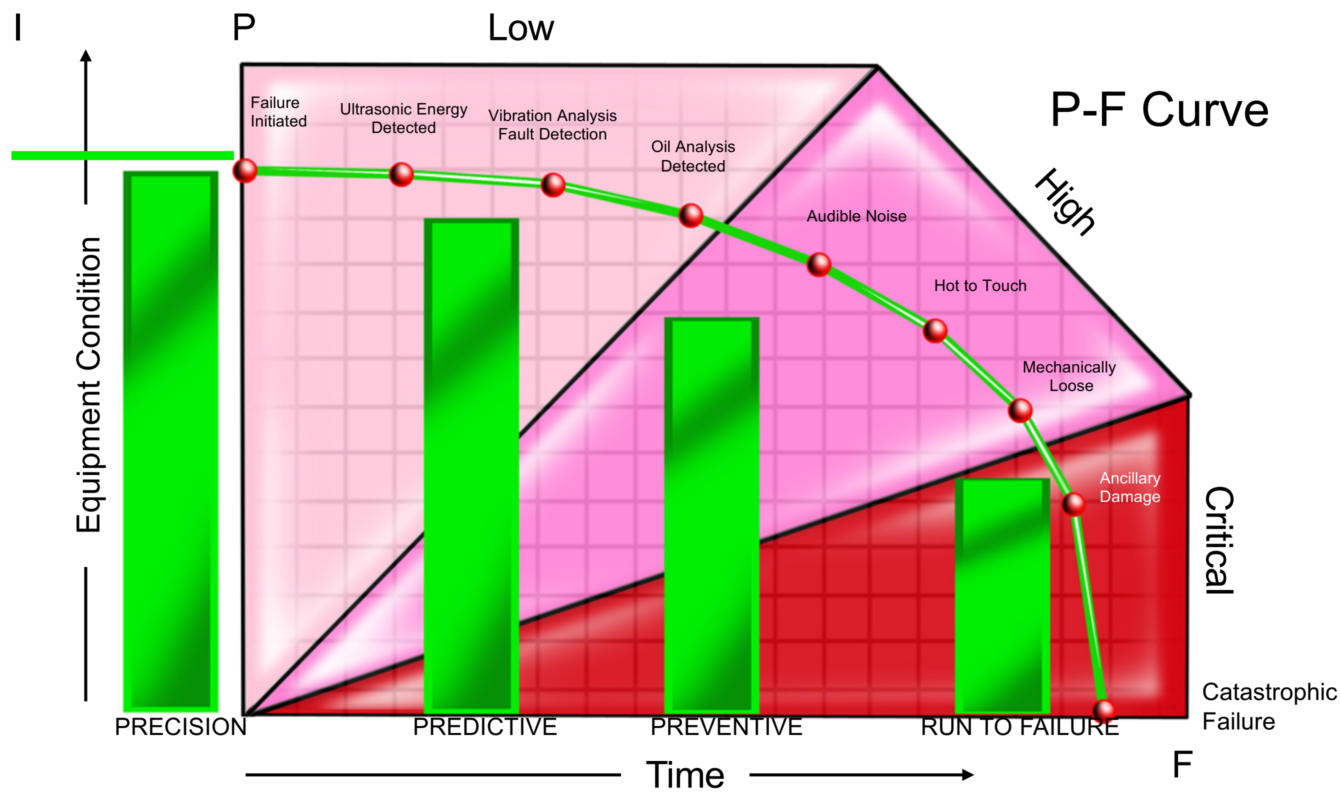
- Has to include Failure Mechanism
  - When the mechanism is descriptive
  - Knowing the mechanism might change the countermeasure (task)
  - Example: Adhesive Wear versus Abrasive Wear

Reason

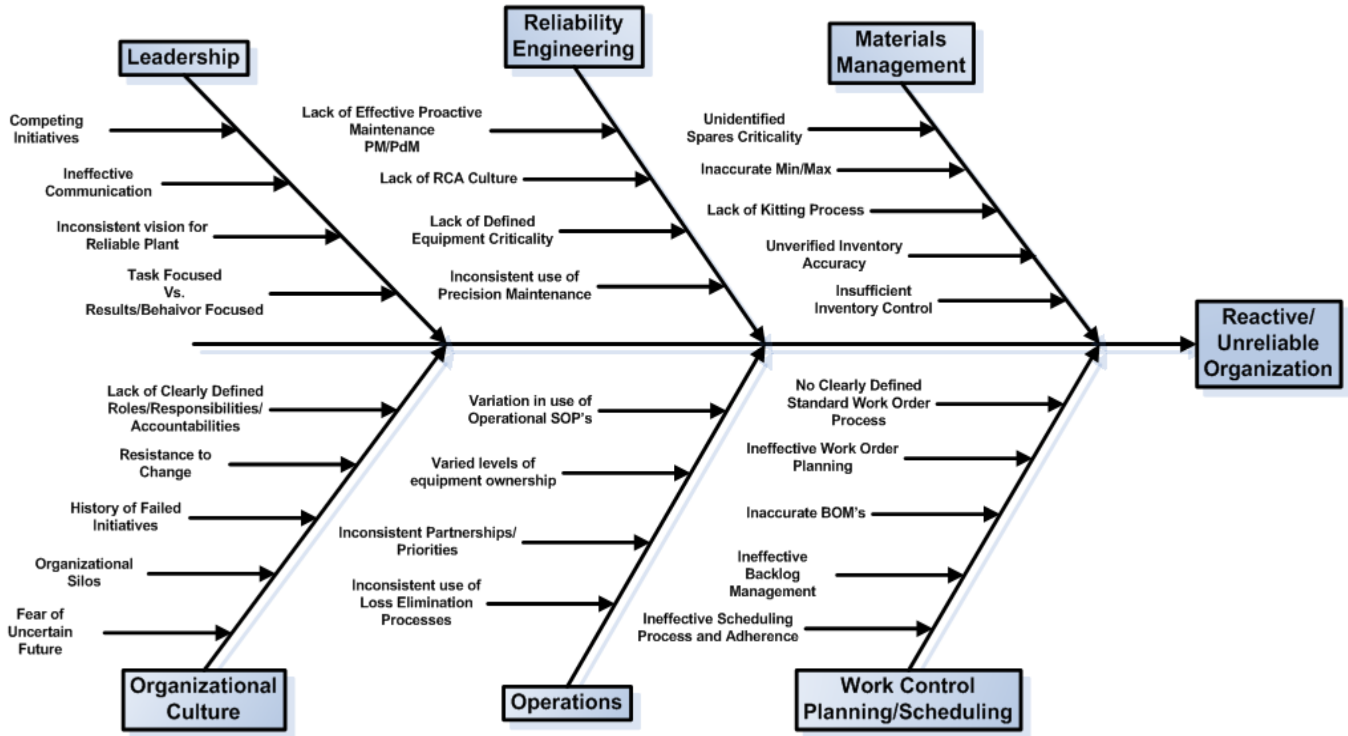
- Describes the action or condition that was physically responsible for the problem
  - Example: Improper Installation

- NOT another failure
  - Cannot reference another failure mode as the reason why this failure mode is present
  - These are called "Secondary Effects"
  - Example: Bearing – Abrasive Wear – Seal Failed

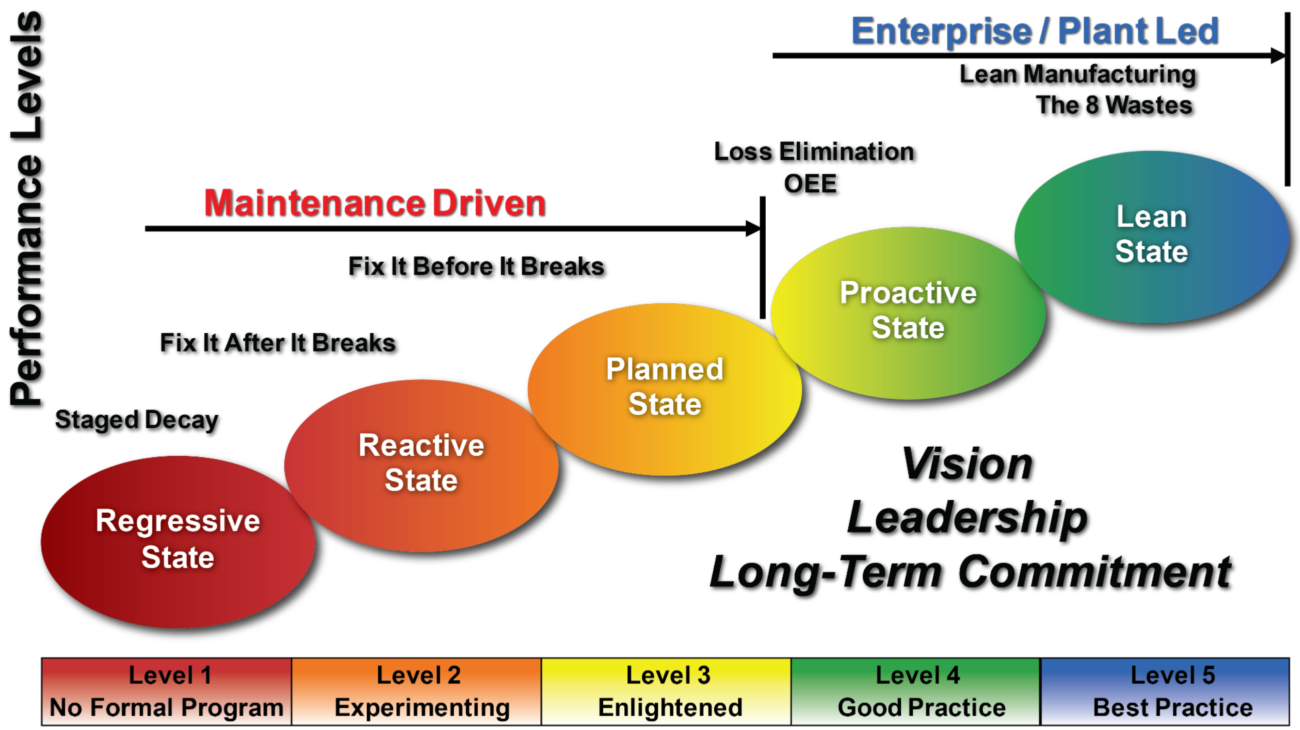
Reliability Improvement Philosophy



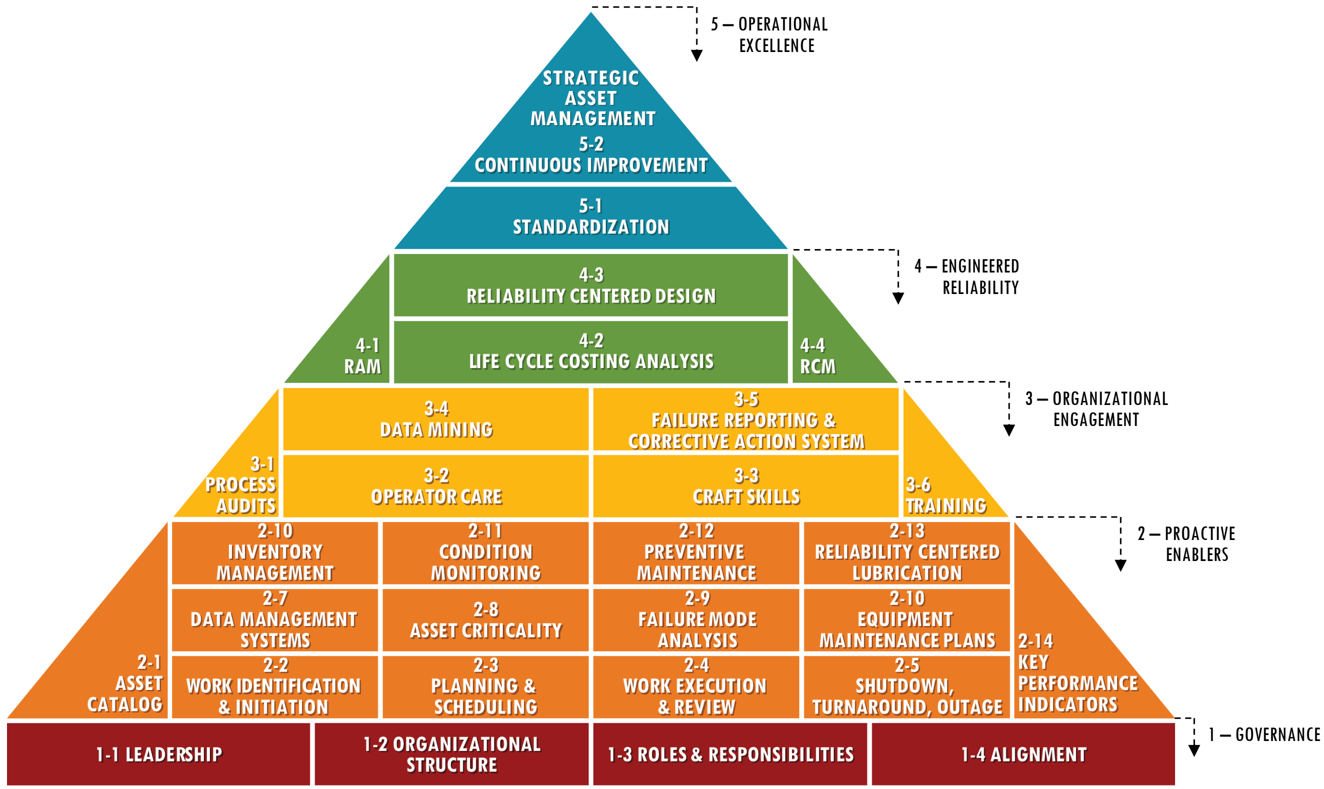
Reliability Waste Cause and Effect



The "Reliability" Journey



Reliability Systems Model



Weibull History

Weibull History

- Waloddi Weibull - 1887 - 1979
  - Professor at Royal Institute of Technology - England
  - Weibull distribution first introduced by W. Weibull in 1937
    - When he was studying the issue of structural strength and life data analysis
  - Hallmark paper in 1951 described a probability distribution function that we now call Weibull distribution
  - Much of Weibull's work involved life prediction of ball bearings
- In probability theory and statistics, Weibull distribution is one of most important continuous probability distributions
- Data could select the distribution and fit the parameters
- Weibull analysis is leading method for fitting life data

Weibull History

- Dr. Bob Abernathy
  - Co-Patent holder of Pratt Whitney's SR71 "Blackbird" Jet Engine
  - Author of the ASAF Weibull Analysis Handbook - 1981
  - Author of the New Weibull Handbook – 1993, 1996, 1998, 2000
  - Main proponent of Weibull Analysis in areas outside of aviation / aerospace industries
  - Author of "The New Weibull Handbook" (used to develop this course)

Reliability Definitions

Reliability Definitions (1)

- **Availability:** A measure of the degree to which an item is in an operable and committable state at the start of the mission when the mission is called at an unknown and random time.

$$\text{Availability} = \frac{\text{System uptime}}{\text{Total operating time + Downtime + All fee time categories}}$$

$$= \frac{\text{Time available for a specified use during a stated period}}{\text{Total length of stated period}}$$

$$\text{Availability} = \frac{\text{Uptime}}{(\text{Uptime + Downtime})}$$

$$\text{Availability} + \text{Unavailability} = 1$$

Reliability Definitions (2)

- Achieved Availability (A_A): includes the measure of preventative and corrective maintenance. It is defined as:

$$A_A = \frac{MTBMA}{MTBMA + MMT}$$

Where: MTBMA = mean time between maintenance actions
MMT = mean maintenance action time

$$MMT = \frac{F_C M_{CT} + F_P M_{PT}}{(MTBMA + MMT)}$$

Where: F_C = Number of corrective actions per 1000 hours
F_P = Number of preventative actions per 1000 hours
M_{CT} = Mean Active Corrective Mainteance Time (MTTR)
M_{PT} = Mean Active Preventive Mainteance Time (Scheduled downtime)

Reliability Definitions (3)

- Inherent Availability (A_I): Availability in the ideal state. It is defined as:

$$A_I = \frac{MTBF}{MTBF + MTTR}$$

Where: MTBF = Mean Time Before Failure
MTTR = Mean Time To Repair

- Operational Availability (A_O): Operational availability includes the time for corrective action and response to system faults. It is defined as:

$$A_O = \frac{MTBMA}{MTBMA + MDT}$$

Where: MTBMA = mean time between maintenance actions
MDT = Mean Down Time

Reliability Definitions (4)

- Average Effectiveness Level: A figure of merit for quantifying system effectiveness. It is defined as:

$$A_E = \frac{\text{Total performance hours - Total machine downtime}}{\text{Total performance hours}}$$

- Benign failure: A failure which does not affect performance of the system and goes unnoticed as a problem until the system receives an in-depth inspection.
- Burn-in: An accelerated test under higher than normal stress to screen-out infantile mortality problems in a short time interval and thus stabilize the failure pattern under normal stress conditions.
- Capability: A quantification of an item's ability to achieve mission objectives considering the conditions during mission.
- Censored data: Data which has been "cur-out" of the life analysis for a variety of reasons. See suspended data for more details.

Reliability Definitions (5)

- Cost effectiveness: Spending small amounts of money to prevent expenditure of large amounts with due consideration to the time value of money.
  - Small amounts are usually spent on improvements in the design, production, or maintenance of a system to avoid larger expenditures resulting from short life, high maintenance costs, human injuries, replacement costs, etc.
- Dependability: A quantification of the degree to which an item is operable and capable of performing its required function at any random time during a specified mission profile based on its availability at the start of the mission. It is defined as:

$$D = \frac{\text{Time available}}{\text{Time available + Time required}}$$

- Derating: Upgrading component reliability by applying stresses below rated values to gain an advantage in life expectancy for improving reliability of a component or system.

Reliability Definitions (6)

- Duane Plot: A learning curve type of graph showing the rate at which the cumulative MTTF or the cumulative failure rate can be expected to change over time when plotted on log-log paper.
- Durability: A measurement of useful life which equals the probability that an item will survive its projected service life, overhaul point, or rebuild point without a durability failure.
- Effectiveness: The potential or actual probability of a system to perform a mission for a given level of performance under specified operating conditions. It is defined as:

Effectiveness = Reliability * Availability * Maintainability * (Capability Of Meeting Goals = E * U)

Where: **E = Effectiveness = Input/Output**
U = Utilization + (Time used productively)/(Total time)

Reliability Definitions (7)

- **Exponential failure law:** The probability of survival of equipment showing only a chance failure rate such that the die-off is the same always for any size of surviving unfailed population. It is defined by the reliability function: $R(t) = e^{-\left(\frac{t}{\theta}\right)} = e^{-(\lambda t)}$

Where: R = exponential reliability
e = 2.718281828… or Naperian logarithm
t = Time of usage by which reliability is measure in cycles, time,
θ = Mean life which is measured in the same units as time, t
λ = Failure rate in some specified time interval = $1/\theta$

- **Failure:** An event which renders equipment as non-useful for the intended or specified purpose during a designated time interval.
  - The failure can be sudden, partial, one-shot, intermittent, gradual, complete, or catastrophic. The degree of failure can be degradation or gradual, sudden or one-shot, from weakness, from imperfections, from misuse and so forth.
- **Failure mechanism:** A variety of physical processes which results in failure from chemical, electrical, thermal, or other mechanisms.

Reliability Definitions (8)

- **Failure mode:** The result of a mechanism caused by a type of imperfection which contributes to failure.
  - In general, the three major failure modes are infantile mortality, chance failures, and old age wear-out. In specific, the failure mode may be due to open circuit, short circuit, fatigue, wear, and so forth.
- Failure mode and effect analysis (FMEA): The study of potential failures that might occur in any part of a system to determine the probable effect of each on all other parts of the system and on probable operational success.
- Failure mode and effect and criticality analysis (FMECA): A widely used and effective design reliability analysis considers from the bottom up each potential mode of failure that might occur of every component of a system and determines the probable effects on system operation of each failure mode in turn on probable operational success and the results of which are ranked in order of seriousness.
  - FMECA can be performed from different viewpoints such as safety, mission success, availability, repair cost, failure mode, reliability reputation , and so forth.

Reliability Definitions (9)

- Fault tree analysis (FTA): Top down study of sequence of events for failure of a system using diagrammatic method of symbols and considering multiple failures as a matter of course.
- **Failure rate:** While operating under stated conditions it is the total number of failures of an item within a population divided by the total number of life units expended by that population during a particular measurement interval.
- Hazard: A set of existing conditions with the potential for initiating an accident sequence in the operation of a product or system.
  - Hazards may be classified as catastrophic, critical, controlled/marginal, or negligible.
- Hazard function: It is a measure of proneness to failure and a descriptor of the force of mortality.
  - The hazard rate or hazard function is the conditional probability of failure in the interval x to (x + dx) given that no failures occurred prior to time interval X. Hazard functions are a general approach to derivation of time-to-failure distributions.

Reliability Definitions (10)

- **Hazard rate:** The number of units of failures per unit of time.
  - It is the failure rate of the survivors to time t in the very next instant following t. Hazard rate failure rate, and instantaneous failure rate are equivalent terms. Hazard rate, h(t), is defined as follows:

$$h(t) = \frac{f(t)}{R(t)} = \frac{PDF}{RF} = \frac{PDF}{1 - CDF}$$

Where: h(t) = Hazard rate
f(t) = PDF = Probability density function
R(t) = RF = Reliability function
F(t) = CDF = Cummulative distribution function

Reliability Definitions (11)

- Infant mortality: Failures/deaths at an early age. Infant morality is often due to inadequate burn-in or stress screening; production problems, mis-assembly, quality control difficulties; overhaul problems; solid state electronic failures; inadequate test specifications, components, engineering; inadequate materials; improper handling or packaging; or subsystem interactions.
  - Overhauling components surviving from a population with infant mortality problems is not appropriate because very old parts are better than new (unless new parts infant mortality has been fixed).
- Life units: A measure of the duration of use applicable to the item including events such as operating hours, cycles, distance, rounds fired, attempts to operate, starts/stops, takeoffs/landings, shelf/storage time.
  - Time at high temperature, time at high stress, and other counting criteria used for measuring life.

Reliability Definitions (12)

- Log-normal distribution: A mathematical probability distribution with long tails to the right for modeling certain types of life data such as metal fatigue and electrical insulation life, and for describing distributions of repair times of equipment. It is related to the normal distribution when logs are taken of the data.
  - The descriptors in the equations often cause much confusion and should not be confused with the normal distribution. For example, for the log-normal case, m is the mean of the log of life, not of life and it is called the log mean. The parameter s is the standard deviation of the log of life, not life and it is called the log standard deviation. Note also the logarithms can be base 10 for log or the natural base e for ln. The log (or ln) mean m determines the median point and thus the spread of the distribution. The log (or ln) standard deviation s determines the shape of distribution. Both the log mean and the log standard deviation are pure dimensionless numbers and do not have the same units as the life data.
  - The log-normal model is usually too optimistic when projecting results to small percentiles as compared to a projection based on a Weibull distribution: log normal and Weibull are competing failure distributions. The precise model that leads to a log-normal distribution is called a multiplicative (or proportional) growth model. The model undergoes a random increase of degradation that is proportional to its present state and thus the multiplicative effect of all the random effects growth and thus builds up to failure.

Reliability Definitions (13)

- Maintainability: The measure of the ability of an item to be retained in or restored to specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair.
- Maintenance action: An element of a maintenance event. One or more tasks (i.e., determine the approximate location of a fault and the extent necessary to effect repair, servicing and inspection) necessary to retain an item or restore it to a specified condition.
- Maintenance, corrective/repair: All actions performed as a result of failure including restoring an item to a specified condition.
  - Corrective/repair maintenance can include any or all of the following steps: determining the approximate location of a fault and the extent necessary to effect repair, disassembly, removing items to be replaced and installing replacement items, reassembly, alignment, and checkout.

Reliability Definitions (14)

- Maintenance event: One or more maintenance actions required to effect corrective and preventative maintenance due to any type of failure or malfunction, false alarm, or scheduled maintenance plan.
- Maintenance, preventive: All actions performed in an attempt to retain an item in specified condition by providing systemic inspection, detection, and prevention of incipient failures.
- Maintenance, scheduled: Preventive maintenance performed at prescribed points in the item's life.
- **Mean time between failures (MTBF for repairable equipment):** A basic measure of reliability for repairable items during which the parts perform within their specified limits under stated conditions. Mean time between failures is often used as a synonym for MTTF. It is defined as:

$$\text{MTBF} = \frac{\text{Total operating hours for specified units}}{\text{Total failures for those units in a measurement interval}}$$

Reliability Definitions (15)

- Mean time between maintenance (MTBM): A measure of system effectiveness and reliability taking into account maintenance policy. It is defined as:

$$\text{MTBM} = \frac{\text{Total number of life units expended in a given time}}{\text{Total number of scheduled and unscheduled maintenance events due to that item}}$$

- Mean time between maintenance actions (MTBMA): A measure of system reliability related to demand for maintenance manpower. It is defined as:

$$\text{MTBMA} = \frac{\text{Total number of system life units}}{\text{Number of corrective and preventive maintenance actions during a stated period of time}}$$

- **Mean time to failure (MTTF for non-repairable equipment):** A basic measure of reliability for non-repairable items during which the parts perform within their specified limits under stated conditions. Mean time between failures is often used as a synonym for MTBF. It is defined as:

$$\text{MTTF} = \frac{\text{Total number of system life units}}{\text{Total number of failures within that population, during a particular measurement interval under stated conditions}}$$

Reliability Definitions (16)

- **Mean time to repair (MTTR):** A measure of system maintainability equal to the average system repair time, and this value is the reciprocal of repair rate in the exponential case. It is defined as:

$$\text{MTTR} = \frac{\text{Total diagnose, repair, and test hours for specified units}}{\text{Total number of completed repair actions for those units}}$$

- Mission: An event which is often considered a single cycle, depending on how it is specified, and which is the ultimate output of a system for which the design objective is intended to accomplish.
- Mission profile: A time-phased description from start to finish for all usage and operation cycles required by the system to perform throughout the life cycle for which reliability is specified.
  - It includes: a criteria to judge success or failure, modes of the task or missions, operation requirements, task length, system environment for helping access operational reliability. Tasks for the mission profile must describe in detail how the system complexity is described such as: multifunctional, single function, continuous, cyclic, or a one-time function.

Reliability Definitions (17)

- Probability: The likelihood of an occurrence on a scale from 0 (zero change for an occurrence) to 1 (100% certainty for an occurrence) attached to a random event based on a particular mode for which the event can occur.
- Probability paper: Special graph paper with divisions on one scale apportioned to a specific statistical distribution so that life units from the distribution will plot as a straight line.
- Random failure: A failure whose cause and/or mechanism make the exact time of failure unpredictable but the failure may be anticipated in a probabilistic or statistical sense.
  - Random failures are independent of time and this failures show lack of memory. Causes of random failures are: insufficient/inadequate design margins, misapplication/overstress, part used in wrong environment, predictable failure levels from a statistical chance occurrence basis, non-pattern failures, maintenance/human errors, and failures due to nature/foreign objects. Surviving parts from a population suffering from random failures cannot be corrected by overhauls since an old part is as good as a new part (unless the new one has been fixed from the assignable cause for random failures).

Reliability Definitions (18)

- Redundancy: The existence of more than one way for performing a given function whereby a provision is made for more than one element to share a load in order to improve life performance.
- Redundancy, active: Redundancy where all means for performing a given function are operating simultaneously.
- Redundancy, standby: Redundancy where alternative means for performing a given function are inoperative until needed.
- **Reliability:**
  - As a general sense, reliability is the ability of an item to perform a required function under stated conditions for a stated period of time.
  - As a characteristic, reliability denotes the probability of success or the success ratio.
  - As a measure of quality, reliability exists by design as an objective or a requirement of a product from its inception to the end of its working life.

Reliability Definitions (19)

- **Reliability (continued):**
  - As a probabilistic statement: reliability is concerned with the probability of future events based on past observations.
  - As a concept, reliability is a special development of engineering industries for the collective name of measures of quality that reflect the effect of time in storage or time in use of a product as distinct from measures that show the state of the product at time of delivery. Some industries are concerned about the time aspect of product quality and the reliability concept is expressed in other terms.
  - As a basic concept, durable and high probability of failure-free performance under stated conditions including all item life units, not just mission time and all failure with the item, not just mission-critical failures at the time level of assembly.
- Reliability block diagram: A method of using reliability analysis based on functional black box diagrams to understand the reliability relationship of components in a system by which the black box are connected in a manner not unsimilar to analyzing electrical circuits.

Reliability Definitions (20)

- Reliability engineering: The application of appropriate engineering disciplines, techniques, skills, and improvements to achieve the required reliability, maintainability, serviceability exchangeability, and availability of both products and processes at a cost that is affordable for the business.
- Reliability growth: Improvement in reliability caused by successful learning experiences during correction of faults or deficiencies in the design, manufacture, sales, and service of a product or component.
- Repair: see definition of maintenance, corrective.
- Series system: A system or subsystem with components arranged whereby the failure of one item results in the failure of the system.
- Series parallel system: A system with active redundancy which uses redundant elements in series along with units in series for enhanced reliability.

Reliability Definitions (21)

- Standby system: A system with components arranged in parallel and usually connected with a switch to detect failure in the main component so that the standby unit can be quickly switched into service to function as active redundancy for improving reliability.
  - The standby element does not undergo degradation or consume power as if it were operating in "spinning reserve".
- Suspension: A test or operational unit that has not failed at the time of the life analysis. Testing on the un-failed unit may been stopped for practical or economical reasons.
  - Or the unit may be suspended from analysis because the failure mode is not the same as the units under analysis. Suspended data is also known as censored data.
- Suspension, left: Test data which is censored before the first failure time.
- Suspension, right: Test data which is censored after the last failure time.
- Test, accelerated: A test which increases a stress parameter on the component above the normal operating conditions such as temperature, pressure, voltage, chemicals, etc. so the deterioration in life can be observed in a short time.

Reliability Definitions (22)

- Test, substantiation: A test demonstrating that a redesigned part or system has eliminated or significantly improved a known failure mode.
- Test, reliability: A test demonstrating that a reliability requirement has been met.
- **Unreliability:** The probability that a device will fail to perform a required or intended function under stated conditions for a specified period of time. It is the complement of reliability. It is defir

$$Q = 1 - R$$

Where: Q = Unreliability specified as a probability
R = Reliability specified as a probability

- Wear-out failure: A malfunction resulting from equipment deterioration because of applied stresses whereby the failure rate increases with age which results in decreasing reliability during the period of deterioration.
  - Causes of wear-out are: Time, aging, incipient stresses, limited-life components, wear, scratching, inadequate/improper preventive maintenance, misalignment/interferences, low cycle fatigue, bearing fatigue failures, corrosion, erosion, mechanical fatigue, and material property deterioration with time/stress/cycles. Overhauls and inspections may be cost effective for parts which are near the end of their useful life, and replacements may be required where overhaul is not appropriate.

Reliability Definitions (22)

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- **Weibull distribution:** A mathematical distribution valuable in reliability application because of its versatility to model different failure modes.
  - The family of curves associated with the distribution are determined by selecting various values for the three parameters: h is the scale parameter known as characteristic life, b is the scale parameter or slope of the data when plotted on 1:1 probability paper, and t_0 is the location parameter which shifts the starting point (either in the + or – direction) for the distribution. In the Weibull failure model many small defect sites compete with each other to be the one that causes the earliest time of failure, thus its designation as failure of the weakest link.

What is Reliability?

What is Reliability?

Basics…

- Reliability $\neq$ Availability

$$\text{Availability} = \frac{\text{Uptime}}{(\text{Uptime} + \text{Downtime})} \qquad \text{Reliability} = \frac{\text{Successes}}{(\text{Success} + \text{Failures})}$$

- Lusser's Equation: $R(t) = e^{-\left(\frac{t}{\theta}\right)} = e^{-(\lambda t)} = e^{-N}$

Where: R = exponential reliability
e = 2.718281828… or Naperian logarithm
t = Mission time
θ = MTBF
λ = Failure rate
N = # failures during mission

- One year = (365 days) * (24 hrs/day) = 8760 hours = t
- Availability measures proportion of time system is alive and well
- Reliability measures probability for failure free operation

What is Reliability?
Real world

- Plant with assorted equipment
  - Base Case (Reactive)
    - Reactive Maintenance: Breakdown list, Overtime list
  - Optimize Manpower Use (Planned)
    - Planned Maintenance: Schedules, Job Plans, Work Orders
  - Implement Reliability Improvements (Proactive)
    - Pro-active Maintenance: Pareto Cost List, Failure Data & Analysis, MTBF Improvements, Root Cause Analysis, Life Cycle Analysis, Cost of Unreliability Analysis

	A	B	C
Availability	Good	Better	Best
MTBF	Low	Low	High
Reliability	Low	Low	High
Failure Costs	High	Lower	Low
New Tools Used	None	Few	Many

What is Reliability?
Real world

- Uptime = 6730 hrs
- Downtime = 2030 hrs
- Availability = 76.83%
- Failures = 12
- Reliability = 0.00061%

- Hours per failure ~ 169

- Uptime = 7760 hrs
- Downtime = 1000 hrs
- Availability = 88.58%
- Failures = 10
- Reliability = 0.0045%

- Hours per failure - 100

- Uptime = 8560 hrs
- Downtime = 200 hrs
- Availability = 97.72%
- Failures = 2
- Reliability = 13.53%

- Hours per failure ~ 100

Reliability Definitions (1)

- **Availability:** A measure of the degree to which an item is in an operable and committable state at the start of the mission when the mission is called at an unknown and random time.

$$\text{Availability} = \frac{\text{System uptime}}{\text{Total operating time + Downtime + All fee time categories}}$$

$$= \frac{\text{Time available for a specified use during a stated period}}{\text{Total length of stated period}}$$

$$\text{Availability} = \frac{\text{Uptime}}{\text{(Uptime + Downtime)}}$$

$$\text{Availability} + \text{Unavailability} = 1$$

What is Reliability?
Availability Problem

$$\text{Availability} = \frac{\text{MTBF}}{(\text{MTBF} + \text{MTTR})} \times 100\%$$

Availability Calculation Example 1

Component	MTBF (hours)	MTTR (hours)	Availability	in %
Power Supply	100,000	8	0.9999200	99.99200
Fan	100,000	8		
System Board	300,000	8		
memory	1,000,000	8		
CPU	500,000	8		
Network Interface Controller	250,000	8		

What is Reliability?

Availability Probelm

$$\text{Availability} = \frac{\text{MTBF}}{(\text{MTBF} + \text{MTTR})} \times 100\%$$

Availability Calculation Example 1

Component	MTBF (hours)	MTTR (hours)	Availability	in %
Power Supply	100,000	8	0.9999200	99.99200
Fan	100,000	8	0.9999200	99.99200
System Board	300,000	8	0.9999733	99.99733
memory	1,000,000	8		
CPU	500,000	8		
Network Interface Controller	250,000	8		

What is Reliability?

Availability Problem

$$\text{Availability} = \frac{\text{MTBF}}{(\text{MTBF} + \text{MTTR})} \times 100\%$$

Availability Calculation Example 1

Component	MTBF (hours)	MTTR (hours)	Availability	in %
Power Supply	100,000	8	0.9999200	99.99200
Fan	100,000	8	0.9999200	99.99200
System Board	300,000	8	0.9999733	99.99733
memory	1,000,000	8	0.9999920	99.99920
CPU	500,000	8	0.9999840	99.99840
Network Interface Controller	250,000	8	0.9999680	99.99680

What is Reliability?

Availability Problem

$$\text{Availability} = \frac{\text{Uptime}}{(\text{Uptime} + \text{Downtime})}$$

Availability Caculation Example 2

Plant Availability	Uptime (hours)	Downtime (hours)	Availability	in %
Plant A	6,815	1,945	0.7779680	77.79680
Plant B	7,612	1,148		
Plant C	8,471	289		
Plant D	8,550	210		
Plant E	8,606	154		
Plant F	8,715	45		

What is Reliability?

Availability Problem

$$\text{Availability} = \frac{\text{Uptime}}{(\text{Uptime} + \text{Downtime})}$$

Availability Caculation Example 2

Plant Availability	Uptime (hours)	Downtime (hours)	Availability	in %
Plant A	6,815	1,945	0.7779680	77.79680
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Plant C	8,471	289	0.9670091	96.70091
Plant D	8,550	210	0.9760274	97.60274
Plant E	8,606	154	0.9824201	98.24201
Plant F	8,715	45	0.9948630	99.48630

What is Reliability?

Reliability is focused on:

- Avoiding events called failures
- Calculated based on lack of failures
- Involves uncertainty since time of future failures are unknown
- Reliability concepts apply to both products sold or products used
- Measure of time oriented performance avoiding failures
- When failures occur and modes of failure are very important
- Failures in industry always have cost impacts, thus cost reductions are motivators for making improvements
- Probabilities are involved in failures, you never know precisely when a failure will occur

What is Reliability?
What is failure?

- All reliability problems have failures
- Failure: Event which renders equipment non-useful for intended or specified purpose during designated time interval. Includes:
  - Stoppage due to malfunction
  - Unexpected occurrence that interrupts routine operation of a system
  - Cessation of component function
  - Cessation of meeting predetermined quality, quantity, or cost expectations
- Failures have classes, degrees, and/or grades. Examples:
  - Critical – causing downtime 8 hours or greater
  - Major – causing downtime between 4 to 8 hours
  - Incidental – causing downtime between ½ to 4 hours
  - Nuisance – causing downtime less than 30 minutes
- Failure for one case may be ignored in another situation…use good judgement when failures
- When recording failures be consistent…correct data is essential

What is Reliability?

Failure Example:

- How many failures can you afford?

Failures	10	9	8	7	6	5	4	3	2	1
exp (-N)	4.53999E-05	0.00012341	0.000335463	0.000911882	0.002478752	0.006737947	0.018315639	0.049787068	0.135335283	0.367879441
Reliability	0.00454%	0.01234%	0.03355%	0.09119%	0.24788%	0.67379%	1.83156%	4.97871%	13.53353%	36.78794%
Failures	20	19	18	17	16	15	14	13	12	11
exp (-N)	2.06115E-09	5.6028E-09	1.523E-08	4.13994E-08	1.12535E-07	3.05902E-07	8.31529E-07	2.26033E-06	6.14421E-06	1.67017E-05
Reliability	0.0000002%	0.0000006%	0.0000015%	0.0000041%	0.0000113%	0.0000306%	0.0000832%	0.0002260%	0.0006144%	0.0016702%

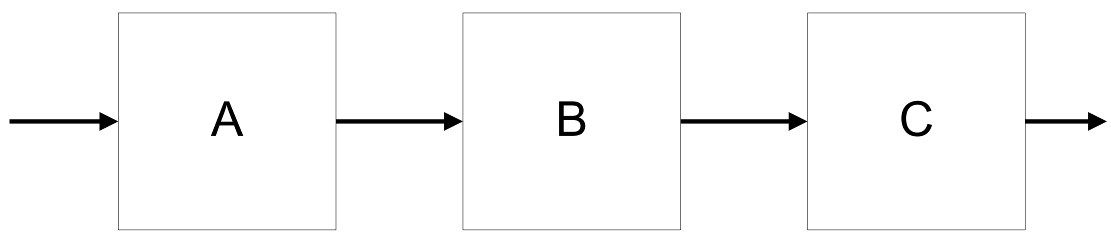
$$R(t) = e^{-N}$$

Where: R = exponential reliability
e = 2.718281828… or Naperian logarithm
N = # failures during mission

What is Reliability?

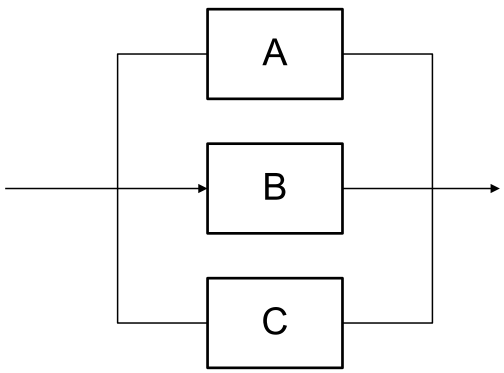
Series Networks

- Series components – all must function.
- R = $(R_A)(R_B)(R_C)$ *(multiply R's)*
- R = $e^{-(\lambda_A+\lambda_B+\ldots+\lambda_n)t}$ *(add λ's)*



What is Reliability?
Parallel Networks

- Parallel components – all must fail for system to fail.



- $R = R_A + R_B - (R_A R_B)$

- $R = 1 - (1 - R_A)\ (1 - R_B)\ (1 - R_C)\ldots$
  - (n components)

What is Reliability?

Reliability and Redundancy

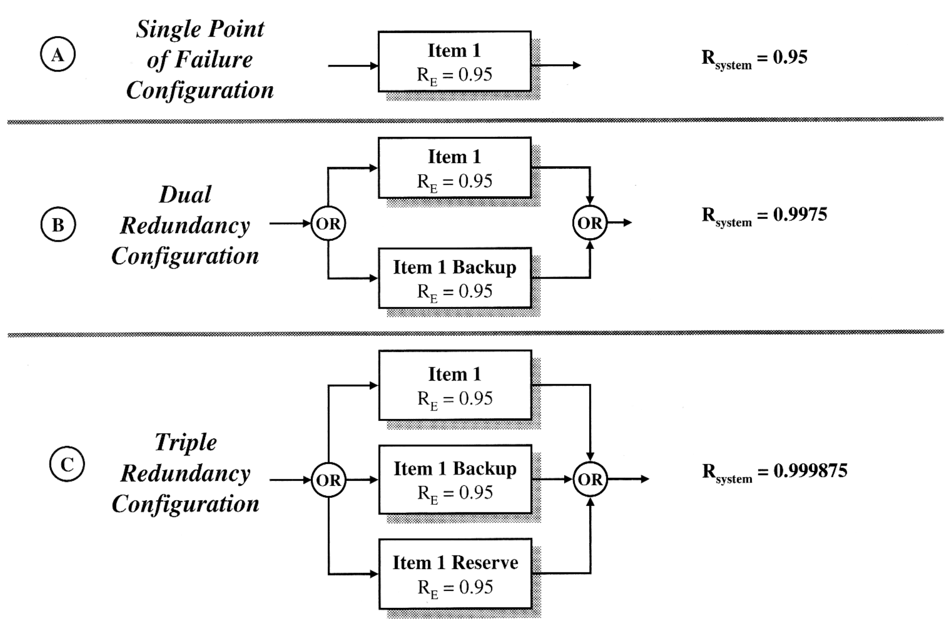


Figure 50.8 Improving System Reliability via Redundancy

What is Reliability?

Series and Parallel Networks

- Figure 12.10- Reduce parallel blocks to equivalent series element.

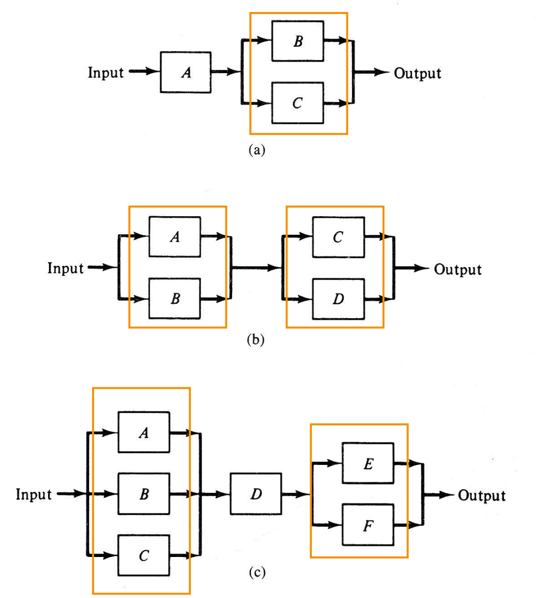


Figure 12.10 Some combined series-parallel networks.

What is Reliability?

The Probabilistic/Deterministic View

- Study of probabilities of failure over time intervals
  - Chances for survival or complement chances for failure $R(t) = 1 - U(t)$
  - Statistical models frequently used:
    - Continuous distributions – normal, log-normal, exponential, and Weibull
    - Discrete distributions – Poisson
- Failures and reliability focus on three methods:
  - Accommodate failures – probabilistic viewpoint
    - Measure rates of failure on broad statistical basis
    - Plan for redundancies to increase reliability for sustaining operations while accommodating failures
  - Measure and predict failures – deterministic viewpoint
    - Find and solve the root causes of individual failures with general view of preventing failures to increase reliability
  - Detecting and reducing failures to increase reliability
    - Expected end result of both viewpoints when used with predictive methods for finding potential problems

What is Reliability?

Availability					Reliability			
Availability	Lost Time (hours)	Lost Time (minutes)	Lost Time (seconds)		Reliability	Failures Per Year	Failures Per 10 Years	Failures Per 100 Years
60.00%	3504				10.00%	2.3		
65.00%	3066				20.00%	1.61		
70.00%	2628				30.00%	1.2		
75.00%	2190				40.00%	0.92		
85.00%	1314				50.00%	0.69		
90.00%	876				60.00%	0.51		
95.00%	438				70.00%	0.36		
96.00%	350.4				80.00%	0.22	2.23	
97.00%	262.8				90.00%	0.11	1.05	
98.00%	175.2				95.00%	0.05	0.51	
99.00%	87.6				99.00%	0.01	0.1	1.01
99.50%	43.8				99.50%	0.005	0.05	0.50
99.90%	8.76	525.6			99.90%	0.001	0.01	0.10
99.99%	0.876	52.6	3153.6		99.99%	0.0001	0.001	0.01
99.999%	0.0876	5.3	315.36		99.999%	0.00001	0.0001	0.001
99.9999%	0.00876	0.5	31.536		99.9999%	0.000001	0.00001	0.0001
99.99999%	0.000876	0.1	3.1536		99.99999%	0.0000001	0.000001	0.00001
Time Lost					Number of Failures			

What is Reliability?
What causes the Defects?

- Production 23%
  - Operating above or below design parameters
  - Improper operating procedures
  - Operator error
- Engineering 22%
  - Undefined or unclear specifications
  - Improper design
  - Undocumented changes
- Maintenance 17%
  - Poorly designed maintenance strategies
  - Improper maintenance procedures
  - Craft errors
- Sales/Customer 15%
  - Expectations exceed production capabilities
- Procurement 12%
  - Providing out of specification materials
  - Improper storage and handling procedures
  - Material degradation in stores
- Management Philosophies 11%
  - Postponing capital replacement
  - Maintenance/reliability budget cuts

Source: A.T. Kearney study of U.S. Manufacturing published by Newsweek in 1999

What is Reliability?
Reliability/People/Costs

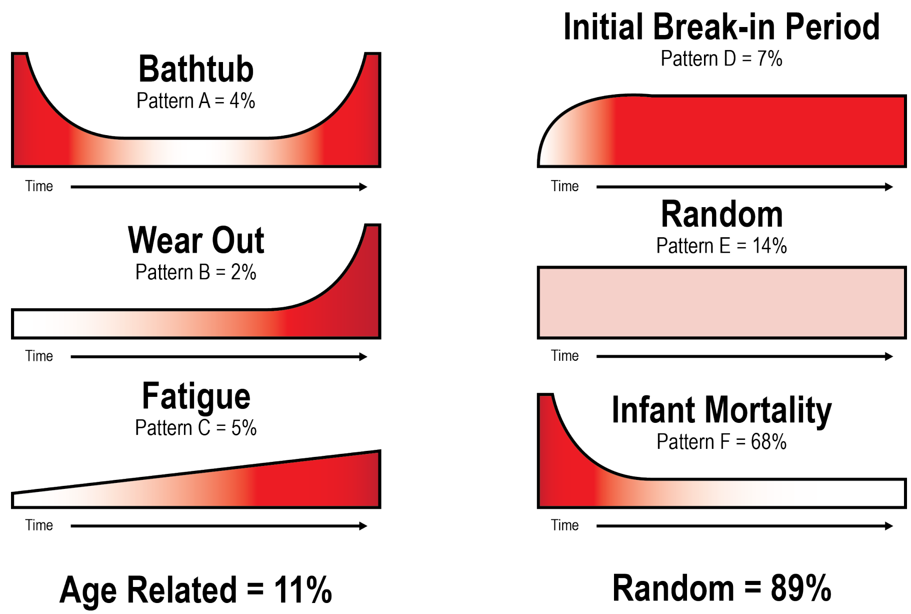
- People who make products and use products affect reliability by introducing large sources of uncertainty and cause failures
- People influence the environment where products must operate and they introduce variability which cannot be easily quantified
- People who have the role of reliability, maintenance, and process engineers influence reliability and failures by their actions
- People strongly influence reliability costs (+ and -) by means not anticipated by designer

- Reliability must be view like Safety
- Safety - All Incidents Are Preventable
- Relaiblity – All Failures are Preventable

What is Reliability?

Reliability/People/Costs

- Equipment Maintenance Strategy:
  - 89% of failures are random in nature
  - 11% are a function of time

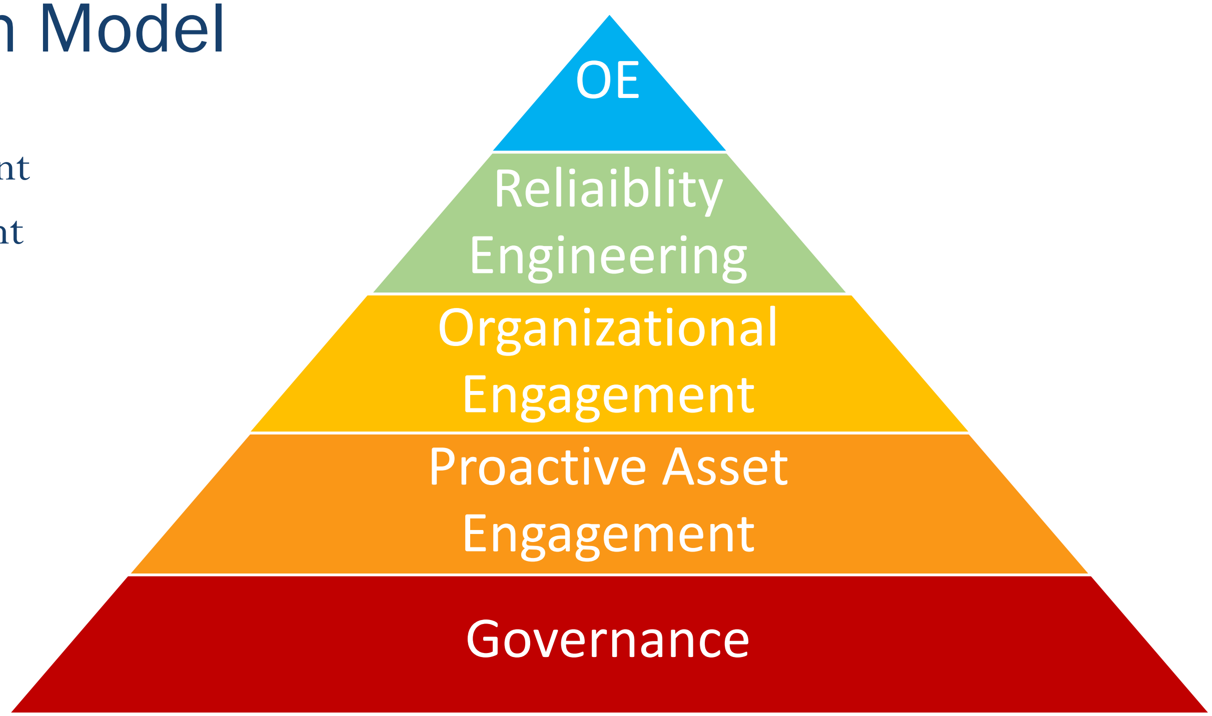


Source: John Moubray, Nowlan & Heap

What is Reliability?

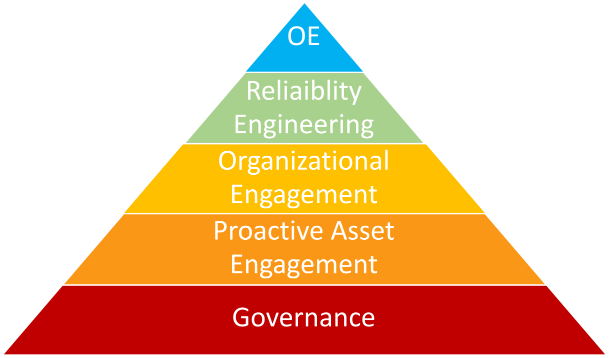
Reliability System Model

- Governance
- Proactive Asset Engagement
- Organizational Engagement
- Reliability Engineering
- Operational Excellence



What is Reliability?

Reliability System Model



- Governance:
  - Leadership, organizational structure, roles & responsibilities, alignment
- Proactive Asset Engagement
  - Asset catalog, work identification/initiation, planning & scheduling, maintenance plans, work execution & review, spare parts, data management systems, shutdown/turnaround/outage, asset criticality, failure mode analysis, condition monitoring, preventative maintenance, and KPI's
- Organizational Engagement
  - Operator care, craft skills, training, data mining, failure modes and effects analysis (FMEA)
- Reliability Engineering
  - Reliability, availability, maintainability (RAM) modeling, lifecycle cost analysis (LCC), reliability centered maintenance (RCM), reliability centered design
- Operational Excellence
  - Standardization, overall equipment effectiveness (OEE), continuous improvement, asset management, audit

What is Reliability?

Reliability & Total Productive Maintenance (TPM) Programs

- How to reduce unreliability by uncovering hidden defects:
  - Eliminate accelerating deterioration by cleaning, lubricating, & tightening
    - Problems are found early for low cost corrections
  - Eliminate accelerated deterioration by using equipment as designed
    - Do not abuse, operate above design criteria
  - Restore equipment to its optimal condition
    - Perform maintenance repairs to reverse deterioration
  - Restore processes to their optimum conditions
    - Renew process and process equipment to restore deterioration
  - Extend equipment lifetime by correcting design deficiencies
    - Improve equipment for a longer life
  - Eliminate unexpected failures by improving operations/maintenance skillset
    - Train to improve skills and reduce errors

What is Reliability?

Reliability & Total Productive Maintenance (TPM) Programs

- How to reduce unreliability by uncovering hidden defects (continued):
  - Reduce dispersion in failure intervals so PM replacements are effective
  - Prevent accelerated deterioration so as to extend life and reduce variation
  - Lengthing equipment life by avoiding operating and maintenance errors
  - Periodic servicing, diagnostics, and inspection to restore deterioration
  - Predict equipment life from its conditions and replace before failure

What is Reliability?

How to Quantify Reliability

- Establish reliability requirements and objectives
  - Define the overall reliability required for process or product
- Reliability budgeting or allocation
  - Allocate the overall reliability objective to assets
- Reliability prediction
  - Estimate asset reliability using data and experience
- Reliability analysis
  - Identify defective components or systems for implementing improvements

What is Reliability?

How to Quantify Reliability

- Establish reliability requirements and objectives
  - Define the overall reliability required for process or product
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  - Estimate asset reliability using data and experience
- Reliability analysis
  - Identify defective components or systems for implementing improvements

Reliability Statistics

Reliability Statistics

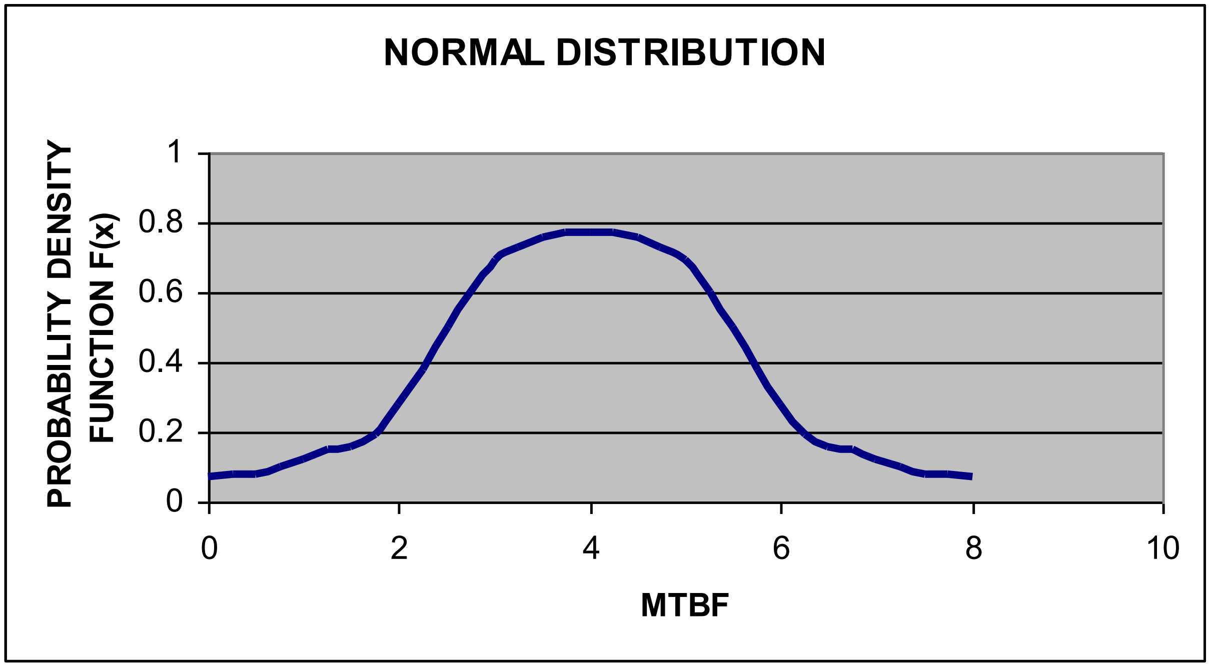
Weibull Analysis - What is it good for?

- Life prediction with very few failures
- Life prediction with very small sample sizes
- Prediction of when is the first failure expected - Weibayes
- Determination of: Has a problem been fixed? - improving / deteriorating failure rate - Crow - AMSAA Reliability Grow Modeling

Reliability Statistics

Normal Distribution

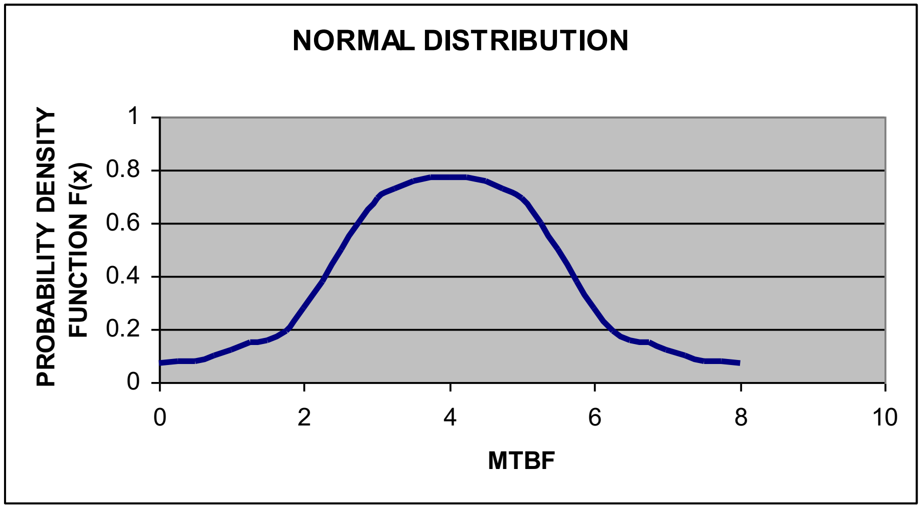
- Events where the Probability of occurrence follows a "Bell Curve"
- Failures are not age dependent
  - Probability of occurrence does not change with time
- Not typically used as left tail extends to negative infinity
  - Could cause incorrect modeling of negative times to failure



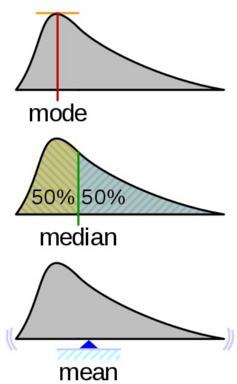
Reliability Statistics

Normal Distribution

- Mode, median & mean
- If, mean of data > 0 & variation relatively low, useful for modeling certain types of life data



$$f(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}(x)^2}$$



Where: f(x) = probability density function

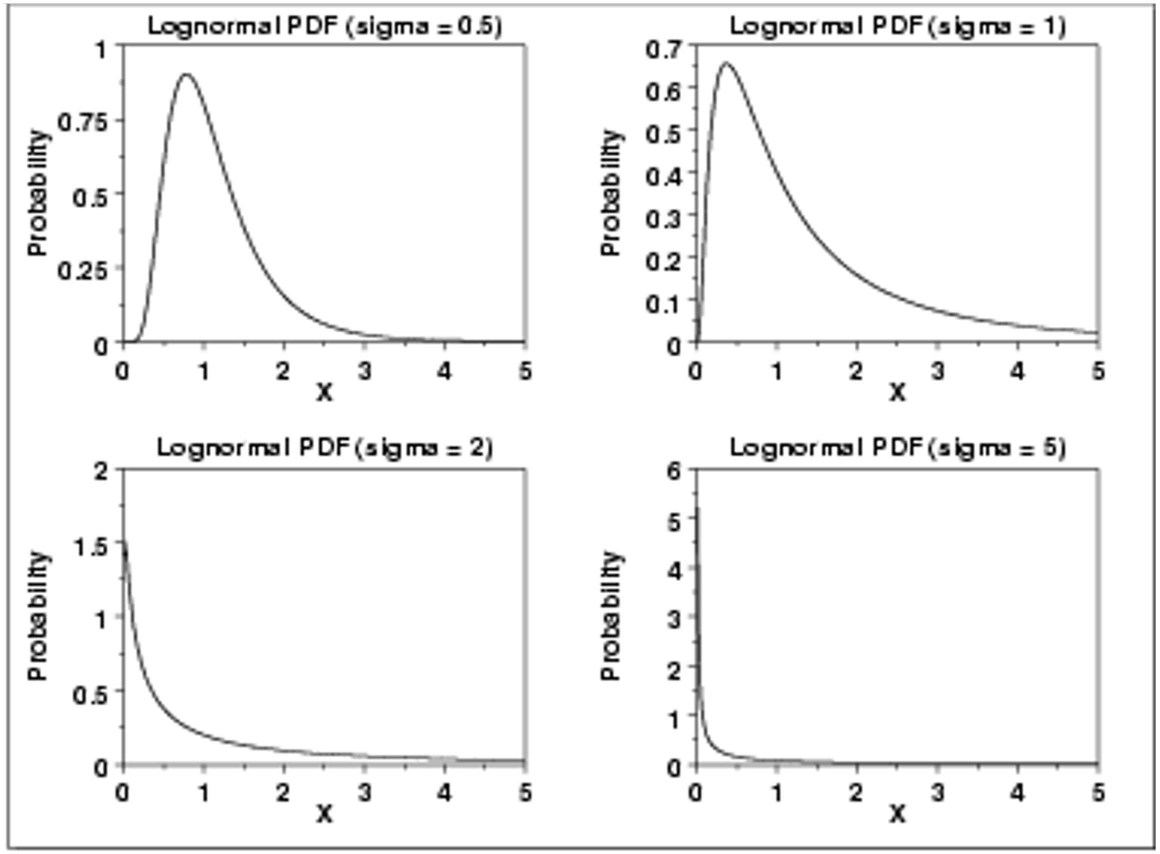
x = event

π = 3.14159

e = natural log (2.718)

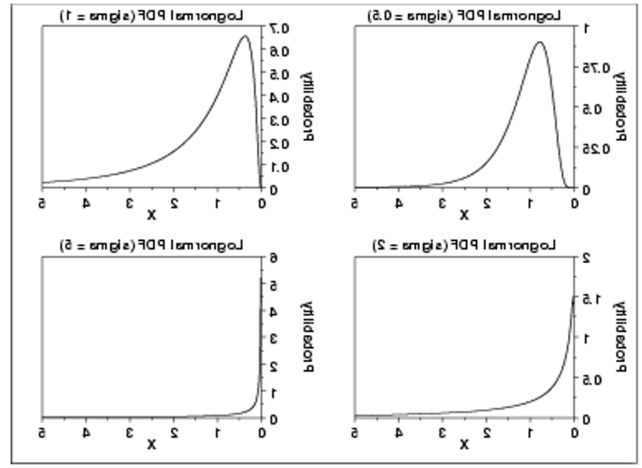
Weibull Analysis
Log-Normal Distribution

- Events where the Probability of occurrence follows a "Exponential Curve"
- Failures are dependent with time (age)
  - Probability of occurrence increases / decreases with time



Weibull Analysis
Log-Normal Distribution

- Will predict lower average failure rates at earlier times than Weibull distribution
  - If extrapolate beyond the range of sample data
- Failures caused by chemical reactions or corrosion usually model with log-normal distribution

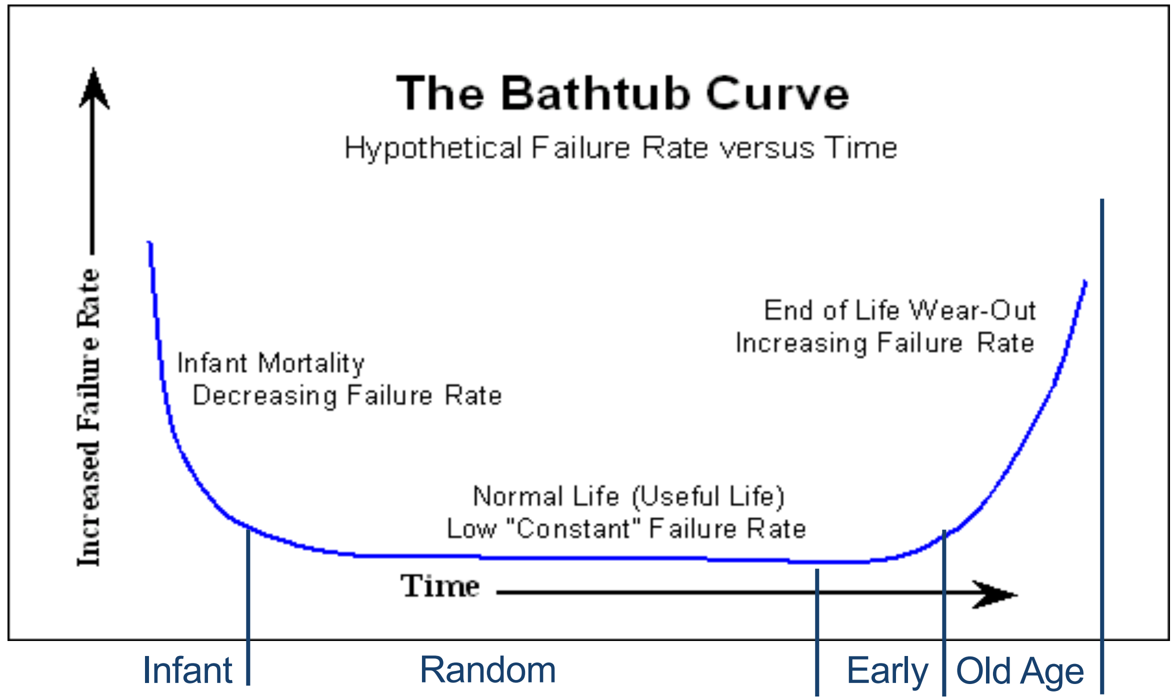


$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\left(\left(\frac{(\ln x)^2}{2\sigma^2}\right)\right)}$$

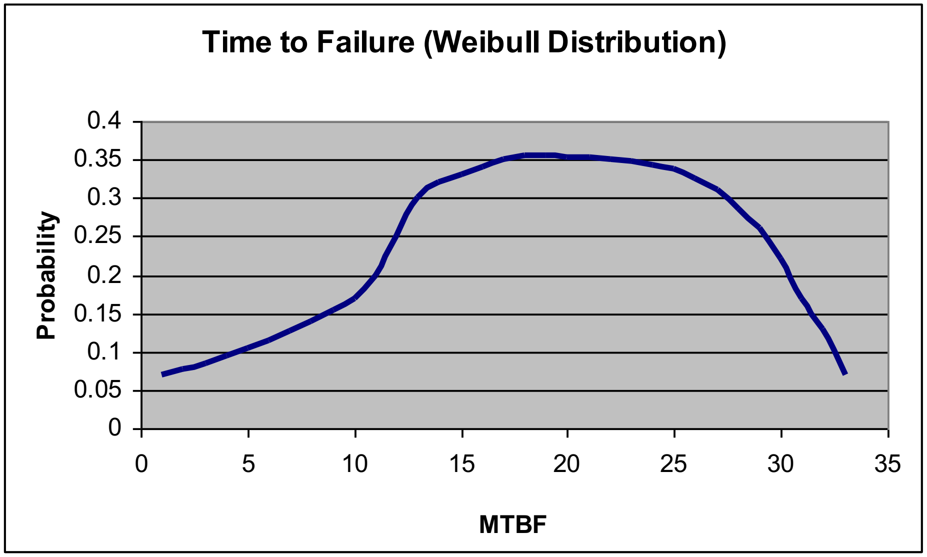
Where: f(x) = probability density function
x = event, x >= 1
π = 3.14159
Sigma (σ) = shape parameter, sigma > 0
e = natural log (2.718)

Weibull Distribution

- Events where the Probability of occurrence follows a "Bathtub Curve"
- Failures are age dependant
  - Probability of occurrence changes (increases or decreases) with time (age)
- Describes well the failure rate of real world components

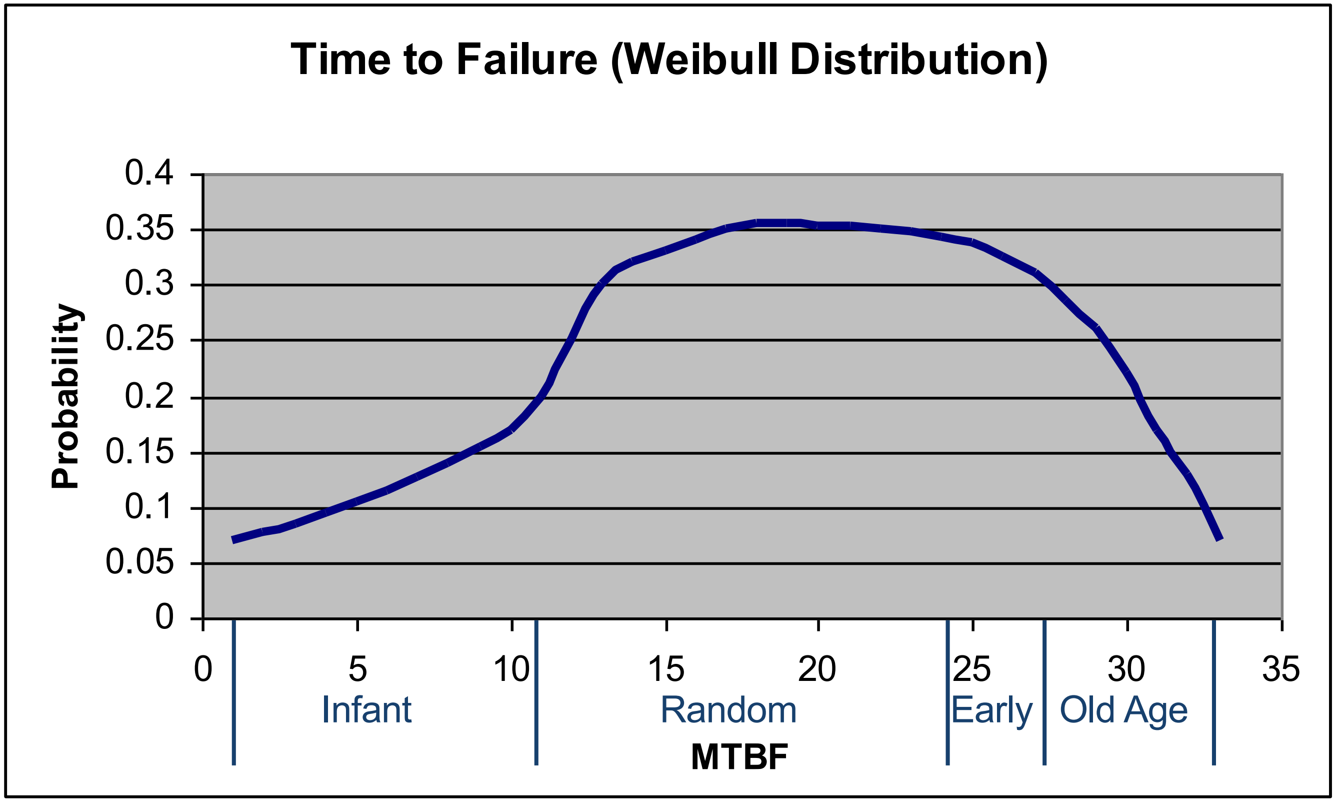


Weibull Distribution



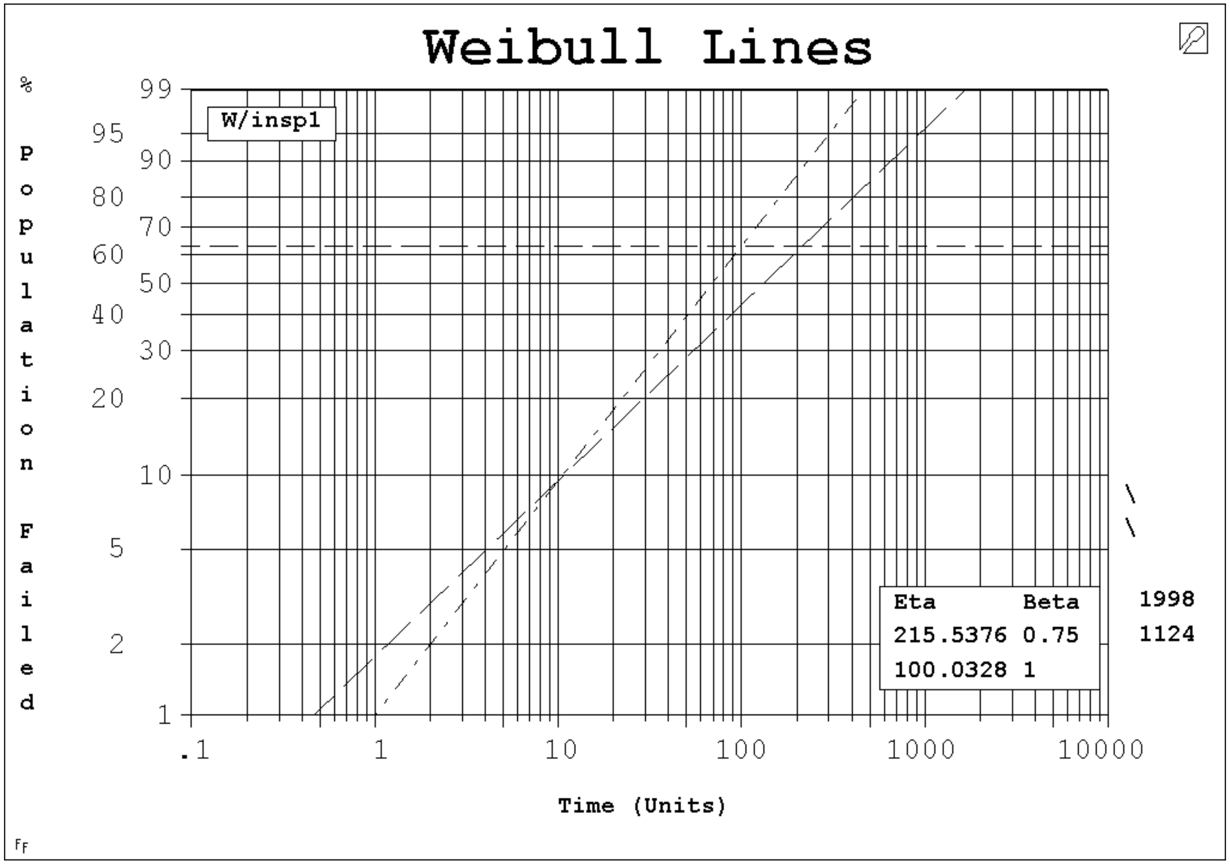
$$f(t) = 1 - e^{-(t/\eta)^{\beta}}$$

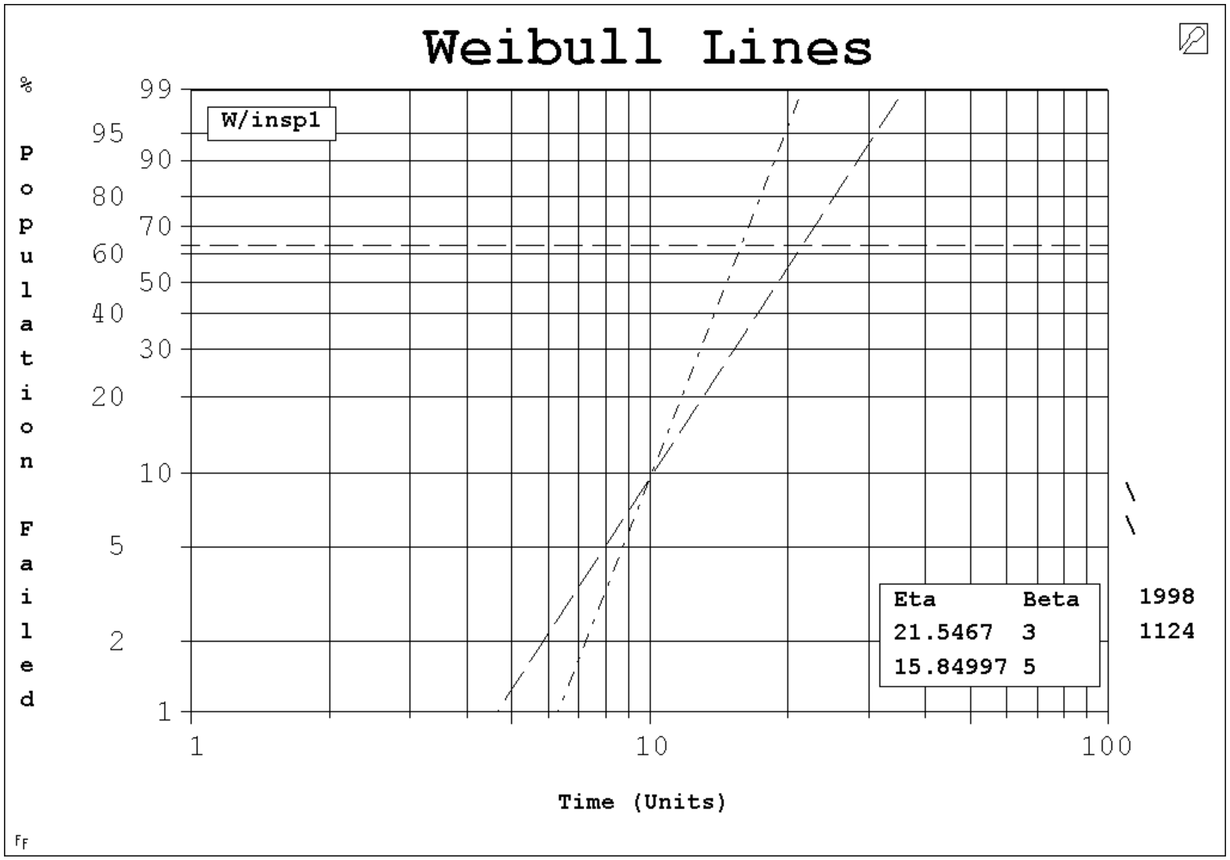
Where: **f(t) = cumulative fraction failing**
t = failure time
eta (η) = characteristic life
beta (β) = slope (shape parameter)
e = natural log (2.718)


Time to Failure (Weibull Distribution)
Probability
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20
25
30
35
Infant
Random
Early
Old Age
MTBF

Weibull Paper

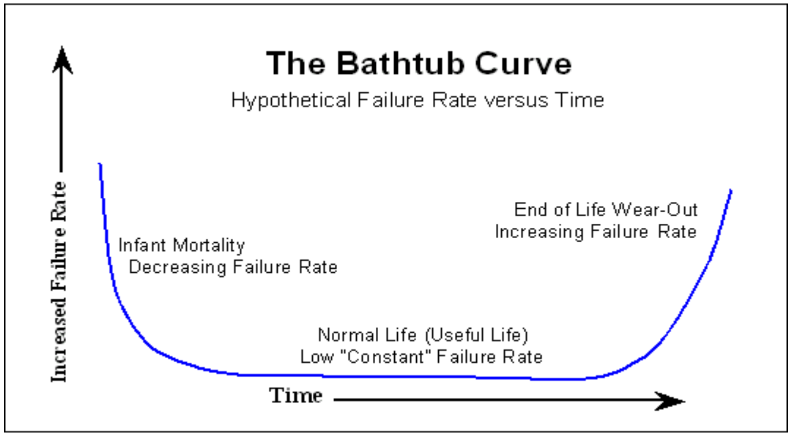
- Weibull Paper is a *ln* X vs. *lnln* Y scale
- Weibull probability function plotted on Weibull Paper produces a straight line with:
  - Beta as the slope (shape parameter)
  - Eta as the value of Y = 63.2%
- Even Engineers can draw a straight line


Weibull Lines
W/insp1
% Population Failed
99
95
90
80
70
60
50
40
30
20
10
5
2
1
.1
1
10
100
1000
10000
Time (Units)
Eta Beta
215.5376 0.75
100.0328 1
1998
1124



Weibull Lines
W/insp1
% Population Failed
99
95
90
80
70
60
50
40
30
20
10
5
2
1
1
10
100
Time (Units)
Eta Beta
21.5467 3
15.84997 5
1998
1124

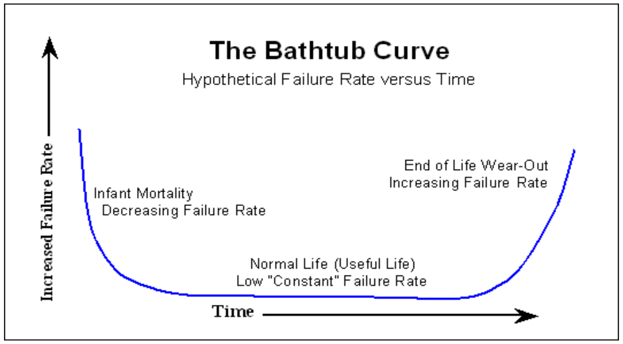
Failure Modes



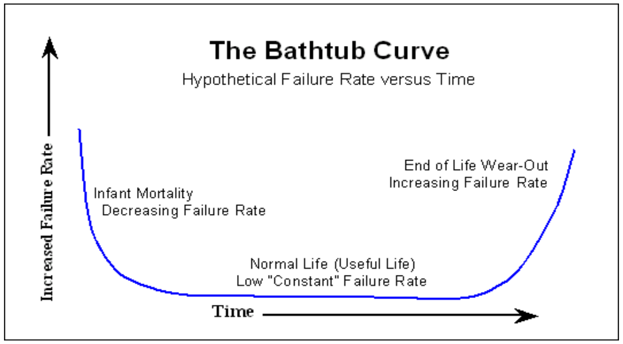
- Beta < 1 - infant mortality
- Beta = 1 - random
- 1 < Beta < 4 - early wear out
- Beta > 4 - old age wear out

Infant Mortality

- Beta < 1
  - Inadequate burn-in or stress screening
  - Production problems
    - Assembly Error
  - Overhaul (maintenance) problems
  - Solid state electronic failures
  - Overhaul not appropriate - old parts are better than new parts



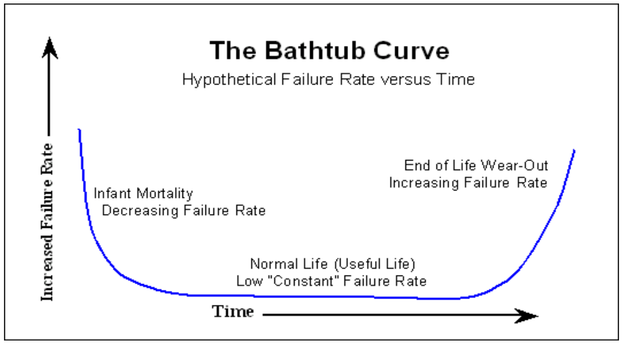
Random Failures



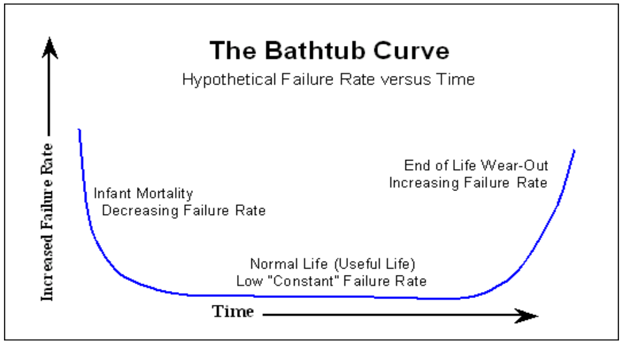
- Beta = 1
  - Random - failures independent of time
  - Identical to Exponential Distribution - of those that survive, a constant % fail in the next unit time.
    - Maintenance errors, human error
    - Failures due to nature, foreign object damage, lightening strikes
    - Mixed failure modes (3 or more)
  - Overhauls not appropriate - repair what breaks

Early Wear Out

- 1.0 < Beta < 4.0
  - Low Cycle Fatigue
  - Most Bearing Failures
  - Corrosion, erosion
  - Overhauls or parts replacement at low B lives may be cost effective - this restores the machine to start over again



Old Age Wear Out



- Beta > 4.0
  - Steep Beta mean things are wearing out rapidly
    - Bad news if trying to run longer
    - Good news if well past overhaul / replace interval
  - Stress Corrosion
  - Material properties (high cycle fatigue)
  - Brittle materials like ceramics
  - Some forms of erosion
  - Inspection and overhaul with parts replacement may be cost effective

Weibull Analysis - Example 1

Baseline Rivet Data		
Serial Number	Failure Time (Minutes)	Remarks
1	90	Failure
2	96	Failure
3	100	Flare loosened
4	30	Failure
5	49	Failure
6	45	Flare loosened
7	10	Lug failed
8	82	Failure

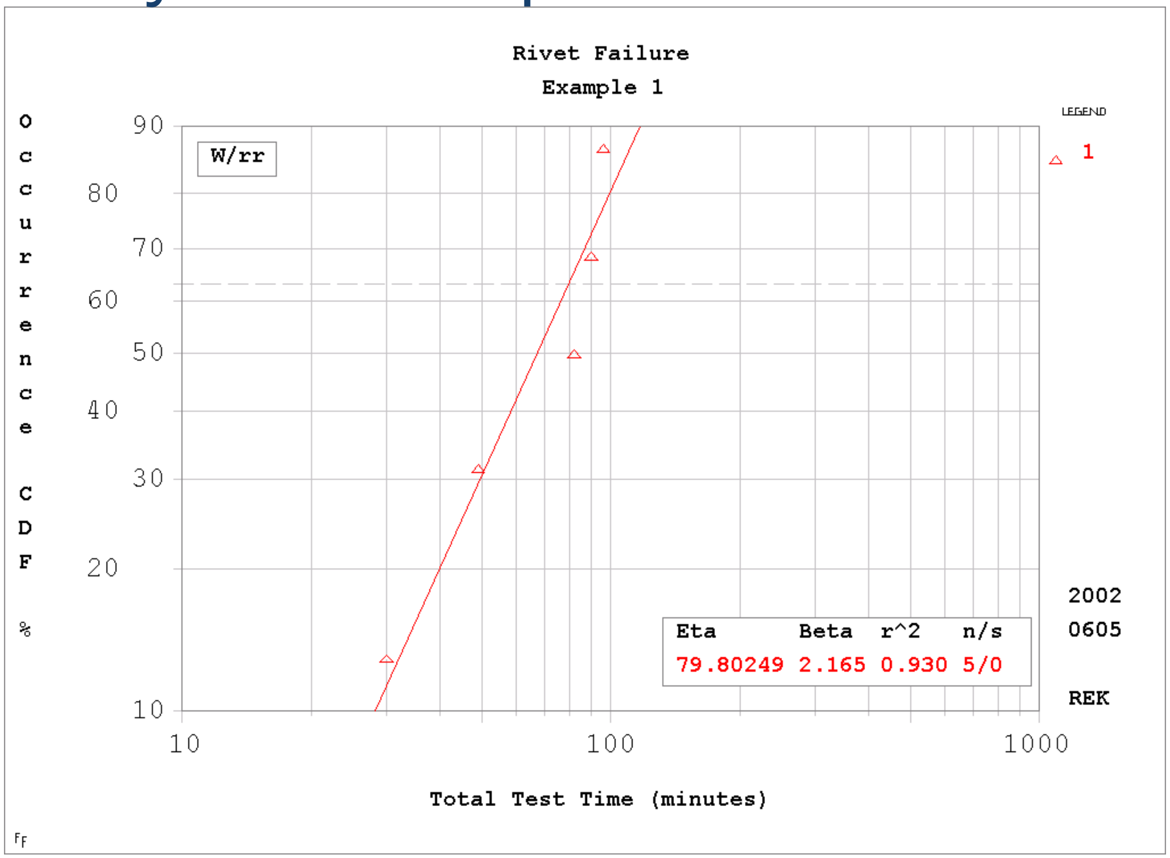
Weibull Analysis - Example 1

- Rank Order the data by failure / suspension time
- Determine the Median Rank using (Weibull.com)
- Plot the Data on Weibull Paper
- Draw the Weibull Line
- Determine Eta and Beta

Weibull Analysis - Example 1

Ranked Rivet Data		
Order Number (i)	Failure Time - t	Median
	(Minutes) (X)	Rank % (Y)
1	30	12.94
2	49	31.38
3	82	50
4	90	68.62
5	96	87.06
Median Rank From Weibull.com, Sample size 5		

Weibull Analysis - Example 1



Suspended Data

- Non-failed units or units that fail due to a different failure mode are "censored" or "suspended" units
- Non-failed units, while not having a failure time associated with them have at least made it to some life without failure of the evaluated failure mode
- Such suspended data must be accounted for in the analysis
- To include suspended data - the rank must be adjusted to account for the data

$$\textbf{Adjusted Rank} = \frac{\textbf{(Inverse Rank) x (Previous Adjusted Rank) + (N + 1)}}{\textbf{(Inverse Rank) + 1}}$$

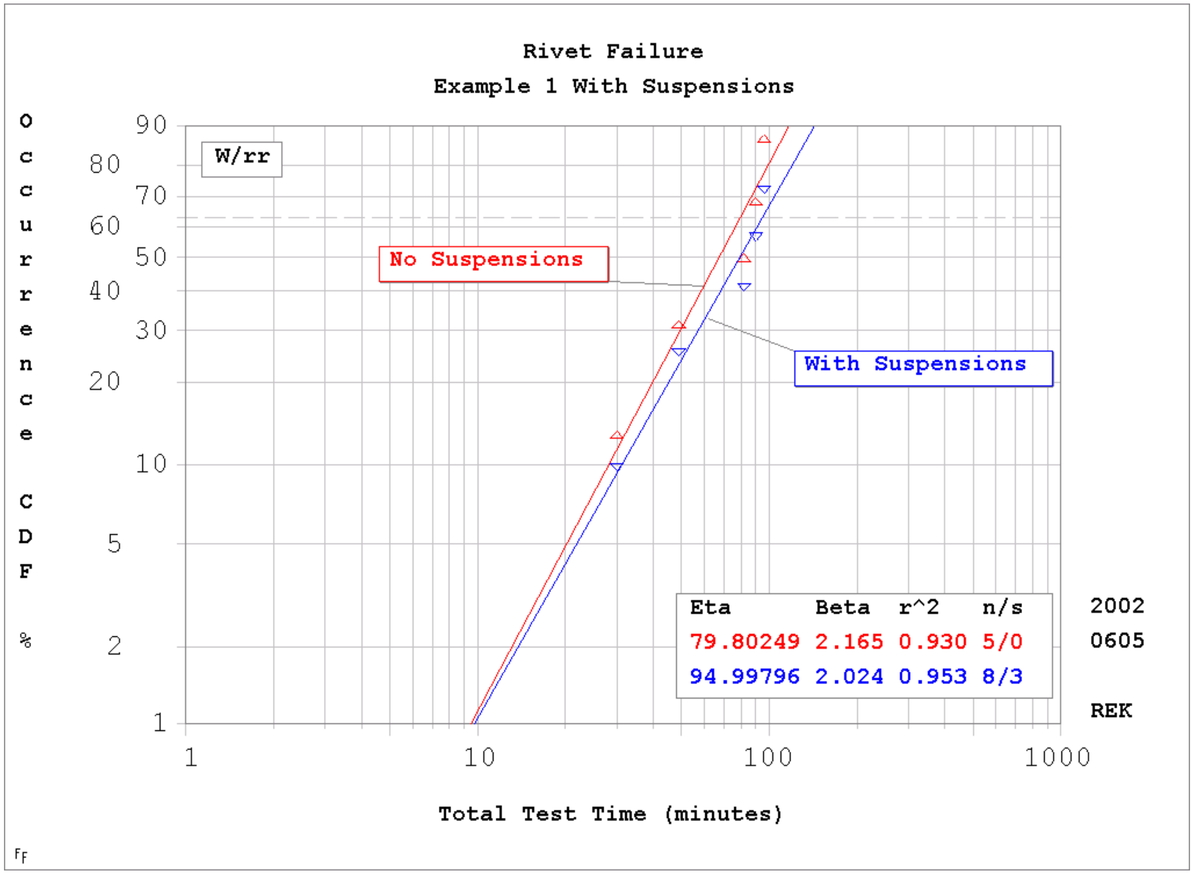
Weibull Analysis - Example 1

Adjusted Rank Rivet Data				
Rank Order Number	Failure Time - t (Minutes) (X)	Inverse Rank	Adjusted Rank (i)	Median Rank
1	10S	8	Suspended	
2	30F	7	[(7x0) + (8+1)] / (7 + 1) = 1.125	9.80%
3	45S	6	Suspended	
4		5		
5		4		
6		3		
7		2		
8		1		
Median Rank from Weibull.com, Sample size of 8 using Adjusted Rank (i) and interpolating the table				

Weibull Analysis - Example 1

Adjusted Rank Rivet Data				
Rank Order Number	Failure Time - t (Minutes) (X)	Inverse Rank	Adjusted Rank (i)	Median Rank
1	10S	8	Suspended	
2	30F	7	[(7x0) + (8+1)] / (7 + 1) = 1.125	9.80%
3	45S	6	Suspended	
4	49F	5	[(5x1.125) + (8+1)] / (5 + 1) = 2.438	25.50%
5	82F	4	[(4x2.438) + (8+1)] / (4 + 1) = 3.750	41.10%
6	90F	3	[(3x3.750) + (8+1)] / (3 + 1) = 5.063	56.70%
7	96F	2	[(2x5.063) + (8+1)] / (2 + 1) = 6.375	72.30%
8	100S	1	Suspended	
Median Rank from Weibull.com, Sample size of 8 using Adjusted Rank (i) and interpolating the table				

Weibull Analysis - Example 1



Weibull Plot Information

- Eta - Characteristic Life
- Beta - Slope (Shape Factor)
- B1, B10 Lives - % of population that has failed - 1%, 10%, etc.
- R **2 - Goodness of fit, line-to-data 1.00 is perfect fit

Benard's Approximation

- To prevent interpolation of Appendix I Benard determined an approximation for the Median Rank
  - Benard's Median Rank = (i - 0.3) / (N + 0.4)
  - Where: i = Adjusted Rank, N = Sum of failures and suspensions
  - The Median Rank is converted to %'s for plotting by multiplying by 100
  - Accurate to 1% for N = 5 and 0.1% for N = 50

Benard's Approximation

Adjusted Rank Rivet Data					
Rank Order Number	Failure Time - t (Minutes) (X)	Inverse Rank	Adjusted Rank (i)	Median Rank Interpolated Table	Median Rank Benard's Approx.
1	10S	8	Suspended		
2	30F	7	1.125	9.77%	(1.125 - 0.3) X 100 / (8 + 0.4) = 9.82%
3	45S	6	Suspended		
4	49F	5	2.438	25.34%	
5	82F	4	3.75	41.03%	
6	90F	3	5.063	56.73%	
7	96F	2	6.375	72.42%	
8	100S	1	Suspended		
Median Rank from Interpolated Appendix I compared to Benard's Approximation					

Benard's Approximation

Adjusted Rank Rivet Data					
Rank Order Number	Failure Time - t (Minutes) (X)	Inverse Rank	Adjusted Rank (i)	Median Rank Interpolated Table	Median Rank Benard's Approx.
1	10S	8	Suspended		
2	30F	7	1.125	9.77%	(1.125 - 0.3) X 100 / (8 + 0.4) = 9.82%
3	45S	6	Suspended		
4	49F	5	2.438	25.34%	(2.438 - 0.3) X 100 / (8 + 0.4) = 25.45%
5	82F	4	3.75	41.03%	(3.75 - 0.3) X 100 / (8 + 0.4) = 41.07%
6	90F	3	5.063	56.73%	(5.063 - 0.3) X 100 / (8 + 0.4) = 56.70%
7	96F	2	6.375	72.42%	(6.375 - 0.3) X 100 / (8 + 0.4) = 72.32%
8	100S	1	Suspended		
Median Rank from Interpolated Appendix I compared to Benard's Approximation					

Suspended Data

- The Characteristic Life (Eta) increases with suspensions
- Beta remains fairly unchanged
- To ignore suspensions is to ignore survival data - results in an overly pessimistic answer

Weibull Data Regression Methods (Drawing the Line)

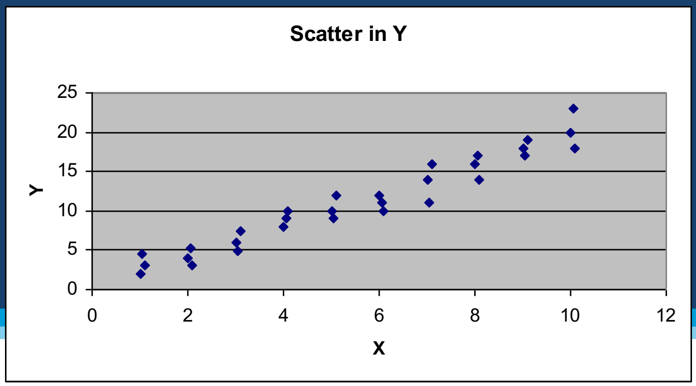
- Median Rank Regression (RR)
  - Time-to-failure as dependant variable (X on Y)
  - Median Ranks as the dependant variable (Y on X)
- Maximum Likelihood Estimation (MLE)
- Grouped or interval data
  - Coarse Data
  - Inspection Data
- Interval Analysis
  - Destructive Testing
  - NDE Data

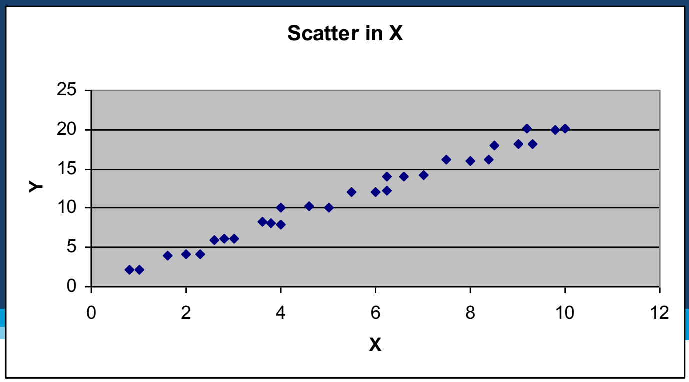
Cover Later

Median Rank Regression

- Uses least squares regression curve fitting method to minimize the sum of squares of the dependant variable
- For Weibulls, the X variable time-to-failure has the greatest scatter and error than the Y variable median ranks
- Best method for Weibull plots is to regress X on Y

If Scatter is in the Y direction, Regress Y on X
But if the Scatter is in the X direction, Regress X on Y





Weibull scatter is in the X direction,
Regress X on Y

Regression Comparison

Comparison of X on Y versus Y on X Regression - Most Accurate in Bold Face						
Based on 1000 Data Sets - Weibull True Values Eta=1000, Beta=3.0 B1=216.0						
Sample Size	**X on Y Eta**	**Y on X Eta**	**X on Y Beta**	**Y on X Beta**	**X on Y B1**	**Y on X B1**
N=4	**994**	1009	**3.02**	2.75	**213**	190
N=10	**996**	1014	**2.95**	2.79	**210**	193
N=30	**999**	1011	**2.98**	2.86	**212**	204
N=100	**1000**	1006	**2.98**	2.92	**212**	208
N=500	**1000**	1002	**2.99**	2.97	**214**	213
N=1000	**1000**	1001	**2.99**	2.98	**215**	213

Maximum Likelihood Estimation

- MLE - Uses statistics to calculate Beta and Eta that maximizes the "likelihood" of obtaining the observed data
- MLE is a function of the data
- Requires complex computer driven calculations
- Provides better estimation on large data sets

Regression vs. MLE Comparison

Comparison of X on Y Regression with Maximum Likelihood Estimate						
Most Accurate is Boldfaced						
Based on 1000 Data Sets - Weibull True Values Eta=1000, Beta=3.0 B1=216.0						
Sample Size	**X on Y Eta**	**MLE Eta**	**X on Y Beta**	**MLE Beta**	**X on Y B1**	**MLE B1**
N=4	**994**	981	**3.02**	4.00	**213**	312
N=10	**996**	990	**2.95**	3.32	**210**	245
N=30	**999**	998	**2.98**	3.11	**212**	227
N=100	**1000**	999	**2.98**	3.03	212	**219**
N=500	**1000**	999	2.99	**3.00**	214	**216**
N=1000	**1000**	999	2.99	**3.00**	**215**	**215**

Weibull Data Methods

- Use Rank Regression - X on Y for small to medium data sets
- Use MLE for:
  - large samples (>500 points)
  - real random errors are suspected except for small data sets (<30 points)
- Use Rank Regression - Y on X only with special inspection method (Probit data)

Weibull Analysis - Example 2

Parts Failure / Run Time Data		
Serial #	Time On Part (hours)	Remarks
831	9.00	Fail
832	6.00	Fail
833	14.60	Susp
834	1.10	Fail
835	20.00	Fail
836	7.00	Susp
837	65.00	Fail
838	8.00	Susp

Weibull Analysis - Example 2

- Rank Order the data by failure / suspension time
- Calculate the Adjusted Rank (i)
  - [(IR X Prev Adj Rank) + (N+1)] / (IR + 1)
- Calculate the Median Rank using Benard's Approximation
  - [(i - 0.3) / (N + 0.4)] X 100
- Plot the Data on Weibull Paper

Weibull Analysis - Example 2

- What is Eta?
- What is Beta?
- What is failure mode?
- What is B1? What is B10?
- What % of the parts will fail by 10 hours?
- What is the reliability at 50 hours?

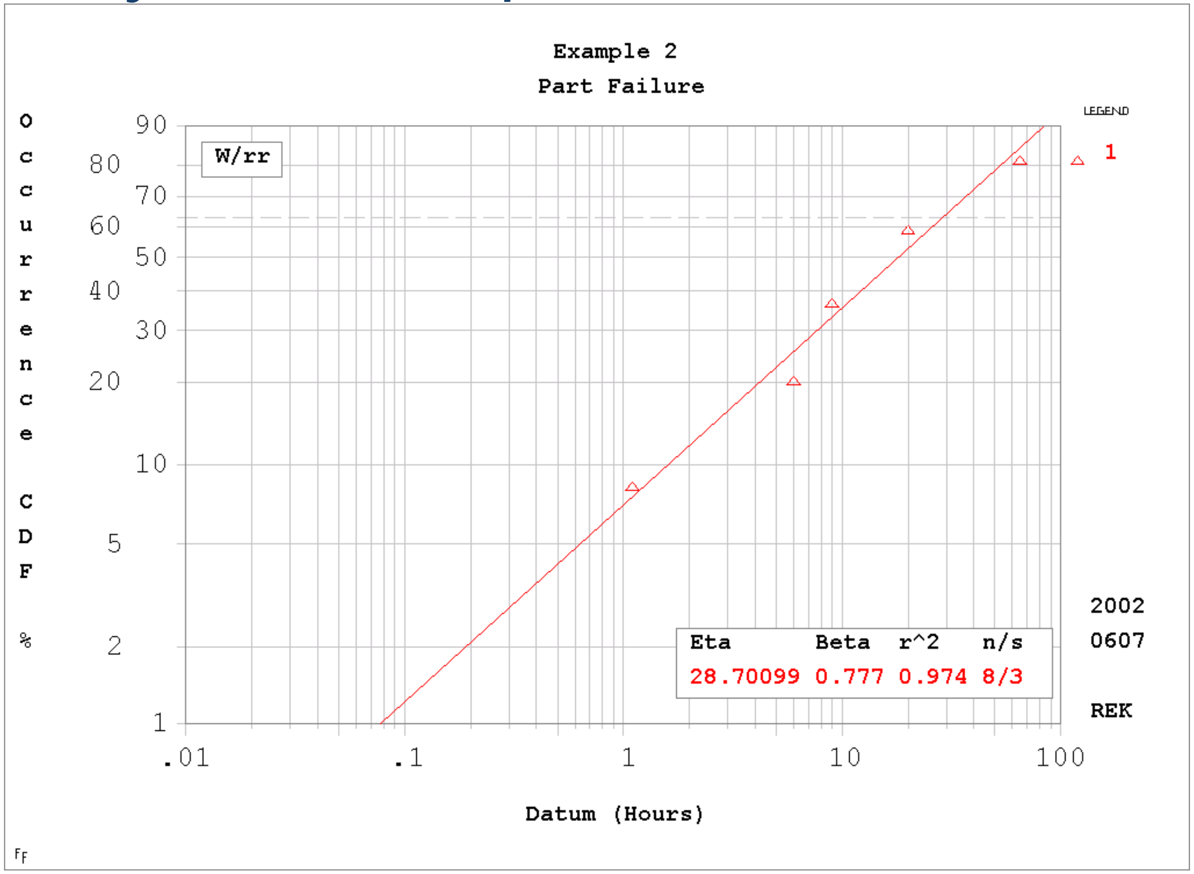
Weibull Analysis - Example 2

Parts Failure / Run Time Data						
Serial Number	Rank Order Number	Failure Time - t (Hours) (X)	Fail / Susp	Inverse Rank	Adjusted Rank (i) [(IR X Prev Adj Rank) + (N+1)] / (IR + 1)	Median Rank (Benard's Approx.) [(i - 0.3) / (N + 0.4)] X 100
834	1	1.1	F	8	[(8x0) + (8+1)] / (8 + 1) = **1.000**	[(1.0 - 0.3) / (8 + 0.4)] x 100 = **8.33%**
	2			7		
	3			6		
	4			5		
	5			4		
	6			3		
	7			2		
	8			1		

Weibull Analysis - Example 2

Parts Failure / Run Time Data						
Serial Number	Rank Order Number	Failure Time - t (Hours) (X)	Fail / Susp	Inverse Rank	Adjusted Rank (i) [(IR X Prev Adj Rank) + (N+1)] / (IR + 1)	Median Rank (Benard's Approx.) [(i - 0.3) / (N + 0.4)] X 100
834	1	1.1	F	8	[(8x0) + (8+1)] / (8 + 1) = **1.000**	[(1.0 - 0.3) / (8 + 0.4)] x 100 = **8.33%**
832	2	6	F	7	[(7x1) + (8+1)] / (7 + 1) = **2.000**	[(2.0 - 0.3) / (8 + 0.4)] x 100 = **20.24%**
836	3	7	S	6	Suspended	
838	4	8	S	5	Suspended	
831	5	9	F	4	[(4x2) + (8+1)] / (4 + 1) = **3.400**	[(3.4 - 0.3) / (8 + 0.4)] x 100 = **36.90%**
833	6	14.6	S	3	Suspended	
835	7	20	F	2	[(2x3.4) + (8+1)] / (2 + 1) = **5.267**	[(5.267 - 0.3) / (8 + 0.4)] x 100 = **59.13%**
837	8	65	F	1	[(1x5.267) + (8+1)] / (1 + 1) = **7.133**	[(7.133 - 0.3) / (8 + 0.4)] x 100 = **81.34%**

Weibull Analysis - Example 2



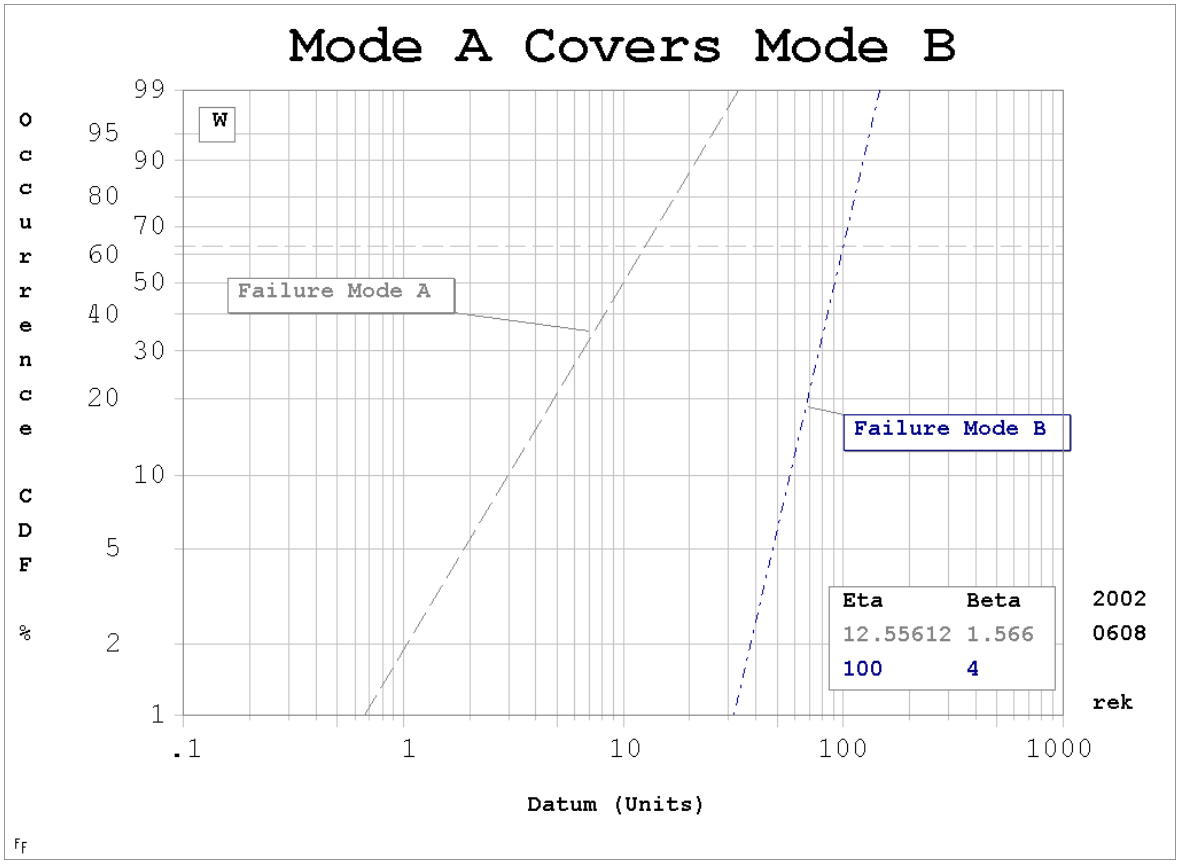
Weibull Analysis - Example 2

- What is Eta? - 29 hours
- What is Beta? - 0.8
- What is failure mode? - Infant (<1)
- What is B1? - 0.08 hours
- What is B10? - 1.75 hours
- What % of the parts will fail by 10 hours? - 35%
- What is the reliability at 50 hours? - 20%

Failure Modes Cover Other Modes

- The first (shortest life) failure mode "governs" the Weibull
  - Weibull line covers all other (later) Weibulls
- All units fail due to the shortest failure mode and never get a chance to encounter the second failure mode
- There is always additional failure modes to the right of a given Weibull
  - There is always some new failure mode

Failure Modes Cover



Dirty Data

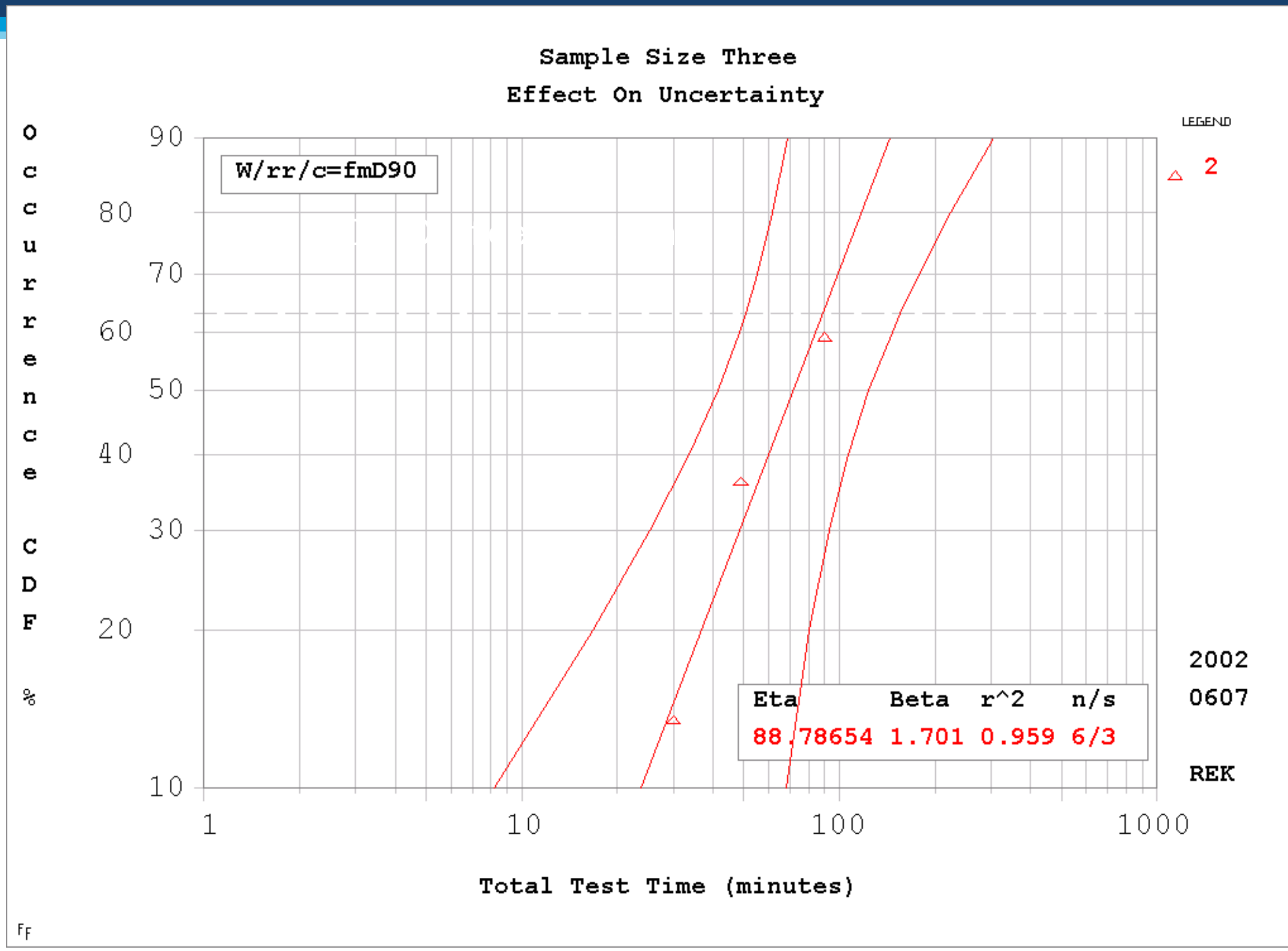
Weibull Analysis meets
the Real World

Dirty Data Problems

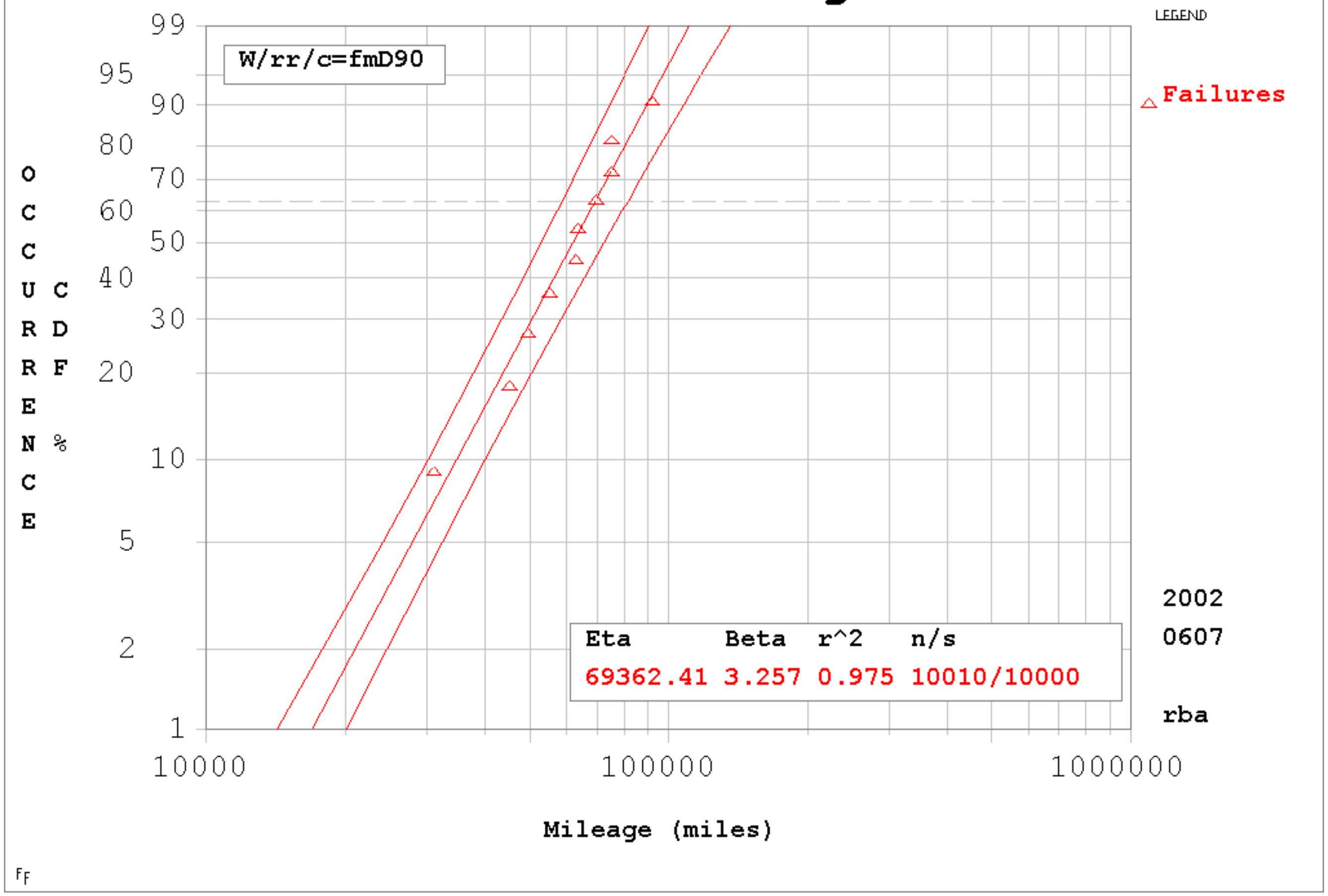
- Small Sample - few failures
- Poor Fit to data - Goodness-Of-Fit
- Suspensions - lack data of failures
- Curved Weibulls - three parameter Weibull
- Curve Weibulls - Log Normal Distribution

Dirty Data Problems

- Data Inconsistencies
  - Low Time Failures
  - Close Serial Numbers
  - Mixed Failure Modes
  - Suspension times unknown (unknown life of those left in the fleet)
  - Inspection or Interval Data
  - Steep Slope (Beta > 10)


Sample Size Three
Effect On Uncertainty
W/rr/c=fmD90
LEGEND
2
Occurrence CDF %
90
80
70
60
50
40
30
20
10
1
10
100
1000
Total Test Time (minutes)
Eta Beta r^2 n/s
88.78654 1.701 0.959 6/3
2002
0607
REK

18 Wheeler Steering Failures



Sample Size

- The larger the sample size:
  - Failures
  - Suspensions

- Improves reliability (reduces probability bounds)

Goodness -Of-Fit

- Correlation Coefficient (r)
  - Measures the strength of a linear relationship to two variables
    - Closer to 1.00 the better the fit
- Critical Correlation Coefficient (CCC)
  - Monte Carlo simulation of an ideal Weibull
  - Uses a 90% bound for goodness of fit
  - If "r" is > CCC - Good Fit
- Critical Coefficient of Determination
  - The square of "r" (r^2)
  - Closer to 1.0 the better the fit
  - Good quick measure of Goodness-Of-Fit

Goodness -Of-Fit

- Tables of CCC vs Number of Failures
  - Used to determine if calculated line fits the data based on the number of failures with an ideal distribution (Weibull or Log Normal)
- WinsmithWeibull automatically evaluates “r” against the CCC

Suspensions

- Suspensions occur two ways
  - Unit has not failed yet
  - Unit failed due to some other failure mode
- Suspensions increase the Characteristic Life (Eta) but have little effect on Slope (Beta)
- Suspensions past the last failure have a slight effect in reducing the Slope (Beta)

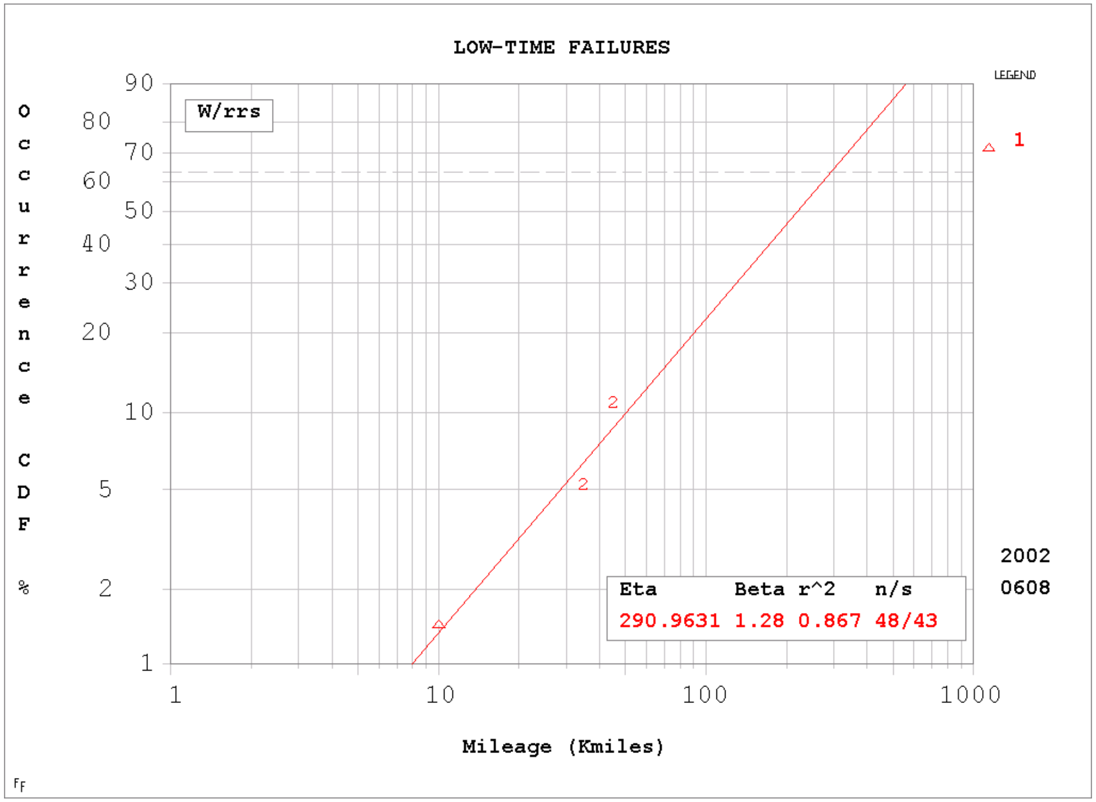
Data Inconsistencies

Common Data Problems

Low Time Failures

- Failures that occur very early (short life) often after substantial number are operating (late suspensions) well past current failures
- Suspect Batch Problem
  - Change in manufacturing
  - Change (error) in overhaul or maintenance

Low-Time Failures



Close Serial Numbers

- Anytime failures occur in a group of serial numbers - batch problems should be suspected
- Failures can occur anytime in fleet life
  - Mid production change
  - Change in suppliers
- Implications are the same as Low-Time Failures - look for cause of batch grouping

Mixed Failure Modes

- Not sorting data by failure mode results in a Beta = ~1.0 with Eta = ~MTTF which is the Exponential Distribution
- Sorting data by the part that failed is NOT sufficient (i.e. bearing failures)
  - Must sort by failure mode (i.e. lack of lubrication, overload, brinelling, false brinelling, contamination, etc.)
  - All failures NOT of the mode being evaluated must be suspended

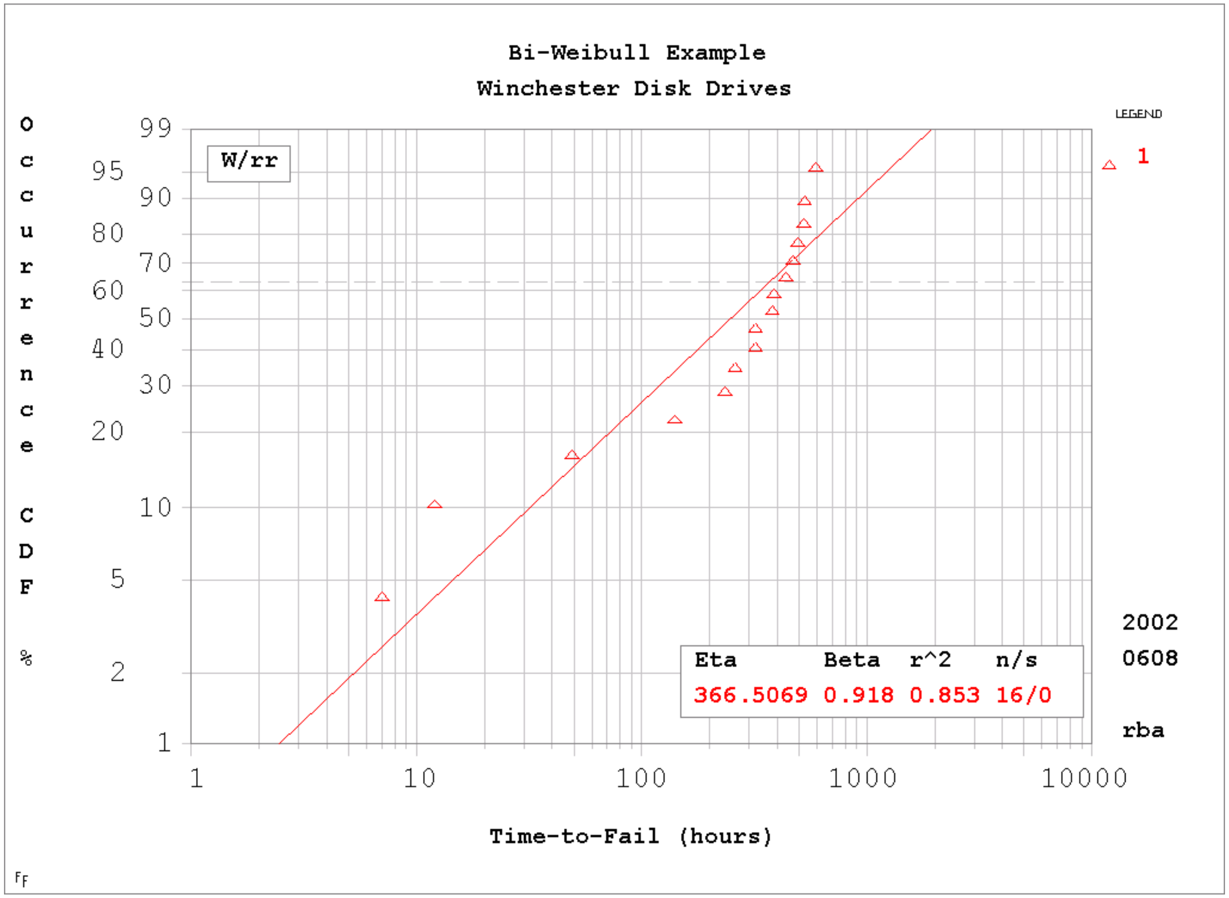
Mixed Failure Modes

- Getting data in the failure mode specific format is the biggest challenge in getting good Weibull results
  - Takes discipline to determine true root cause failure mode for each failure and to record with failure code
- Getting the suspension lives is the second biggest challenge (more to come on this issue)
- Two failure modes in the data is a common problem - Called Bi-Weibull

Bi-Weibull

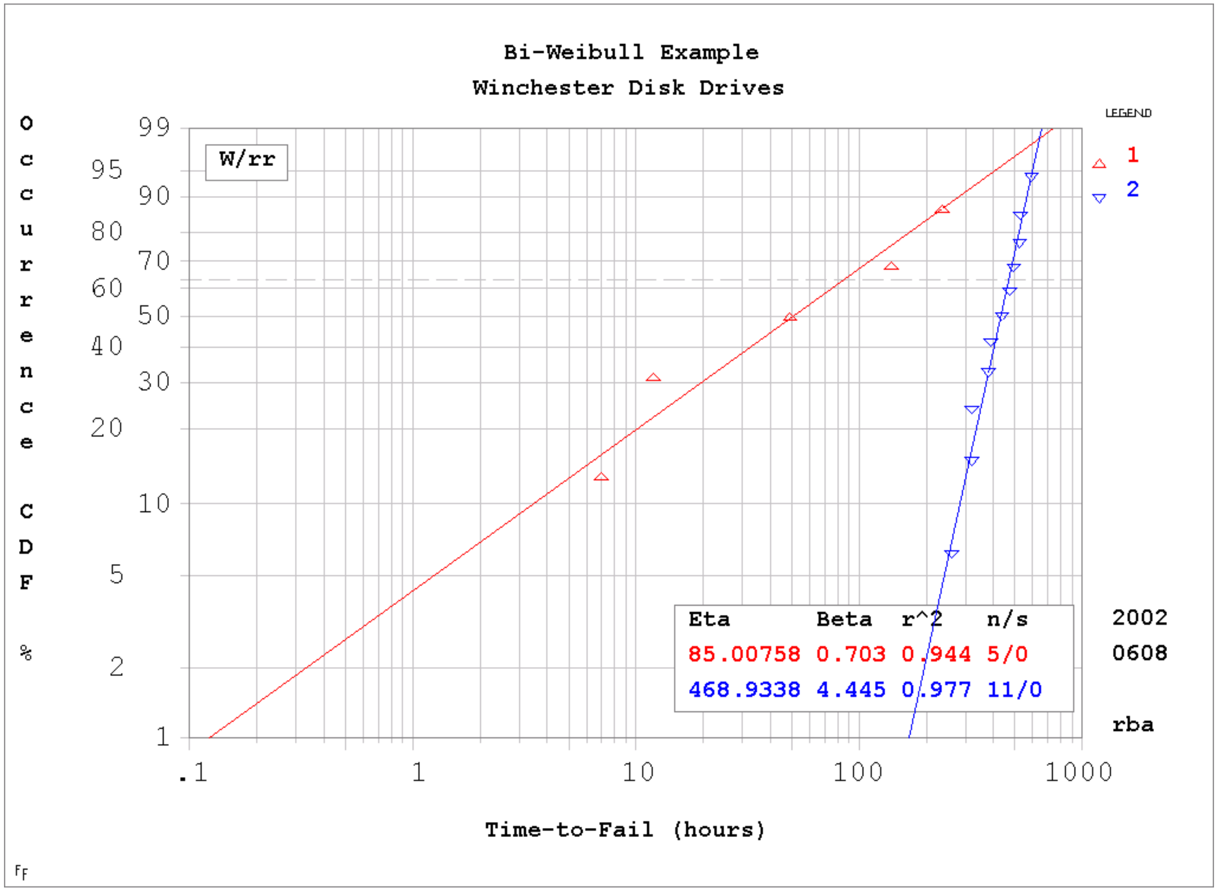
- A Weibull Plot with a "dogleg bend" in the data (data is telling a story)
- Engineering basis for two different failure modes must be determined
- Segregation of the data sets into two Weibulls is justified if two different failure modes can be determined
- Steep slope followed by a shallow slope indicates a Batch Problem (perpetual survivors)

Bi-Weibull



Bi-Weibull Example
Winchester Disk Drives
Occurrence CDF %
99
95
90
80
70
60
50
40
30
20
10
5
2
1
W/rr
LEGEND
1
Eta Beta r^2 n/s
366.5069 0.918 0.853 16/0
2002
0608
rba
1
10
100
1000
10000
Time-to-Fail (hours)

Bi-Weibull


Bi-Weibull Example
Winchester Disk Drives
W/rr
LEGEND
1
2
Occurrence CDF %
99
95
90
80
70
60
50
40
30
20
10
5
2
1
.1
1
10
100
1000
Time-to-Fail (hours)
Eta Beta r^2 n/s
85.00758 0.703 0.944 5/0
468.9338 4.445 0.977 11/0
2002
0608
rba

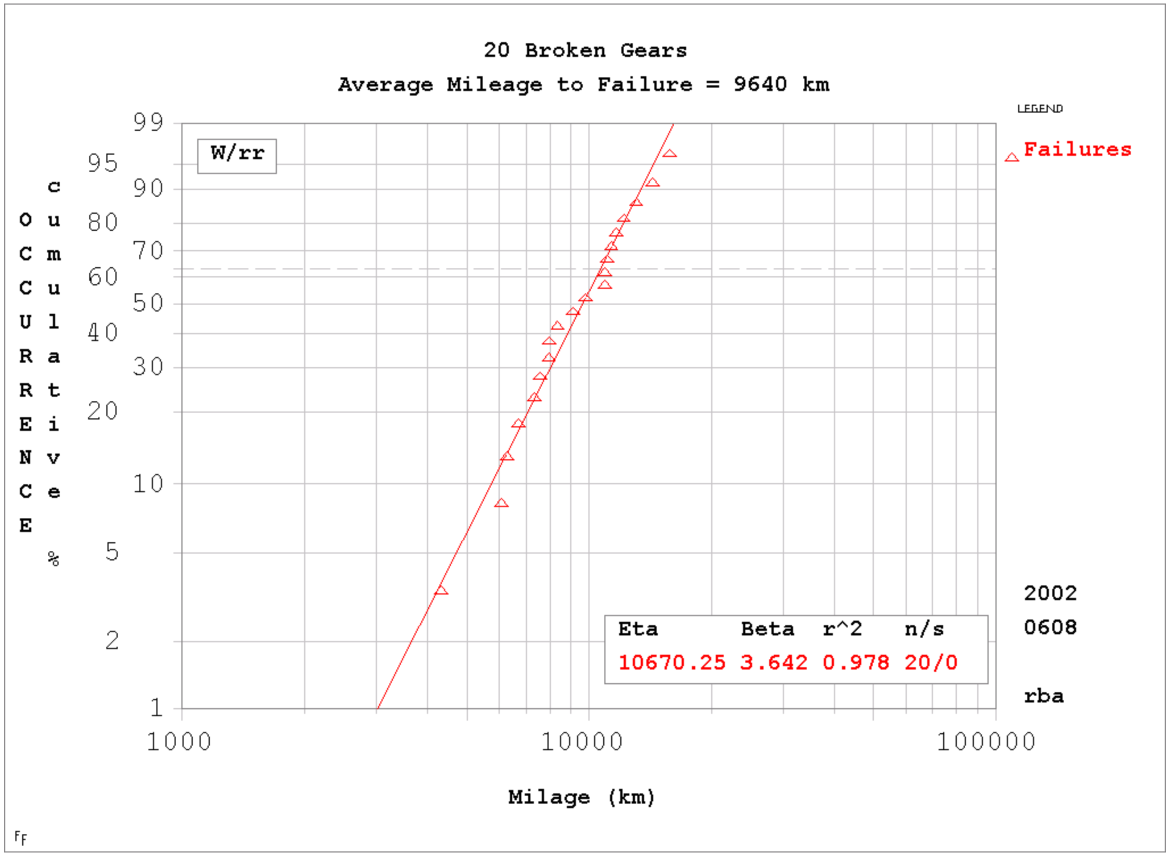
Suspension Times Unknown

- Have time of failures
- Don't know the run time on the units that have NOT failed (don't know suspensions)
- May not even know the number of units that require suspension (unknown fleet size)

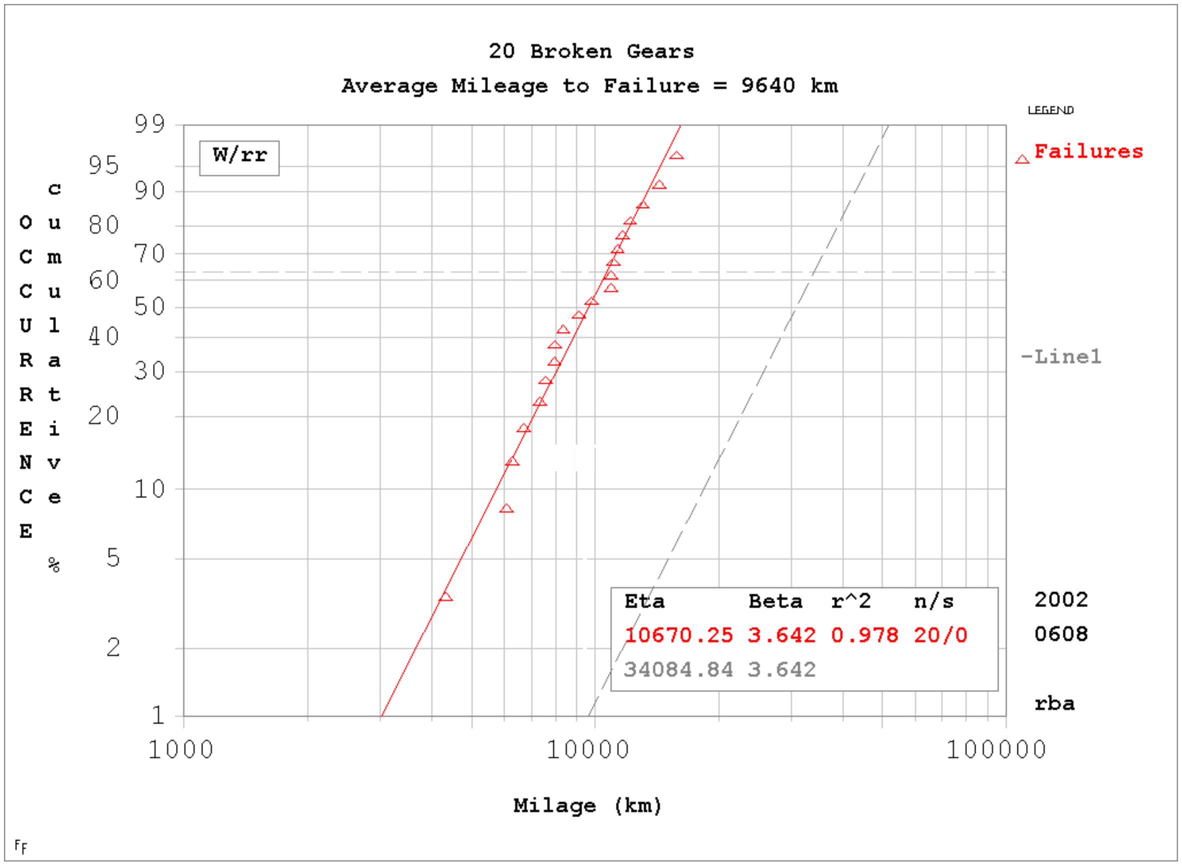
Dauser Shift

- Suspension Times Unknown
- Do know some information
  - Time on each failure
  - Average time to failure
  - From the initial Weibull - know Beta
- Assumes future failures of un-failed units will on average have the same MTTF
- Last Resort
  - No mathematical support for this approach
  - Even a gross estimation of suspension times (histogram) is better than Dauser Shift
  - Some data is better than no data

Dauser Shift



Dauser Shift



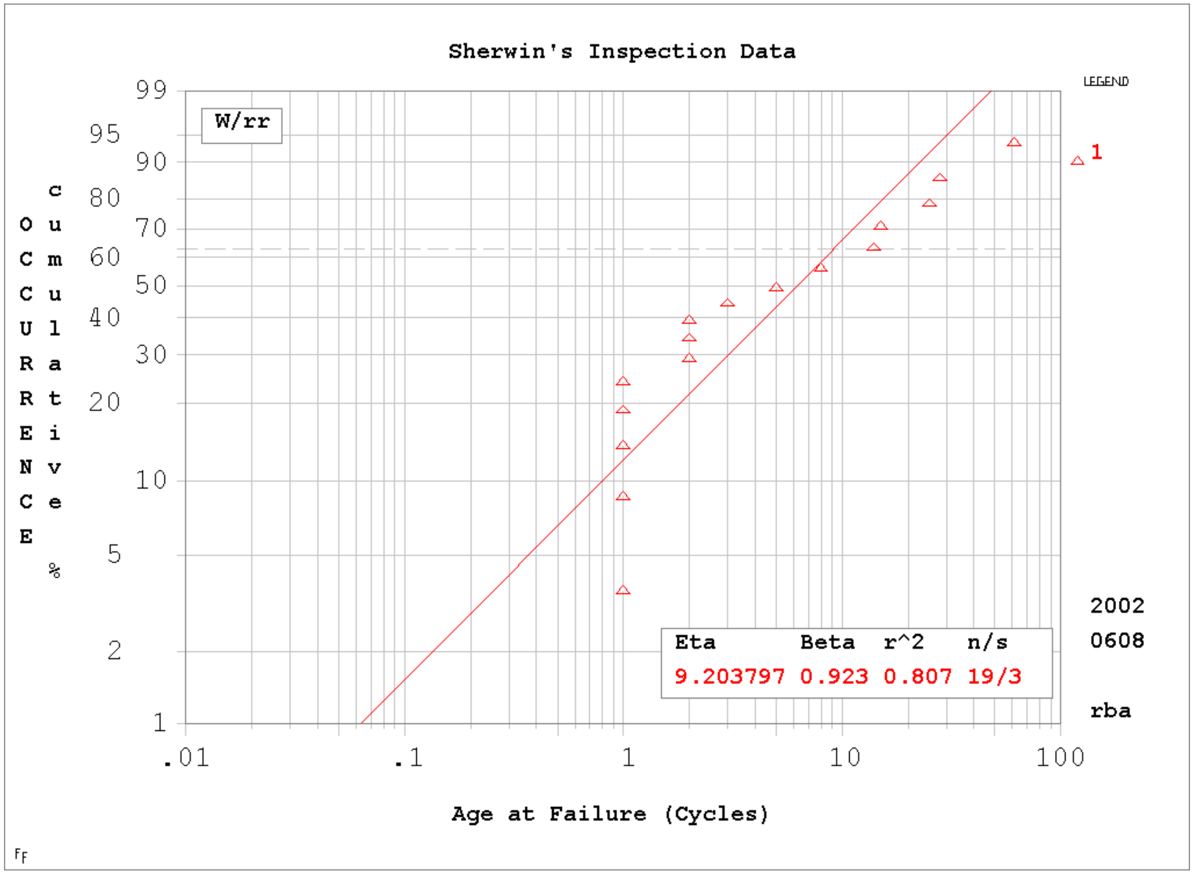
Inspection Interval Data and Course Data

When Benign Failures Occur

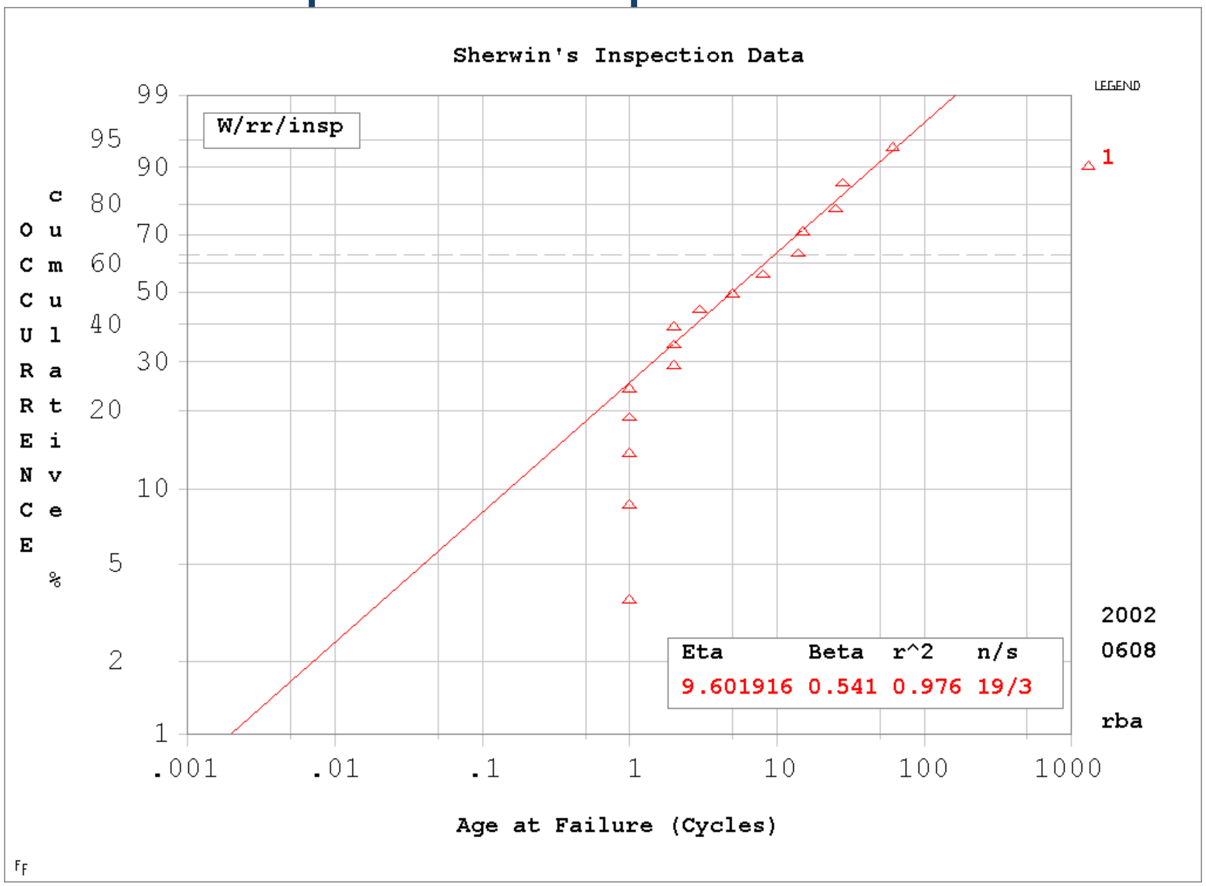
Inspection Interval Data

- Failure detected and noted on inspection
  - Called Interval data
  - Failure could have occurred anytime after the last inspection - time of exact failure is unknown but bracketed between the inspections
  - Unknown failure time results in less certainty in the Y (% failures) than the inspection time - should regress Y on X
- Probit Data Options
  - Option 1 - Use only the last failure from the inspection to determine the Weibull
  - Option 2 - Regress Y on X

Inspection Interval Data



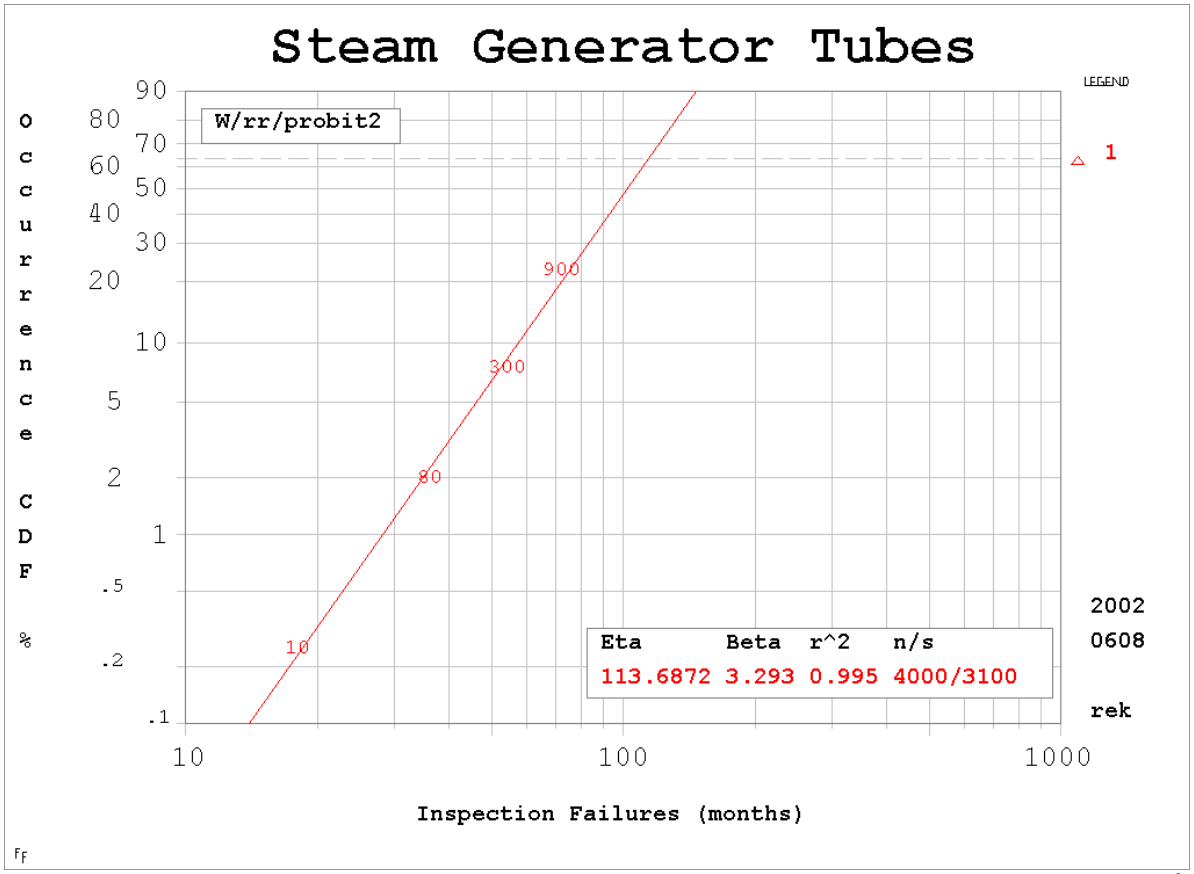
Interval Data - Inspection Option



Interval Data

- Heat Exchanger Tube Failures (cracking)
  - Fixed number of tubes inspected - 4000
  - Cumulative failure is the total # of tubes plugged after each inspection (#plugs this inspection + previous # of plugs)
  - Inspection interval every 18 months
- Use "Probit" data (regress Y on X)
  - Median Rank not used to plot data - use Cumulative % Failure for plotting position
  - Data has three components
    - Inspection Time
    - Constant number inspected
    - Cumulative number failed

Interval Data - Inspection Option



Course Data

- When data not recorded in the correct time frame
  - Recorded annually instead of monthly
  - Quarterly instead of weekly, etc.
- Same problems as Inspection Data
- Data will have vertical data sets
- Handle the same way as Inspection Data

Steep Beta (Slope)

- Hide data problems
  - Failures are compressed by the scale
  - Hides data issues such as
    - Curved data
    - Outlier data points
- Indicative of possible data selection problems (liars figure and figures lie)
- If real - failures are very rapid (sudden death)

Steep Beta

Steep Beta Hide Problems
W/rr
LEGEND
1
OCCURRENCE
Cumulative %
99
95
90
80
70
60
50
40
30
20
10
5
2
1
100
1000
Datum (units)
Eta Beta r^2 n/s
190.0851 17.13 0.863 25/0
2002
0608
rek

Interpreting the Plot

- Look at each figure
  - Is it a good Weibull?
  - Is the data trying to tell us something?
  - What steps (if any) should be taken to improve the analysis?
  - Anything to be concluded?

WEIBAYES

WHEN WEIBULLS ARE UNCERTAIN OR IMPOSSIBLE

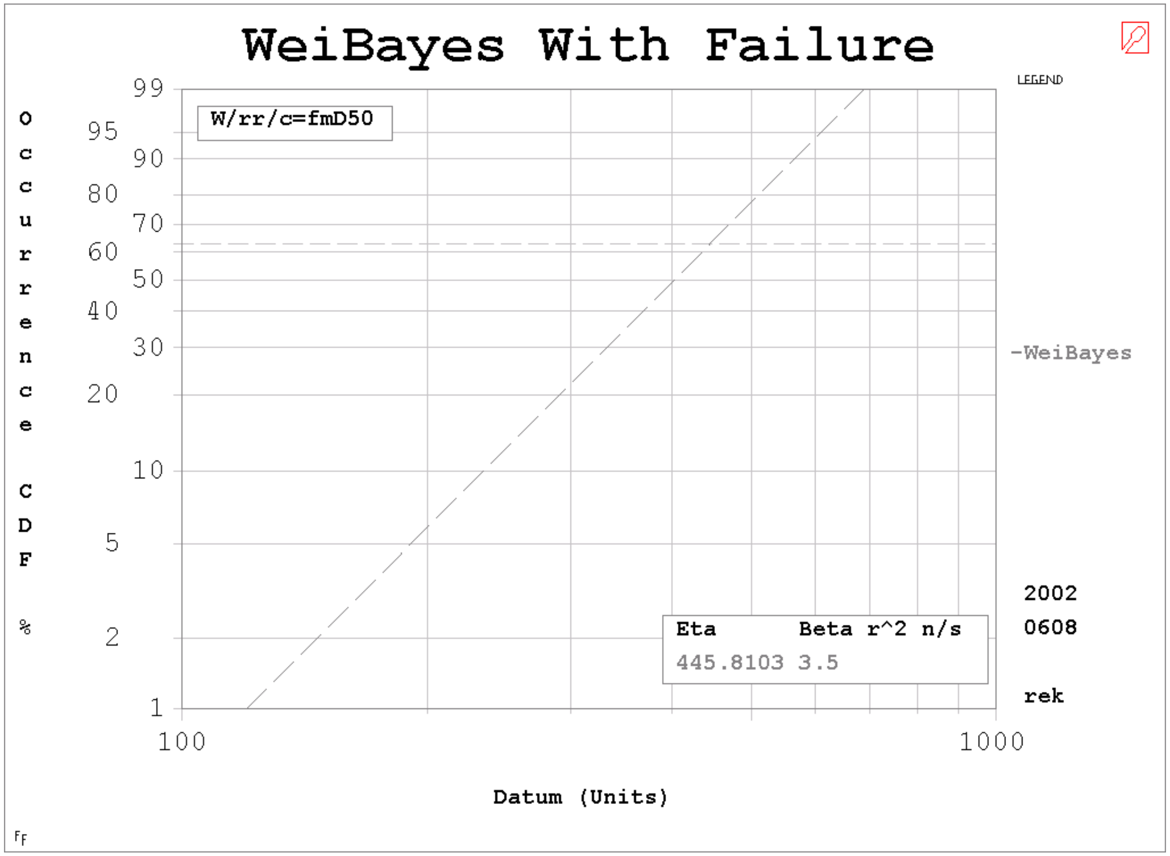
Weibayes

- $$\text{Eta} = \left[\sum_{i=1}^{N} t_i^{\text{Beta}} / r \right]^{1/\text{Beta}}$$
- t_i = time / cycle on unit
- r = number of failed units
- Eta = MLE of Characteristic Life
- N = total number of failures + suspensions

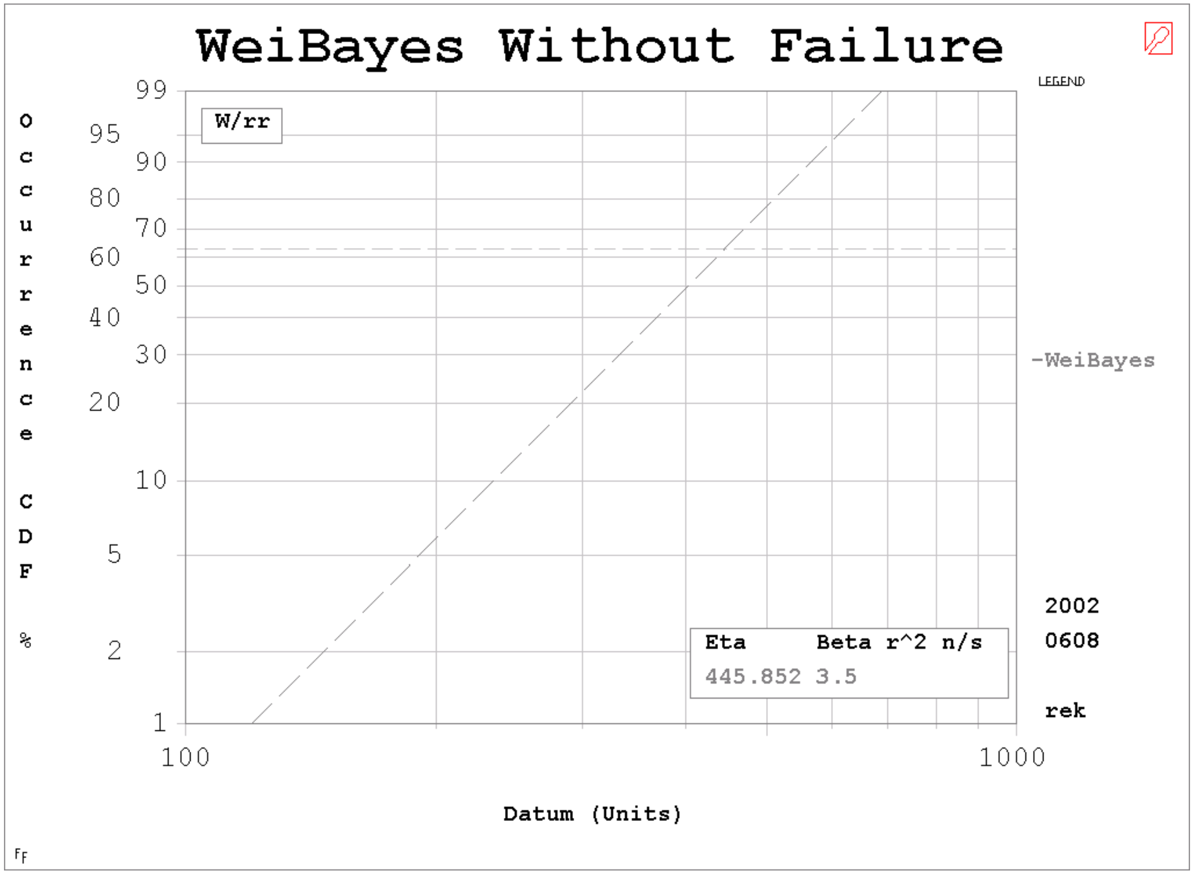
Weibayes

- Weibull Analysis with an assumed Beta
  - From historical or test data
  - Assumes first (next) failure is imminent
- With defined failure modes - significantly improved accuracy over small data set Weibulls
- Useful under two conditions
  - No failures
  - With failures (typically very few data sets)

Weibayes with Failure



Weibayes Without Failure



Weibayes

- Past experience good source of Betas
- Weibull data sources
  - Paul Barringer - http://www.barringer1.com/
  - Dr. Bob Abernethy / Mr. Wes Fulton - http://www.weibullnews.com/
  - Reliability Engineering - http://www.Weibull.com

Crow - AMSAA
Reliability Growth Model

When Weibull and Weibayes Won't Work

Reliability Growth Model

- Used when:
  - Have multiple failure modes
  - Don't know the size of the fleet
  - Constant change (improving / solving)
- Provides graphic of status - better / worse than past
- Provides method to predict next failure
- Manager friendly!!!

Reliability Growth Model

- Plots Cumulative Failures vs. Cumulative Time
- Log - log curve fit (line)
- Parameters (Beta, Lambda) determined from fit line
- Developed by Larry Crow at the Army Material Systems Analysis Activity (AMSAA)

Reliability Growth Model

- Rho (t) = Lambda x Beta x $t^{(\text{Beta -1})}$
- Log of cumulative failures N(t) versus log cumulative time (t) is linear if model applies
- N(t) = Lambda x t^{Beta}
- *ln* N(t) = *ln* (Lambda) + *ln* (t)   which is a straight line

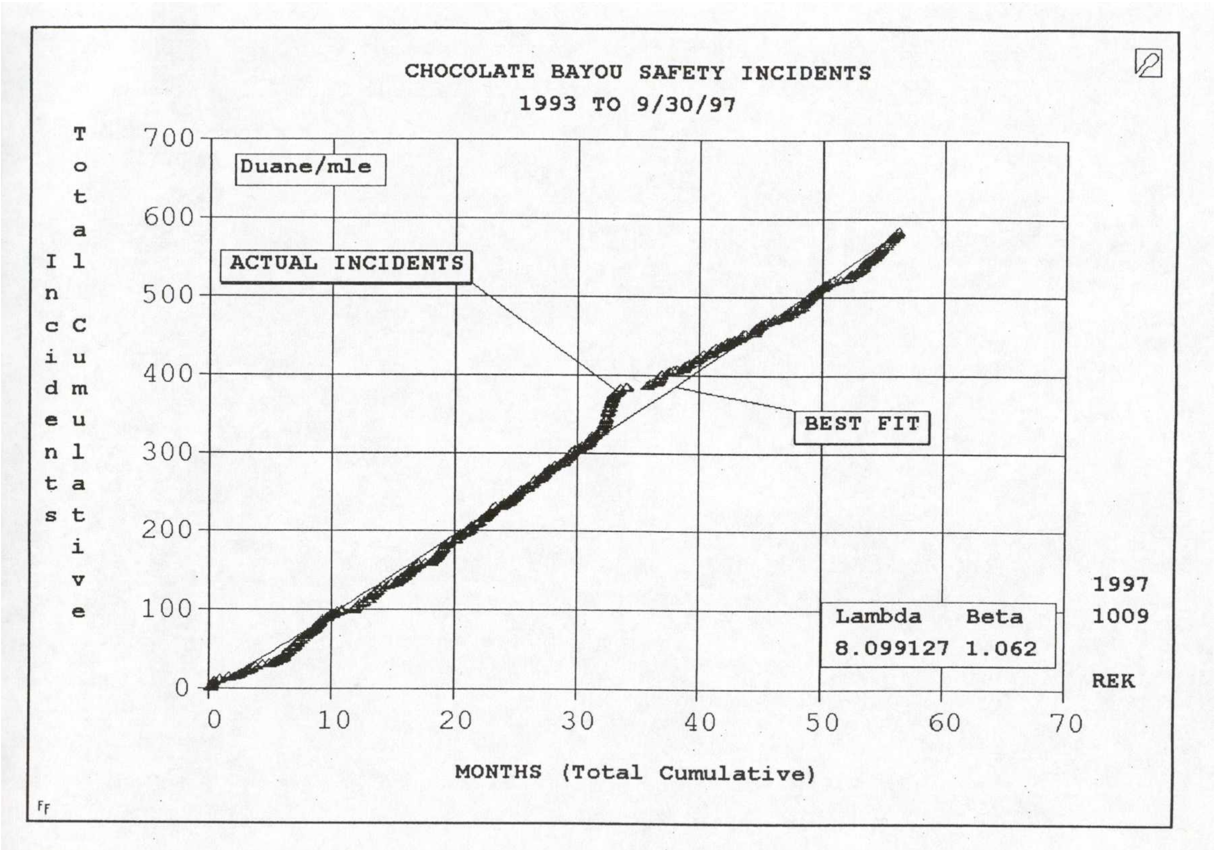
Reliability Growth Model

- Cumulative failure rate C(t) = N(t) / t
- $C(t) = \text{Lambda} \times t^{(\text{Beta} - 1)}$

- $\text{Rho}(t) = \text{Lambda} \times \text{Beta} \times t^{(\text{Beta} - 1)}$
- MTTF = 1 / Rho (t)

- Beta < 1.0 indicates that failure rate is decreasing (things getting better)
- Beta = 1.0 indicates that failure rate is the same (status quo - nothing changing)
- Beta > 1.0 indicates failure rate is increasing (getting worse - NOT good)

CPO Safety Growth Model



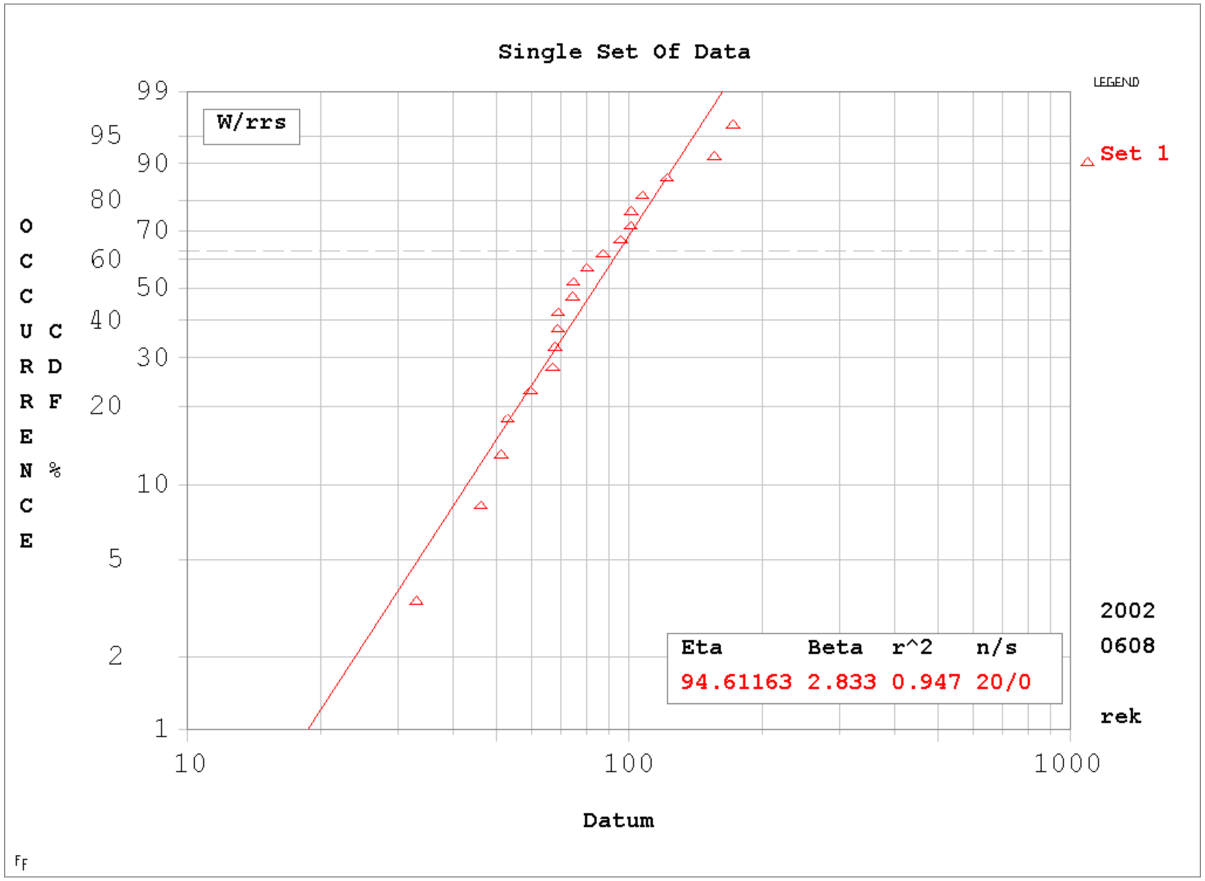
DATA SET ISSUES

When Mixed Failure Modes Occur

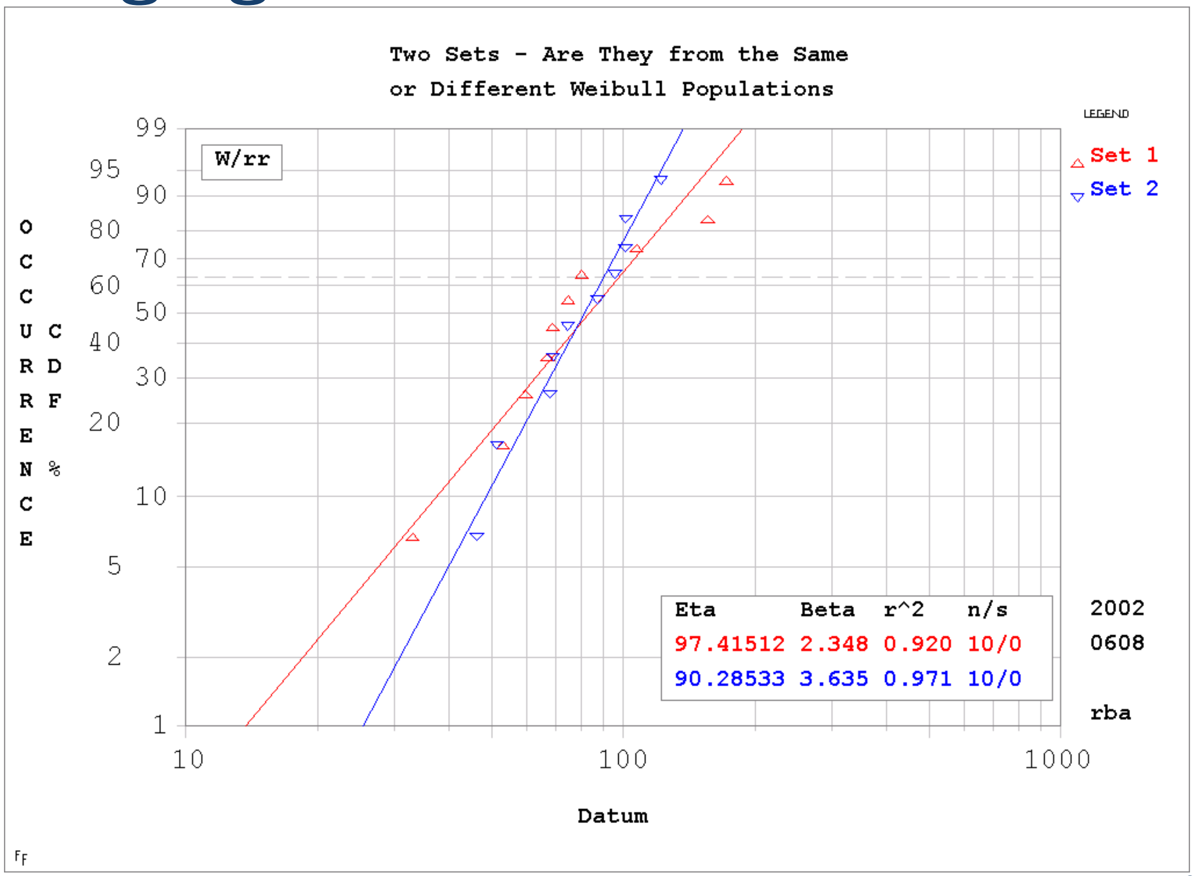
Data Set Issues

- When evaluating Weibulls that clearly have mixed failure modes
  - Have Engineering justification to segregate the data
  - How do we know that the data sets are really different sets?
- Don't want to be fooling ourselves into seeing differences that are not statistically significant

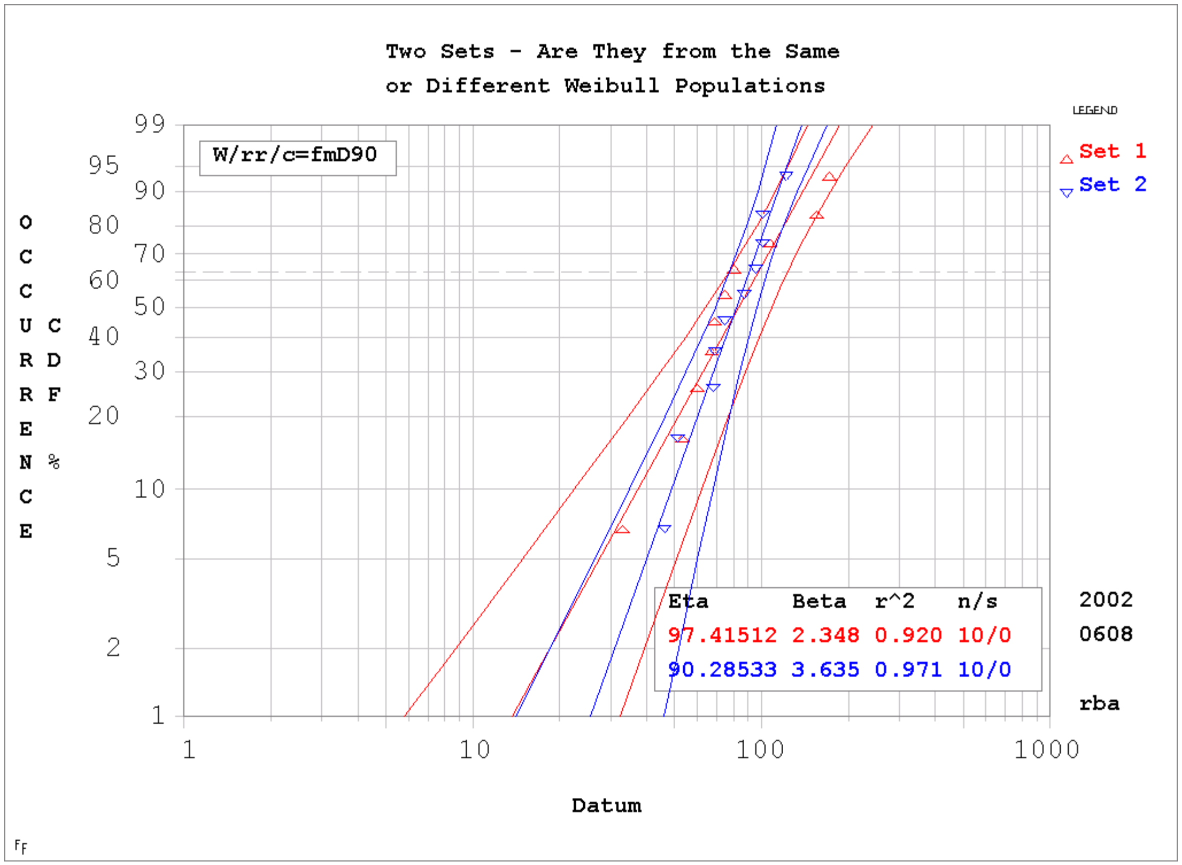
Single Data Set



Data Set Segregated



Segregated Data Set



Segregated Data Set

- Notice that the 90% confidence bounds overlap
  - Data sets are NOT significantly different
  - No statistical justification to segregate the data
  - May not have two different failure modes

Meridium Problems

- Data is limited to since SAP came on line - no previous MWO data
- Data is very dirty, has all work orders
  - Mixed failure modes
  - Some data is flat wrong
- Difficult to cull data from a Query
- Analysis tools set is limited in ability to handle dirty data / inspection data issues

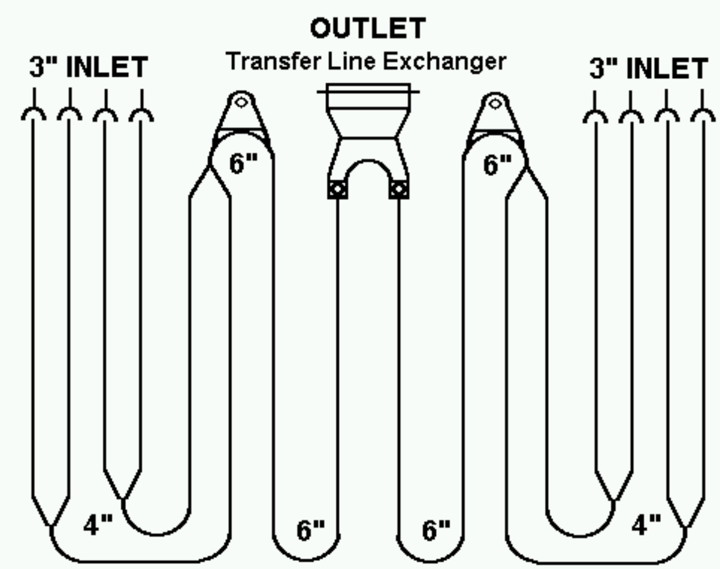
Meridium Solutions

- Use Meridium to Query SAP and generate a data set
- Export data set with descriptions (short text, etc.) to Excel
- Clean data set of extraneous errors
- Use Excel to calculated TOF by subtracting dates - generate a complete data set
- Paste data into WinSmith Weibull

Example Analysis

Carburization Failures of Olefin Cracking Furnace Tubes

Cracking Furnace Design



Olefins Cracking Furnace Coil Design
Figure 1

TUBE CONDITIONS

- Operating = 6 - 20 psig @ 2,000 °F
- Decoke = 6 - 30 psig @ 2,050 °F
- Alloys used (% Cr / % Ni)
    - 25/20 (HK 40)
    - 25/35 (HP45 and HP-MOD)
    - 35/45

Original Operation

- Heavy Feedstock
- Substantial Steam-to-Feed Ratio
- Low to Moderate Feed Rates (50-75%)
- Moderate Severity (outlet temperature)

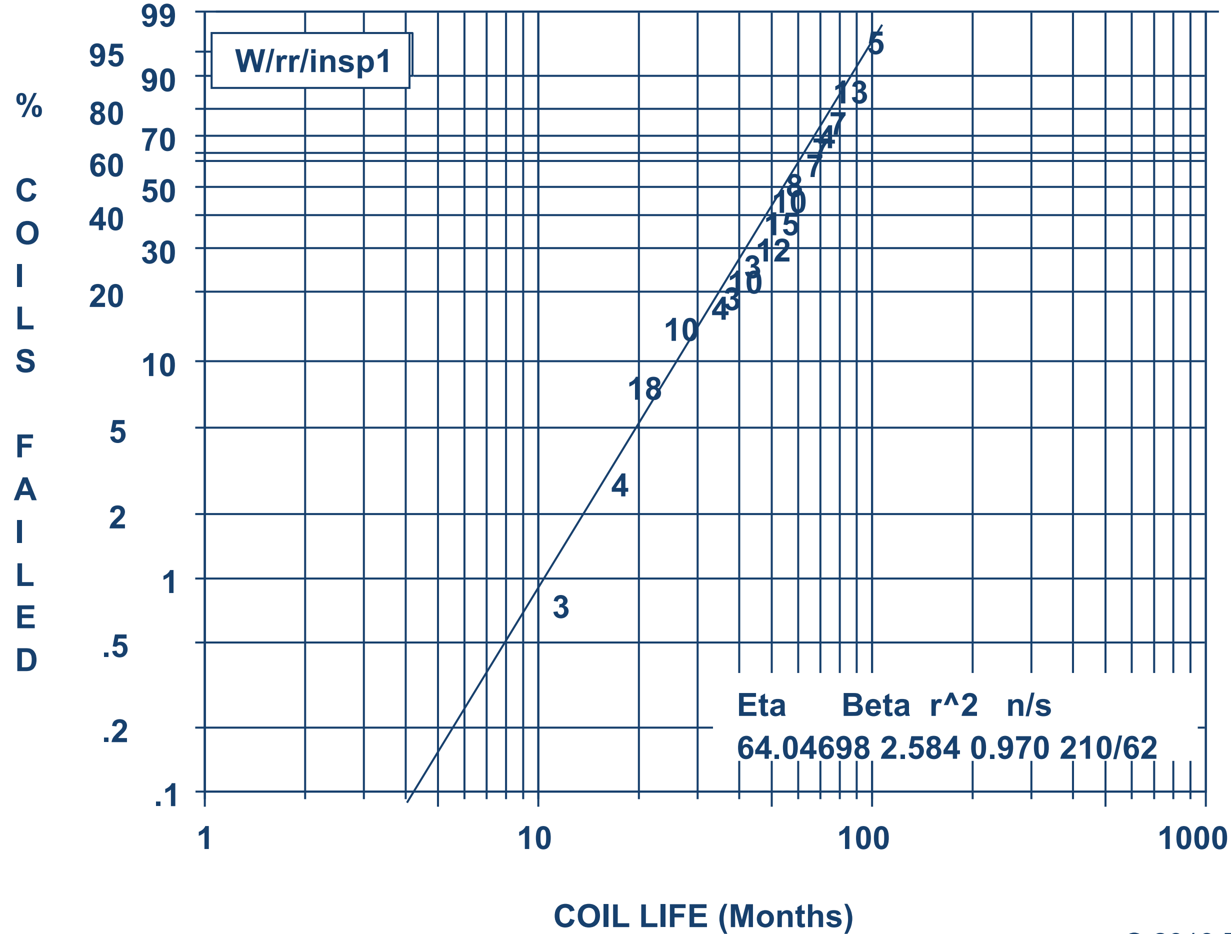
Revised Operation

- Lighter Feedstock
- Higher Feed Rates (125%)
- Lower Steam-to Feed Ratio
- Slight Increase in Severity

Weibull Analysis

- Evaluate 6" Outlet Tubes
  - Highest Temperature
  - Data on originals and replacements
  - Catastrophic failure could result in loss of furnace

FURNACE OUTLET TUBE FAILURE

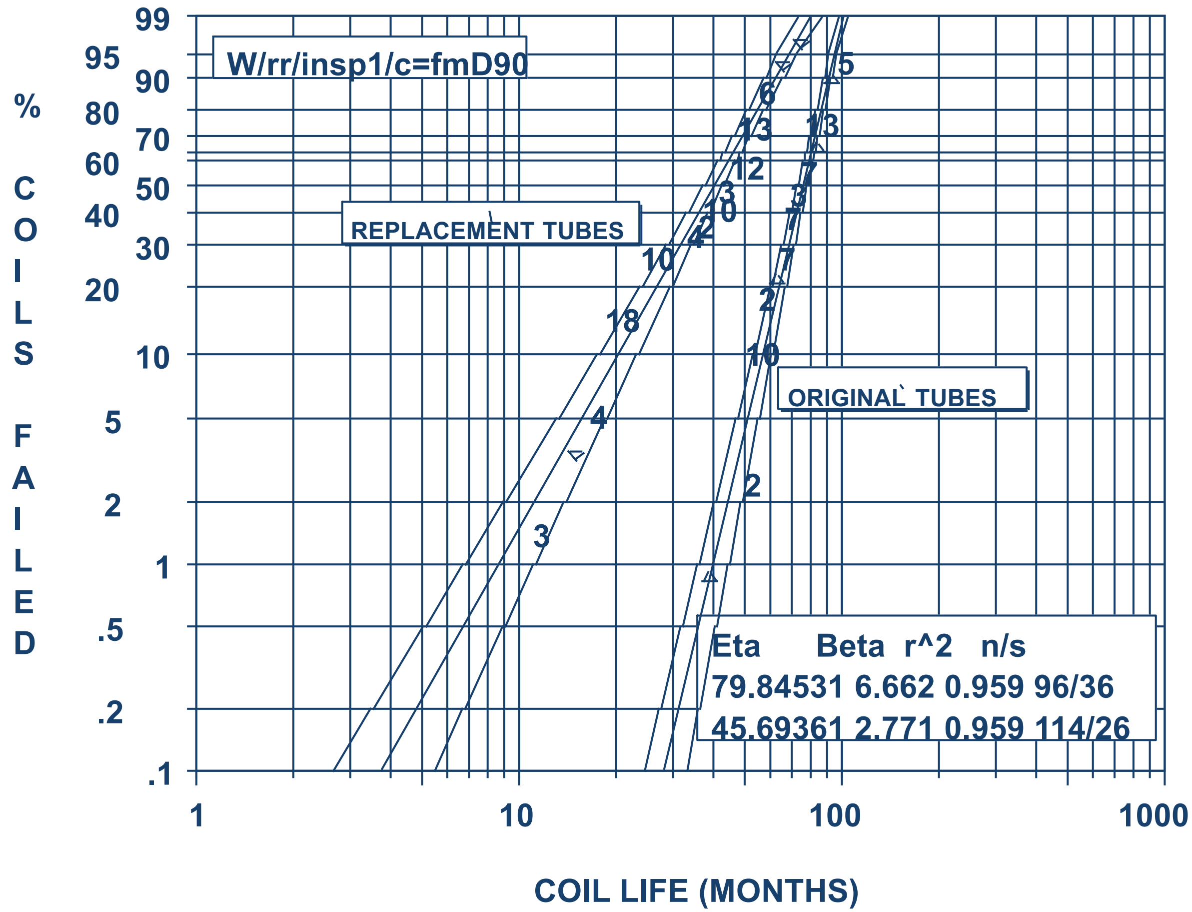


Initial Weibull Analysis

Eta	Beta	r^2
64 months	2.584	0.970

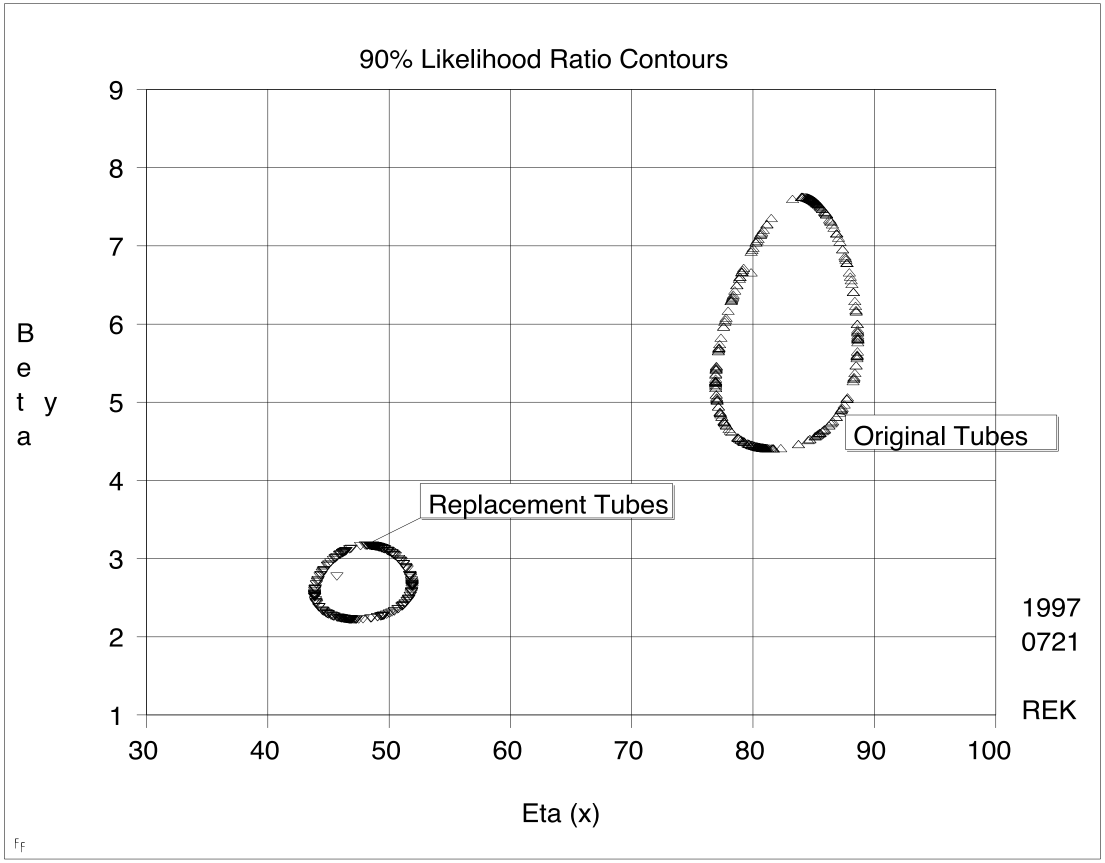
- Good fit with inspection data
- Weibull Distribution
- Visual Evaluation - Slightly Curved Data

FURNACE OUTLET TUBE FAILURE



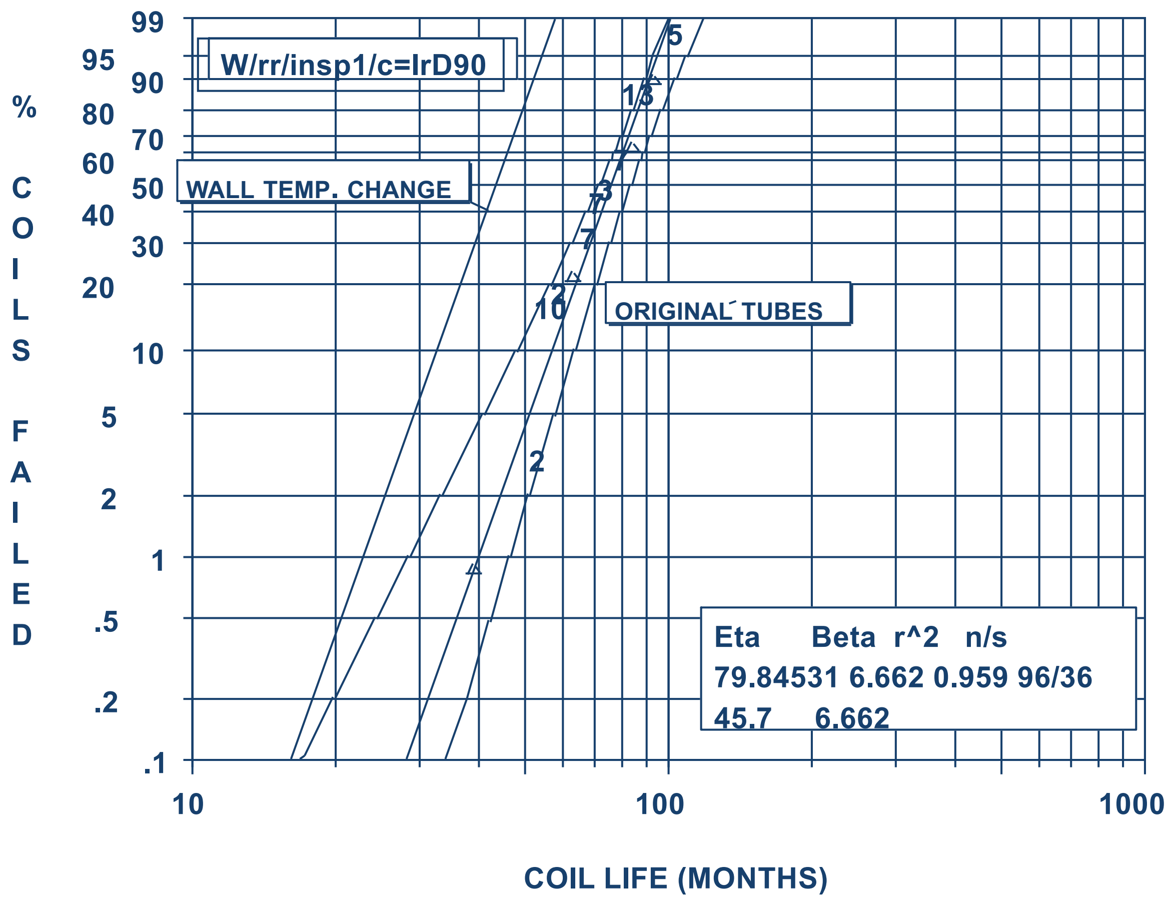
Second Weibull Analysis

Set -	Eta (months)	Beta	Wear Out
Original	79.8	6.662	Old Age
Repl.	45.7	2.771	Early

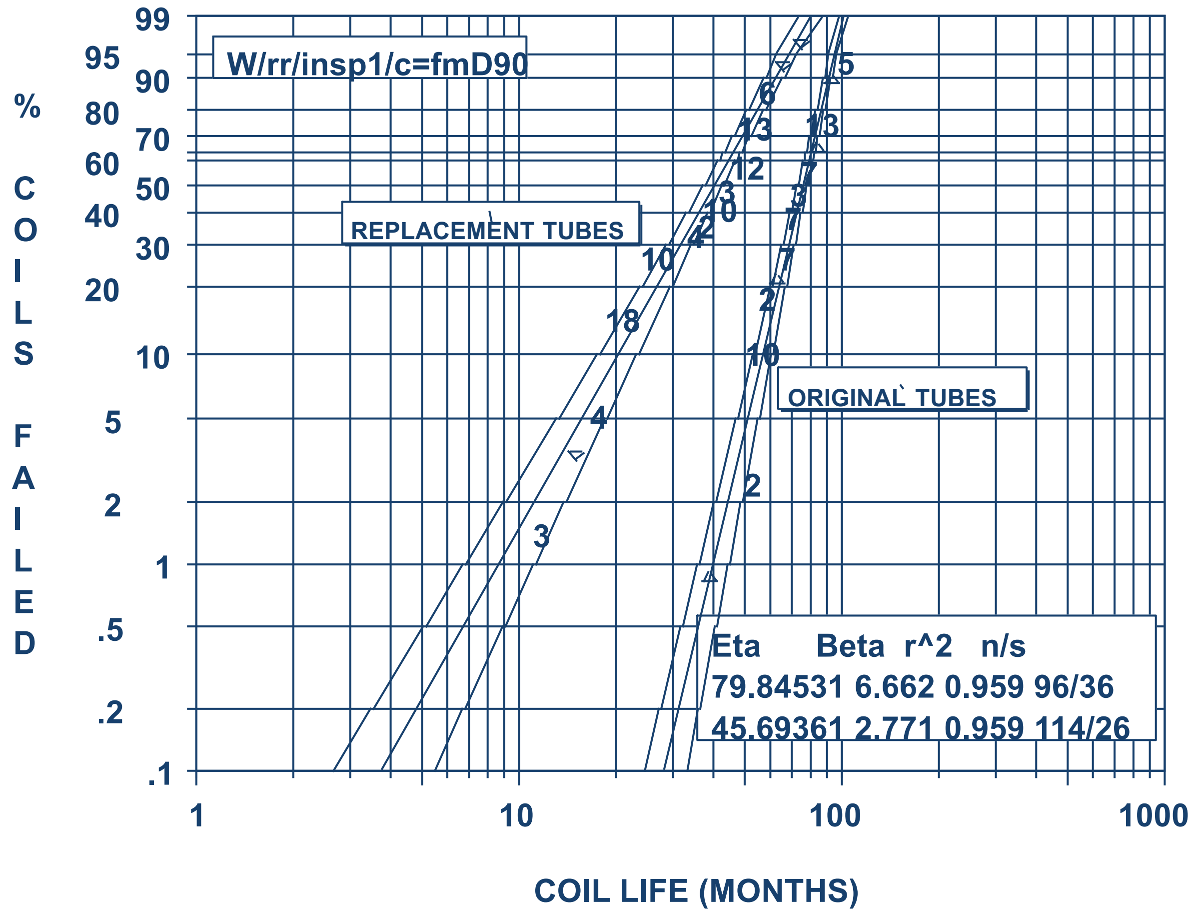


90% Likelihood Ratio Contours
9
8
7
6
5
4
3
2
1
B
e
t y
a
30
40
50
60
70
80
90
100
Eta (x)
Original Tubes
Replacement Tubes
1997
0721
REK

FURNACE OUTLET TUBE FAILURE

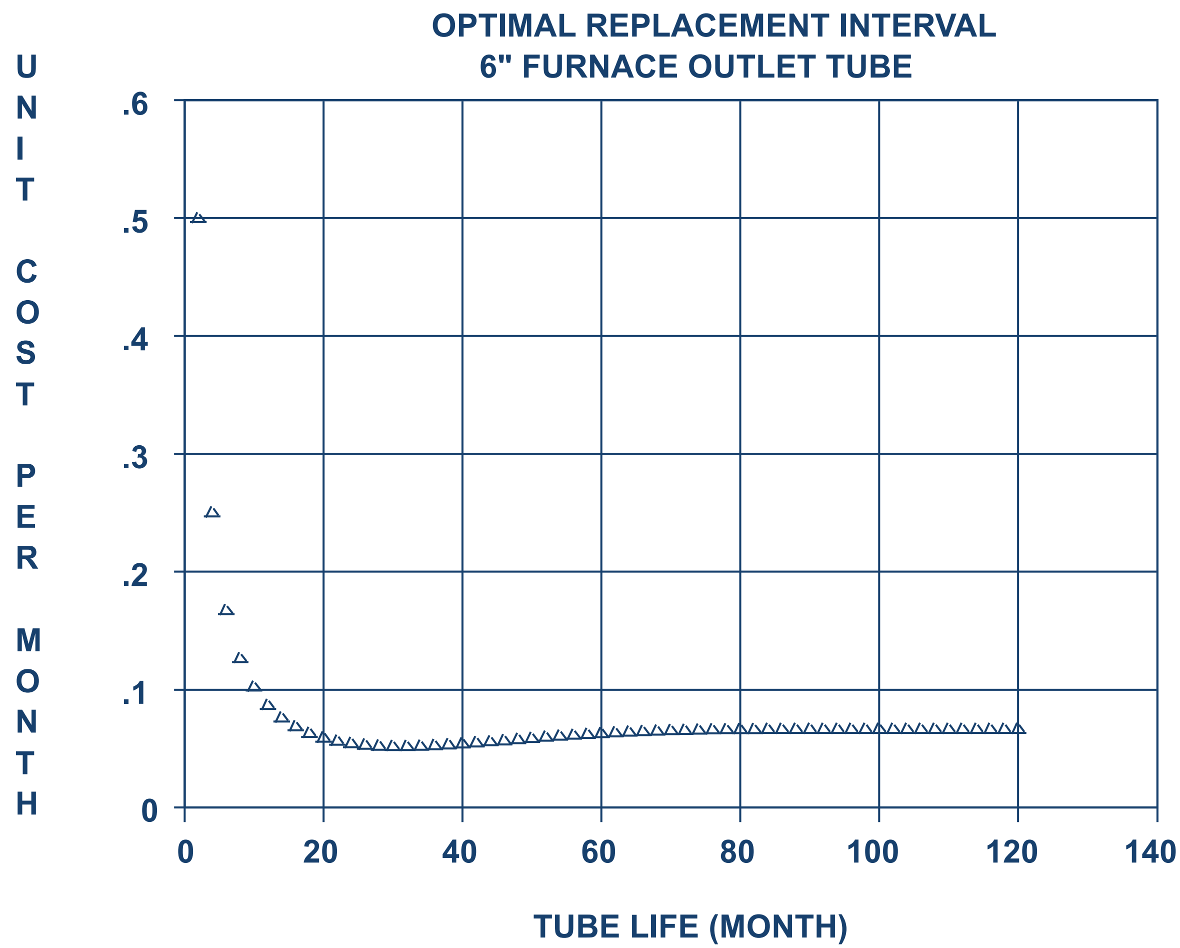


FURNACE OUTLET TUBE FAILURE



Root Cause

- Carburization Rate is limited by SiO_2 scale barrier in 25/20 and 25/35 alloys
- Reduction of steam-to-feed ratio destabilizes the SiO_2 layer
- Explains changes in Beta


OPTIMAL REPLACEMENT INTERVAL
6" FURNACE OUTLET TUBE
UNIT COST PER MONTH
.6
.5
.4
.3
.2
.1
0
0
20
40
60
80
100
120
140
TUBE LIFE (MONTH)

Maintenance Philosophy

- Optimum replacement verifies low penalty for extending tube replacements
- Use Characteristic Life to predict tube replacement.
- Limit repairs to two attempts before requiring replacement.

Other Weibulls

Item	Eta	Beta
4”- Ethane	67.9	3.139
4”- Oil	118.1	2.901
3”- Ethane	231	1.254
3”- Oil	234	6.815

Other Weibulls

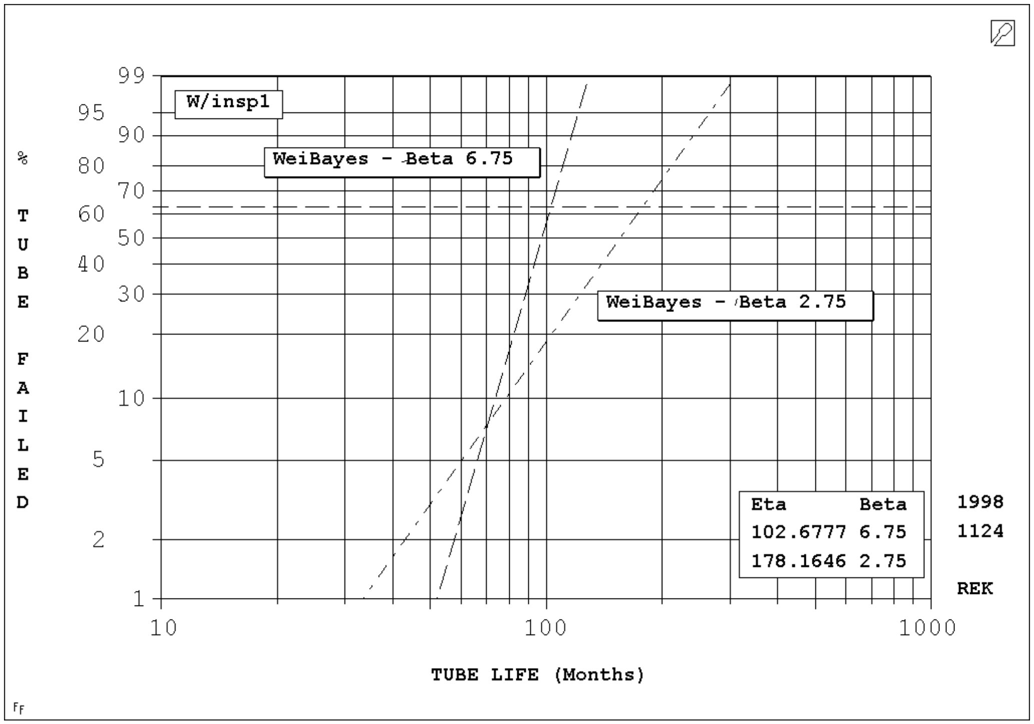
Item	Eta	Beta
3” to 4”- Ethane	117	2.754
3” to 4”- Oil	185	6.815
4” to 6”- Ethane	46*	1.157*

* Log-Normal distribution (Mu, SigF)

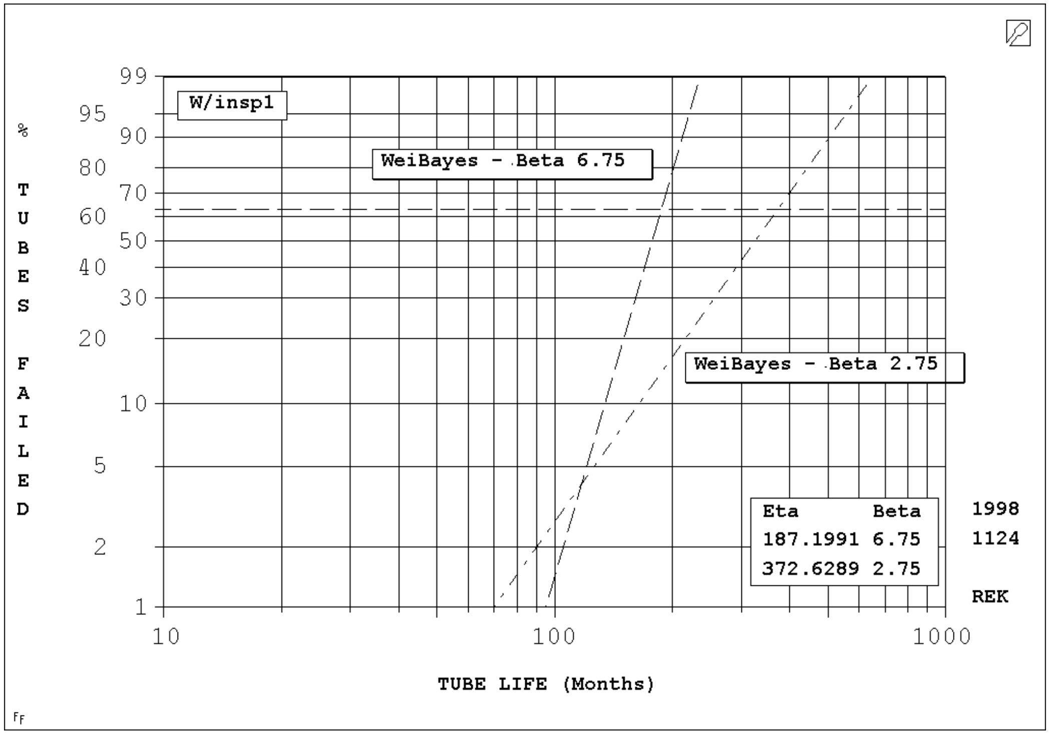
Weibayes

- Weibayes is a Weibull without (or few) failures
- Must have a known failure mode - good estimate of Beta
- Use where few or no failures exist
- Uses the ages of non-failed components to estimate the Weibayes

6” Ethane Furnace Tube



6” Oil Furnace Tube



Conclusions

Weibull Analysis Provides

- Clear method to evaluate tube life
- Quantifies maintenance vs replacement decisions
- Insight into changes of failure mechanisms
- Excellent means to include the $ side of the solution.

References Utilized to Develop these Materials

- New Weibull Handbook
  - Available at: http://www.barringer1.com/
- PlayTIME With SuperSMITH - Source of most example problems