Reliability Lessons From The Automotive Industry

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A Special ½ Hour Presentation For The Danish Wind Turbine Industry
The “Lessons” In a Nutshell

- **Use Reliability Allocation** to translate the big “I Want This Wind Turbine To Be Reliable” into **reliability requirements** for devices.

- At the device level - **Use the three step AQQ process** shown below to develop a mature device on time:
  
  1. Analysis  
  2. Qualitative Testing  
  3. Quantitative Testing

- Define the “severe customer” or “severe environment” and use this to **quantify “one-life of damage”** for each failure mechanism.

- **Develop and Demonstrate the needed level of reliability** relative to the “severe level of damage” for each critical failure mechanism for each device. Combine statistical rigor with engineering physics.

- **You** should define the requirements and the tests to be conducted by your suppliers... do not assume that your supplier is the expert and will do your job for you.
Starting Point - The Three “Faces” of Reliability

- We see “Reliability” as three phenomena that are often lumped together to form a “bathtub” curve:

  1. Quality Issues – Failure Rate Improves With Time
  2. Reliability Issues – Failure Rate Gets Worse With Time
  3. Random Chance Failure

We Control This With SPC Or Screening

Stress Exceeds Strength – An Umbrella May Help But May Not Be Sufficient... Difficult To Engineer A Solution To The Un-Predictable

We Must Engineer Robustness Into The Product To Move This To The Right
The Problem Addressed by The Reliability Engineer is...

- The product starts to wear out as soon as you get the quality issues sorted out....not fair to the customer!

We Must Engineer Robustness Into The Product To Move The Wear Out Curve To The Right

Random Chance Failure

Failure Rate

Wear Out Curve

When Do I Get The Chance To See The Falling Piano?

Lets Focus On Moving The Wear Out Curve To The Right!
The Basic Concept of Stress-Strength Interference

Reliability and Failure Mechanisms → **Stress-Strength Interference** → Targeting The Severe User → Analytical Activities “A” → Qualitative Activities “Q” → Quantitative Activities “Q”

**The World Of Stress**

**Valid for Cumulative and Non-Cumulative Damage**

**Product Strength**

Beginning Of One Life

Valid for Cumulative and Non-Cumulative Damage

**Product Degrades From Fatigue or Similar**

End Of One Life

“**One Life**” = 20 Yrs.

Valid for Cumulative Damage

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How Much **Overlap** is There When We Demonstrate Reliability For The Average User?

Reliability is good for the below average user…. but not for anyone more severe than average.

**Not Good!**

Legend

- Distribution of Usage Stress
- Nominal Design Point and Variation in Product Strength
- Unreliability for the Average User
Do Not Use MTBF or Cookbook Reliability Prediction Methods

- **MTBF by definition is when 63% of the product has failed and 37% of the product has not yet failed.**
- MTBF is useful for light bulbs but not for wind turbines.
- Shown is a typical “Electrical” failure distribution with MTBF = 100.
- The automotive industry never uses MTBF.
- The automotive industry never uses cookbook reliability prediction methods (Mil-Std 217).
Assessing Reliability of Existing Wind Turbines

Information taken from the following will be identified with an *

Survey of Failures in Wind Power Systems With Focus on Swedish Wind Power Plants During 1997–2005

Johan Ribrant and Lina Margareta Bertling, Member, IEEE

Abstract—The wind power industry has expanded greatly during the past few years, has served a growing market, and has spawned the development of larger wind turbines. Different designs and technical advances now make it possible to erect wind turbines offshore. The fast expansion of the wind power market faces some problems. The new designs are not always fully tested, and the designed 20-year lifetime is typically never achieved before the next generation of turbines are erected. This paper presents results from an investigation of failure statistics from four sources, i.e., two separate sources from Sweden, one from Finland, and one from Germany. Statistics reveal reliability performance of the different components within the wind turbine. The gearbox is the most critical, because downtime per failure is high compared to the other components. The statistical data for larger turbines also show trends toward higher, ever-increasing failure frequency when compared to small turbines, which have a decreasing failure rate over the operational years.

Index Terms—Availability, failures, statistics, reliability, wind power generation.

Fig. 6. Failure rate in respective rated power group versus operational year.
Field Data* Shown As An Entropy Based Cumulative Hazard Plot

Note: The Cumulative Hazard Plot is appropriate for a “repairable system” where the failure rate could exceed 100%. The trending of the lines can be modeled and extrapolated as needed for future projections.
Average Downtime Per Failure by Sub-System In The Current Products*

Average Downtime Per Failure by Sub-System
Extended Segments Are Electrical

- Control System
- Electrical System
- Sensors
- Generator
- Blades/Pitch
- Yaw System
- Drive Train
- Gears
- Mechanical Brake
- Structure
- Hydraulics
- Hub
OK... So We See That Things Could be Better...and Electrical is a Big Contributor

• **Strategy of Solution:**
  – You **cannot** jump from **today’s biggest problem to tomorrow’s biggest problem** as an effective strategy.
  – You must have **good reliability requirements for all of the components** in a wind turbine as they are all interconnected.
  – **Electrical is a major contributor**
    • **Electrical devices fail for mechanical reasons.**
    • The Electrical Engineering community has historically not been trained in dealing with mechanical issues.
  – **Reliability Apportionment, AQQ, and Accelerated Testing for “Quick Learning Cycles” is a good strategy......**
We Look to One of The Greatest Engineers In History For Guidance – Leonardo Da Vinci

• What would Da Vinci tell us to do? (Draw The Big Picture)
The Big Picture of Tonight's “Dinner”

From the book: “How To Think Like Leonardo da Vinci” by Michael J. Gelb
The Reliability Engineer Responds With “Reliability Allocation”

Complete Wind Turbine With Reliability = 5% (3 Failures In 20 Years)

- Blades & Rotor: 56%
  - Blades: 99%
  - Hub: 85%
  - Slip Ring: 90%
  - Speed Sensor: 90%
- Generator: 56%
- Gearbox: 56%
- System Electrical: 56%
- Converter: 56%
- Nacelle: 95%
- Tower: 99.99%
- Foundation: 99.99%
- Pitch System: 90%
  - Pitch Motor: 98%
  - Pitch Gearbox: 98%
  - Pitch Bearings: 98%
  - Pitch Bearing Lube System: 98%
- *Pitch Controller Box: 98%
  - *Thermal Fatigue: 98.9%
  - *Vibration: 98.9%

*These are the two Reliability Tests on this electronic device (thermal cycling and vibration).
Improved Reliability At The System Level

Complete Wind Turbine
R = 63.7% at 20 years (1/2 of a Failure In 20 Years)
OK...So Now That I Have A Reliability Requirement For a Device...What’s Next?

• We turn to one of the world’s greatest quality leaders... What would Dr. W. Edwards Deming tell us to do?

“By What Method Will You Make Your Engineering ‘Wants’ Become Reality?”

• “Just saying the words won’t make it happen.”
• We need methods and processes by which we “engineer reliability into the product.”
• “Quick Learning Cycles” must be the “religion” of thought during product development.
By What Method?….AQQ

• **Identify critical failure mechanisms**
• **“Design In”** adequate design margins during the Analytical Step.
• **Remove** un-wanted **surprises** with Qualitative Testing
• **Validate** the existence of adequate design margins with accelerated testing relative to the severe user or severe environment.

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**Analysis** Phase  
Development Phase = **Qualitative**  
Validation Phase = **Quantitative**

**Squeeze Out Time**

**AQ^2** as a Strategy
1. Analysis – Selecting The Design Life Target That Will Result In My Desired Reliability?

Weibull Probability Plot

If my life requirement is 507 thermal cycles then I need to design to at least 1500 thermal cycles.
Thermal Cycling Example (part 1)

- We have a requirement for this device to withstand 507 thermal cycles with a reliability of 97%. We will assume a Weibull Slope value of 3. We want to design our joint to last for 1500 thermal cycles. Will our intended design pass this requirement?

Epoxy-Fiberglass FR-4 Circuit Board CTE = $\alpha_2$

Ceramic Semiconductor CTE = $\alpha_1$

Solder Joint

L = .75 inches

$E_p = 2 \times 10^6 \text{ lb/in}^2 = K$

CTE Ceramic = $6.7 \times 10^{-6}$ ($\alpha_1$)

CTE Fiberglass = $17.5 \times 10^{-6}$ ($\alpha_2$)

$\Delta T = -40 \text{ to } +85 = 125^0 \text{C}$

$Y = \Delta D = (\alpha_2 - \alpha_1) \times L \times \Delta T$

$Y = \Delta D = (17.5 \times 10^{-6} - 6.7 \times 10^{-6}) \times .75 \times 125 = .001$

$P = K \times Y$ (spring equation)

$P = 2 \times 10^6 \times .001 = 2000 \text{ lbs/in}^2$

2000 lbs/in$^2$ is pulling the solder joints apart
Thermal Cycling Example (part 2)

- Area of soldered end surface:

\[
\text{Area} = \text{height} \times \text{width}
\]

\[
\text{Area} = .125 \times .25 = .03125 \text{ inches}^2
\]

\[
\text{Force} = 2000 \frac{\text{lbs.}}{\text{inch}^2} \times .03125 \text{ inches}^2 = 62.5 \text{ lbs}
\]
The 2000 lbs/in$^2$ is applied through the two solder joints, thus each solder joint experiences this force.

The equation for the life-stress line:

$$\frac{N_2}{N_1} = \left( \frac{S_1}{S_2} \right)^m$$

$$\frac{80000}{N_1} = \left( \frac{2000}{200} \right)^{2.5}$$

$$\frac{80,000}{200^{2.5}} = N_1 = 253 \text{ Cycles}$$

Our current design will fail in 253 cycles and we need it to last for 1500 thermal cycles. We need to redesign this joint. **We have not wasted our money by prototyping a joint that would fail!**
2. Qualitative Testing - Used to Confirm Failure Modes and Remove Outlier Weaknesses

HALT Testing is a good example of Qualitative Testing

Conducted As An Accelerated Test To Produce A Quick Learning Cycle

- Patch It Up And Keep Testing
- Limit of Technology Equals Design Maturity

Weak

Strong

Broken Seal

Time on Test

Errors That Crept Into The Design

If you do not fix these then you waste the money you spent to get these
3. Quantitative Testing – Connecting Statistical Rigor to Engineering Physics

The Five Critical Parameters That Pin-down The Reliability Requirement

- **R**
  - Probability of proper function at the end of time T
  - 95% or 99%

- **C**
  - Confidence in the above statement
  - 50% or 70% or 90%

- **Stress Condition**
  - Failure Mechanism
  - Vibration
  - Thermal Fatigue

- **Time T**
  - Time after which the R & C apply
  - “One Life”
  - 10 years
  - 20 years

- **Definition of Failure and Success**
  - Technical failure
  - Perceived failure
Road Map of Reliability Statistical Methods

Failures Are Required!
- Testing To Failure
  - Test To Failure At Normal Stress With Weibull Plotting
- Sudden Death Testing

No Failures Permitted!
- Success-Run
  - Normal Sample Size and Normal Test Duration
- Reduced Sample Size With Extended Test Duration
A Wind Turbine Vibration Example
Quantify 20 Years Worth of Damage

- The damaging energy is obtained by integration under the blue curve = \(0.45 \text{ Grms}\)
- This level of vibration will occur for 175,200 hours
- The fatigue exponent used is based upon the material being stressed (a value of 5 is used for steel)
- The “damage” from this is calculated below:

\[
\text{Damage} = N \times (\text{Stress})^m
\]

\[
3191.27 = 175,200 \times (0.45)^5
\]

- An “equivalent-damage test” is 8 hours at 3.31 Grms:

\[
3191.27 = 8 \times (3.31)^5
\]
Applying Success-Run Statistics to Our Vibration Example

Using Success-Run and Weibayes statistics, we need to test:

- 6 parts to 1.56 “lives” or **12.48 hours at 3.31 Grms**
- 1 part to 2.83 “lives” or **22.67 hours at 3.31 Grms**

**Introducing Statistical Considerations Into The Test**

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*Old values:
- \( X_{old} = 22.8 \) Duration of Test at Standard Sample Size
- \( N_{old} = 6 \) Sample Size Has Been Reduced To This Value
- \( X_{new} = 1.56 \) Duration Of Test At Reduced Sample Size
- \( N_{new} = 2.83 \) Sample Size Has Been Reduced To This Value

*Ratio of:
- \( X_{new} to X_{old} = 1.56 \)
- \( X_{new} to X_{old} = 2.83 \)
Mechanical Cycling Example – CALT Testing to Quantify Reliability and The Fatigue Exponent

IPL/Weibull Data 1
- Eta

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<th>Foolish Stress Level</th>
<th>Third Stress Level Identified</th>
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All Data Points Translated to Normal Stress and Plotted on Weibull Paper

Collapsing our 2+2+2 data points into a single plot of 6 data points by transposing the failures at higher stress to the normal stress level.

Life_{normal\ stress} = Data Value_{accelerated} \times \left( \frac{Stress_{accelerated}}{Stress_{normal}} \right)^m

Beta = 3.9678, K = 1.1493E-14, m = 4.9162
Summary – Coaching The Supplier

• “Reliability” is just another form of engineering made consistent through a process. No magic here.

• The AQQ process is well proven and effective...most people only make use of the last letter.

• Learn to focus on the concept of defining “one-life.”

• Focus on the “severe user” or “severe environment.”

• Design accelerated tests based upon the concept of “Damage equals Damage.”

• Apply the right kind of statistical methods to best fit the needs of the situation.

• Reliability Apportionment can help rationalize the reliability requirements being used (sanity check).