Accelerated Life Testing (ALT)

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Overview

1. Reliability Requirements and Decomposition
2. ALT Applications
3. Categories of ALT
4. ALT Models
5. Methodology (Weibull Analysis)
6. Test Strategies and Analysis
7. ALT and Reliability Growth
1. Reliability Requirement & Decomposition

- ALT is used in process of **ensuring customer Reliability Requirements**
- Good requirement writing practices need to apply to;
  - Represent **customer needs**
  - Avoid **Scope Creep**
  - Robust across the **product life** (Cradle to Grave)
Systems Engineering V-Model

Reliability Testing

Source: http://ops.fhwa.dot.gov
Examples of Reliability Requirements

• Top Level Requirement: 1.0 System shall perform customer’s intended purpose over 20 years in the given operational environment at 90.00% reliability at 95% confidence

• 1.0 Washing machine shall perform 10000 wash cycles for maximum 25 lbs of dry cloth loads in household environment with 90.00% reliability at 95% confidence
Examples of Bad Reliability Requirements

- **Top Level Requirement:**
  1.0 Vehicle shall perform to have a reliability of 100,000 miles of MTBF

- **Pacemaker** shall have a reliability of 10 years MTBF with 90.00% at 95% confidence

**Issues:**
- **Ambiguity:** Left Units doesn’t match right units
- **Marketing & Regulatory nightmare:** Mean indicates you satisfy ~50% customers
System Reliability

\[ \text{System Reliability} = \prod_{i=1}^{n} R_i(t) \]

\[ = 0.9000 \]
Decomposition of System Requirements

■ 1.0 Washing Machine (System)

■ 1.1. Spinner Assembly (Subsystem)

■ 1.1.1 Spinner Bearing Assembly (Subassembly)

■ 1.1.1.2 Front Spinner Bearing (Component)
Examples of Decomposed Component Requirement

• A Component Level Requirement:

1.1.1.1. Journal Bearing shall turn 6.5 million rev’s with 300 lbs radial load at 1000 rpm with 99.95% reliability at 95% confidence.

• Traced to : 1.0

• Journal Bearing
Component Reliability

\[
R_{\text{Component}}(t) = \left[R_i(\text{Life})\right]^{1/n}
\]

\[
= \left[ 0.9000 \right]^{1/n}
\]

If # of Components at Risk, \( n = 100 \)

\[
= 0.9989 = 99.90\%
\]
2. ALT Applications
Traditional Design Practices

- **Safety Factor**

  Factor of Safety = \( \frac{\text{Failure Strength}}{\text{Applied Stress}} \)

  Example: \( N = \frac{S_y}{\sigma} \)

- **Stress-Life Diagram (S-N Diagram)**

  ![Stress-Life Diagram](image)
Traditional Design Practices

- Traditional Engineering Designs done with traditional tools such as “Safety Factor” may miss real life application issues

- A 5% - 10% miss is enough to,
  - Exhaust your resources from caring customers
  - Damage the Reliability Reputation
Factors Effecting Design Factor

■ Application
- How many will be produced?
- What manufacturing methods will be used?
- What are the consequences of failure?
  • Danger to people
  • Cost
- Size and weight important?
- What is the life of the component?
- Justify design expense?

■ Confidence
- Reliability of data for
  • Loads
  • Material properties
  • Stress calculations
- How good is manufacturing quality control
- Will subsequent handling, use and environmental conditions affect the safety or life of the component?

■ Loads
- Nature of the load considering all modes of operation:
  • Startup, shutdown, normal operation, any foreseeable overloads
- Load characteristic
  • Static, repeated & reversed, fluctuating, shock or impact
- Variations of loads over time.
- Magnitudes
  • Maximum, minimum, mean

■ Material
- Material properties
- Ultimate strength, yield strength, endurance strength,
- Ductility
  • Ductile: %E ≥ 5%
  • Brittle: %E < 5%
- Ductile materials are preferred for fatigue, shock or impact loads.

■ Environment
- Temperature range.
- Exposure to electrical voltage or current.
- Susceptible to corrosion
- Is noise control important?
- Is vibration control important?
- Will the component be protected?
  • Guard
  • Housing

■ Types of Stresses
- What kind of stress?
  • Direct tension or compression
  • Direct shear
  • Bending
  • Torsional shear
- Application
  • Uniaxial
  • Biaxial
  • Triaxial
Reliability Definitions

- Reliability is:
  - The conditional probability
  - at a given confidence level,
  - that equipment of a given age,
  - will perform its intended function
  - for a specified time,
  - while operating in its operational environment.
Summary; Why ALT?

- Lack of assurance for Life Reliability in Traditional Mechanical Design approach
- ALT Attempts to take factors effecting design factors into account
- ALT provides
  - Statistical Assurance that Reliability Goals are met.
  - Early Warnings, if they are not
Accelerated Life Testing

- **Definition**
  - A method for **stress-testing** of manufactured products that attempts to duplicate the normal wear and tear that would normally be **experienced over the usable lifetime** of the product in a shorter time period.
Accelerated Life Testing

1. Accel·er·ate - cause (something) to happen sooner
   - ac·cel·er·ate
   - verb \-Iə-, rāt\: to move faster: to gain speed
   - : to cause (something) to happen sooner or more quickly

2. Life - birth to death (Cradle to Grave!)
   - the period from birth to death
   - the period of duration, usefulness, or popularity of something <the expected life of the batteries>

3. Testing – determine quality, or genuineness
   - noun
   - the means by which the presence, quality, or genuineness of anything is determined; a means of trial.
   - the trial of the quality of something: to put to the test.
   - a particular process or method for trying or assessing.
Life?

* 500 cycles/year x 20 years
  = 10000 cycles

Usage Probability Density Function

95% of Customers

5% Special Customers

Number of Cycles

10,000 cycles
Goals of

**ALT**- *Accelerated Life Testing*

- **Most Important Goals of Up Front Product Life Testing (In-house or Beta Sites) & Data Analyses are**
  - To gain information for Fundamental Improvements
  - Proactive Reliability Improvement before Product Release
HALT—Highly Accelerated Life Testing

- A test in which stresses are applied to the product well beyond normal shipping, storage and in-use levels.
- HALT is Scientific.
- HALT has Statistical Differences with ALT

Advantages
- Quick Screening of Weak Products.
- At Highly Stressed Levels, a few samples can be used. (Ex. Prototypes)
- Compresses Design Time. Therefore, shortens the Design Iterations and Allow Mature Production.
2.1 HALT & ALT

**Purpose of HALT**
- Speedier Uncovering weaknesses & Corrective action identification
- Design robustness determination

**Purpose of ALT**
- Reliability Estimation at User Level
- Dominant failures mechanism identification
3. Categorizing ALTs

ALT

- Acceleration Factor, AF = 1
- Acceleration Factor, AF > 1
**Stressed Testing**

AF > 1

2-3 Stressed Levels

**Time Compressed Testing**

AF = 1

Normal Cycles, 24/7 run round the clock

*AF - Acceleration Factor*
Acceleration Factor,
AF = 1
User-Rate Acceleration

- Many Products are not in Continuous Use.
- So we Capitalize on them.
Acceleration Factor, AF = 1

User-Rate Acceleration

- Advantages
  i) Results,
  ii) Failure Modes,
  iii) Sequence of Occurrences of Failure Modes are Directly Correlated, therefore Analyses is easy
Acceleration Factor, AF = 1

User-Rate Acceleration

- **Disadvantages**
  - Not applicable in every case.
    - Ex. Chemical Degradation
    - **Corrosion** in a Refrigerator-Door may not happen in a shorter time.
Acceleration Factor, \( AF > 1 \) - Case I

- Exposing tests Units to more severe than normal Stresses.
  - Ex.
    - Higher Temperature
    - Higher Humidity
    - Higher Vibration

To Accelerate Chemical/Physical Degradation
Acceleration Factor, AF > 1 - Case I

- Accelerating Chemical/Physical Degradation

Ex.

- Weakening an Insulation of Motor Winding due to High Temperature and Moisture
- Weakening the Lubricant in bearing with exposure to moisture and high Temperature
Acceleration Factor,
AF > 1 - Case II

- Product Stress Acceleration
  Load
  Pressure
  - Ex of Results;
  - Wear, Fatigue Failures
**Log Life - Log Stress Graph**

HALT and ALT

- **HALT**...Not proportional
- **ALT**...Proportional

Log Stress

Log life

Optimum Load

Normally operated stress

Log Life

Log Stress
4. ALT Models

Parametric

Ex.  
- Exponential Distribution  
  \[ f(t) = e^{-\lambda t} \]  
- Parameter - \( \lambda \)

Non-Parametric

“Model Free”  
No Parameters
ALT Models

• Parametric

  - Statistics based Models
    - Ex. Weibull Distribution

  - Physics-Statistics based Models
    - Ex. Arrhenius Model
    - Eyring model
    - Inverse Power Law
ALT Models

• Non-Parametric
  - Statistics based Models
  - “Model Free” — Analyze as it is.
  - Ex. Proportional Hazard Rate
Acceleration Life Test Planning

- Need to find an Accelerating Parameter
- Need 2-3 Stress Levels for Better Estimation
5. Methodology

- Weibull Analysis
Reliability Plots

- There are **four** important Reliability Plots.
- If one of the four is known, rest can be found.
  1. Probability Density Function - PDF, \( f(t) \)
  2. Cum Distribution Function - CDF, \( F(t) \)
  3. Reliability (Survival Function), \( R(t) \)
  4. Bath-Tub Hazard Rate Function, \( h(t) \)

- Next important plot is, 5) Cum Hazard function, \( H(t) \)
Weibull Distribution

- Parameters:
  - \( \beta \) - Slope or Shape Parameter
  - \( \eta \) - Characteristic Life
    - It has Time Units, Ex. Hrs, Cycles

PDF: 
\[
f(t) = \frac{\beta}{\eta} \left( \frac{t}{\eta} \right)^{\beta-1} e^{-\left( \frac{t}{\eta} \right)^\beta}
\]
Weibull Distribution

Reliability Function

\[ R(t) = e^{-\left(\frac{t}{\eta}\right)^\beta} \]

Failure Probability (or Unreliability) Function

\[ F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^\beta} \]

Hazard Function

\[ h(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{(\beta - 1)} \]

Development Testing, Warranty Assessment

Field Data
Beauty of Weibull Distribution - FLEXIBILITY

With various $\beta$ values, it can take different shapes

- $\beta = 1$, Exponential Distribution
- $\beta = 2$, Rayleigh’s Distribution
- $\beta = 3.439$, Normal Distribution
Beauty of Weibull Distribution

PDF

Hazard Function
6. Test Strategies and Analysis with Weibull
a) I have large # of Components; Are Component Level Tests Required?

- **Required** when they are underdeveloped.
- **Off-the-shelf** items, tests may not require.

**Problems**
- It is **Difficult to simulate** with operating conditions.
- In real life, they interact with other components
- Little value in determining the absolute reliability.
Solution: Test Subsystems ..!

- Subsystem testing serves the purpose of
  - **Subsystem Level** Reliability Analysis
  +
  - **Component Level** Reliability Analysis

**Benefits.**
- Results are more relevant and accurate
- Reduces the large # of component level testing.
b) Failure Mode-wise Reliability Analysis

- Each failure mode has its own unique distributions.
- If treated all as one, the result will be an unfit curve.
- Right thing to do: “Failure Mode-wise Reliability Analysis.”
- It is done by right censoring the data of other failure modes.

**Benefits.**
- Focus on each failure mode, individually.
- Find the impact on reliability growth, if fixed.
- Justify resources allocation base on the impact.
Shaft Life & Failure Modes

200kg flywheel 500 RPM (Perfect balance)

Shaft

500mm

250mm

FIXED BEARING

FLOATING BEARING

Wire Heads Together

Diam?

Wear

Pitting

Fatigue

Failure Modes

T = Life

Time line →

t = 0
Failure Mode-wise Reliability Analysis

Example

A Shaft Failures in a Bearing Assembly
- Fatigue Failure
- Journal Wear

<table>
<thead>
<tr>
<th>Status</th>
<th>Hours</th>
</tr>
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<tbody>
<tr>
<td>S</td>
<td>1016.1</td>
</tr>
<tr>
<td>S</td>
<td>1183.5</td>
</tr>
<tr>
<td>S</td>
<td>2701.9</td>
</tr>
<tr>
<td>S</td>
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<td>S</td>
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<tr>
<td>F_sw</td>
<td>10710</td>
</tr>
<tr>
<td>F-fatigue</td>
<td>11539</td>
</tr>
<tr>
<td>F_fatigue</td>
<td>11691</td>
</tr>
</tbody>
</table>
c) Nearest Slope for the Improved “Zero Failure Design” in Reliability Growth Monitoring

- In PDP, when reliability improves, parts don’t fail.
- Improvements cause failures to delay.
- The failure distribution’s shape will remain unchanged.
- Similar distributions carry same $\beta$-shape parameter.
- Therefore, use the nearest slope for the $\beta$ with zero failure design.
Nearest Slope for the Improved “Zero Failure Design” Example...

Reliability Growth of a Power Transmission Subsystem

\[ \begin{align*}
\beta_1 &= 0.69, \quad \eta_1 = 171.22, \quad \rho = 0.96 \\
\beta_2 &= 1.96, \quad \eta_2 = 1239.77, \quad \rho = 0.98 \\
\beta_3 &= 2.48, \quad \eta_3 = 2632.67, \quad \rho = 0.99 \\
\beta_4 &= 2.94, \quad \eta_4 = 3477.67 \\
\beta_5 &= 2.94, \quad \eta_5 = 4528.71
\end{align*} \]
d) Early-Phase Subsystem Testing in Simulated Fixtures

During early test phases,
- Fixtures get debugged &
- Well correlated to the application

Weibull Plot for a Bearing Assembly Reliability Growth

\[
\begin{align*}
F_1 & = 13 & S_1 & = 0 \\
\beta_1 & = 0.96, \eta_1 = 14.71, \rho = 0.99 \\
F_2 & = 4 & S_2 & = 8 \\
\beta_2 & = 14.84, \eta_2 = 1206.46 \\
F_3 & = 3 & S_3 & = 1 \\
\beta_3 & = 4.31, \eta_3 = 1939.76, \rho = 0.96
\end{align*}
\]
e. Comparison of Options with ALT

Ex. Two Options in Valve Spring Suppliers
e. Comparison of Options

Ex. Failure Data for Three Options in Spring Suppliers

% Failures $F(t)$

Supplier 1
Supplier 3
Supplier 2

Time
e) Comparison of Options

Ex. Failure Data for Two Options in Transmission Belt Design

<table>
<thead>
<tr>
<th>Type I</th>
<th>Type II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status</td>
<td>Hrs</td>
</tr>
<tr>
<td>F</td>
<td>92</td>
</tr>
<tr>
<td>F</td>
<td>99</td>
</tr>
<tr>
<td>F</td>
<td>119</td>
</tr>
<tr>
<td>F</td>
<td>160</td>
</tr>
<tr>
<td>F</td>
<td>176</td>
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</tbody>
</table>
Two Material Options in Transmission Belt Design

Type I and Type II belts at 100 lbs Load

$\beta_1 = 1.93, \eta_1 = 57.17, \rho = 0.99$

$\beta_2 = 3.81, \eta_2 = 142.19, \rho = 0.95$
f) Correlating Life Cycles to Accelerated Life Cycles

- Normal Operating Cycles = \[\text{Damaging Cycles} + \text{Non-Damaging Cycles}\]

- ALTs = Only \[\text{Damaging Cycles}\]

- This situation creates a mismatch between Time Units
Correlating Life Cycles to Accelerated Life Cycles

Superimposed Two Time Units

Unreliability

Fixture Test

Life Test

Real Target

R(life) > 99.90%

Fixture Life

True Life

Superimposed Two Time Units
Correlating Life Cycles to Accelerated Life Cycles

Example- A fatigue failure in a machine base

- A **late-life fatigue failure** was discovered during time-compressed life testing.

- A **test fixture** was made and reproduced the same failure in a very short time.
Correlating Life Cycles with Accelerate Life Cycles

Example- A fatigue failure in a machine base

\[
\eta_{ALT\_TC\_new} = \frac{\eta_{ALT\_new}}{\eta_{ALT\_old}} \eta_{ALT\_TC\_old}
\]

<table>
<thead>
<tr>
<th>ALT_old</th>
<th>ALT_TC_old</th>
<th>ALT_new</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Hrs)</td>
<td>(Cycles)</td>
<td>(Hrs)</td>
</tr>
<tr>
<td>3.6</td>
<td>580+</td>
<td>102</td>
</tr>
<tr>
<td>4.6</td>
<td>1384</td>
<td>165.1</td>
</tr>
<tr>
<td>4.8</td>
<td>1613</td>
<td>167.1</td>
</tr>
<tr>
<td>6.3</td>
<td>1901</td>
<td></td>
</tr>
</tbody>
</table>
7. ALT & Reliability Growth
Facts about Duane’s Theory

- Applicable to measure RG across test phases
- Duane didn’t discuss or suggested MTBF unlike many texts have reflected later
- It is based on only one assumption, therefore it is a very powerful model
- Two trend lines; Cum Failure Rate and Current (Instantaneous) Failure Rate
Traditional Evidence of Reliability Growth

Failure Rates drops Between Modification

Assumption: Failure is constant between development phases
Reliability Growth Pattern in Weibull Plots

Signs of Reliability Growth
1. Each next iteration plot moves to right
2. As the line moves right, it becomes steeper
3. Towards the right-most iterations, lines tend to be parallel
Traditional Evidence of Reliability Growth

Reliability Growth of a Power Transmission Subsystem

Can I know the future of the reliability progress after 1 or 2 design iterations

\[ \beta_1 = 0.69, \eta_1 = 171.22, \rho = 0.96 \]
\[ \beta_2 = 1.96, \eta_2 = 1239.77, \rho = 0.98 \]
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\[ \beta_4 = 2.94, \eta_4 = 3477.67 \]
\[ \beta_5 = 2.94, \eta_5 = 4528.71 \]
Duane provided the Predictions from early learning

**Base Assumption:**

- Repeatable trends occur during development cycles.

I. These trends provide the basis for a learning curve

II. Extremely useful in;

   a) Monitoring the progress of reliability improvement
   b) Predicting the duration and end result of such program
Duane’s Evidence on Repeatable Trends

1 & 2: Complex hydro-mechanical system, completely different from each other.

3: An aircraft generator - after placed in operational service.

4: Very early stage of new radically different aircraft generator.

5: Complete aircraft jet engine during early stages of field introduction.
Duane Model

\[
\frac{\Sigma F}{\Sigma H} = K[\Sigma H]^{-\alpha}
\]

\(\alpha = \text{Shape}\)

\(K = \text{Scale}\)

- In general, cumulative failure rate \((\Sigma F/\Sigma H)\) will vary in a manner directly proportional to some negative power of cumulative operating hours \((\Sigma H)\)
- Cum. Failure Rate = \((\Sigma F/\Sigma H)\)
- Cum. Failures = \(\Sigma F\)
- Cum. Operating Hrs = \(\Sigma H\)
Duane Postulate

Proof in 30 seconds

\[ \ln \left| \frac{N(t)}{t} \right| = -\alpha \ln |t| + \delta \]

\[ \frac{N(t)}{t} = \lambda t^{-\alpha}, \quad \ln |\lambda| = \delta \]

\[ N(t) = \lambda t^{(1-\alpha)} \]

Differentiating with res. 't'

\[ \frac{d}{dt} \frac{N(t)}{t} = (1-\alpha) \lambda t^{-\alpha} \]

\[ \frac{d}{dt} \frac{N(t)}{t} = (1-\alpha) \frac{N(t)}{t} \]

Inst. Failure Rate = (1-\alpha) Cum. Failure Rate

\[ N(t) = \text{Cum. # of failures} \]

\[ t = \text{Cum. time} \]
Plotting Each Design Gen/Iteration for Reliability Measurement, Comparison and Growth Communication

- Plot each design iteration reliability data on
  - All iterations in one Weibull Plot
  - All iterations in one Duane Plot
    - No matter if you had huge improvements
Weibull Plots for Reliability Growth Communication

Reliability Growth of a Power Transmission Subsystem

\[ \beta_1 = 0.69, \eta_1 = 171.22, \rho = 0.96 \]
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\[ \beta_4 = 2.94, \eta_4 = 3477.67 \]
\[ \beta_5 = 2.94, \eta_5 = 4528.71 \]
Duane Model

Example for the Transmission
using individual data across Development Program

\[ Y = -0.5947X - 0.6933 \]

Overall slope gives the vigor of the program

\[ R^2 = 0.9946 \]

Target

Y = -0.5947X - 0.6933

R² = 0.9946
Key Messages

Duane Plot

We are here, not doing good.

Need one more resources to bend the curve.

Need 3 more test fixtures to get there on time.

Target
Example 2.
An Appliance Component Reliability Growth

![Reliability Growth Graph](image-url)

### Phase 1
- **Weibull-2P**: $F=6$, $S=3$
- **Data Points**
- **Probability Line**

### Phase 2
- **Weibull-2P**: $F=13$, $S=1$
- **Data Points**
- **Probability Line**

### Phase 3
- **Weibull-2P**: $F=2$, $S=13$
- **Data Points**
- **Probability Line**

### Phase 4
- **Weibull-1P**: $F=1$, $S=33$
- **Data Points**
- **Probability Line**

**Sarath Jayatilleka**
Beckman Coulter Inc
11/05/2010
3:59:07 PM
An Appliance Component Reliability Growth

Duane Plot for An Appliance Component

Cum. failure rate
Inst. failure rate
Slope improved from 0.395 to 0.647

Phase 1
Phase 2
Phase 3
Phase 4

Exceeding the target
Example 3. A Shaft Failure

Weibull Plot for a Bearing Assembly Reliability Growth

- Early state: F=13, S=0, β1=0.96, η1=414.71, ρ=0.99
- Matured Design: F=4, S=8, β2=14.84, η2=11206.46
- Middle state: F=3, S=1, β3=4.31, η3=1939.76, ρ=0.96
Example 3.
A Shaft Failure

**Duane Plot for Shaft Failure**

- **Phase 1**
- **Phase 2**
- **Phase 3**

**Improvements are shown as data gaps/jumps and downward bend of**

**Slope Improvement from 0.54 to 0.89**

**Cum Hours of Operation**
Thank You