Accelerated Reliability Growth Test Design for a Complex System

Milena Krasich, P. E.

Raytheon
Integrated Defense Systems

The Goals of This Paper

- Show the Physics of Failure (PoF) basics for acceleration of a reliability growth test and measures of achieved reliability
- Show how the test is structured as a combination of reliability growth and demonstration tests
- Explain how to translate the use profile of a system and its expected life into a series of accelerated stress tests
- Show how to determine duration of specific stresses and their combination to achieve a reliability goal
- Show data analysis and the achieved reliability growth through a test example

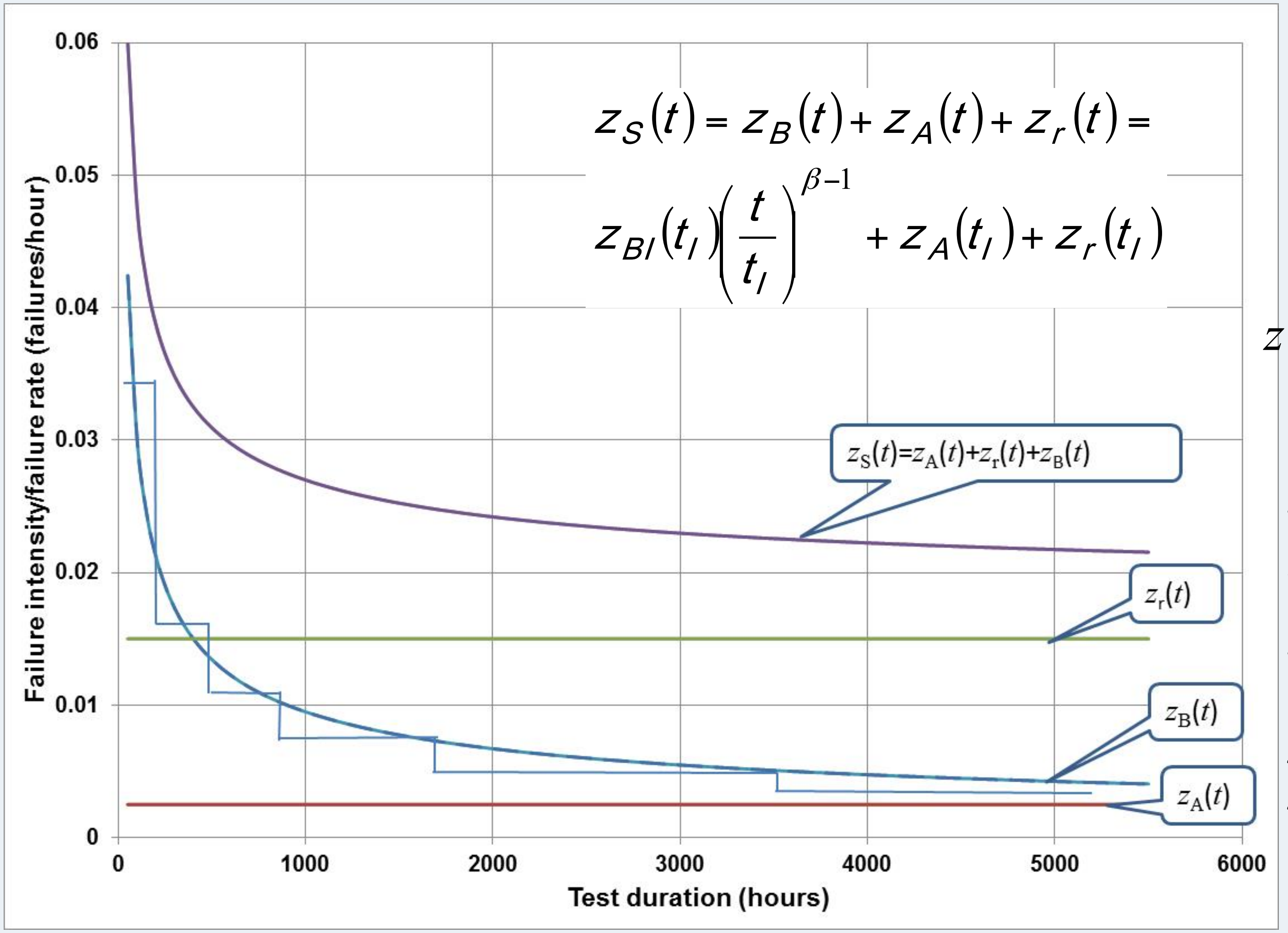
Reliability Growth Tests

- A well known test technique has been practiced for decades to
  - Expose test items (or systems) to stresses expected in their use
  - Determine the duration of the test to increase reliability from what was thought to be the initial reliability to the desired goal by recording and mitigating the test failures (systematic failures) with design improvements
- Uncertainties for test design and results
  - Stresses were applied at levels assumed equal to those expected in use, however:
    - Their duration and sequence of application was arbitrary
    - Both, stress levels and duration, were unrelated to the product life
  - Duration of the entire test was calculated mathematically for assumed improvement rates, without considering product life duration

The Concepts of Reliability Growth

- There are two kinds of failure modes in a product:
  - Systematic failure modes (occur whenever the identified cause is present – the existence of a systematic fault)
    - They originate from design or manufacturing or other process
    - They are expected to occur in all produced items
    - In literature they are referred to as type A and type B failure modes
      - Type A: Cannot be mitigated because of technical, economic, or schedule reasons
      - Type B: Can be mitigated by product design changes (technically and in a cost effective manner)
  - Random failure modes
    - The causes are not easily identifiable
    - Their failure rate is considered constant
    - They are not subject to mitigation in reliability growth but must be accounted for in the results

Failure Modes and Their Failure Rates



Mathematical fit for the number of failures vs. time:

$$E[N(t)] = \lambda \cdot t^{\beta}$$

$$z(t) = \frac{dN(t)}{dt} = \lambda \cdot \beta \cdot t^{\beta-1}$$

$N(t)$ = number of failures as a function of test time: t;

λ and β = scale and shape parameters of the Weibull Intensity Function;

$z_A(t) = z_A$=constant;

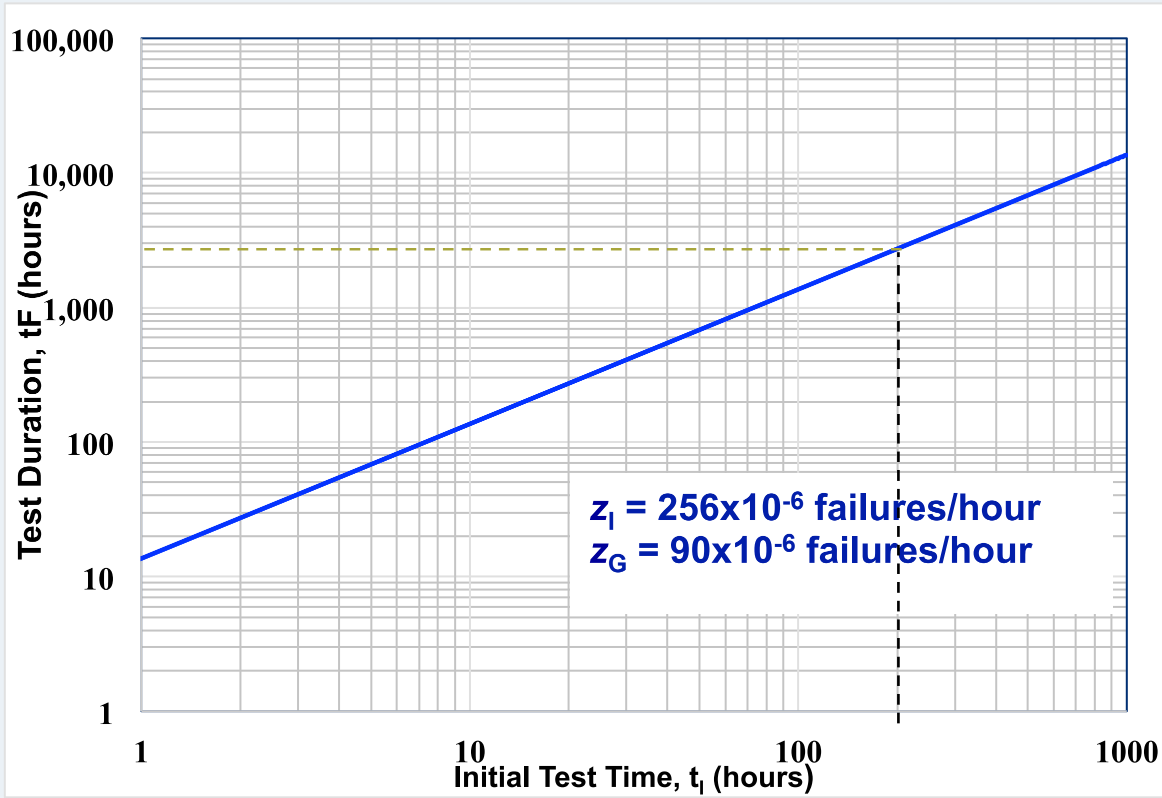
$z_B(t) = z_B$=constant

Planning Reliability Growth Test: Traditional Approach

- The test duration is planned based on the assumed or known initial test duration and the reliability (low failure rate) goal:

$$t_{F_{Old}} = e^{\frac{ln(z_F) - ln(z_I)}{\beta - 1} + ln(t_I)}$$

- z_i is the total system failure rate
- Because of counting and reporting only B failure modes, z_G was small
- With a large initial and a small goal failure rate, the calculated test duration was reasonable and affordable (for t_i = 200 hours and t_G = 3,000 hours)



Planning Reliability Growth Test: Corrected Approach

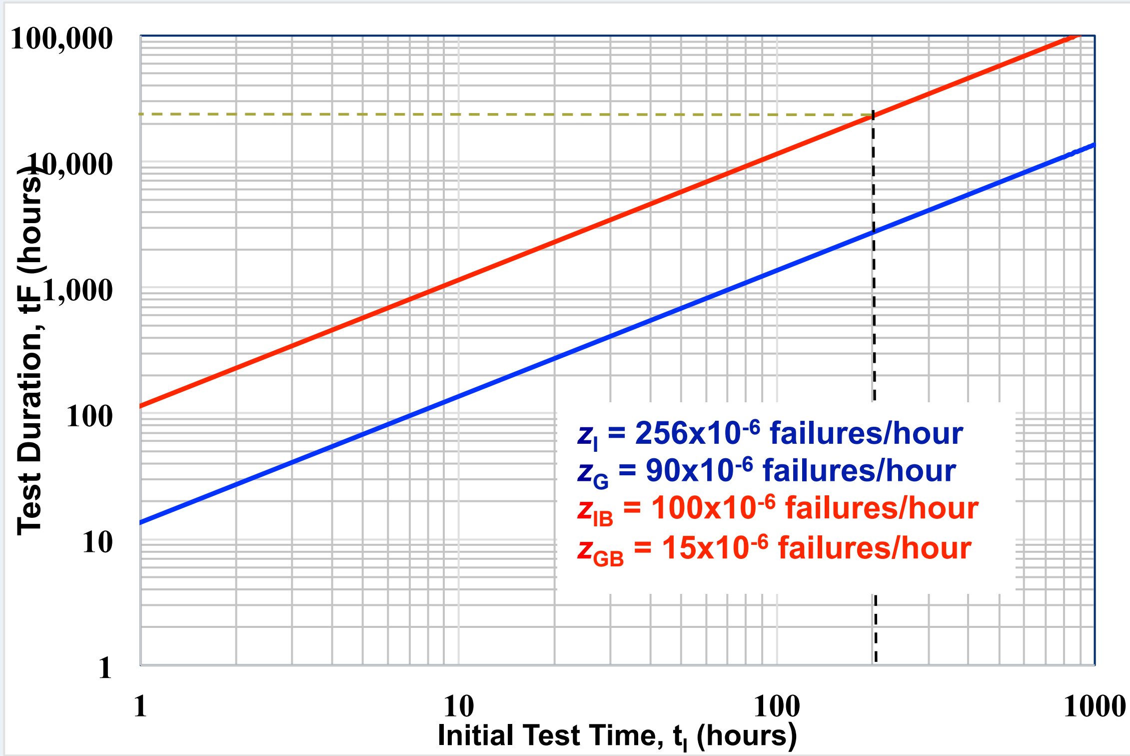
- Remembering that only B failure modes are corrected (Power Law is valid)

$$z_{SG}(t) = z_{BG}(t) + z_A(t) + z_r(t) = z_{BI}(t_I)\left(\frac{t}{t_I}\right)^{\beta-1} + z_A(t_I) + z_r(t_I)$$

$$t_F = e^{\frac{ln(z_{BF}) - ln(z_{BI})}{\beta-1} + ln(t_I)}$$

$$z_{BI} << z_I; \quad z_{BI} \approx 0.4 z_I$$

- z_{BI} is not much greater than z_{BG}
- The correct test duration becomes an order of the magnitude longer – and unaffordable;
- Not enough test time to determine constant failure rate
- Accelerated tests do not depend on initial test time, only on the reliability goal



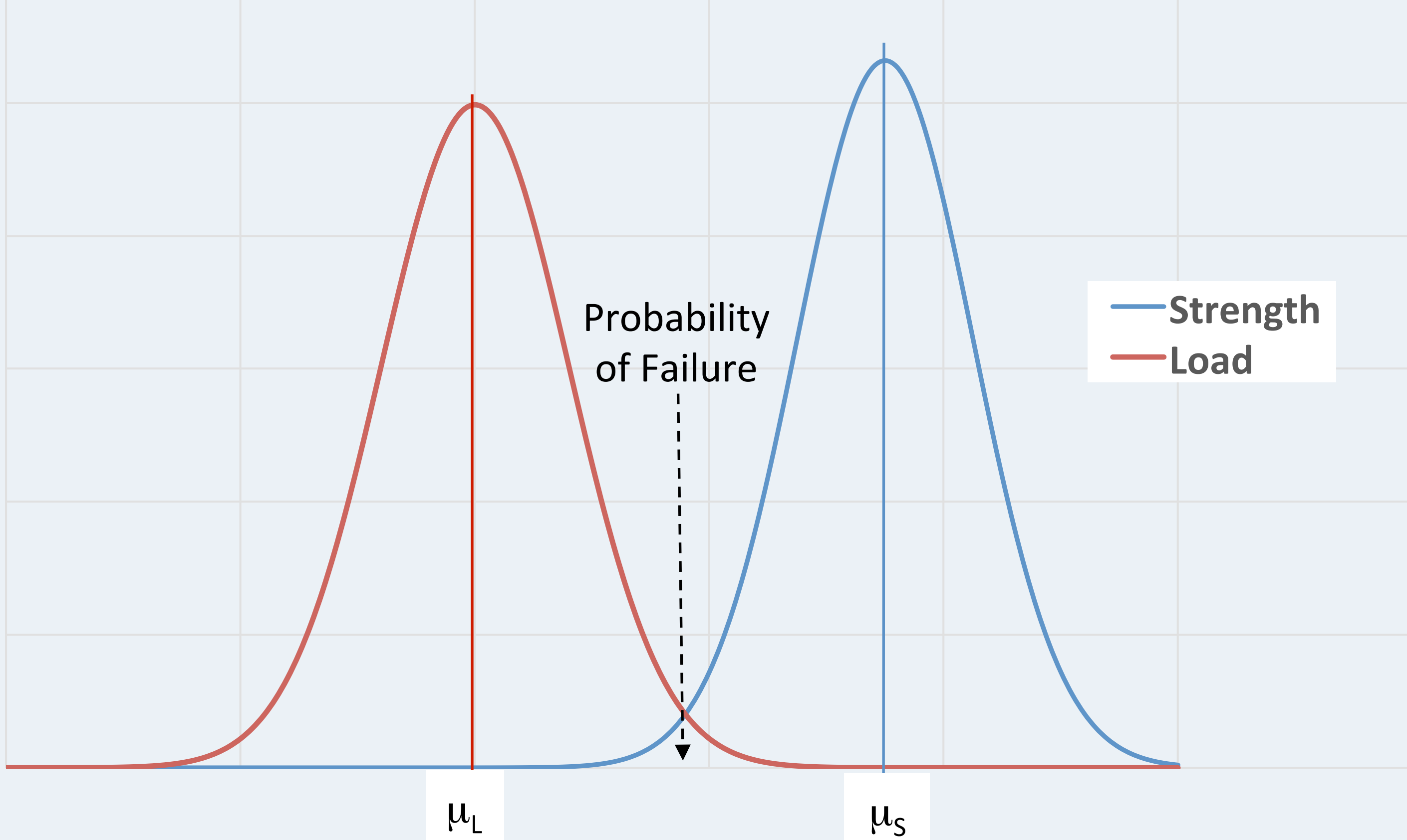
The affordable solution: Accelerated Reliability Growth Testing

Physics of Failure Reliability Growth Test Approach

- The Physics of Failure approach considers the rationale for appearance of failures as a result of stress applied to an item which exceeds the magnitude of its strength in regards to this type of stress
- Another fact is the cumulative damage of an item in the course of its use and life
- The principle of reliability testing is to validate that the cumulative damage from each stress expected in use life is lower than the cumulative damage applied in stress by a margin which provides or IS the reliability measure
- The margin with which the cumulative damage is induced in test becomes the reliability measure in stress vs. strength criteria
- Strength and stress (load) are modeled by a normal distribution and their overlap represents the probability of failure

Physics of Failure and Reliability Principle

- Failures occur when an item is not strong enough to withstand one or more attributes of a stress
  - Level and duration, or repetitions of any stress application



Lifetime Reliability and Stresses

- Reliability of a system/item can be shown as: $R_{Item}(t_0) = \prod_{i=1}^{N_S} R_{Item}(Stress_i, t_i)$

  Where:
  - N_S = Number of stresses expected in life
  - $R_{Item}(t_0)$ = item lifetime reliability
  - t_0 = duration of item life
  - $R_{Item}(Stress_i, t_i)$ = Reliability of an item regarding one individual stress for its total duration in life, t_i
- Besides the magnitude of stresses expected during actual use, it is the cumulative effect which affects product reliability
  - The test duration is then calculated based on the duration of each of the stresses applied in actual use – the use or application profile
  - The test results for a product in one use are not valid for the same product in a different use
  - When the purpose of the test is to estimate reliability in the field, an average user stress profile should be used (e.g. where less than 1 % of the customers heavily load the product)

Cumulative Degradation and Reliability Principle

- When the cumulative degradation is assumed proportional to duration of a stress, then reliability for each individual stress can be expressed as:

$$R_i\left(Stress_i, t_0\right) = \Phi\left\{\frac{\mu_{S\_i} \cdot t_i - \mu_{L\_i} \cdot t_i}{\sqrt{\left(a \cdot \mu_{S\_i} \cdot t_i\right)^2 + \left(b \cdot \mu_{L\_i} \cdot t_i\right)^2}}\right\}$$

Where:

- $R_i(t_0)$ = lifetime reliability regarding the stress *i*
- μ_{S_i} = mean of the strength regarding stress *i*
- μ_{L_i} = mean of the load
- Φ = symbol for the cumulative normal distribution
- t_i = lifetime-equivalent duration of the stress *i*
- *a* = multiple of the mean strength to obtain the value of the strength standard deviation
- *b* = multiple of the mean load to obtain the stress standard deviation

Reduction of Reliability Formula

- The ratio between the strength and load can be expressed with a constant *k*, where $\mu_S t_i = k\mu_L t_i$. Therefore the previous equation will become:

$$R_i\left(Stress_i, t_0\right) = \Phi\left\{\frac{k \cdot \mu_{L\_i} \cdot t_i - \mu_{L\_i} \cdot t_i}{\sqrt{\left(a \cdot k \cdot \mu_{L\_i} \cdot t_i\right)^2 + \left(b \cdot \mu_{L\_i} \cdot t_i\right)^2}}\right\}$$

- After reduction
  - Reliability is a function of the ratio of the duration of stress application in test and in life:

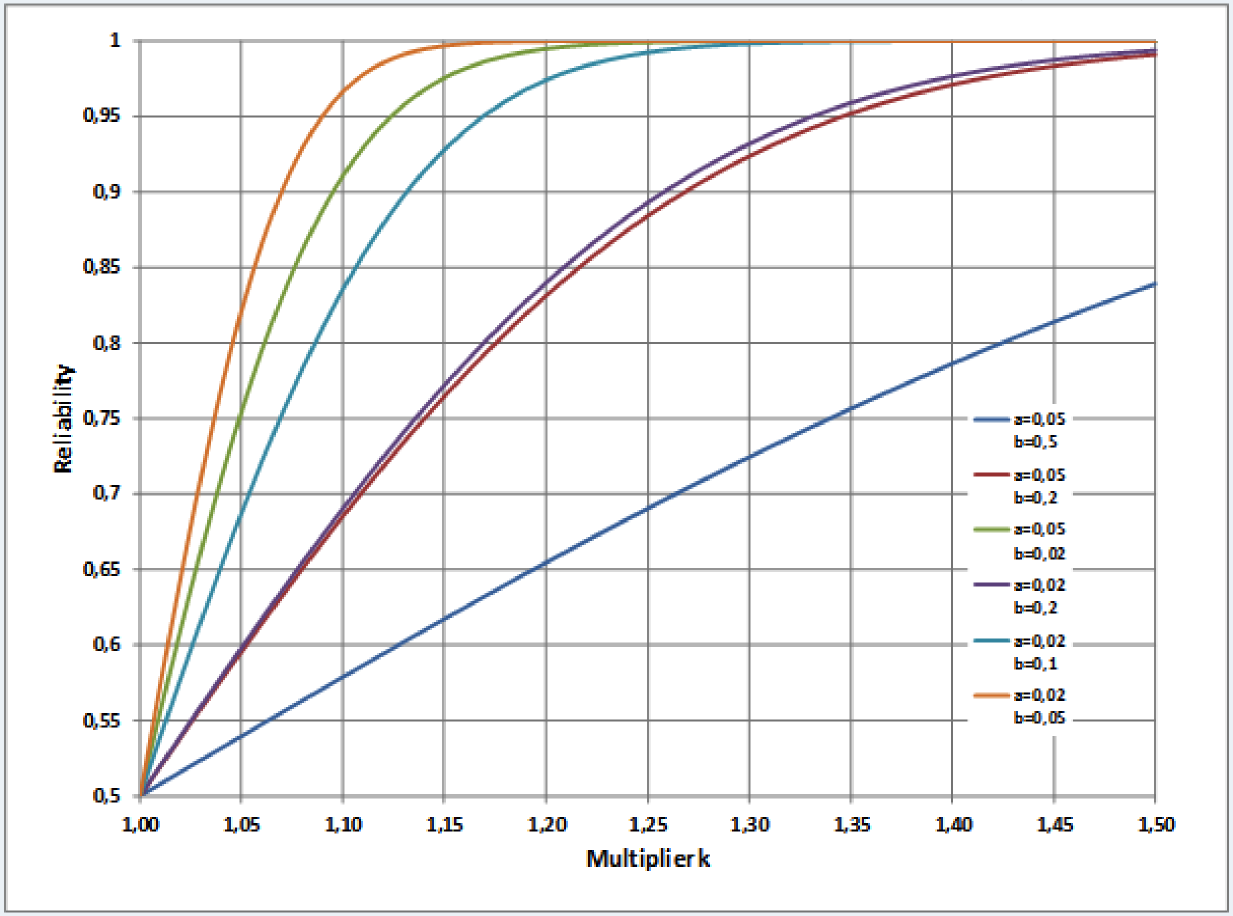
$$R_i\left(Stress_i, t_0\right) = R_i\left(k, \mu_{L\_i}\right) = \Phi\left\{\frac{k-1}{\sqrt{\left(a \cdot k\right)^2 + \left(b\right)^2}}\right\}$$

Where:

- *k* = multiplier of the actual stress duration, assuming the cumulative damage models

Determination of Multiplier k for the Required Reliability

- The curves are drawn for different combinations of assumed factors *a* and *b* (variations of use and test environments)



Reliability Requirements and Test Duration Multiplier *k*

- The calculated reliability value is valid for all of the stresses together. If there are N_S stresses applied and equal contribution is allocated to each, the reliability per one stress will be: $R_i(T,k) = \sqrt[N_S]{R_G(T,k)}$
- If the stresses are basic such as vibration, thermal cycling, thermal exposure, humidity, and shock (five stresses total), then the required reliability for each of them would be equal to the fifth root of 0.8
- $R_i(k) \approx 0.97$
- Assuming that the variations are as earlier mentioned, a = 0.05 and b = 0.2, the multiplier k from the graph (slide 13) is: k = 1.4
- Given the product life of 10 years, the required test duration for the example reliability growth represents:
  T = 122,600 hours or 14 years

Actions to be Taken for PoF Reliability Growth Test

- Express reliability of an item in terms used for Reliability Growth and Tests for Constant Failure Rates
  - System final reliability has to account for both, improved design reliability and the constant rate of random and type A failure modes
- Apply stresses expected in life for a duration that will provide margin on cumulative degradation to mathematically ensure reliability for all failure modes
- Record time distribution of the systematic failures
- Record random and type A failure modes
- Calculate all failure rate types and achieved total final reliability
  - Two different test types are performed simultaneously:
    - ***Reliability Growth and Reliability Demonstration***

Correlating Reliability Measures

- Reliability Growth and Demonstrated Reliability are usually measured in terms of increase or demonstration of a system Mean Time Between Failures, MTBF, θ (for repaired items)

$$\theta_G = \frac{1}{z_{BG} + (z_A + z_r)} = \frac{1}{z_{BG} + z_{Constant}}$$

$$\theta_I = \frac{1}{z_{BI} + (z_A + z_r)} = \frac{1}{z_{BI} + z_{Constant}}$$

$$R_G(T) = e^{-(z_{BG} + z_{Constant}) \cdot T}$$

- For a selected $T > t_m$ (t_m = determined maintenance period), calculate required $R_G(T)$ for the system
- The calculated reliability value is valid for all of the stresses together. If there are N_S stresses applied and equal contribution is allocated to each, reliability per one stress will be: $R_i(T,k) = \sqrt[N_S]{R_G(T,k)}$

Translating Use Profile to Exposures in Test - Thermal

- A system (e.g. an outdoor transportable system) is exposed to variable climatic (thermal) environments
  - Climatic environments vary with
    - geographic locations
    - nocturnal and diurnal monthly temperatures and variations
    - thermal conditions in both when ON or OFF
  - To streamline calculations for thermal exposures in each, a good practice is to apply thermal acceleration model for recalculating all ON and all OFF exposures separately
  - First for the nocturnal/diurnal temperatures
    - Convert to the equivalent exposure to the highest diurnal temperature of the warmer location
  - Convert OFF time to ON time for diurnal exposure

Translating Use Profile to Exposures in Test - Thermal

- Recalculate durations of all exposures to lower temperatures into one – the highest temperature in use:

$$t_{s\_e} = t_s + \sum_{i=1}^{s-1} t_i \cdot exp\left[-\frac{E_a}{k_B} \cdot \left(\frac{1}{T_i + 273} - \frac{1}{T_s + 273}\right)\right]$$

Where:

  - s = the latest in series of the number of different thermal stresses ordered by magnitude
  - T_s = the highest use temperature
  - T_i = lower stress temperatures
  - E_a and k_B – activation energy (eV) and Boltzmann constant: 8.62x10-5 eV/K
- This will be the equivalent duration of exposure to the highest temperature
- Thermal acceleration will then be acceleration of this equivalent exposure to the test temperature
- Example for a system – Summer and Winter:
  – OFF: 16 hours per day; average: Summer 45^0C, Winter 10^0C
  – ON: 8 hours per day with ΔT = 40^0C (85^0C and 55^0C)
  – Life 10 years

Translating Use Profile to Exposures in Test - Thermal

- Find total equivalent duration at the highest, 85 ^{0}C (E_a = 1.5 eV):

$$t_{m\_e} = \left\{ \begin{array}{l} 16 \cdot exp\left[-\frac{E_a}{k_B}\left(\frac{1}{10+273} - \frac{1}{85+273} \right) \right] + 16 \cdot exp\left[-\frac{E_a}{k_B}\left(\frac{1}{45+273} - \frac{1}{85+273} \right) \right] \\ +8\, exp\left[-\frac{E_a}{k_B}\left(\frac{1}{55+273} - \frac{1}{85+273} \right) \right] + 8 \end{array} \right\} \cdot \frac{3{,}650}{2} = 18{,}190$$

- This will be the high temperature which will be used for test
  - t_m would have been the test duration at maximum temperature in use without additional acceleration
- To provide for reliability requirements and account for the cumulative degradation, t_m is multiplied by the factor k before accelerated
- Each life segment and its duration needs to be accounted for to obtain the equivalent duration on the highest use temperature

Thermal Cycling Conversion

- Done in a similar manner as thermal exposure:

$$N_{TC_{n\_e}} = N_{TC_n} + \sum_{j=1}^{n-1} N_{TC\,j} \cdot \left(\frac{\Delta T_j}{\Delta T_n} \right)^m$$

Where:

- *n* = the latest in series of the number of different thermal stresses ordered by magnitude
- ΔT_n = the highest use span of the thermal cycle
- ΔT_i = lower thermal changes ("deltas")
- *m* = constant specific to the material thermal fatigue

- Example for a system – Summer and Winter:
  - OFF: 16 hours per day; average: Summer 45^{0}C, Winter 10^{0}C Diurnal temperature changes from nocturnal: 15^{0}C Summer, 25^{0}C Winter
  - ON: 8 hours per day with ΔT = 40^{0}C (85^{0}C and 55^{0}C)
  - Life 10 years

Thermal Cycling Example

- The thermal cycling temperature changes are:
  - $\Delta T_1 = 15^0$C, $\Delta T_2 = 25^0$C, $\Delta T_3 = 40^0$C ; $N_{TC3} = 3{,}660$
  - $N_{TC31} = N_{TC32} = 1{,}830$
  - $m = 2.5$ (for the weakest link - solder

$$N_{TC_{3\_e}} = 3{,}660 + 1{,}830 \cdot \left(\frac{15}{40}\right)^{2.5} + 1{,}830 \cdot \left(\frac{20}{40}\right)^{2.5} = 4{,}141$$

  - The equivalent number of thermal cycles at temperature changes of 40^0C will them be multiplied by k to get the number of thermal cycles required for reliability test, which then will be accelerated
  - For this example, k was determined to be $k = 1.4$ (slides 13 and 14)

Combining the Stresses

- In real use the thermal cycles and thermal exposures are distributed through the life of the product
- To better represent the real use, thermal cycling and thermal exposure are combined so that the duration of thermal exposure is distributed over the high temperature of thermal cycling
- Expanding the same example and assuming that from the requirements it was determined that k = 1.4 and safe high and low temperatures for the product were +115^{0}C and – 20^{0}C , the combined test is:

  T_{Test_HI} = +115^{0}C T_{Test_Low} = - 10^{0}C ; ΔT_{Test} = 125^{0}C

  – With the test item ON the chamber temperatures would be

  T_{Ch_HI} = +75^{0}C T_{Ch_Low} = - 50^{0}C (approximate – to be regulated)

Accelerated Thermal Cycling - Test

- Total exposure to high temperature in test:

$$t_{Th\_Test} = exp\left[-\frac{E_a}{k_B}\left(\frac{1}{85+273}-\frac{1}{115+273}\right)\right]\cdot k = 593.96\ \ hours$$

- Total number of thermal cycles:

$$N_{TC_{Test}} = 4{,}141\cdot\left(\frac{40}{125}\right)^{2.5}\cdot k = 336$$

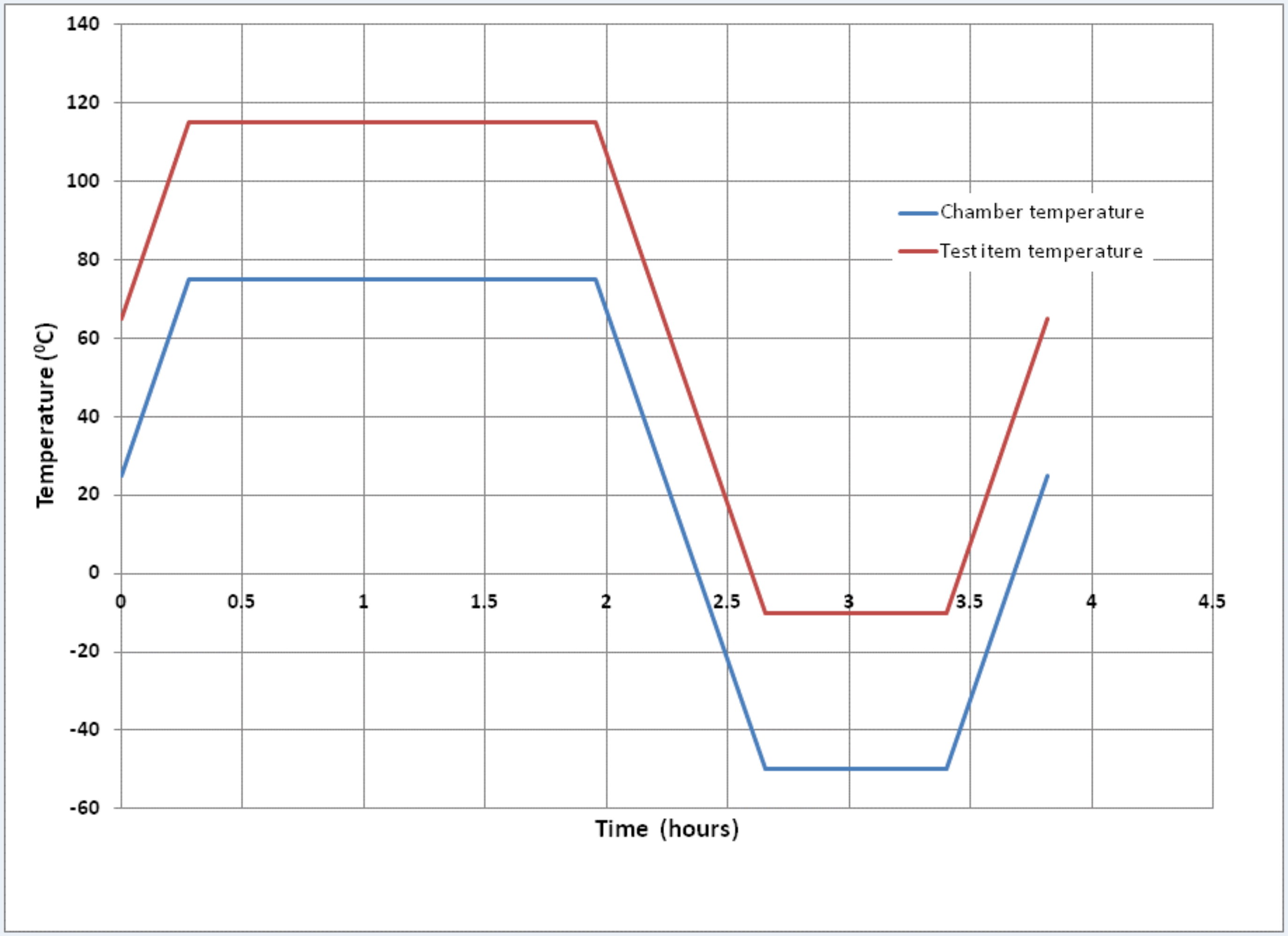
- Duration of thermal dwell at high temperature:

$$t_{TD\_Test} = \frac{593.96}{336} = 1.769\ \ hours$$

- Time at low temperature should accommodate stabilization with some additional time: t_{ST} = 0.5 hours, t_{Low_Test} = 0.75 hours

Thermal Cycle

- Assume chamber ramp rate to be $\zeta=3^0C/min$



Acceleration of Other Stresses

- Humidity acceleration:

$$t_{Test} = t_{ON_e} \cdot k \cdot \left(\frac{RH_{Use}}{RH_{Test}} \right)^h \cdot exp\left[-\frac{E_a}{k_B} \cdot \left(\frac{1}{T_{ON} + 273} - \frac{1}{T_{RH} + 273} \right) \right]$$

Often, the value for the exponent $h = 2.3$

- To determine t_{ON_e} the process is similar to the determination of equivalent duration for thermal exposure and thermal cycling
- Vibration:
  - The test duration to be determined is from equivalent test time for mileage (e.g. 500 miles equivalent to one hour exposure)

$$t_{Vib\_Test} = k \cdot t_{Vib\_Use} \cdot \left(\frac{W_{Use}}{W_{Test}} \right)^w$$

Multiple Stress Acceleration Methodology

- Failure rate of an item as a function of stress is a sum of failure rates for failure modes caused by individual stresses:

$$\lambda_{Item}(Stress) = \lambda_U + \sum_{i=1}^{N_S} \lambda_i(Stress_i)$$

- To accelerate failure of an item for a number of stresses N_S, each of the stresses is accelerated:

$$A \cdot \lambda_{Item} = \lambda_U + \sum_{i=1}^{N_S} A_i \cdot \lambda_{Item}(Stress_i)$$

- If there are some stresses (*j*) that accelerate the same failure mode, then:

$$\lambda_A = A_{Test} \cdot \lambda_0 = \sum_{i=1}^{N_S}\left(\left(\prod_j A_j\right)_i \cdot \lambda_i\right) \qquad A_{Test} = \frac{\sum_{i=1}^{N_S}\left(\left(\prod_k A_k\right)_i \cdot \lambda_i\right)}{\lambda_0}$$

- Acceleration factors multiply **ONLY** if they affect the same failure mode

Test Data Analysis

- There are two simultaneous tests in one accelerated reliability growth test
  - Remembering the total system failure rate:

$$z_S(t) = z_B(t) + z_A(t) + z_r(t) = z_{BI}(t_I)\left(\frac{t}{t_I}\right)^{\beta-1} + z_A(t_I) + z_r(t_I)$$

  - The test duration is built to decrease failure rate of systematic *B* failure modes and to account for *A* and *r* failure modes – to determine their failure rates
- There are two separate data analysis done:
  - Reliability growth (*B*): using the power law methodology
  - Reliability demonstration assuming constant failure rates of *A* and *r*

Reliability Growth Analysis

- The step curve is a result of design improvements during test where constant failure rate decreased to a lower level as a step function fitted with a power law curve –Weibull Intensity Function

$$z_B(t) = \frac{dN_B(t)}{dt} = \lambda \cdot \beta \cdot t^{\beta-1} \qquad \hat{\beta} = \frac{M}{M \cdot \ln(t_M) - \sum_{i=1}^{M-1} \ln(t_i)} \qquad \hat{\lambda} = \frac{M}{t_M^{\hat{\beta}}} \quad \hat{\beta} = \frac{M}{M \cdot \ln(t_0) - \sum_{i=1}^{M} \ln(t_i)} \qquad \hat{\lambda} = \frac{M}{t_0^{\hat{\beta}}}$$

  - M = number of observed failures
  - t_M and t_0 : end of test, failure and time terminated – respectively
  - t_i = cumulative test time to appearance of a failure *i*

  – Unbiased values:

$$\bar{\beta} = \frac{M-2}{M \cdot ln(t_M) - \sum_{i=1}^{M} ln(t_i)} \qquad \bar{\lambda} = \frac{M}{A \cdot t_M^{\bar{\beta}}} \qquad \bar{\beta} = \frac{M-1}{M \cdot ln(T) - \sum_{i=1}^{M} ln(t_i)} \qquad \bar{\lambda} = \frac{M}{A \cdot T^{\bar{\beta}}}$$

$$\bar{z}(t_M) = \bar{\lambda} \cdot \bar{\beta} \cdot t_M^{\bar{\beta}-1} \qquad \bar{z}(t_0) = \bar{\lambda} \cdot \bar{\beta} \cdot t_0^{\bar{\beta}-1}$$

- The remaining task and question: *Who or what are "t_i"s?*

Reliability Growth Analysis, continued

- Times to failure occurrences need to be projected to their respective occurrences in life
  - Each of the stresses is applied for its calculated effective life duration
  - Time to failure occurrence of the failure mode determined to be caused by that stress is straight time to failure multiplied by the acceleration factor of the related stress
  - When the stresses are combined, the cause of failure indicates what the related stress is for selection of the proper acceleration factor
- When all of the failure times are projected to their occurrence in use, they are then ordered by their magnitude and the appropriate equations are used to find the parameters and the final failure rate
- This procedure applies to the systematic failure modes *B*

Reliability Demonstration and the Final Result

- All random and A type failure modes are monitored and their time of arrival is recorded; the test item is repaired and the test is continued
- The total test duration as it is recalculated to its normal use divides the number of failures to estimate the value of the constant failure rate:

$$z_A + z_r = \frac{m_A + m_r}{k \cdot t_L}$$

  - Where: m_A and m_r are the number of A and random failures respectively
- The final test result or demonstrated product failure rate is the sum of the improved and constant failure rates
- Reliability is then expressed as the time between failures:

$$\boxed{\theta_S(k \cdot t_L) = \frac{1}{z_B(k \cdot t_L) + z_A(k \cdot t_L) + z_r(k \cdot t_L)}}$$

Conclusions

- Physics of failure accelerated reliability growth test approach
  - Considers lifetime cumulative damage to a product during its use
  - Provides information on reliability for the product's expected life and at the end of that life
  - Provides measure for the failure rates of the random failure modes which were forgotten and omitted from test results for all of the past years of reliability growth programs
  - Presents realistic test results
  - Achieves test durations equal or shorter than traditional reliability growth and considerably shorter than the fixed duration tests
  - Provides extremely valuable insight into potential product weaknesses not found in traditional reliability growth tests

Additional Information

- IEC 61710 Power law model – goodness of fit tests and estimation methods
- IEC 61014 Programmes for reliability growth
- IEC 61164 Statistical methods for reliability growth
- MIL-HDBK-198C Reliability Growth Management
- IEC 62506 Methods for products accelerated reliability testing
- IEC 61124 Tests for constant failure rate and failure intensity
- M. Krasich; Accelerated Reliability Growth and Data Analysis, Journal of the IEST; V. 50, No.2© 2007
- M. Krasich; Reliability Growth Testing, What is the Real Final Result? Tutorial Paper RAMS 2014 Tutorial Proceedings, January 2014

Biography

- Milena Krasich (milena_krasich@raytheon.com) is a Senior Principal Systems Engineer at Raytheon Integrated Defense Systems, Whole Life Engineering, RAM Engineering Group - Sudbury, MA.
- Prior to joining Raytheon, she was a Senior Technical Lead of Reliability Engineering in Design Quality Engineering of Bose Corporation, Automotive Systems Division after the five year tenure at the Jet Propulsion Laboratory in Pasadena, California. While in California, she was a part-time professor at the California State University Dominguez Hills Graduate School. She holds a BS and MS in Electrical Engineering from the University of Belgrade, Yugoslavia, and is a California registered Professional Electrical Engineer. Technical Advisor (Chair) to the US Technical Advisory Group (TAG) to the International Electrotechnical Committee, IEC, Technical Committee, TC56, Dependability.