Reliability Growth Test Planning and Data Analysis What are the Final Results?

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Content of this Presentation

- Importance of Reliability Growth Testing
- Reliability Growth in the Past and Today
- The Essence and Physics of Reliability Growth
- Mathematical Approach to RG Test Design and Resultant Errors in Delivered Test Results
- Correction off Mathematical Approach and the Resultant Test Duration Problems
- Physics of Failure Approach for Reliability Growth and Demonstration Tests
- Accelerated Reliability Growth and Demonstration Testing and Test Results Analysis
- A real life example shown with data analysis and representation of test results.

RAMS 2014 – Tutorial 8B – Willing, et al

Reliability Growth in Design and Test

- Increasing reliability of a product is a process to realize reliability requirements or goals to satisfy customers’ needs of producers’ competitiveness
- Reliability growth in design:
  - Analytical as explained in IEC/ANSI 61164, Statistical methods for reliability growth two methods:
    - Bayesian method (Walls-Quigley)
    - Modified power law method (Krasich)
- Reliability growth in test:
  - Traditional mathematical reliability growth test using (used for 3+ decades)
    - Different evolving mathematical models which originated from the power law, Weibull Intensity Function and applied by Duane, Crow, Fenton, and others
  - Accelerated reliability growth based on Physics of Failure principles
    - IEC 62506 Methods for product accelerated testing (used for past 10 years)

The importance of Reliability Growth Testing

- Goal:
  - Increase the current (existing reliability – measured in item failure rate (failure frequency) or mean time between failures, MTBF
  - Goal magnitude guided by:
    - Requirement or commercial logic
- Assumptions:
  - Item as designed and built might contain errors
    - Design or process errors that can be mitigated through analysis or test; correction implemented in present or future time
    - Errors that originate in design or process but cannot be fixed (for economic or technical reason
      - Subject of corrective maintenance
    - Random errors of unknown causes subject to corrective maintenance
    - The test continuation will evaluate success of the fix.

Types of Failure Modes in an Item

- Systematic failure modes
  - Resultant from design and/or manufacturing process errors
  - They are expected to occur in all produced (ad tested) items of the same design or manufacture
    - The terms “systematic” means that they would occur whenever the identified cause is present and in all copies of the product
  - Type B: The failure modes that can be mitigated by product design changes (technically and in a cost effective manner)
  - Type A failure modes that cannot be mitigated in the product because of technical, economic, or schedule reasons
- Random failure modes
  - The causes are not easily identifiable
  - Their failure rate is considered constant
  - They are not subject to mitigation in reliability growth
  - They may be recorded but are not accounted for in test

Background of the Traditional Mathematical Model

- The basic principle in reliability growth:
  - The failure rate of the item is constant between the step improvement, and improvement occurs only while mitigating a systematic failure mode
  - This process when fitted with the Non-Homogenous Poisson Process (NHPP) and the power law (exponential fitting) curve

$$\Pr[N(t) = n] = \frac{\left(\lambda t^{\beta}\right)^{n} e^{-\lambda t^{\beta}}}{n!} \qquad E[N(t)] = \lambda \cdot t^{\beta} \qquad z(t) = \lambda \cdot \beta \cdot t^{\beta-1}$$

where:

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

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

n = a constant number

- The problem (or a question):

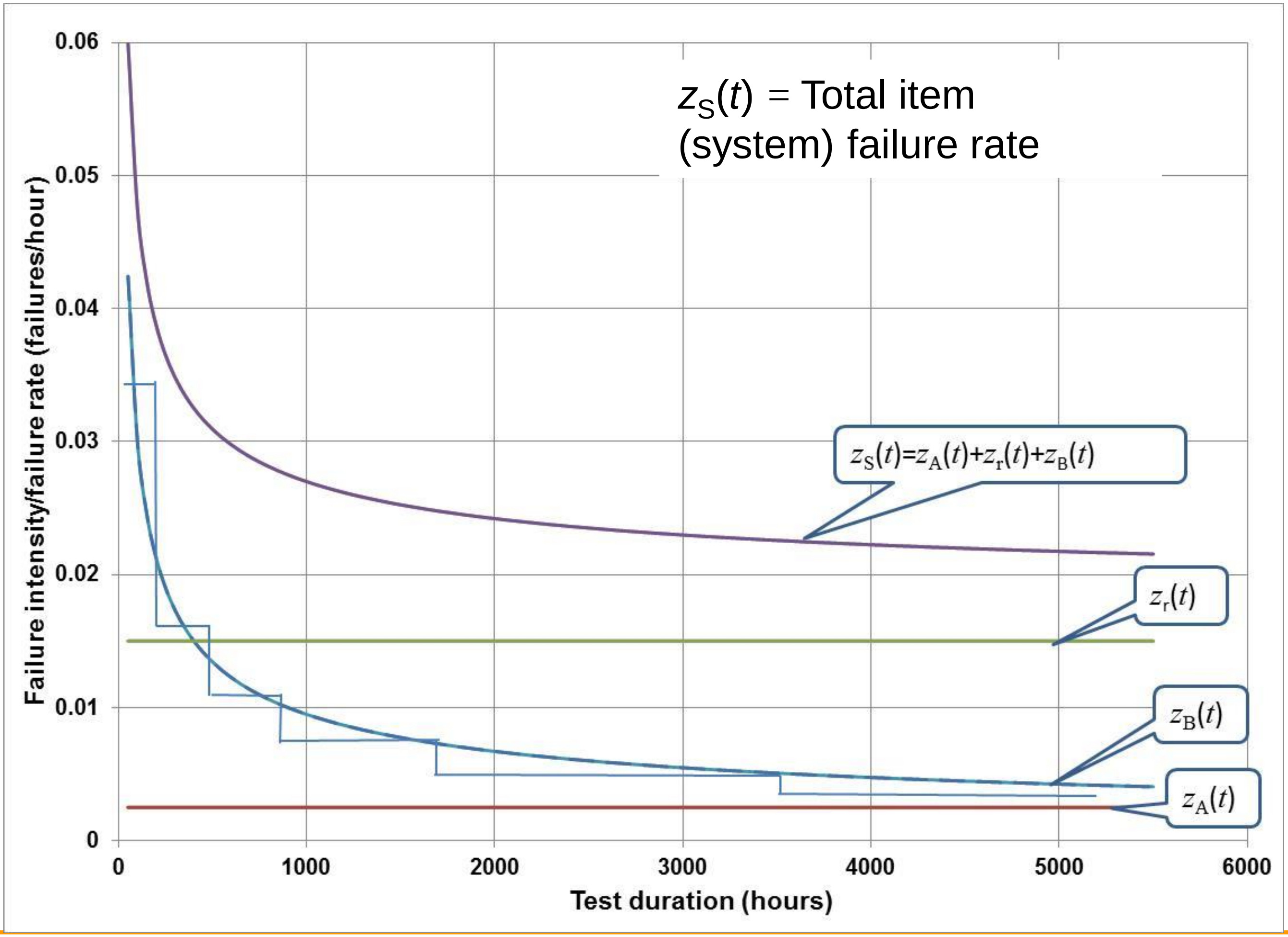
What or who are *N*(*t*) and *z*(*t*)? What do they consist of?

Principles of Reliability Growth Modeling Regarding Failure Modes Types

- Reviewing the major failure modes in a product published in editions of MIL-HDBK-189 (currently C):
  - $z_B(t)$: B-type failure modes are corrected, their cumulative times of arrival are recorded once and are used to calculate the shape parameter for the reliability growth curves (Weibull Intensity Function) failure distribution and failure rate
  - $z_{\mathrm{A}}(t)$: A-type failure modes are repaired but not corrected, their cumulative time of arrival is recorded every time they repeat after their repair
    - MIL-HFBK-189C does not show that A-modes are entered in calculation and there is no mention of how they are analyzed
  - $z_{\mathrm{r}}(t)$: Random failure modes are repaired but not recorded nor their time of appearance is used for any failure rate calculation Failure rate of these failure modes is constant but unknown.

Failure Mode Types Within a Test Item

- Graphically (physically correctly) represented the process even as described in traditional reliability growth but then not followed) is:



Planning of the Traditional Mathematical RG Test – Potential Errors

- Planning Crow/AMSAA/Duane Model expressed with the shape parameter β instead the growth rate α (189C)

$$z(t) = z_I \cdot \left(\frac{t}{t_I}\right)^{\beta-1} \quad \text{or:} \qquad z_F(t_F) = z_I \cdot \left(\frac{t_F}{t_I}\right)^{\beta-1}$$

  - where:

    $z(t)$ = total failure rate of the tested item in time t

    z_I = initial failure rate of the item at the beginning of test

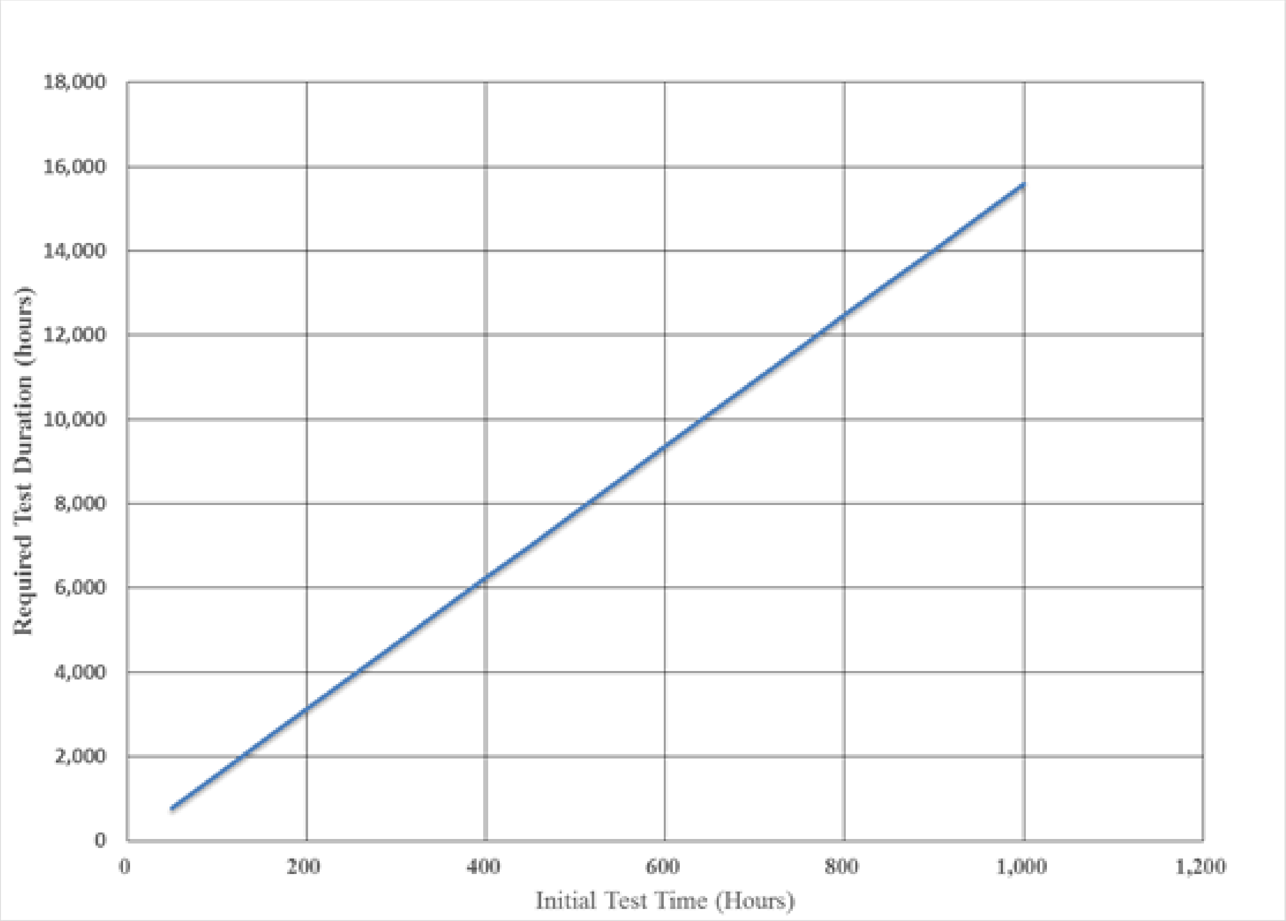
    $z_F(t_F)$ = final failure rate of the tested item at the end of test, t_F

    t_I = initial test time (dependent on assumptions)

  - Determination of the test duration for the planning: $t_F = e^{\frac{\ln(z_F)-\ln(z_I)}{\beta-1}+\ln(t_I)}$
    - Test duration is highly dependent on the “initial test time”, its physical meaning or significance – remains unclear
    - But the assumption value can be very useful to obtain the desired test duration

Mathematical Test Duration

- The test duration is highly dependent of the initial test time and its *understanding*:
  - ❑ Time to first failure
  - ❑ Time to end infant mortality
  - ❑ Time to weed out "integration" failures
  - ❑ ?
  - ❑ .
  - ❑ .
  - ❑ .



The Currently Known Reliability Growth Test – Procedure and Mathematics

- Record times to failure of B-failure modes, t_i;
- Record times to failure of A-failure modes every time when they repeat: $t_{??}$ (no guidance how to include them in calculations since they remain random)
- If a failure is scored random, gather the information but do not count or include into computations
- Calculate point estimates and unbiased shape and scale parameters for the Weibull Intensity Function (power law curve) for time or failure terminated test (as the test is performed)
- Determine goodness of fit
- Determine the final failure rate of the tested item (system)
- Determine confidence limits
- Prepare failure rate or MTBF projections as desired
- Complete a report.

The Reliability Growth Test – Procedure and Current Mathematics, cont.

- Failure terminated test, t_M - time to M-th (last) failure mode

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

$$\hat{\lambda} = \frac{M}{t_M{}^{\hat{\beta}}} \qquad \bar{\lambda} = \frac{M}{A \cdot t_M{}^{\bar{\beta}}} \qquad \bar{z}(t_M) = \bar{\lambda} \cdot \bar{\beta} \cdot t_M{}^{\bar{\beta}-1}$$

- Time terminated test terminated test, t_0 :

$$\hat{\beta} = \frac{M}{M \cdot \ln(t_0) - \sum_{i=1}^{M} \ln(t_i)} \qquad \bar{\beta} = \frac{M-2}{M \cdot \ln(t_0) - \sum_{i=1}^{M} \ln(t_i)}$$

$$\hat{\lambda} = \frac{M}{t_0{}^{\hat{\beta}}} \qquad \bar{\lambda} = \frac{M}{A \cdot t_0{}^{\bar{\beta}}} \qquad \bar{z}(t_0) = \bar{\lambda} \cdot \bar{\beta} \cdot t_0{}^{\bar{\beta}-1}$$

- Now, who is $z(t)$?:
  - It is calculated from information on B failure modes only
  - What happened to A and random failure modes?

Understanding the Reliability Growth Process

- Components of an item under test can fail in three different ways:
  - Some parts fail due to overstress or other design/process errors
  - Those failure modes that can be improved (***B***-type failure modes)
  - With improvements their failure rate forms a step down curve– then they are fitted with the Weibull Intensity Function (power law)
  - When the changes stop, the that failure rate remains constant
    - Unless the design is indeed inferior, the B-modes will come from a smaller (considerably) part of the tested item total failure rate
- The part of an item where improvements of systematic failure modes (their faults) were not possible (***A***-type failure modes)
  - ***A*** failure modes continue to have constant failure rate
- The remaining part of the test item will have random failure rates
  - Random failure rates are also considered constant

Understanding the Reliability Growth Process, cont.

- The total failure rate of an item has three components at any time then consists of:
    - *B*-modes which can be mitigated and its failure rate is fitted with the power law
    - *A*-modes that remain unchanged and continue to have constant failure rate
    - Random failure modes (those which are predicted), which the constant failure rates
- The reliability growth process can only be represented as:

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

Understanding the Reliability Growth Process, cont.

- Since there are no changes of design where random and A failure modes originate from, they remain constant:

$$z_A(t) = z_A(t_I) = z_A$$

$$z_r(t) = z_r(t_I) = z_r$$

- The only failure modes where any reliability growth planning is applicable:

$$z_B(t) = z_{BI}(t_I)$$

$$z_{BF}(t_F) = z_{BI}(t_I) \cdot \left(\frac{t_F}{t_I} \right)^{\beta - 1} = \lambda_B \cdot \beta_B \cdot t_F^{\beta_B - 1}$$

- The final achieved reliability (failure rate or MTBF) to be reported:

$$z_F(t_F) \neq [z_{BI}(t_I) + z_A + z_r] \cdot \left(\frac{t_F}{t_I} \right)^{\beta - 1} ; z_I(t_I) = z_{BI}(t_I) \neq z_{BI}(t_I) + z_A + z_r$$

$$z_F(t_F) = z_{BF}(t_F) + z_A + z_r = z_{BI}(t_I) \cdot \left(\frac{t_F}{t_I} \right)^{\beta_B - 1} + z_A + z_r = \lambda_B \cdot \beta_B \cdot t_F^{\beta_B - 1} + z_A + z_r$$

Understanding the Reliability Growth Process, cont.

- Only B-type failure modes can be “fixed”
  - The best possible improvement could be mitigation of all (almost all) *B* failure modes.
  - Even then, it may not be possible to achieve a failure rate lower that the sum of *A* and random failure rates

$$z_{BF}(t_F) = z_{BI}(t_I) \cdot \left(\frac{t_F}{t_I} \right)^{\beta - 1} = \lambda_B \cdot \beta_B \cdot t_F^{\beta_B - 1}$$

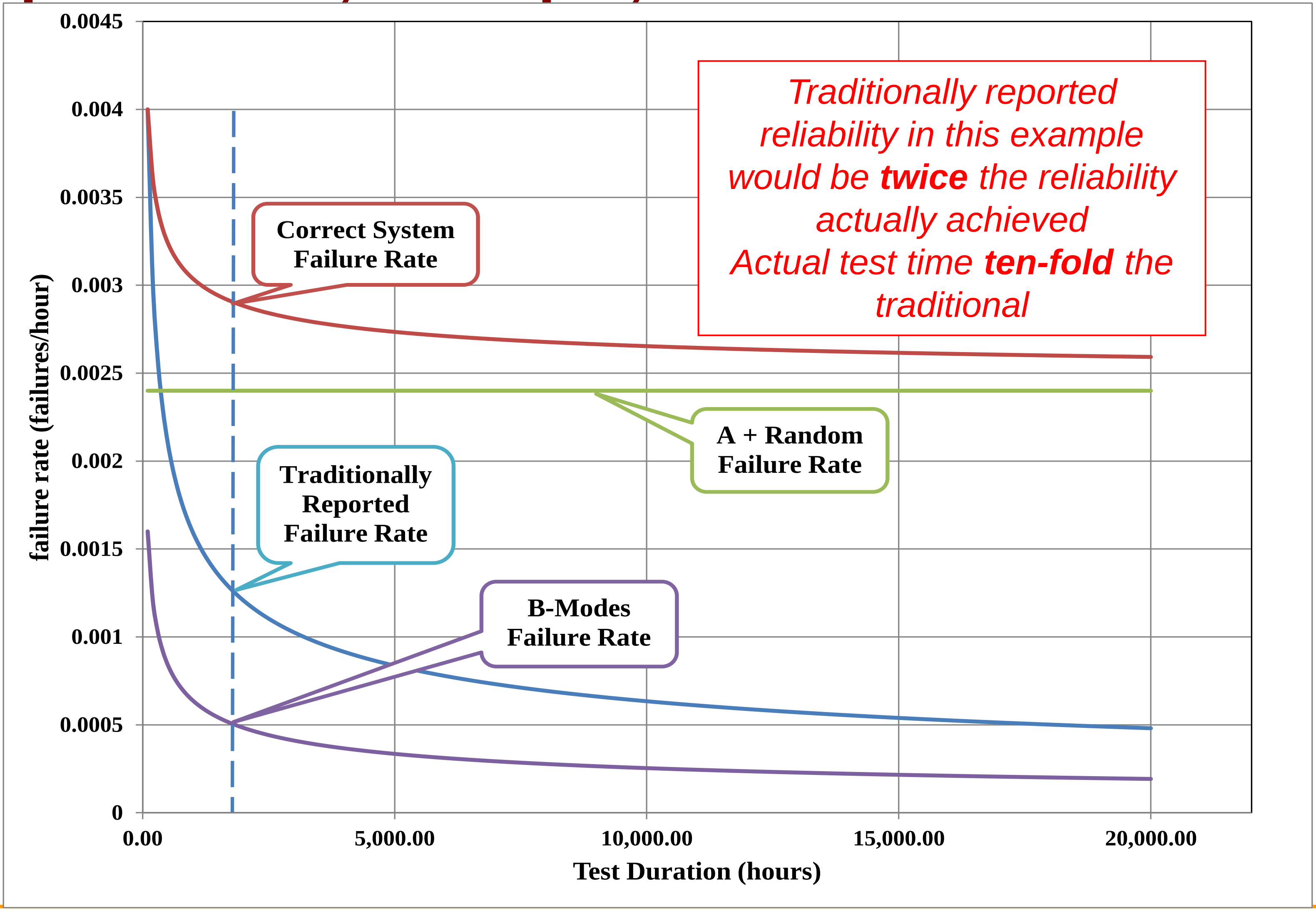
$$z_F(t_F) \geq z_A + z_r$$

- The summary of the traditional approach
  - The initial failure rate for power law was the total item failure rate
  - What is reported as final failure rate is only what was fixed
  - The final result reported – calculations for *B* and *A*(?) failure modes
  - The major part of total failure rate of the item – the random failure modes – is ***FORGOTEN. Consequently the results are - impressive***

Traditional and Corrected Approach to Improvement, Example

- The initial and goal reliability are as follows:
  - Initial MTBF of an item: $\theta_I = 250$ hours ($z_I = 0.004$ failures/hour)
  - Shape parameter: $\beta = 0.6$
  - *Traditional* approach requirement: Increase product reliability by a factor of 3
- Traditional approach: $\theta_G = 750$ hours ($z_I = 0.00133$ failures/hour)
  - Traditional test duration calculated: **$t_{F\_traditional}$ = 1,559** hours
- Corrected approach: $z_{BI} = 0.4 \times z_I$; $z_{A+Random} = z_A + z_r = 0.6 \times z_I$;
  - Corrected requirement/goal: $z_{BG} = 0.01 \times z_{BI}$; $\theta_G = 384$ hours
  - Corrected test duration: ***$t_{F\_corrected}$ = 18,102*** hours (Not affordable?)
- For significant improvement and attainment of the goal, B modes failure rate had to be reduced eight times rather than three times
  - *Corrected* approach requirement should be:
  - Increase product reliability as high as reasonably possible

Traditional and Corrected Approach to Improvement, Example, cont.



*Traditionally reported reliability in this example would be **twice** the reliability actually achieved*

*Actual test time **ten-fold** the traditional*

Correcting the Test Duration, Conclusion

- To correct the methodology and include the “forgotten” failure rates in the test results, the reliability growth model had to be modified
- The correction results in significant increase in the required test time – an order of magnitude or greater
- The test duration must allow two tests to be performed concurrently:
  - The test for constant failure rate (the sum of the failure rates of A and truly random failure modes)
  - The test for reduction of failure rate resultant from design or process deficiencies
- The test duration must allow for the number of failures that would guarantee reasonable confidence in the test results
- The test duration must be reasonably affordable in view of cost and schedule

Alternative for Mathematical Approach to the Reliability Growth Testing

- Problems that need to be resolved:
  - To apply the correct **mathematical** approach, the required test time well exceeds the test durations historically seen or affordable
    - Both, reliability correction of design or process errors, and reliability demonstration of the constant failure rates of the product need to be addressed in test
  - Duration of mathematical reliability growth tests only partially addresses stresses the product is expected to see in life and their level and use profile
    - The guidance usually provided is to: “apply stresses at the same level as expected in use”, does not explain why and why with “that” duration
    - All types of failure modes have failure rates dependent on the stresses and their duration
  - Mathematically determine tests are unrelated to the physical causes of failures

Physics of Failure (PoF) Test Approach

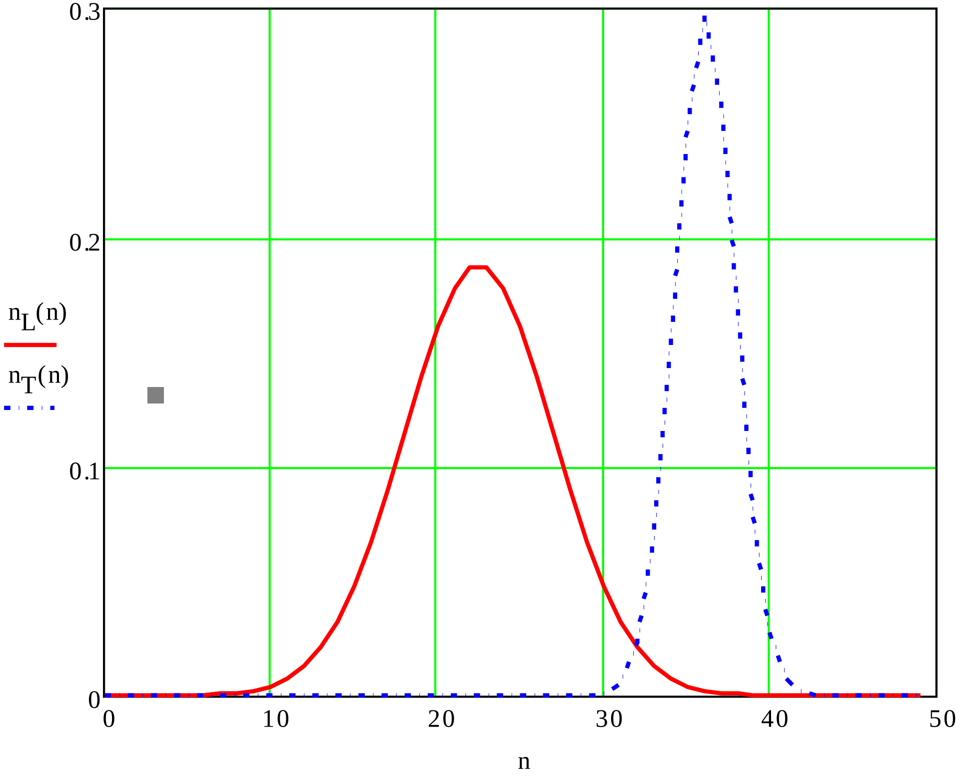
- The Physics of Failure approach considers the rationale for appearance of failures as a result of stress applied to an item which exceeds the magnitude of its strength in regard of this type of stress
    - Another fact is the cumulative damage of an item in the course of its use and life
- The principle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

Accelerated Testing Methods

- Qualitative accelerated testing:
  - Highly Accelerated Limit Test (HALT) for identification of potential design weakness
  - Highly Accelerated Stress Tests or High Accelerated Stress Audit (HAST, HASA) for screening out the production defects
- Quantitative accelerated testing
  - Single stress testing, components and systems
  - Multiple stress testing, components and systems
  - Reliability testing (mission or life reliability):
    - Fixed duration tests (single stress and multiple stresses)
    - Reliability growth test (single and multiple stresses)
- All test methods, including the reliability growth shown in this presentation published in the IEC 62506, Methods for product accelerated testing, published in June 2013

Physics of Failure and Reliability Principle

- Failures occur when an item ceases to be strong enough to withstand one or more attributes of a stress: level or duration or both
  - Level and duration in life depend on users – assume normally distributed
  - Looking at the same stress, longer duration of test allows for certainty that number of failures resultant from degradation in test covers the failures in use



$$n_L(n) := \frac{1}{\sqrt{2\cdot\pi\cdot\sigma_L}}\cdot\exp\left[\frac{-1}{2\cdot\sigma_L{}^2}\cdot(n-\mu_L)^2\right]$$

$$n_T(n) := \frac{1}{\sqrt{2\cdot\pi\cdot\sigma_T}}\cdot\exp\left[\frac{-1}{2\cdot\sigma_T{}^2}\cdot(n-\mu_T)^2\right]$$

$\mu_L := \lambda_L\cdot t_L$ $\mu_T := \lambda_L\cdot t_T$ $t_T := k\cdot t_L$ $\mu_T := \lambda_L\cdot k\cdot t_L$

$\sigma_L := b\cdot\mu_L$ $\sigma_T := a\cdot\mu_T$

$k := 1.6$ $b := 0.2$ $a := 0.05$

$$R_S(t_T) = \Phi\left[\frac{\lambda_T\cdot t_T - \lambda_L\cdot t_L}{\sqrt{\sigma_T^2+\sigma_L^2}}\right] = 0.997$$

Physics of Failure and the Test Duration

- Besides the magnitude of stresses expected in the actual use, their cumulative effect affects product reliability.
  - The test duration is then calculated based on the duration of each of the stresses applied in actual use.
  - The test results for a product in one use might not be 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). It is not advisable to transfer a test result from one environmental and user profile to another.
  - Often, products are tested with a combined stress cycle in order to expose the product to several stresses in combination or sequentially.
  - Ideally, the stresses should be applied both combined and intermittent in order to simulate the field conditions as well as possible.

Physics of Failure and Reliability Principle

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

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

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 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 stress to obtain the stress standard deviation

Physics of Failure and Reliability Principle

- The ratio between the stress and stress can be expressed as a constant *k*, therefore the previous equation will become:

$$R_i\left(t_T\right)=\Phi\left[\frac{\lambda_{L\_i}\cdot t_{T\_i}-\lambda_{L\_i}\cdot t_{L\_i}}{\sqrt{\sigma_{T\_i}^2+\sigma_{L\_i}^2}}\right]=\Phi\left[\frac{\lambda_{L\_i}\cdot k\cdot t_{L\_i}-\lambda_{L\_i}\cdot t_{L\_i}}{\sqrt{\left(\lambda_{L\_i}\cdot k\cdot t_{L\_i}\cdot a\right)^2+\left(\lambda_{L\_i}\cdot t_{L\_i}\cdot b\right)^2}}\right]$$

- After reduction:

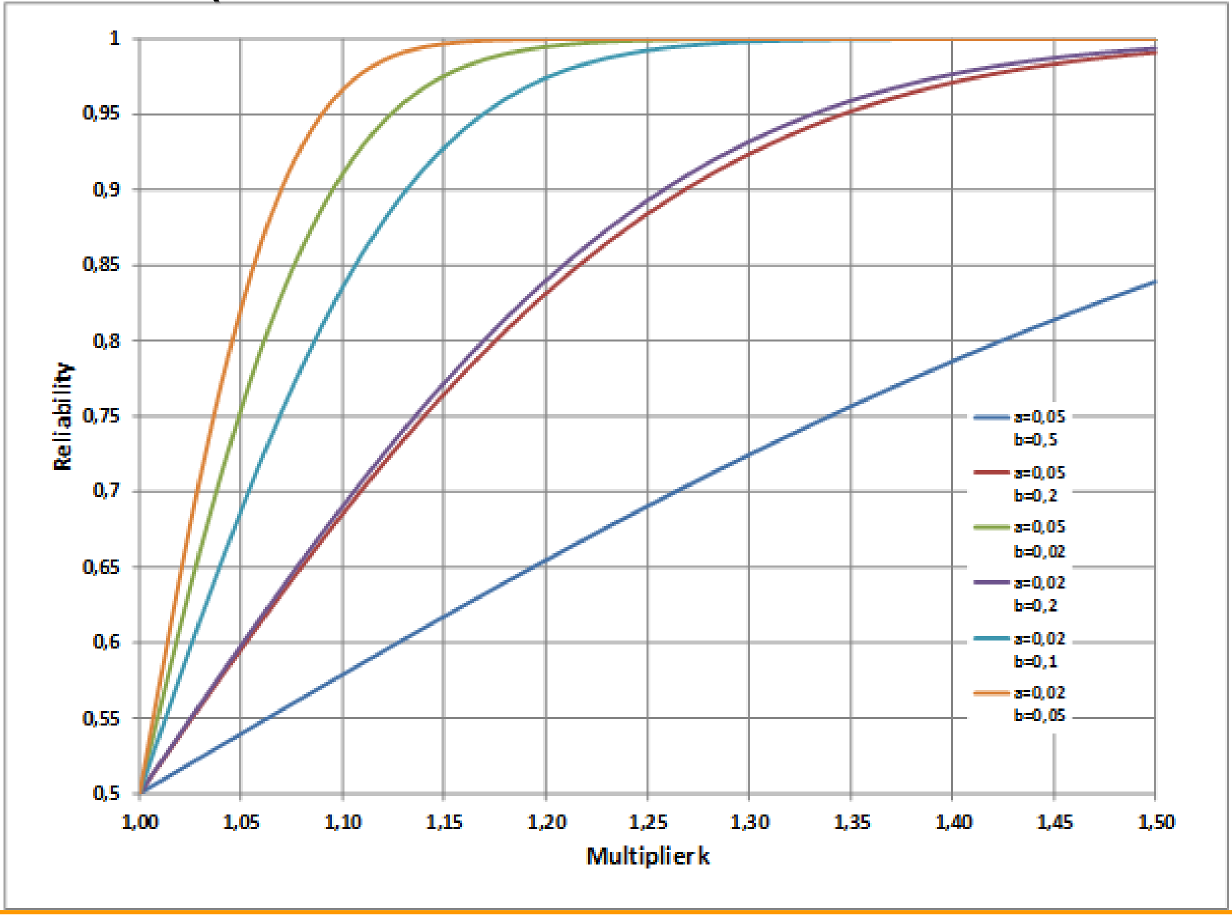
$$R_i\left(t_0\right)=R_i\left(k,\mu_{L\_i}\right)=\Phi\left\{\frac{k-1}{\sqrt{\left(a\cdot k\right)^2+\left(b\right)^2}}\right\}$$

Where:

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

Determination of Multiplier k for a Set Reliability Goal in Reliability Growth and Demonstration

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



Correlating Reliability Requirements and Test Duration with Reliability Growth, cont.

- If there are N_S stresses applied and equal contribution is allocated to each, reliability per one stress will be:

$$R_i(T,k) = \sqrt[N_S]{R_G(T,k)}$$

- If the stresses are those known as 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 0.6:
- $R_i(k) = 0.882 \approx 0.9$
- Assuming that the variations are as earlier mentioned, $a = 0.05$ and $b = 0.2$, the multiplier k from the graph: $k = 1.27$.
- If the product life of 10 years, the required test duration for the example reliability growth is:
  T = 111,252 hours or 12.7 years

Duration of Application of Each Expected Stress

- Duration and profile of each stress in use during the total predetermined use time needs to be calculated
    - Total exposure duration for the duration of that period.
    - Total number of cycling stresses at each of the stresses
        - If exposed to different stress levels, all the lower stress levels need to be recalculated to the values of highest level using acceleration factors appropriate for the specific stress
- The maximum duration of each stress (in hours or cycles) is multiplied with the factor *k* and then accelerated to a reasonable duration and to a reasonable stress (recommended: lower than the rating for that item).
- Thermal exposure is usually distributed over thermal cycling
- A good idea to apply synergism wherever possible
- Times to failure recorded for all be-types of failure modes
    - They can be recorded for the A-type and random failure modes.

Monitoring and Accounting for the Random Failure Modes

- It is recommended to separate analyses of the A-type failure modes from the simply random failure modes.
  - This is to not mix the test data in the case of a later management or engineering decision to correct some of those failure modes at a later time and achieve further reliability improvement
- The mathematics used here is for simple Homogenous Poisson Process where:

$$z_A = \frac{N_A}{T}; \qquad \mathrm{z_r} = \frac{N_r}{T}$$

  - Appropriate confidence limits are also determined for the desired level of confidence for those constant failure rates
  - The final failure rate (failure frequency) of the tested item is then the sum of failure rates of all three failure mode types
  - The physics of failure reliability growth test does not allow shortening of the test time by using the multiple units.

Accelerated Fixed Duration Tests, cont.

- An important caution against a rather common practice is that the acceleration factors for individual stresses cannot be multiplied with each other to calculate an overall test acceleration factors
  - They multiply only when one or more stresses accelerate the same failure mode (e.g. humidity where the thermal acceleration during humidity test multiplies the humidity acceleration)
  - Such erroneous practice may lead to unreasonably high acceleration factors and the very unreasonable test acceleration at times reaching a value of 90,000 times, thus leading to unreasonably short life test durations of several minutes
  - This practice can unfortunately be found in many military standards for Weibull Distribution for components (capacitors) testing
    - One also might notice added test accumulated test times between components (for Weibull distribution - ?!?)

Accelerated Reliability Growth Test, cont.

- For other environmental or operational stresses, the time to failure should be calculated factoring the use profile into the calculations.
- Once the times to all relevant B-type (corrected) failure modes are recorded and ordered in accordance of their time of appearance, the Weibull intensity function (power law) parameters are determined
  - The failure rate will be:

$$\hat{z}_B(t_0) = \frac{d}{dt} N_B(t)$$

$\hat{\lambda}$

$$\hat{z}_B(t_0) = \hat{\lambda} \cdot \hat{\beta} \cdot \left(k \cdot t_0\right)^{\hat{\beta}-1}$$

where:

- N_B= number of B failures mitigated
- $\hat{\lambda}$ = point estimate of the scale parameter
- $\hat{\beta}$ = point estimate of the shape parameter
- $\hat{z}_B(t)$= point estimate of the B-modes’ failure rate

The Reliability Growth Test – Procedure and Current Mathematics, cont.

- Recalculate times to failures in accelerated tests to the time to their arrival in use in their respective environments
  - Failure terminated test, t_M - time to *M*-th (last)   failure mode

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

- Time terminated test terminated test, t_0 :

$$\hat{\beta} = \frac{M}{M \cdot \ln(t_0) - \sum_{i=1}^{M} \ln(t_i)} \qquad \hat{\lambda} = \frac{M}{t_0^{\hat{\beta}}} \qquad \bar{\beta} = \frac{M-2}{M \cdot \ln(t_0) - \sum_{i=1}^{M} \ln(t_i)} \qquad \bar{\lambda} = \frac{M}{t_0^{\bar{\beta}}}$$

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

$$z_S(t_{0/M}) = z_A(t_{0/M}) + z_{random}(t_{0/M}) + z_B(t_{0/M})$$

Accelerated Reliability Growth Test and Data Analysis, Example

- Automotive electronic device with the use profile:

Parameter	Symbol	Value
Required life	t_0	10 years = 87,600 h
Required reliability	$R_0(t_0)$	0.72
Time ON	t_{ON}	2 h/day=7 300 h
Temperature ON	T_{ON}	65 °C
Time OFF	t_{OFF}	22 h/day=80 300 h
Temperature OFF	T_{OFF}	35 °C
Thermal cycling	ΔT_{Use}	45 °C, two times per day
Total cycles	N_{Use}	7,300 cycles
Temperature ramp rate	ξ	1.5 °C/min
Vibrations, random	W_{Use}	1.7 G r.m.s
Relative humidity	RH_{Use}	50 %
Activation energy	E_a	1.2 eV

Accelerated Reliability Growth Test and Data Analysis, Example, cont.

- Stresses and stress multiplier:
  - There are four major individual environmental stresses identified: thermal cycling, thermal exposure, humidity and vibration. The reliability requirements allocated to each are:

$$R_{A+random} = 0.8$$

$$R_{i\_A+random} = 0.946 \qquad k = 1.5$$

$$R_B = 0.9$$

$$R_{i\_B} = 0.974 \qquad k = 1.68$$

  - Since only one test is performed, one multiplier is selected; *k* = 1.68
  - The parameter *k* is determined for constants *a* = 0.05 and *b* = 0.2.

Accelerated Reliability Growth Test and Data Analysis, Example

- The required reliability value is a total reliability regarding all types of failure modes. Allocated reliability for total random and for the B-type failure modes were
  - $R_{\text{A+Rrandom}}(t_0) = 0.8$, and $R_B(t_0)=0.9$ respectively,
- The corresponding failure rates and MTBFs will be:

$$z_{A+random} = 2.58\times10^{-6} \text{ failures/hour}$$

$$\theta_{A+random} = 3.88\times10^{5} \text{ hours}$$

$$z_B = 1.17\times10^{-6} \text{ failures/hour}$$

$$\theta_B = 8.53\times10^{5} \text{ hours}$$

  - The tested item, even though repairable, was not to be repaired during its required life; therefore, the required reliability is projected to the entire life of the product and converted into the failure rate and MTBF.

Accelerated Reliability Growth Test and Data Analysis, Example, cont.

- Stress acceleration: Thermal cycling:
  - Total cycles in use = 7,200 cycles
  - ΔT_{Use} = 45 °C
  - T_{Test} = 105 °C
  - ΔT_{Test} = 105 – (-20) = 125 °C
  - ξ_{Use} = 1.5 °C/min
  - ξ_{Test} = 10 °C/min
  - m = 2.5

$$N_{Test} = N_{Use} \cdot k \cdot \left(\frac{\Delta T_{Use}}{\Delta T_{Test}}\right)^{m} \cdot \left(\frac{\xi_{Use}}{\xi_{Test}}\right)^{1/3}$$

$$N_{Test} = 500 \text{ cycles}$$

Accelerated Reliability Growth Test and Data Analysis, Example, cont.

- <u>Thermal exposure, thermal dwell:</u>
  - Normalize duration in OFF condition to the duration of the ON condition:

$$t_{ON\_N} = t_{ON} + t_{OFF} \cdot \exp\left[-\frac{E_a}{k_B} \cdot \left(\frac{1}{T_{OFF} + 273} - \frac{1}{T_{ON} + 273} \right) \right]$$

$$t_{ON\_N} = 8{,}754 \text{ hours}$$

  - Calculate necessary test duration:

$$t_{T\_Test} = t_{ON\_N} \cdot k \cdot \exp\left[-\frac{E_a}{k_B} \cdot \left(\frac{1}{T_{ON} + 273} - \frac{1}{T_{Test} + 273} \right) \right]$$

$$t_{T\_Test} = 188 \text{ h}$$

Accelerated Reliability Growth Test and Data Analysis, Example, cont.

- Distribute thermal exposure over thermal cycling:

$$t_{TD} = \frac{t_{T\_Test}}{N_{Test}} = 0{,}38\,\mathrm{h} = 22.6\,\mathrm{min}$$

- Determine duration of a thermal cycle:

$$t_{TC} = 2 \cdot (\mathrm{ramptime}) + (\mathrm{temp.stabilization} + \mathrm{ThermalDwell})$$

$$+ \mathrm{Dwell\ at\ cold}$$

$$t_{TC} = 2 \cdot \frac{125}{10} + (time.st.hot + 22.6) + (time.st.cold + 5) =$$

$$= 52.6\,\mathrm{min} + st.hot + st.cold \approx 689\,hours$$

$$(st.hot = 15\,\mathrm{min}; st.cold = 15\,\mathrm{min})$$

Accelerated Reliability Growth Test and Data Analysis, Example, cont.

- Humidity:
  - The test parameters are:
  - RH_{Test}=95%
  - T_{RH}=65 ^{0}C chamber+ 20 ^{0}C internal temperature rise = 85^{0}C

$$t_{RH\_Test\_Test} = t_{ON\_N} \cdot k \cdot \left(\frac{RH_{Use}}{RH_{Test}}\right)^{h}$$

$$\exp\left[-\frac{E_a}{k_B} \cdot \left(\frac{1}{T_{ON}+273} - \frac{1}{T_{RH}+273}\right)\right]$$

$$h = 2.3$$

$$t_{RH\_Test} = 336\,\mathrm{h}$$

Accelerated Reliability Growth Test and Data Analysis, Example, cont.

- Vibration Test
  - Required mileage for 10 years: 150,000 miles, 150 hours per axis in test).
  - Vibration level in use: $W_{\text{Use}} = 1.7$ G rms;
  - Vibration level in test: $W_{\text{Test}} = 3.2$ G rms;
  - Duration of vibration test per axis:

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

$$\text{With}: \; w = 4$$

$$t_{Vib\_Test} = 20 \text{ hours (per axis)}$$

  - A total of 60 hours

Test Acceleration Summary

- Test Accelerations:

$$A_{TC} = \left(\frac{\Delta T_{Use}}{\Delta T_{Test}}\right)^{m} \cdot \left(\frac{\varsigma_{Use}}{\varsigma_{Test}}\right)^{1/3} = \frac{k \cdot N_{Use}}{N_{Test}} = 24.2$$

$$A_{TD} = \exp\left[-\frac{E_a}{k_B} \cdot \left(\frac{1}{T_{OFF} + 273} - \frac{1}{T_{ON} + 273}\right)\right]$$

$$= \frac{k \cdot t_{ON\_N}}{t_{T\_Test}} = 52.1$$

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

$$= \frac{k \cdot t_{ON\_N}}{t_{RH\_Test}} = 43.7$$

$$A_{Vib} = \left(\frac{W_{Use}}{W_{Test}}\right)^{w} = \frac{k \cdot t_{Vib\_Use}}{t_{Vib\_Test}} = 12.6$$

- Acceleration for use with the random failure rates:

$$A = \frac{A_{TC} \cdot A_{Vib} + A_{RH} \cdot A_{TD}}{S} = 645$$

Random (Constant) failure rate

- The total test duration for the constant failure rates (A-modes and random) is: $t_{\mathrm{Test\_C}} = k^* t_0 = 1.472\times10^5$ hours
- With no test failures, the final test dynamic constant failure rate is:

$$z_{A+random} = -\frac{\ln\left[R_{A+random}(t_0)\right]}{t_0 \cdot k} = 1.516\cdot10^{-6}\ \text{failures/hour}$$

Or expressed as MTTF :

$$\theta_{A+random} = 6.505\cdot10^{5}\ \text{hours}$$

- Total accelerated test duration: 1,124 hours; considerably shorter than the mathematical reliability growth.

Test Data Analysis – Conversion of the Test Data into Time to Failure Data

- For data plotting, the necessary information is time to failure. In a test designed such that duration of each stress in the test represents duration of that stress type in life, the times or cycles to failure in tests need to be translated in the corresponding time in the product life for each of the applied stresses.

- This is done by test "deceleration" and by conversion of applied test cycles or hours of duration into the real use time duration

- For the basic stresses the conversions are shown in following slides

Test Results for the B – Type Failure Modes

Failure	Time to failure (h)	ln (*ti*)
1	821.33	6.710925
2	2781.33	7.930685
3	9016	9.106756
4	10563.44	9.265154
t_0*k	147168	11.89933

- The final B-modes failure rate calculated using power law model is:
- $z_{BF}(t_0) = 2\times10^{-7}$ failures/hour
- The total item final failure rate is:
- $z_{\mathrm{Item\_F}} = z_{BF}(t_0) + z_{\mathrm{A+random}}(t_0) = 1.72\times10^{-6}$ failures/hour
- The final system reliability is 0.86 considerably greater than the required reliability of 0.72.

Conclusions

- Traditional mathematical approach to reliability growth test design
  - Applies NHPP and the power law mathematics to the reliability measures of total item in test but reports the results from the systematic failure modes only
    - Random failure rates representing the majority of system failure modes are forgotten and the item reliability – overestimated while test duration is under estimated
  - Uses stresses expected in life at the same levels but with arbitrary duration
- Physics of failure accelerated test approach
  - Considers lifetime cumulative damage to a product in use
  - Provides information on reliability for the product expected life
  - Provides measure for the failure rates of the random failure modes
  - Presents realistic test results
  - Achieves test durations equal or shorter than traditional reliability growth and considerably shorter than the fixed duration tests.

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