Determine and Design the Best ALT

Fred Schenkelberg, Ops A La Carte, LLC

Key Words: Accelerated Reliability Test, planning

SUMMARY & CONCLUSIONS

Over the many years of development concerning accelerated life testing (ALT), our peers have found many ways to take advantage of the interaction of stress and failure mechanisms [1-15]. In an ideal situation, the reliability engineer will have ample time, samples, test resources and knowledge to conduct an ALT. This is often not the case.

Trading off the risks in conducting the ALT and fitting within the myriad of constraints and expectations is a challenge. Understanding the basics of ALT approaches and associated assumptions, permits one to select the right ALT. 'Right' being the ALT that provides meaningful results in time for technical and business decisions, plus meets the budget and risk tolerance limits.

There is no one-way to design an ALT that will meet the specific set of conditions presented to the test designer. Being able to clearly articulate the tradeoffs involved permits the entire design team to fully understand the results when produced. The 'best' ALT is one that adds value to the design process.

The most accurate results involve testing all of the production units in actual customer application or use until they all have failed. While this is clearly not practical, neither is the simple-minded approach guessing at the results. In between these two extremes lies an optimal value: being the most efficient ALT that provides meaningful results. When the results provide information to make design or program decisions, the ALT adds value.

Reducing ALT costs by reducing sample size or test duration is possible, yet may significantly increase uncertainly around the results. Running the test longer to achieve more accurate results is often constrained by the timeline to make decisions. It is this and similar tradeoffs that force us to carefully design each ALT and determine the best path forward.

1 INTRODUCTION

There are many books and papers on the topic of ALT, plus many papers that use ALT as a tool as they explore a new material, component, or system. What is often missing in many cases is why the author chose the particular ALT given their particular circumstance. This paper explores the array of available options for life testing, exposing the key tradeoffs any one test includes. Plus, we will examine the process to judge the options to select the right test method given the requirements and constraints.

The paper provides practical guidance based on years of experience across many industries. We will focus on actually getting results in time to make design or business decisions. Plus, we will explore how to describe the benefits, assumptions, and risks associated with accelerated life testing. The paper provides a framework to think though and properly select an ALT approach. Establishing the number and nature of the criteria will vary for each situation and organization.

2 ALT SELECTION CRITERIA

The 'best' ALT is the test that provides meaningful results within the constraints with the least uncertainty and cost. This an arbitrary definition, yet does provide a means to determine the appropriate ALT approach for a particular situation.

'Meaningful results' implies the findings of the ALT truly represent the unknown actual lifetime performance of the item under test. Having statistical confidence at or less than 50% means the result is 50/50 within or outside the stated confidence bounds, i.e., not meaningful. Using too few samples in the test may cause this.

Also, consider testing the right performance parameter. Measuring the parameter directly and with respect to the customer's definition of failure is often best, yet may be difficult to actually accomplish. Consider a rechargeable battery as an example. Measuring the number of recharges the battery can accept is a destructive and long test. There is a quicker test that provides a surrogate result, yet with some uncertainty, and is not destructive and does not take too long to accomplish. Measuring the battery radial diameter may be an easy way to accomplish measurement, yet really doesn't have any known relationship to battery recharge life.

As may be apparent there may be many ways to measure the performance of a product. Selecting a means that is closest to the way the customer determines performance failure is often best. However, it may be too costly, time consuming or difficult to actually accomplish, therefore, using measurements that are indicators or surrogates may provide a means to detect a failure with modest additional experimental risk or cost. Measuring something unrelated to the performance parameter in question is clearly not going to produce a meaningful result.

A direct, surrogate or unrelated measure creates a continuum of possibilities and there is a threshold where the measurement is or is not related to the performance parameter. Using a simple line with three points to represent the three measurements may be useful to illustrate the possibilities, as in figure 1.

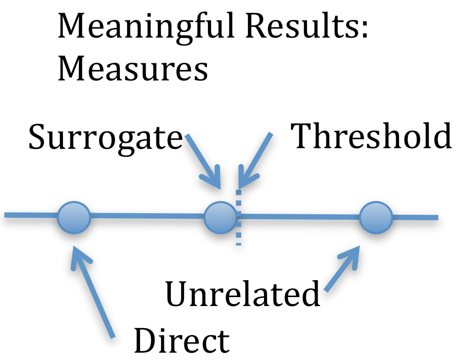

Figure 1 Meaningful Results Criterion

Likewise for other ALT design considerations, there are similar continuums of possibilities. Cost, for example, can range from no cost to infinity, or in practical terms from relatively inexpensive to prohibitively expensive. The threshold may be defined by the budget allocated to the ALT.

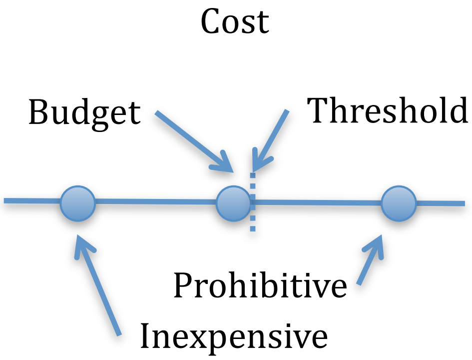

Figure 2 Cost Criteria

Besides meaningful results and cost, other considerations may include precision, test duration, realistic conditions, and number of samples. Like cost, test duration and number of samples have simple ranges and often a clear threshold. One can create a linear scale as in figures 1 and 2 for each criterion.

Precision is the ability of the ALT to determine a result with sufficient accuracy. This may be either to determine the difference between two alternatives or the ability to clearly conclude the items will last beyond a specific lifetime. Either way, precision is similar to size of the confidence bound about the result. A result stated at 10 years plus/minus 1 day is much more precise than a result stated as 10 years plus/minus 10 years. Unlike cost, more precision is preferred.

Realistic conditions ranges from testing the items in actual customer conditions to highly controlled environmental conditions on material coupons with surrogate indicators for performance (i.e., tensile strength bar testing with temperature only aging). The more unrealistic the testing the more assumptions involved. Each deviation from use conditions requires some translation back to use conditions. Some changes in conditions are assumed insignificant and ignored. In short, the less realistic the testing, the more complex the set of assumptions, models and extrapolations.

One way to view these six criteria is with a radar plot and using a ten-point criteria scale as in figure 3.

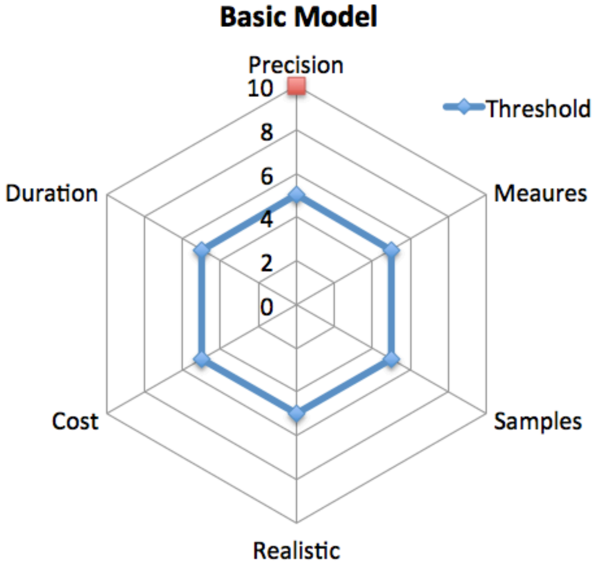

Figure 3 Radar Plot of Criterion

Arrange the axes such that the criteria critical to the value of the ALT are above the horizontal line. In this case, test duration, precision, and meaningful result are absolutely required. This may be based on local policy or criteria of the approval authority. That leaves the three criteria to optimize as the number of samples, realism, and cost.

The arrangement of the ranges along each axis permits the graphical comparison of various test approaches. For the requirements, above the dashed line, the approach must be within the mid point of the criteria range. For the other three criteria, smaller is better. Therefore, the best test is the one with the smallest area and meets the minimum requirements.

Of course for any particular situation the list of requirements and constraints may be different and the definition of the acceptable threshold may vary. The idea is to make sure the selected ALT meets all of requirements and optimizes the other constraints so as to produce the most efficient and effective ALT. In general though, the approach of carefully considering these and related criteria during the selection of an ALT process permits the selection of the best ALT.

3 ALT APPROACHES

Now let's examine a few of the ALT approaches commonly considered. The five approaches considered in this paper provide a broad range and have different benefits and limitations. The following short description of each approach is not to provide adequate information to fully design the ALT plan, but to provide a common understanding of the terminology used in this paper. Furthermore, this section highlights the strengths and weaknesses of each approach.

3.1 Time Compression Approach

The time compression approach simply operates the item more often then it actually runs during normal use. The classic example is a toaster. A typically family may use the toaster at an assumed rate of twice a day during the preparation of breakfast. This would translate into an expected total number of use cycles of 365 times twice a day or 730 cycles per year. Therefore, to create a time compression ALT would require simply cycling the toaster 730 times to replicate a year's use. The testing may take 10.2 days (20 minutes per cycle, 24 hours per day) to accomplish and would not require any chambers or special equipment.

The acceleration factor equation becomes equation (1).

$$AF = \frac{\text{Use Duration}}{\text{Test Duration}} = \frac{720}{20} = 36 \qquad (1)$$

In this case with 2 cycles per day, each cycle runs for on average 720 minutes. With a test cycle of only 20 minutes, the lab can achieve an AF of 36.

Of course this approach only works for items that are not in use 24/7 or to such an extent that there is little time left for 'compression'. For example, a taxi in use 18 hours per day would not benefit significantly by running the vehicle the remaining 6 hours, providing a 1.33 acceleration factor. While this does provide some acceleration, it would take about 274 days to replicate one year of use.

One assumption to consider is that the failure mechanism is related to use. Many failure mechanisms are not accelerated by use. For example paint degradation due to UV proceeds on cars whenever they are in the sun, not whether or not the car is running (some may argue the heat generated by operating may contribute to the degradation rate). Therefore, consider the failure mechanism and if it is directly caused by use.

3.2 Build a Stress to Life Relationship Approach

A common ALT approach is to apply higher than expected stress (like temperature, voltage, etc.) to the product in such a way that the failure mechanism of interest is accelerated in it's progression toward failure. The trick is to relate the use and test stress in such a way that the results from the higher testing stress provide meaningful predictions at use conditions.

Without assuming an existing acceleration model, the ALT design should produce sufficient data to determine the acceleration model. For example, using temperature as the accelerant and using the Arrhenius rate equation as the form of the model (unknown activation energy), an approach could be to use three high temperatures. The plot of the time to failure relative to each temperature may provide a suitable relationship between temperature and life, permitting the extrapolation of expected life at normal usage temperatures.

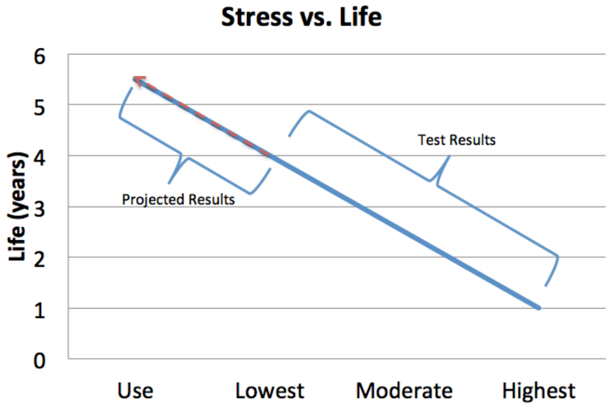

Figure 4 Test results projecting to use conditions

This approach provides the model parameters directly and does not assume the work on similar items will apply. For example, even for well-known failure mechanisms, the activation energy for the acceleration models is provided in a range. The spread of possible values reflects the many different specific design, processing, assembly and use variations that can affect durability.

Following the temperature stress and Arrhenius model [1] the acceleration factor may be stated as in equation (2).

$$AF = \exp\left[\frac{E_a}{k}\left(\frac{1}{T_u} - \frac{1}{T_t}\right)\right]$$

(2)

Where,

AF is the acceleration factor
E_a is the activation energy
k is Boltzmann's constant
T_u and T_t are the use and test temperature in Kelvin.

Two downsides of this approach are the necessity to select appropriate high stresses that do not cause unwanted failure mechanisms, and that higher stresses often require special equipment and set up. A major assumption is the higher stresses cause the failure mechanism to accelerate in a fashion that is similar to when the item is under use conditions. Failure analysis is critical to validate this assumption.

A third downside is that this approach generally takes sufficient samples at multiple stress levels to fit lifetime distributions. As a general guideline each of the three stresses should produce at least 5 failures, and an efficient design is to place twice as many samples in the middle stress relative to the highest stress, and four times as many in the lowest stress. Placing more in the stress closest to the use conditions weights the regression with the lowest applied stress and increases the chance to quickly cause at least 5 failures. This 4:2:1 ratio implies at least 30 samples and precision is significantly improved with additional samples [3].

3.3 Given Acceleration Model Approach

Peck's relationship, the Norris-Landzberg equation, and Booser's equation are all examples of common models used to describe the effects of stress on unit life for a particular failure mechanism [6]. Using one of these equations, and there are many others that have been developed, saves the time of creating the model or finding parameters through extensive experimentation. In some cases, you may have previous work that provides the model and parameters that is specific for your product.

These models are time savers, if and only if, the model is accurate, describes your particular situation in terms of construction, materials, assembly process, and usage. These models provide a framework for planning the ALT and a structure for the analysis. Many models are listed at the RiAC WARP site [13].

The models are useful when they apply, and misleading when they don't. You will get a number at the end of the analysis and it is only with the validation of the assumptions that you will know whether or not the number is representative of your product's lifetime. Several implicit assumptions include 1) the model and its creation is similar enough to the item and environment in question, 2) other elements of the item or environment do not influence the life behavior, and 3) all of the normal statistical assumptions apply.

This approach uses fewer samples and resources than the previous approach, yet does rely on more assumptions. As with the model in section 3.2, this one uses elevated stress conditions, which are 'unrealistic' with respect to use conditions. Done properly, this is often a very efficient approach. This assumes a suitable model exists.

3.4 Step Stress Approach

Step stress ALT works well in particular situations only. Specifically, only when the damage leading to failure accumulates proportionally with the application of stress, so that higher stress means more damage. Typically items are started at a modest stress and the stress is increase in steps until sufficient units have failed.

This approach assumes the Markov property that the remaining life distribution depends only on the current stress and fraction failed, and that the damage accumulation does not occur during the change of stress level. A model describing the failure mechanism's relationship to stress certainly aids in the design and analysis of the ALT.

Nelson discusses an example of step stress on cable insulation [1]. Yuan and Liu [14] presents an approach to develop an optimum step stress plan. Yet, in practice, step stress ALT is limited to those items with a known cumulative damage model, where the experimenter desires to verify the model parameters. The sample size is about the same as for the approach with a given model, yet the precision is lower due to the multiple fits at various stress levels.

3.5 Degradation Approach

A feature of some failure mechanisms is the measureable deterioration of performance. When the deterioration leads to failure in a predictable manner and it responds to higher stresses with an acceleration of the time to failure, a degradation ALT approach may be a good option.

Having an acceleration model may permit the use of a single accelerating stress, yet all the same considerations apply related to the model's ability to describe the failure mechanism. When a model is not known, using multiple stresses will produce sufficient information to create a model. As with the approach in section 3.3, this will take more samples and test resources than situations where the failure model is known. The statistical fit is more complex, thus for the same sample size there is a modest loss of precision. Yet, when the degradation is predictable this method has the distinct benefit of not requiring that the test duration lasts until items fail. Collecting sufficient data to predict the time to failure is sufficient to build the overall life model [1].

4 EXAMPLE CASE

Consider an industrial grade component within an electrical substation. The expectation is the equipment will last with little chance of failure over extended periods of time in an outdoor location. The application involves high loads of voltage, which tend to damage the insulation materials of the component. The question facing the team is:

Will the new capacitor design survive 10 years with 98% reliability?

The new design is very similar to previous designs with changes to the insulation material processing. The program team desires results as soon as possible with a decision date in 6 weeks. The life estimate precision is also important and expected to be at least within 20% or better of the 10-year objective. The last critical test plan requirement is the measurement used for the testing, which is given as time to insulation breakdown. The team decided to optimize cost, sample size, and realistic test conditions. Let's step through each of the ALT approaches in the process to select the best path forward.

4.1 Time Compression Approach

The electrical substation is expected to operate continuously, so this approach will not provide any means to accelerate the testing. While this method may have the most realistic set of conditions and adequately meet the other criteria, the inability to determine a result before the decision point eliminates this approach.

4.2 Build a Stress to Life Relationship Approach

The new design is expected to have the same fundamental failure mechanism as the previous design, but the life model parameters may be slightly different due to the changes in material process. If we assume the changes are significant enough to alter the underlying failure mechanism or the form of the life model describing the failure mechanism, then creating a test plan to create a new model is appropriate.

Using voltage at three different levels as an accelerant may permit the creation of an appropriate model. The lowest stress level will have to be selected to produce failures within the test duration permitted. Thus, this approach will extend over the full duration permitted, and precision will meet the requirements at the expense of samples size and cost.

4.3 Given Acceleration Model Approach

Assume the failure mechanism is known and described by the power law model in equation (3)

$$t_{meanlife} = kv^{-n} \tag{3}$$

where k is a constant, v is voltage and n is the power law constant [14]. This model assumes that the power law constant is known and, therefore, permits the design of a single stress test that will meet the duration and precision requirements along with minimizing the sample size and cost considerations. The constant voltage conditions, while not exactly realistic, are closer to field conditions than altering the voltage as in step stress testing.

4.4 Step Stress Approach

Assuming both the power law model as above, and that the dielectric healing effects do not occur in this product's construction, it may be possible to use a step stress ALT approach. One of the key assumptions is that the order of the stress application does not alter the accumulation of damage at following stress applications. Furthermore, this approach assumes that the transition between stresses does not cause damage or failure and does not alter the time to failure mechanism. While it is common to steadily increase stresses, that is not required.

This approach does alter the stress in stages, thus it is not as realistic as the previous approaches, yet the approach does tend to minimize test duration with the sample size. The modeling is slightly more complicated than the approach in section 4.3, but may cost slightly less, given a shorter duration than the approach in section 4.3. Of course, the precision could be improved with additional samples, duration and associated cost.

4.5 Degradation Approach

While it is possible to measure the dielectric properties directly, it is a poor surrogate to time to dielectric breakdown and lifetime distribution. Here the measurement method would not meet the requirements of directly measuring the voltage. Thus, this method is eliminated from consideration.

4.6 Approach Selection

The three approaches briefly discussed in sections 4.2, 4.3, and 4.4 will all meet the test plan requirements. They each have strengths and weaknesses that vary across the various selection criteria.

In the discussion about each viable approach, the "measure criteria" has been constant. All of the approaches directly measure the time to dielectric breakdown, yet each makes different assumptions in the ability of the approach to translate test conditions to field conditions.

The approach in section 4.2 assumes the accelerated test conditions will provide sufficient information to project time-to-failure results to normal usage conditions. The approach in section 4.3 assumes the power law model adequately describes the failure mechanism at both normal usage and accelerated conditions, permitting the translation of test results to usage conditions. Likewise, the approach in section 4.4 makes the same assumption as in the approach in section 4.3, yet also includes the assumption that the transition between stresses does not alter that time to failure results.

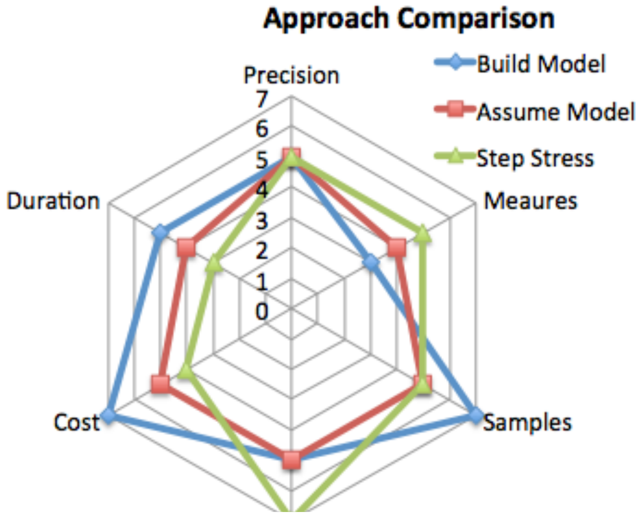

Figure 5 Results Comparison

The “Given Acceleration Model Approach” in section 4.3 is just slightly better than the “Step Stress Approach” in section 4.4. See figure 5 for a graphical comparison of the three considered models. Using a weight decision matrix or other technique may refine this decision, but given the subjective nature of a few of the criteria, it becomes important to think through each approach carefully. As in this example, the difference between the two approaches is very slight; carefully considering the risks and details of each approach will reveal the best approach.

There are often multiple ALT approaches that will serve the needs of the team. Selecting the best approach relies on both meeting the project requirements and optimizing important considerations. Using available literature, development testing, engineering judgment, and experience all contribute to the thought process and selection of the best approach.

REFERENCES

1. Nelson, Wayne. *Accelerated Testing: Statistical Models, Test Plans, and Data Analysis.* Edited by S S Wilks Samuel. Wiley Series in Probability and Mathematical Statistics. New York: John Wiley & Sons, 1990.
2. Meeker, William Q, and Luis A Escobar. *Statistical Methods for Reliability Data.* New York: Wiley, 1998.
3. Hallberg, Ö, and D S Peck. "Recent Humidity Accelerations, a Base for Testing Standards." *Quality and Reliability Engineering International, vol.* 7, no. 3, Wiley, 1991: 169-180.
4. Meeker, William Q, and Gerald J Hahn. *How to Plan An Accelerated Life Test.* Edited by American Society for Quality Control. Milwaukee: ASQC, 1985.
5. Meeker, William Q. "Optimum Accelerated Life-Tests for the Weibull and Extreme Value Distributions." *IEEE Transactions on Reliability, IEEE, 1975, vol.* R-24, no. 5 :321-332.
6. Condra, Lloyd W. *Reliability Improvement with Design of Experiments.* New York: Marcel Dekker, 2001.
7. Wasserman, Gary S. *Reliability Verification, Testing and Analysis in Engineering Design.* New York: Marcel Dekker, 2003.
8. Clech, Jean-Paul, Greg Henshall, and Jian Miremadi. “Closed-form, Strain-energy Based Acceleration Factors for Thermal cycling of Lead-free Assemblies.", SMTA International Conference, San Diego, CA. SMTA, October 8, 2009.
9. Salmela, O. "Acceleration Factors for Lead-Free Solder Materials." *IEEE Transactions on Components and Packaging Technologies,* 30, no. 4, IEEE, 2007: 700-707.
10. Baussaron, Julien, Mihaela Barreau-Guérin, Léo Gerville-Réache, and Paul Schimmerling. "Degradation Test Plan for Wiener Degradation Processes." *57th Annual Reliability and Maintainability Symposium Proceedings* IEEE, 2011.
11. White, Mark, Jin Qin, and Joseph B Bernstein. "A Study of Scaling Effects on DRAM Reliability." *57th Annual Reliability and Maintainability Symposium Proceedings* IEEE, 2011.
12. Caruso, H, and A Dasgupta. "A Fundamental Overview of Accelerated-Testing Analytic Models." *Reliability and Maintainability Symposium, 1998. Proceedings., Annual.* IEEE.
13. "WARP." http://www.theriac.org/WARP/about.html (accessed August 21, 2011).
14. Yuan, Tao, and Xi Liu. "Bayesian Planning of Optimal Step-Stress Accelerated Life Test." *57th Annual Reliability and Maintainability Symposium Proceedings* IEEE, 2011.

BIOGRAPHY

Fred Schenkelberg
Ops A La Carte, LLC
990 Richard Avenue, Suite 101
Santa Clara, CA 95050, USA

e-mail: fms@opsalacarte.com

Fred Schenkelberg is a reliability engineering and management consultant with Ops A La Carte, with areas of focus including reliability engineering management training and accelerated life testing. Previously, he co-founded and built the HP corporate reliability program, including consulting on a broad range of HP products. He is a lecturer with the University of Maryland teaching a graduate level course on reliability engineering management. He earned a Master of Science degree in statistics at Stanford University in 1996. He earned his bachelors degrees in Physics at the United State Military Academy in 1983. Fred is an active volunteer with the management committee of RAMS, currently the Chair of the American Society of Quality Reliability Division, active at the local level with the Society of Reliability Engineers and IEEE’s Reliability Society, IEEE reliability standards development teams and recently joined the US delegation as a voting member of the IEC TAG 56 - Durability. He is a Senior Member of ASQ and IEEE. He is an ASQ Certified Quality and Reliability Engineer.