2018 IEEE 59th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON)

Accelerated Life Testing in Reliability Evaluation of Power Electronics Assemblies

M.sc.ing. Oskars Bormanis
Institute of IEEE
Riga Technical University
Riga, Latvia

Dr.habil.sc.ing. Leonīds Ribickis
Institute of IEEE
Riga Technical University
Riga, Latvia

Abstract — **Role of reliability tests in assessment of service life in power electronics product life cycle is investigated. Paper reviews basic principles of highly accelerated life test and multiple environment over stress tests. Failure types revealed during the accelerated life tests are discussed as well as practical examples of the tests from industry.**

Keywords – **Reliability engineering, Electronic equipment manufacture, Electronic equipment testing**

I. INTRODUCTION

In power electronics field there is a constant demand for new products with improved performance [1]. Development of state of the art technologies, such as artificial intelligence, crypto-currency mining, includes engineering of the hardware and introduction of more new solutions and products. Another stimulus to that are the developing countries, which provide new business opportunities and emerging markets, attractive for budget-class products with specific parameters (frequencies, safety standards). All of these factors contribute to wide diversity of electronics products and impacting field of power electronics as well. Therefore involved companies are decreasing the time available for product development process to launch more, in less time.

In addition to previously mentioned factors, studies reveal that advantage in product introduction time can result in profit increase [2]. Manufacturers are often decreasing the duration of product testing, to meet the expected launch window requirements. To avoid loss of product reliability after this accelerated development process, various testing methods [3] are practiced in industry during the reliability tests of product, for example, a 150W DC/DC converter for telecommunications industry, design and development phase.

For product development team reliability testing provides approximate reliability and expected service life data. Physics of failure for specific or similar type of product should be well known and understood, to launch more robust products. Feedback from field failures is a prevention measure. Life tests may be reassigned for each stage of development or manufacturing, to confirm design changes, test for new failure modes and evaluate durability between mass production batches. In the previous example, field failure data would reveal that electrolytic capacitors and fans are some of the critical areas.

Accelerated life tests in reliability plan fit the best in the design verification phase, along with durability and other reliability tests, however, there are reasons to sample test units from various product development stages. For example, prototypes should be tested as early as possible, preproduction units should be tested after corrections, early production units should be tested after design transfer to mass production, and, optionally, samples from currently ongoing production can be retested to confirm that the quality of current production batch is good [9].

Life testing provides useful information about product reliability to both, supplier and customer. Availability of this information provides more confidence about hardware quality and allows install of the previously mentioned converter, developed for telecommunications industry, in systems which require fault tolerant operation with minimum downtime, for example, Tier 4 data centers, or automotive industry.

In the unlikely situation of no time pressure, life data obtained from sampling of normally operated units may help to make general conclusions and predictions about all population of the product. To obtain results in more realistic period of time, units are tested in conditions of accelerated stress [4]. Such accelerated reliability and service life assessment tests can be categorized as both - qualitative and quantitative research.

II. METHODS OF ACCELERATED LIFE TESTING

Qualitative research gains understanding of reasons and causes, providing insights into problem, developing ideas or thesis for following quantitative research. More realistic view on field problems is one of the qualitative research advantages, although failure modes discovered in this research might be misleading due to various effects, mentioned later in the paper.

In qualitative accelerated life testing (ALT) failure modes are identified without prediction of product life under normal conditions. Highly accelerated life test (HALT), highly accelerated stress screening (HASS), other destructive tests belong to qualitative accelerated tests, since they reveal probable failure modes and provide feedback for product engineers for design improvement, and are less useful for predicting service life duration. One of the qualitative testing methods is HALT, which provoke the potential defect, allowing to identify the weak points and to develop various reliability enhancements, based on the results. It can be called provocation testing, since reliability tests focus on accelerated degradation and development of physical degradation model.

During the HALT, environmental stresses are applied incrementally until they are beyond the expected levels of operational use. Environmental loads which will be applied to product during normal use include electromagnetic (electromagnetic sensitivity, electrostatic discharge), chemical (corrosive, cleaners, acid), dust, radiation (ultraviolet, infrared) [6]. HALT is good for identifying design weaknesses, and it is assumed that failure mechanisms observed during this testing will repeat in the field, with use level stress and after longer time [7]. Unfortunately, results often lack relation with field failures [8]. HALT can drive unrealistic failure modes, since level of stress applied during these tests increase failure rate, since it is outside of specification limits. Highly accelerated life tests are also called Elephant tests or in other names, because of their nature to test small sample size at extreme stress until destruction. If test sample is a power converter, it is often hard to evaluate the results from HALT testing due to previously mentioned reasons as well. To decrease time to market for the converter, related operational parameter limits can be questioned in case of a failed HALT test, for example, slightly decreasing rated operating temperature range.

Failure observed during test and failures reported from field failures can differ because of the crossover effect, when the same failure mode is exposed by different stresses. During HALT, vibration could be concluded as the major factor cause for failure, while in the field stress level, temperature or humidity contributes to failures more than vibration. It is common, that focusing on stress which caused product failure during HALT, leads to missed opportunity to solve the stress which cause the same failure mode during field failure [9]. For example a solder joint of an outdoor product DR-QFN chip can fail by mechanical stress and thermal cycling. Effort to limit mechanical stress will only solve part of the issue, outdoor products experience many thermal cycles, and the failure mode will return.

To avoid this, team should focus on failure mode, instead of stress which causes the failure. For example, if product is damaged during transportation, likely it is not an option to avoid this stress, and packaging redesign is required with additional cushioning. Also, more than one failure mode can be affected by the same stress.

Simplified working principle of HALT is to detect the weak link in product design and improve it, then look for the next common failure mode, improve that as well. Theoretically tests can continue until there are no weak links left to cause field failures. HALT includes combined temperature cycling, vibration, power cycling, and other stresses, related to specific product and its application. This test can be performed in special thermal chambers, with 6 degrees of freedom vibration, and one test can last for one or two days. Typical HALT profile is shown in Fig. 1 For power converters often heatsink screw assembly and heatsink solder points become a risk area.

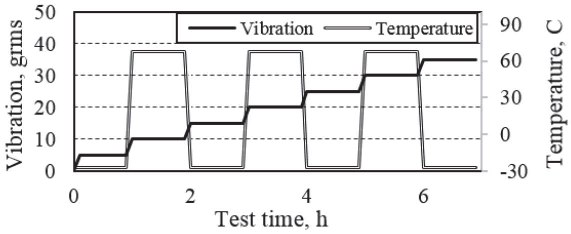

Fig. 1. Vibration and temperature stress application profiles of highly accelerated stress test for power electronics assemblies [19]

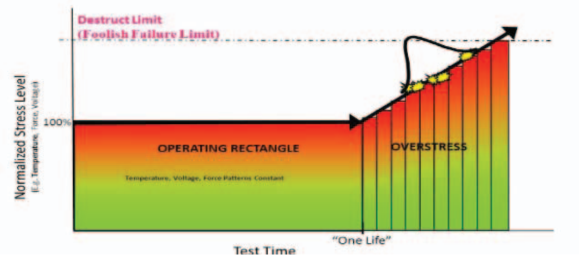

Fig. 2. The distribution of failures during multiple environment over stress test reveal maximal practical overstress, reaching destruct limit [28]

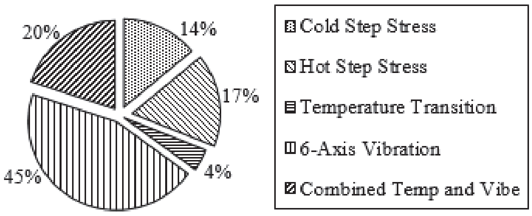

Fig. 3. Defects discovered by various accelerated stress test types reveal importance of vibration tests [16] in testing of power electronics assemblies

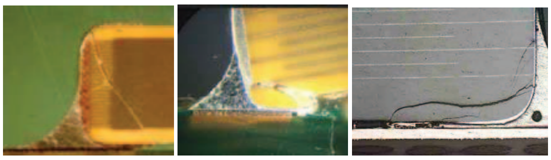

Fig. 4. Cracks of multi-layer ceramic capacitors, due to vibration/mechanical stress, flex of printed circuit board assembly etc. [17],[6],[18]

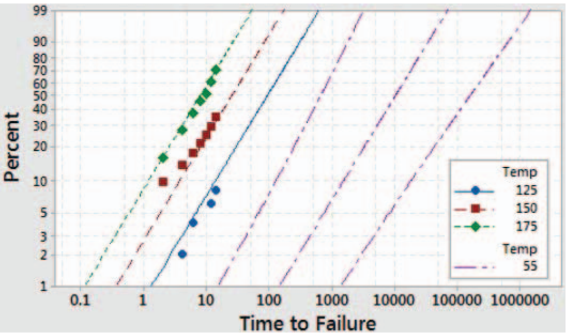

Fig. 5. Probability plot of samples tested in various temperatures according to Arrhenius equation [29]

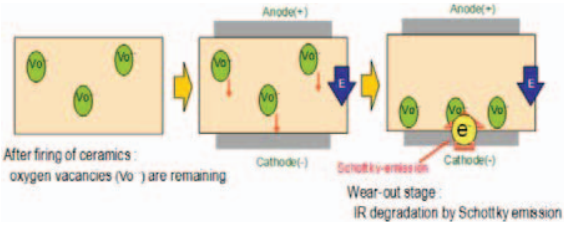

Fig. 6. Movement of atomic scale electrical defects in ceramic material of MLCC, from anode to the cathode [20]

Multiple environment over stress test (MEOST) applies multiple stresses to the product, evaluating it within the destruct limits, determined previously during HALT. Challenge in MEOST is to discover relevant stresses, therefore primary objective is to reveal failure modes. Within this testing method weak points of product design and manufacturing are exposed, during application of combined extreme stresses - including temperature, vibration, humidity and electrical. During MEOST, durability is tested for each individual stress and for the combined interaction of all stresses, as well [9].

Development of effective MEOST requires a significant effort [8]. The design of this test predicts that the last step of overstress is critical for product durability, and every unit should fail before the last overstress increase step, which is at the destruct limit, as shown in Figure 2. Compared to single environment stress, MEOST provides more interaction of combined environments [10].

Multiple environment over stress tests are primarily qualitative, similar to HALT. This testing method is useful, for example, for products where failure modes and times are uncertain. MEOST has the benefit of small sample size, which is reasonable, especially, when the tested parts are expensive or with very limited availability (such as prototypes). To put short, HALT is operating at destruct limits, whereas MEOST reveals maximal practical overstress [11] as shown in Figure 2, helping to find actual stress limits and parameters for the previously mentioned DC/DC converter.

Destruct limit is also called foolish failure limit, since products in the field will not be subjected to such stress levels reaching destruct limit stress values during stress tests will damage the few and valuable samples, and provide very little information of failures at operational range of the product, since there is a very high certainty that samples will fail.

The destruct limit can be unrelated to failure mode in the field, for example, melting of plastic case at 190ºC, or PCB cracking at 10 GRMS random vibration [10]. GRMS metric is a root mean square value of continuously varying pseudorandom broad spectrum vibration signal. It can be addressed both, at source and measured signal [12]. To improve accuracy of the results, destruct limits should be determined by separate tests for each environment.

During MEOST, not each environment stress is increased to destruct level, due to risk of revealing failure modes which does not relate to actual field failures and application. To plot failure data on Weibull plot (stress, time), overstress is normalized and steps are equal increments of both, stress and time [10].

Quantitative research qualifies the problem by generating numerical data, statistics [5]. This type of research defines variables and generalize results from larger samples also formulating facts and uncovering research patterns.

Purpose of quantitative ALT is to predict the product service life at normal use conditions. Performing quantitative research of accelerated life tests allows to extrapolate results and obtain expected life data in shorter time, since during the test products fail by their expected failure mechanisms, which are being provoked [13]. During quantitative ALT usage rate is accelerated to decrease time to failure. Dynamic or static overstress can be applied as well, not reaching destruct limit. By extrapolation of the results, estimated probability density function is constructed, predicting product life in normal use conditions. This function should represent age and reliability relationship of the tested electronics assembly.

When performing quantitative accelerated life test by application of overstress, one or more environmental stress types are applied to samples at carefully increased levels. Time to failure is recorded during these tests for each sample. If normal product operation conditions are at 20°C, accelerated life test may include test points at 30°C, 40°C, 50°C. In such example, stress type is the temperature, stress levels are each of the test temperatures, and normal use stress level is 20°C [13].

Overstress accelerated life tests use environmental factors such as temperature, humidity, vibration, to stimulate physical degradation of materials, leading to earlier failure [14]. Based on experience with similar products and similar design engineering team can predict which stress types are likely to result in field failure and therefore need to be accelerated during test. Thermal cycling precipitated defects include poorly matched expansion coefficients [15], plated through-hole defects, PCB defects. Some of the defects precipitated by vibration include component mounting defects, solder joint defects, stacked resonances, wires not protected from sharp corners. Data gathered by [16] reveal that vibration stress can provide useful information and help to discover various failure modes for many products, as shown in Figure 3.

Acceleration of usage rate is practiced for testing of products that do not operate continuously under normal conditions. During tests of this acceleration method samples are tested at increased usage rate simulating longer periods of operation under normal conditions [13]. Some of the usage rate acceleration examples from industry include service life testing of keyboards, where durability of press buttons is tested by mechanical interaction, connector manufacturing with repetitive plug tests, or automotive industry, where usage rate of electric windows control and drive system is increased and these systems are tested for durability.

To extrapolate previously mentioned probability distribution function, life-stress relationship model needs to be confirmed. This model can be any measure expressed as a function of stress. For example, in Weibull distribution, the life-stress model is assigned to the scale parameter (η) which is considered to be stress dependent. Since extrapolation of accelerated life test data provides a link between test samples and expected field life of product, high accuracy of this extrapolation is significant.

Life-stress relationship model is chosen to fit the type of analyzed data. Available models are Arrhenius, Eyring and inverse power law, processing data with one stress type, for example, temperature [13]. Mathematical models used to analyze various pairs of stress types include combination models of temperature & non-thermal (combined Arrhenius and inverse power law), temperature & humidity (variation of Eyring relationship). Other mathematical models, such as proportional hazard and general log-linear models include up to eight types of stress. If the applied stress varies in time either at overstress or at use stress level, cumulative damage model is used to analyze data of such test [21].

III. FAILURE MECHANISMS REVEALED BY ALT

Reliability transfer from single electronic device to whole assembly is challenging in complex systems since PCBA is composed of many parts with various package configurations, each having different response to stress. For example, potential reliability of PBGA192 (popular in networking hardware) assembly is evaluated in [22], while through-hole assembly parts of the DC/DC converter circuit are more robust. Partial solution is to test and resolve reliability problems focusing on application specific physical models, such as logic integrated circuit, power module and insulation [23].

Even if some parts have already been modeled or tested separately, reliability tests are preferred to obtain more detailed view of failure modes introduced by the assembly process and system design. There are multiple wear-out mechanisms for electronic assemblies, including physical stress of the electronic device being dropped, the thermal stress of temperature differences and the electrical stress applied when the device is powered up. When reliability of complete assembly is being presented as mathematical model of combined reliability data from individual parts, assessment of the previously mentioned risks is missing.

Some of the non-destructive equipment dedicated to approval and investigation of various solder and mechanical defects revealed in accelerated testing include x-ray and acoustic microscopy [22], [25]. This equipment can help to identify MLCC failure modes as well.

Some of the most common failure mechanisms of multilayer ceramic capacitors (widely used in various circuits) include flex cracks, firing cracks and handling cracks [25] as shown in Figure 4. These failures often occur from improper handling (placing in test jig, attachment of covers, heatsinks, mounting connectors) or assembly of the failed unit and are revealed during accelerated life tests. These can be caused by both, manufacturing and poor design defects.

Increased temperature stress test will likely reveal such defects earlier compared to normal field failure. This helps to reveal the weak area of power converters – dry out and shorting of electrolytic capacitors. At the temperature of worst-case scenario devices will fail much earlier than at the design temperature. This is supported by the popular generalization (criticized at [26]) of Arrhenius equation, that failure rate doubles for every increase of 10ºC in temperature. It suggests that the product would fail about eight times earlier, compared results in chamber with temperature of 35°C and one with 65°C. This relationship is also supported by Fig. 5, where Arrhenius relationship with accelerated temperature variable is plotted according to Weibull distribution and maximum likelihood estimation method.

Various defects will initiate the failure to occur earlier. One of multilayer ceramic capacitor (MLCC) manufacturing defects which reveal in long term is oxygen defect. After firing of ceramics, there are remaining oxygen vacancies encapsulated in the crystal structure of solid material of electro ceramics, as shown in Fig. 6. At high temperature environment and when external voltage is applied, over time, vacancies are thought to gradually accumulate in the vicinity of the cathode, shifting from anode to the cathode, leading to breakdown of the ceramics. Therefore service life of multilayer ceramic capacitor is determined by this accumulation of oxygen defects at the cathode [20].

Arrhenius equation is the most common acceleration model which supports the increased voltage and temperature during tests, to estimate service life in actual conditions [20] but it is also possible to obtain estimate values with the following empirical equation:

$$A_L = \frac{L_N}{L_A} = \left(\frac{V_A}{V_N}\right)^n * 2\frac{(T_A - T_N)}{\theta} \tag{1}$$

Where A_L, acceleration factor, L_N- lifetime in standard condition, L_A-lifetime in accelerated condition, V_N- voltage in standard condition, V_A- voltage in accelerated condition, n- voltage acceleration constant, T_N-temperature in standard condition, T_A- temperature in accelerated condition, θ- temperature acceleration constant.

According to (1) and the failure mechanism example of MLCC oxygen defects, an endurance test lasting 41 days at increased temperature and voltage, is estimated to be equivalent to 41 years with reduced voltage. Both – temperature and voltage acceleration constants vary from the ceramic material [20]. Although the test period of ALT is considerably shorter than time until life failure, it is still hard to schedule a reliability test in chamber lasting more than a month, and the accuracy of extrapolation must be considered.

IV. INTERPRETATION OF RESULTS

Estimated maximum failure quantity after the accelerated stress tests is estimated with confidence level of 60% to 95%. Due to sample size differences, it is difficult to compare probability distributions of accelerated tests to field data. An uncertainty is added due the fact that failure mechanisms in studies modeled with Arrhenius, Coffin-Manson equations are assumed to match with the real life, and it is not always perfect match with failure mechanisms from field.

Other factors contributing to difficulty of predicting field life failures and comparison of accelerated stress data, are the ones which have an effect on product during storage, before install and first launch. Such as humidity can penetrate moisture sensitive semiconductor devices from manufacturing date. This could lead to abnormally high failure rate during beginning of service life. Such circumstances are different from typical early failures and are excluded from modeling, adding more uncertainty [27].

Difficulties are expected when trying to assume quantitative correlation from qualitative data. Physics of failure by the reliability team are investigated with qualitative accelerated life tests, rejects from the field are investigated qualitatively as well. Quantitative comparison of failure data and maximum failure quantity estimated after accelerated stress tests is supported by field modeling which is performed on the returns. Case study to this method is presented at [27].

Some of the practical examples which have been verified at previous studies as comparison of accelerated tests to field data, include battery life expectation at various stress levels, as well as fatigue of solder joints, and others. Accelerated life test data can also prove useful when comparing multiple designs and materials, such as GaN to Si FET devices at various operating modes.

V. CONCLUSIONS

This paper continues discussion about reliable assembly of power electronics solutions. Several failure modes prevented and discovered by accelerated life testing, both HALT and MEOST are investigated in this paper with power electronics use-case examples, proving that these test methods have practical use and should be integrated development process of electronics products. In this research it is concluded that the accelerated life tests will not increase the total product confirmation testing time significantly, but will enable install of product in fault tolerant systems, providing failure data in reduced time for the engineering team. HALT and MOEST are destructive tests, since some of the very limited availability prototypes become unusable after the test, but at this cost the tests will reveal all of the three stress limit values (destruct, design and specification limits. It must also be considered, that some uncertainty belongs with the estimated data, since modeled failure mechanisms rarely align perfectly with actual field data, for example, due to parts being slightly damaged during soldering by the previously absorbed humidity.

REFERENCES

[1] G. W.T.Loo, “The next big thing in consumer electronics is already here” [Online]. Available: http://blog.euromonitor.com/2014/07 [Accessed: 14-Nov-2017].

[2] M. Silverman, “Summary of HALT and HASS results at an accelerated reliability test center” 1998. Proceedings. Annual Reliability and Maintainability Symposium, Anaheim, USA, 19-22th January, 1998.

[3] Keithley Instruments, Inc. “Fundamentals of HALT/HASS testing”, 2000., pp. 1-8.

[4] AMSAA, “Design for Reliability Handbook”, 2013

[5] E.R. Babbie, “The Practice of Social Research”, 12th ed., Belmont, USA, 2010

[6] J.Maxwell, “Capacitor cracks: still with us after all these years” [Online]. Available: http://www.johansondielectrics.com/ [Accessed: 15-Nov-2017]

[7] Qualmark, “What is HALT HASS testing?” [Online]. Available: https://www.qualmark.com/whatishalthass [Accessed:14-Nov-2017].

[8] Corinne Bergès and Sting Chung “Innovative methodology in automotive semiconductors for statistical correlation study between reliability accelerated stress tests and real field applications” 2017 IEEE 24th International Symposium on the Physical and Failure Analysis of Integrated Circuits (IPFA), Chengdu, China, 4-7th July, 2017

[9] N.Meadowsong, E.L.Kyser, Cisco Systems “The benefits and costs of overstress testing”, [Online]. Available: https://www.evaluationengineering.com/ [Accessed: 12-Nov-2017]

[10] TDK Corporation, “Flex crack countermeasures in MLCC (Multilayer Ceramic Chip Capacitors)” [Online]. Available: https://product.tdk.com/info/en/products/capacitor/index.html [Accessed: 12-Nov-2017]

[11] K.R.Bhote, A.K.Bhote, “World Class Quality: Using Design of Experiments to Make it Happen”, AMACOM, New York, USA, 2000.

[12] N.Doertenbach, “The calculation of Grms” [Online]. Available: https://www.electronicproducts.com [Accessed: 14-Nov-2017]

[13] HBM Prenscia Inc., “Quantitative accelerated life testing data analysis” [Online]. Available: http://www.weibull.com/basics/accelerated.htm [Accessed: 11-Nov-2017]

[14] S.Jayatilleka, G.Okogbaa “Accelerated Life Testing (ALT)”, 2014 Workshop on Accelerated Stress Testing and Reliability, Minneapolis, 2014

[15] C.DeMilo, C.Bergad, R.Forni, T.Brukilacchio “Thermally induced stresses resulting from coefficient of thermal expansion differentials between an LED sub-mount material and various mounting substrates”

[16] Chet Haibel, ASQ Reliability Division, “Overview of Highly Accelerated Life Test”, 2012

[17] ZVEI, Handbook of Robustness Validation, 2013

[18] [18] Fujitsu Quality Laboratory Ltd., “Failure analysis service” [Online]. Available: http://www.fujitsu.com/jp/group/fql/en/services/ [Accessed: 15-Nov-2017]

[19] J. E. Bullema, TNO Science and Industry “Accelerated testing: ALT, HALT and MEOST”, 2017

[20] Murata Manufacturing Co., Ltd., “Reliability of electronic components (Chapter 2: How do you estimate the lifetime of components?)” [Online]. Available: https://www.murata.com/en-us/products/emiconfun/ [Accessed: 11-Nov-2017]

[21] A.Mettas, P.Vassiliou “Modeling and analysis of time-dependent stress accelerated life data”, 2002 PROCEEDINGS Annual RELIABILITY and MAINTAINABILITY Sym-posium, Seattle, USA, January 28th-31st, 2002

[22] Y.Danto, J.Y.Deletage, F.Verdier, H.Fremont “Evaluation of Reliability Assessment in PCB Assemblies”

[23] L.Wenting, L.Jiang, X.Zongyou, Q.Guangping, Z.Hu, “Step-stress accelerated life testing to predict service life for space vehicle electrical system” 2016 IEEE Chinese Guidance, Navigation and Control Conference (CGNCC), Nanjing, China, 12-14th August, 2016,

[24] Cascade Engineering Services, Inc. “Reliability and failure analysis” [Online]. Available: http://www.cascade-eng.com/ [Accessed: 13-Nov-2017]

[25] CALCE Electronic Products and Systems Center, “Design and process guidelines for use of ceramic chip capacitors” http://www.ieca-inc.com/technicalexpertisecapabilitiesservices.html

[26] Patrick O’Connor, “Arrhenius and Electronics Reliability”, Quality and Reliability Engineering International, Vol. 5, N. 255, 1989

[27] G.K. Hobbs, “Accelerated Reliability Engineering: HALT & HASS”, Hobbs Engineering Corporation, Denver, 2005

[28] J.Kreucher, Delphi Powertrain “Multiple Environment Over Stress Testing (MEOST) A Primer with examples from an automotive component supplier” Michigan, USA, 26th October, 2011

[29] Minitab Inc., “Example for accelerated life testing” [Online]. Available: https://support.minitab.com [Accessed: 14-Nov-2017]

This is a post-print of a paper published in Proceedings of the 2018 IEEE 59th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON 2018)
https://doi.org/10.1109/RTUCON.2018.8659911 and is subject to IEEE copyright.
ISBN 978-1-5386-6904-4. e-ISBN 978-1-5386-6903-7.