NASA Electronic Parts and Packaging (NEPP) Program, Discussion of Highly Accelerated Life Testing (HALT) of Capacitors

Presentation to the Japanese Aerospace Exploration Agency (JAXA)

February 2, 2017

Kenneth A. LaBel ken.label@nasa.gov 301-286-9936

Michael J. Sampson michael.j.sampson@nasa.gov 301-614-6233

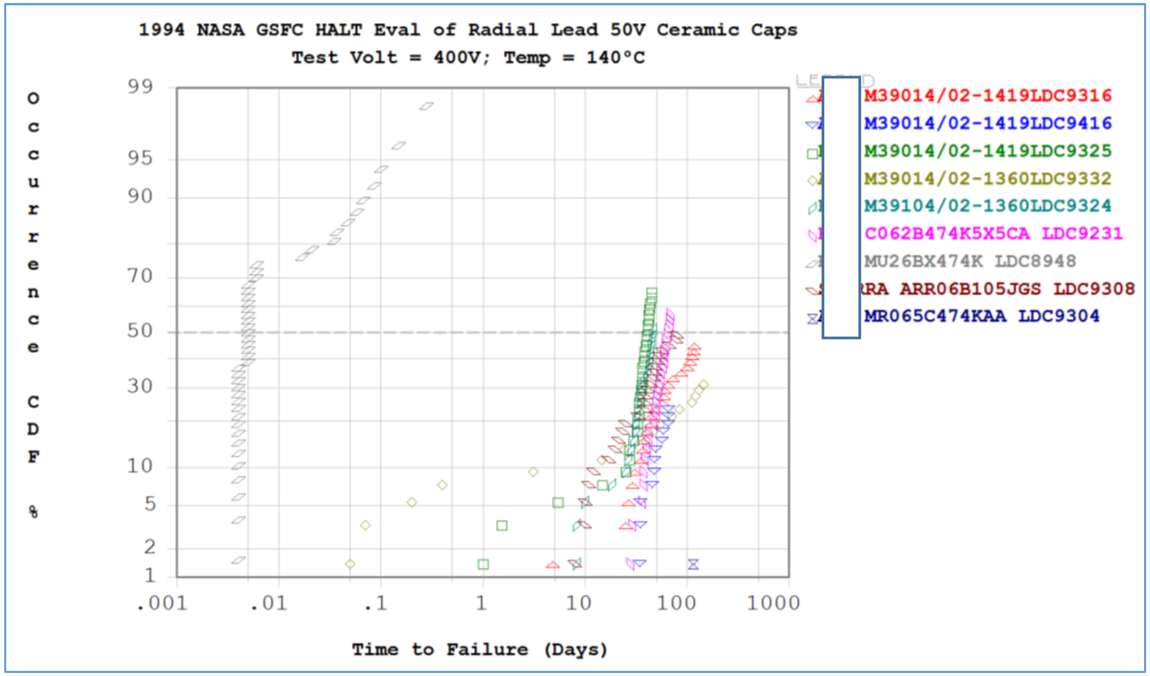
Co- Managers, NEPP Program

NASA/GSFC

http://nepp.nasa.gov

1994 NASA GSFC HALT Evaluation of Radial Leaded, 50V Ceramic Capacitors

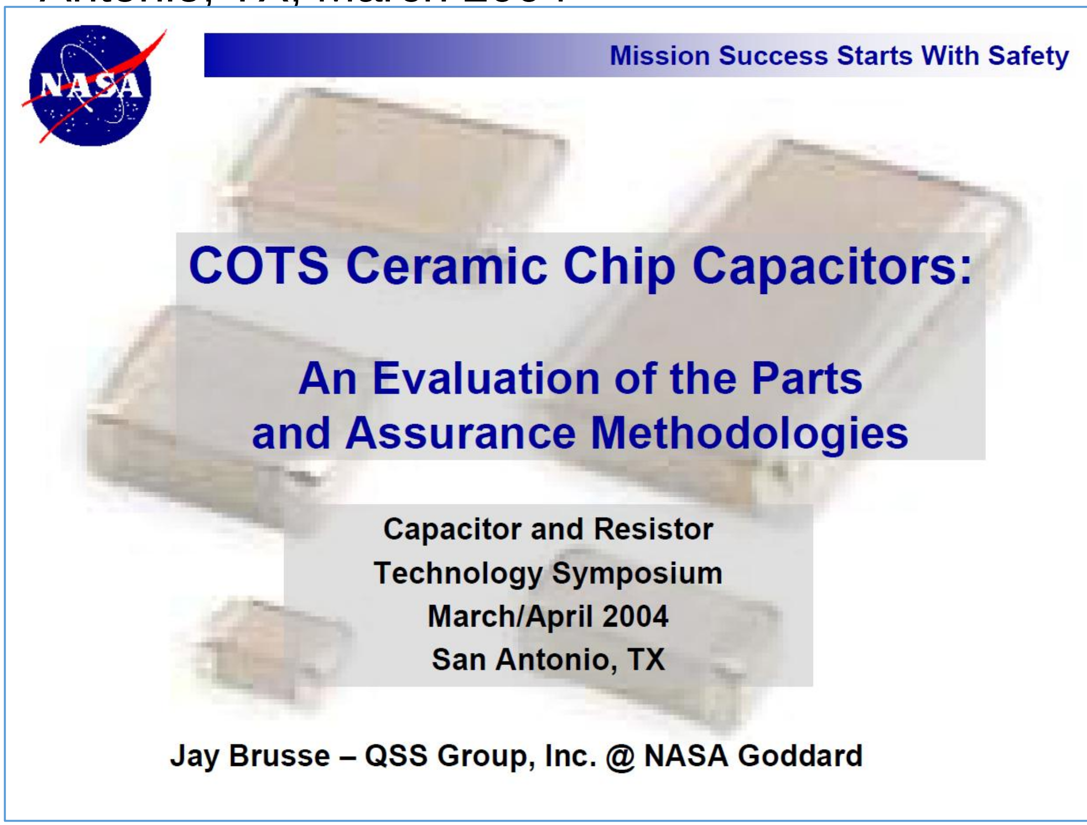
- 8 lots of radial leaded, molded case ceramic capacitors were evaluated using HALT
  - Ratings
    - 3 lots of 1uF, 50V
    - 5 lots of 0.47uF, 50V
  - Sample Size = 50 capacitors per lot
  - MIL and commercial grade



- HALT conditions
  - V = 400V
  - T = 140°C
  - Test until catastrophic short failure (fuse blow)
- 1 commercial lot failed instantly
- 2 MIL lots show 5% to 10% “early failures”

Presentation by Michael Sampson to the Japanese Aerospace Exploration Agency (JAXA), at Goddard Space Flight Center (GSFC), Greenbelt, MD, and WebExed to Langley Research Center (LaRC), Hampton, VA, February 2, 2017.

2004 – NASA GSFC, Navy Crane, Aerospace Corp
"COTS Ceramic Chip Capacitors: An Evaluation of the Parts and Assurance Methodologies", Capacitor and Resistor Technology Symposium (CARTS), San Antonio, TX, March 2004



Capacitor and Resistor Technology Symposium (CARTS) 2004 – San Antonio, TX

COTS Ceramic Chip Capacitors: An Evaluation of the Parts and Assurance Methodologies

Jay A. Brusse
QSS Group, Incorporated
NASA Goddard Space Flight Center
Greenbelt, MD 20771
Phone: 301-286-2019
Fax: 301-286-9778
Jay.A.Brusse.1@gsfc.nasa.gov

Michael J. Sampson
NASA Goddard Space Flight Center
Greenbelt, MD 20771
Phone: 301-286-3335
Fax: 301-286-1667
Michael.J.Sampson@nasa.gov

Abstract

Commercial-Off-The-Shelf (COTS) multilayer ceramic chip capacitors (MLCCs) are continually evolving to reduce physical size and increase volumetric efficiency. Designers of high reliability aerospace and military systems are attracted to these attributes of COTS MLCCs and would like to take advantage of them while maintaining the high standards for long-term reliable operation they are accustomed to when selecting military qualified established reliability (MIL-ER) MLCCs (e.g., MIL-PRF-55681). However, MIL-ER MLCCs are not available in the full range of small chip sizes with high capacitance as found in today's COTS MLCCs.

The objectives for this evaluation were to assess the long-term performance of small case size COTS MLCCs and to identify effective, lower-cost product assurance methodologies. Fifteen (15) lots of COTS X7R dielectric MLCCs from four (4) different manufacturers and two (2) MIL-ER BX dielectric MLCCs from two (2) of the same manufacturers were evaluated. Both 0805 and 0402 chip sizes were included. Several voltage ratings were tested ranging from a high of 50 volts to a low of 6.3 volts. The evaluation consisted of a comprehensive screening and qualification test program based upon MIL-PRF-55681 (i.e., voltage conditioning, thermal shock, moisture resistance, 2000-hour life test, etc.). In addition, several lot characterization tests were performed including Destructive Physical Analysis (DPA), Highly Accelerated Life Test (HALT) and Dielectric Voltage Breakdown Strength. The data analysis included a comparison of the 2000-hour life test results (used as a metric for long-term performance) relative to the screening and characterization test results.

Results of this analysis indicate that the long-term life performance of COTS MLCCs is variable -- some lots perform well, some lots perform poorly. DPA and HALT were found to be promising lot characterization tests to identify substandard COTS MLCC lots prior to conducting more expensive screening and qualification tests. The results indicate that lot-specific screening and qualification are still recommended for high reliability applications. One significant and concerning observation is that MIL-type voltage conditioning (100 hours at twice rated voltage, 125°C) was not an effective screen in removing infant mortality parts for the particular lots of COTS MLCCs evaluated.

Introduction

Multilayer ceramic chip capacitors (MLCCs) are found in essentially every class of electronic product application, including consumer, industrial, telecommunication and automotive. Historically, designers of high reliability aerospace and military electronic systems have selected military established reliability (MIL-ER) MLCCs from MIL-PRF-55681 or MIL-PRF-123 because of their stable construction, rigorous performance test requirements and quantified reliability. As in other industries, hi-rel MIL/Aerospace designers are striving to reduce the size, weight and cost of the electronic assemblies with little or no sacrifice to the long-term performance of the electronic components.

Since their introduction, Commercial-Off-The-Shelf (COTS) MLCCs have continually evolved to reduce physical size and increase volumetric efficiency (capacitance per volume). Today, COTS MLCCs are readily available as small as 0402 (i.e., 40 mils by 20 mils) and 0201 chip sizes with 01005 (10 mils by 5 mils) chips now finding their way to market [1]. To accommodate low voltage applications, COTS MLCCs are also available with voltage ratings as low as 6.3 volts.

One way COTS MLCC suppliers have increased volumetric efficiency is by reducing the dielectric thickness, which in turn provides space for additional dielectric layers/electrodes. With the increase in electrode count, the cost of the electrode materials becomes a more significant factor in the overall cost of the MLCCs. To remain cost competitive, many COTS suppliers have switched to lower cost Base Metal

2004 – NASA GSFC, Navy Crane, Aerospace Corp "COTS Ceramic Chip Capacitors: An Evaluation of the Parts and Assurance Methodologies", Capacitor and Resistor Technology Symposium (CARTS), San Antonio, TX, March 2004

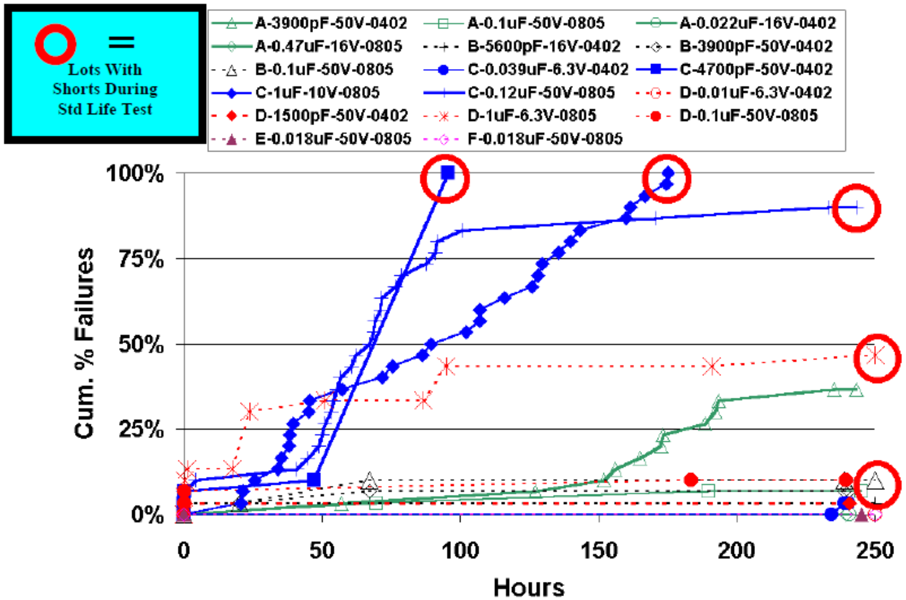


Figure 2: Highly Accelerated Life Test (HALT) Results

Table 6: Highly Accelerated Life Test (HALT) vs. Life Test Results

	Mfr	Lot #	Cap (uF)	Rated Voltage (V)	Size	Highly Accelerated Life Test (HALT)	*Life Test Disposition*
COTS	A	1	0.0039	50	0402	Moderate	*Borderline*
		2	0.1000	50	0805	Good	*Pass*
		3	0.0220	16	0402	Good	*Borderline*
		4	0.4700	16	0805	Good	*Pass*
	B	5	0.0056	16	0402	Good	*Pass*
		6	0.0039	50	0402	Good	*Borderline*
		7	0.1000	50	0805	Good	*Fail*
	C	8	0.0390	6.3	0402	Good	*Pass*
		9	0.0047	50	0402	Poor	*Fail*
		10	1.0000	10	0805	Poor	*Fail*
		11	0.1200	50	0805	Poor	*Fail*
	D	12	0.0100	6.3	0402	Good	*Pass*
		13	0.0015	50	0402	Good	*Pass*
		14	1.0000	6.3	0805	Poor	*Fail*
		15	0.1000	50	0805	Good	*Pass*
MIL	E	16	0.0180	50	0805	Good	*Pass*
	F	17	0.0180	50	0805	Good	*Pass*

2004 – NASA GSFC, Navy Crane, Aerospace Corp "COTS Ceramic Chip Capacitors: An Evaluation of the Parts and Assurance Methodologies", Capacitor and Resistor Technology Symposium (CARTS), San Antonio, TX, March 2004

NASA EEE Parts Program

Highly Accelerated Life Test (HALT) - Recommendations

- **Use HALT as a "Pre-Qualification" Discriminator of "Good" vs. "Poor" Quality Lots**
  - Provides Relatively Quick / Inexpensive Way to Weed Out "Poor Lots" BEFORE Conducting More Time Consuming and Expensive Screen / Qual Test Protocols
- **HALT Methodology Needs More Evaluation to Establish Quantitative Pass/Fail Criteria**
  - Appropriate Test Conditions (Voltage, Temperature, Duration)
  - Acceleration Factors
  - Activation Energies

March/April 2004 COTS Ceramic Chip Capacitors Evaluation 18

2015 – Ceramic Capacitors

Insulation Resistance Degradation in Ni-$BaTiO_3$ Multilayer Ceramic Capacitors

Donhang (David) Liu

ASRC Federal Space and Defense

Work performed for NASA Goddard Space Flight Center

Insulation resistance (IR) degradation in Ni-$BaTiO_3$ multilayer ceramic capacitors has been characterized by the measurement of both time to failure and direct-current (DC) leakage current as a function of stress time under highly accelerated life test conditions. The measured leakage current-time dependence data fit well to an exponential form, and a characteristic growth time τ_{SD} can be determined. A greater value of τ_{SD} represents a slower IR degradation process. Oxygen vacancy migration and localization at the grain boundary region results in the reduction of the Schottky barrier height and has been found to be the main reason for IR degradation in Ni-$BaTiO_3$ capacitors. The reduction of barrier height as a function of time follows an exponential relation of $\phi(t) = \phi(0)e^{-2Kt}$, where the degradation rate constant $K = K_0 e^{-\frac{E_k}{kT}}$ is inversely proportional to the mean time to failure (MTTF) and can be determined using an Arrhenius plot. For oxygen vacancy electromigration, a lower barrier height $\phi(0)$ will favor a slow IR degradation process, but a lower $\phi(0)$ will also promote electronic carrier conduction across the barrier and decrease the insulation resistance. As a result, a moderate barrier height $\phi(0)$ (and therefore a moderate IR value) with a longer MTTF (smaller degradation rate constant K) will result in a minimized IR degradation process and the most improved reliability in Ni-$BaTiO_3$ multilayer ceramic capacitors. **Dielectric degradation; ceramic capacitors; reliability; insulation resistance; barium titanate.**

I. INTRODUCTION

Insulation resistance (IR) degradation related to oxygen vacancy migration has been considered to be the primary cause of reliability degradation of multilayer ceramic capacitors (MLCCs) with base-metal electrodes (BMEs). The behavior is characterized by a slow increase in the leakage current under an applied direct-current (DC) field stress. In order to reveal IR degradation in a timely manner, MLCCs are often degraded under highly accelerated life test (HALT) conditions with different temperatures and applied voltages. Previous studies have shown that there are three possible factors related to the IR degradation of $BaTiO_3$-based BME MLCCs: the dielectric layer, the $BaTiO_3$ grain boundaries, and the Ni-$BaTiO_3$ internal electrode interfaces.[1-4]

Deliverable to NASA Electronic Parts and Packaging (NEPP) Program to be published on nepp.nasa.gov, paper published in the IEEE Transactions on Components, Packaging and Manufacturing Technology, Vol. 5, No. 1, January 2015.

The traditional HALT measures only the time-to-failure (TTF) data of each capacitor at a given stress condition and then uses a statistical model to determine the mean-time-to-failure (MTTF) data at this stress condition.[19-22] This approach is based on a single failure mode assumption and is adequate for most ceramic capacitors with precious-metal electrodes (PMEs). However, as has been previously shown, [26-29] many BME capacitors, when degraded under HALT conditions, reveal a more complicated failure mechanism with two distinct failure modes. A recently performed failure analysis of these degraded BME capacitors also confirms the existence of two distinct failure modes. [37] For this reason, the measurement of TTF data alone will not result in an accurate prediction of the reliability life of these BME capacitors. In order to characterize the multiple failure modes in BME capacitors, the leakage current was also monitored in-situ and was measured every 1-3 seconds for each capacitor unit. The reliability life of a capacitor is thus not only determined by the TTF data, but also by the measured leakage current data used to distinguish the failure modes. To differentiate this new approach from the traditional single-failure mode HALT that measures TTF data only, this modified method that has been used with multiple failure modes has been dubbed HALST, which stands for "highly accelerated life stress testing." [29] The term "HALST" is used through the remainder of this paper as appropriate.

Deliverable to NASA Electronic Parts and Packaging (NEPP) Program to be published on nepp.nasa.gov, paper published in the IEEE Transactions on Components, Packaging and Manufacturing Technology, Vol. 5, No. 1, January 2015.

2010 – Solid Tantalum Capacitors

Effect of Post-HALT Annealing on Leakage Currents in Solid Tantalum Capacitors

Alexander Teverovsky

Dell Perot Systems

GSFC/NASA Code 562, Greenbelt, MD 20771
Alexander.A.Teverovsky@nasa.gov

Abstract

Degradation of leakage currents is often observed during life testing of tantalum capacitors and is sometimes attributed to the field-induced crystallization in amorphous anodic tantalum pentoxide dielectrics. However, degradation of leakage currents and the possibility of annealing of degraded capacitors have not been investigated yet. In this work the effect of annealing after highly accelerated life testing (HALT) on leakage currents in various types of solid tantalum capacitors was analyzed. Variations of leakage currents with time during annealing at temperatures from 125 °C to 180 °C, thermally stimulated depolarization (TSD) currents, and I-V characteristics were measured to understand the conduction mechanism and the reason for current degradation. Annealing resulted in a gradual decrease of leakage currents and restored their initial values. Repeat HALT after annealing resulted in reproducible degradation of leakage currents. The observed results are explained based on ionic charge instability (drift/diffusion of oxygen vacancies) in the tantalum pentoxide dielectrics using a modified Schottky conduction mechanism.

Leakage currents in the parts were monitored during highly accelerated life testing (HALT) and annealing using a PC-based data acquisition system. A typical duration of HALT was 100 hrs, while temperature and voltage varied from 105 °C to 170 °C and from 0.8VR to 2VR. During annealing the parts were shorted, and leakage currents were measured periodically by applying a certain testing voltage, that was typically lower that the stress voltage, for a relatively short period of time (typically for 5 min).

Conclusion.

1. HALT-induced degradation is reversible and leakage currents are gradually decreasing with time during annealing. The recovery is near to completion after annealing at 160 °C for ~ 120 hrs. The activation energy of annealing is in the range from 1.1 eV to 1.3 eV.
2. Repeat HALT after the parts have been annealed resulted in degradation that is similar to the one observed initially thus indicating reproducibility of the degradation process.
3. Degradation of leakage currents with time during HALT and their recovery during annealing are explained based on ionic charge instability in the tantalum pentoxide dielectrics using a modified Schottky conduction mechanism. The ionic drift results in accumulation of positive charges at the cathode interface that enhances injection of electrons and increases leakage currents and diffusion during annealing redistributes ions inside the oxide, reduces the effective charge at the interface, decreases leakage current, and explains reversibility of current degradation.
4. All capacitors had spectrums of TSD current with two characteristic peaks corresponding to relaxation processes with activation energies of 0.93 ± 0.02 eV and to more than 1.1 eV. The first peak reflects electron trapping at the energy states located

HALT may be useful for evaluating or even screening of solid tantalum capacitors but more work is needed to identify optimum test conditions

NASA and HALT Testing of Ceramic Capacitors

- NEPP uses HALT as an evaluation tool
- Manufacturers use HALT as a process improvement tool
- Obstacles have hindered adoption of HALT as a screen or lot acceptance test:
  - Acceleration factors vary by manufacturer, part characteristics and part rating and could be considered proprietary
  - Performance of MIL qualified parts does not seem to merit adding HALT
  - HALT could be useful for COTS and automotive grade parts
- AEC Q200 (automotive) capacitors do not get typical HALT testing but do get tested at full rated voltage and 85°C/85% relative humidity
  - Manufacturers consider the “85/85” test the best for reliability assessment

The P-V Model for Ceramic Capacitors

- Most models used today are still based on acceleration factors derived by T. I. Prokopowicz and A. R. Vaskas, *Research and Development, Intrinsic Reliability, Subminiature Ceramic Capacitors,* Final Report ECOM-90705-F, NTIS AD-864068, (Oct. 1969). Known as the P-V equation.
- The P-V model creates an overall acceleration factor as a product of a power law and an Arrhenius, thermal factor
- The P-V paper found a power law exponent of 2.7 and an Arrhenius Activation Energy of 0.9eV. For convenience often rounded to 3 and 1.
- The P-V model gave credible results for Precious Metal Electrode (PME) parts
- However, the P-V model applied to current Base Metal Electrode (BME)parts creates a wide range of acceleration factors, varying by dielectric type, chip size, capacitance, voltage rating and manufacturer

P-V Acceleration Factor Examples

- In the paper, *Highly Accelerated Testing of Capacitors for Medical Applications*, Ashburn and Skamser, SMTA Medical Electronics Symposium – Anaheim, California – 2008, the authors develop Activation Energies and power exponents for C0G and X7R characteristic BME ceramic capacitors of different sizes and ratings:
  - Ea from 0.91 to 1.39 eV
  - Power exponent from 3.8 to 8.4 (X7R), 16.4 and 17.3 (C0G)
- Using the "corner" values in the P-V equation results in acceleration factors of:
  - 7.0E+3 to 1.7E+8 for X7R
  - 1.7E+15 to 1.8E+16 for C0G
  - Comparing HALT at 8 X Rated Voltage and 140^{o}C to Rated Voltage and operation at 125^{o}C
- Thus one hour of HALT equates to 7000 to 170 million hours at maximum rated conditions for X7R, 1.7 to 18 quadrillion hours for C0G!

Discussion of Acceleration Factors

- Clearly, the previous slide shows the challenges to using HALT as an acceptance test and this was for a very limited data set from one manufacturer
- An attempt to improve on the P-V model is described in: *Lifetime Modeling of Sub 2 Micron Dielectric Thickness BME MLCC,* Randall, et al, CARTS'2003 Conference
- This approach still requires characterization of individual manufacturer product values for key factors to compensate for potential manufacturer-to-manufacturer, lot-to-lot variations and affects of chip size, design and ratings
- Thus it is very difficult to create HALT conditions that are relevant, useful and equable and acceptable to the manufacturers as an acceptance test

Summary

- HALT testing holds promise for affordable efficient acceptance testing of multi-layer ceramic chip capacitors (MLCCs) especially for commercial off the shelf (COTS)
- Variation in key modeling factors makes it difficult to derive test conditions which are fair and meaningful for all suppliers
- Acceleration factors can be enormous, throwing their accuracy into doubt
- HALT will continue to be a useful evaluation and process improvement tool but use as a screen will probably have to be manufacturer specific