Evaluation of Automotive Grade Resistors for Space Flight

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ABSTRACT

Over the past decade, electronic, electrical, and electromechanical (EEE) parts for space applications have undergone significant changes, largely driven by CubeSat and commercial space developers pushing the boundaries on the utilization of commercial parts in space. Global product shortages and shipping delays are still impacting space flight project deadlines. Many projects have turned to automotive grade resistors as an alternate to their MIL-SPEC counterparts to fulfill requirements. In addition, automotive grade resistors may offer designers a wider range of parts to consider.

A recent NASA study recommended the use of high-volume manufactured commercial components for space applications provided these components show evidence of stringent fabrication controls and thorough reliability monitoring practices [1]. Automotive grade components have stringent qualification requirements per the Automotive Electronic Council (AEC). However, the end user usually does not have insight into the practices the manufacturer may use to reduce/eliminate infant mortality nor for compliance to all datasheet specifications.

Screening, Life and Accelerated Life testing on a set of standard automotive-grade chip resistors is proposed to evaluate the reliability of these components. Requirements from both the AEC-Q (Automotive Electronic Council Qualification) and EEE-INST-002 (Instructions for EEE Parts Selection, Screening, Qualification, and Derating) for resistors is compared and discussed. The resistors have been tested by using a modified methodology from EEE-INST-002 to evaluate their reliability for space flight projects.

The findings of this study indicate that the underlying degradation mechanisms at rated temperature and power are best represented by power law models with a fitted exponent between 0 and 1. A linear model is more conservative which compensates for potential model uncertainty given the wide range of design and materials used in automotive resistors, while still providing useful long-term resistance drift estimates. No electrical anomalies or failures were observed throughout the 1000-hour Life Tests other than small in tolerance resistance drift aging. Degradation models were utilized to quantify and extrapolate the long-term resistance drift under operating conditions for the components. The models demonstrated that some automotive-grade resistors are likely to operate 10 years at nominal usage conditions while others might fail earlier.

INTRODUCTION

The methodology for using EEE components in NASA space applications is based on military standards established during the 1960's and 1970's [1]. The NASA EEE-INST-002 document was released in the early 2000's and establishes the baseline criteria for the selection, screening, qualification, and derating of EEE parts for use on NASA Goddard Space Flight Center (GSFC) space flight projects [2]. The AEC-Q200 document applies to passive components and outlines the minimum requirements for stress test driven qualification and details the test conditions required for qualifying these components [3]. The NASA Electronic Parts and Packaging (NEPP) Program has funded a study to assess the reliability of automotive grade chip resistors that have been qualified to the AEC-Q200 set of standards. A comparative study between the AEC-Q200 and EEE-INST-002 standards was conducted as shown in Figure 1 and a test plan for this study was developed consisting of a Screening, Life and an Accelerated Life Test.

NEPP Study Evaluation of Automotive Grade Resistors for Space	**Test 1** Screening to EEE-INST-002, Table 2A	**Test 2** Life Test (shall be from 100% screened samples)	**Test 3** Accelerated Life Test (shall be from 100% screened samples)								
EEE-INST-002 **Table 3A : Fixed Resistor Qualification Requirements**	**Group 1** Screening to Table 2A	**Group 2** Solderability Resistance to Solvents	**Group 3** Thermal Shock Resistance Temperature Characteristic Low Temperature Storage Low Temperature Operation Short-time Overload Terminal Strength Hermetic Seal	**Group 4** Dielectric Withstanding Voltage Insulation Resistance Moisture Resistance Terminal Strength Hermetic Seal	**Group 5** Shock Vibration, High Frequency Hermetic Seal	**Group 6** Life	**Group 7A** Resistance to Bonding Moisture Resistance	**Group 7B** Adhesion	**Group 8** Voltage Coefficient	**Group 9** High Temperature Exposure	**Group 10** Thermal Outgassing
AEC-Q200 (Rev E) **Table 7B-5: Acceptance Criteria for SMD Chip Resistors**	**Test 1** Initial Limits (Pre- and Post Stress Electrical Test)	**Test 3** High Temperature Exposure (storage)	**Test 4** Temperature Cycling	**Test 7** Biased Humidity	**Test 8** Operational Life	**Test 9** External Visual	**Test 10** Physical Dimensions	**Test 12** Resistance to Solvents	**Test 13** Mechanical Shock	**Test 14** Vibration	**Test 15** Resistance to Soldering Heat
AEC-Q200 (Rev E) ***continued*** **Table 7B-5: Acceptance Criteria for SMD Chip Resistors**	**Test 17** ESD	**Test 18** Solderability	**Test 19a** Elec. Char. @25°C	**Test 19b** Elec. Char. @Min. operating temp	**Test 19c** Elec. Char. @Max operating temp.	**Test 20** Flammability	**Test 21** Board Flex (SMD)	**Test 22** Terminal Strength (SMD)	**Test 23** Flame Retardance		

Figure 1. Evaluation test flow used to assess reliability of Automotive Grade Chip Resistors

TEST DATA COLLECTION AND RESULTS

The Screening test flow was performed on all 9 resistor groups followed by the Life and Accelerated Life test flows performed on a sub-selection of the resistor groups that already completed Screening shown in Table 1.

Table 1. Summary of Resistor types evaluated and tests performed

Resistors Evaluated							**Testing Performed**		
Group ID (Part Number)	**Manufacturer**	**Resistance (Ω)**	**Tolerance (%)**	**Wattage (W)**	**Chip Size**	**Resistor Technology**	**Screening**	**Life**	**Accelerated Life**
A	A	0.1	0.5%	1	2512	Metal Strip	Yes	Yes	*No*
B	A	49.9	1%	0.25	1206	Thick Film	Yes	Yes	*No*
C	B	49.9	1%	0.1	0603	Thick Film	Yes	Yes	*No*
D	A	1,000	1%	0.25	1206	Thick Film	Yes	*No*	*No*
E	B	1,000	1%	0.1	0603	Thin Film	Yes	Yes	Yes
F	A	10,000	1%	0.25	1206	Thin Film	Yes	Yes	*No*
G	B	10,000	1%	0.1	0603	Thin Film	Yes	Yes	*No*
H	A	100,000	1%	0.25	1206	Thick Film	Yes	*No*	*No*
I	C	100,000	1%	0.1	0603	Thick Film	Yes	*No*	Yes

The Screening test consisted of both an initial and final external visual examination and Direct Current Resistance (DCR) measurements before and after thermal shock. The thermal shock test (per MIL-STD-202 Method 107) was performed utilizing the following conditions: [4]

- 100 cycles
- -55°C to +125°C
- 30-minute dwell time in air at temperature extremes

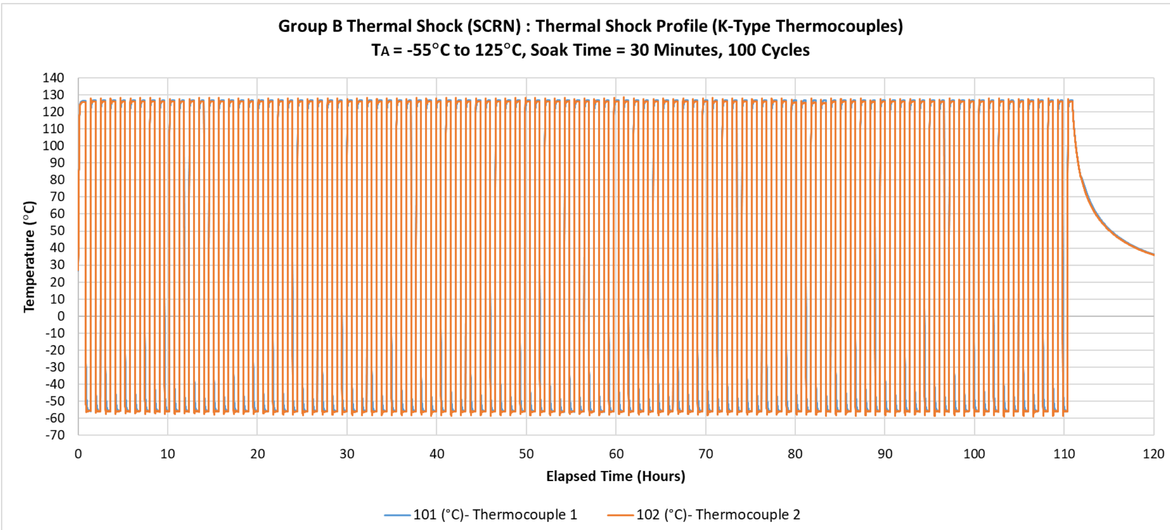

Figure 2. Thermal Shock temperature profile for Group B samples

DCR measurements (per MIL-STD-202, Method 303) were taken before and after thermal shock utilizing a Nano Volt Micro Ohm Meter [5]. A four-wire Kelvin measurement method was utilized so that the voltage drop in the test leads was eliminated and measured at the Device Under Test (DUT) shown in Figure 4.

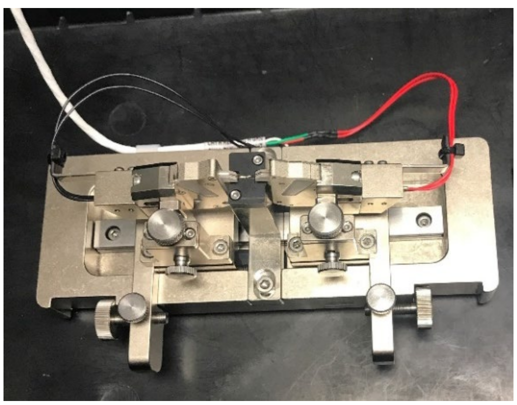

Figure 3. Test fixture used for obtaining DCR measurements

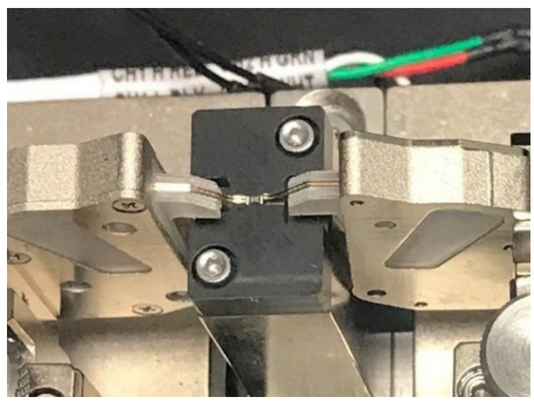

Figure 4. DUT in test fixture

The second test flow (Life Test) was performed on twenty samples from groups A, B, C, E, F and G. The twenty samples were mounted on Printed Circuit Boards (PCB) as shown in Figure 5. The samples were subjected to a

1,000-hour Life Test at 70°C and 1X rated power (90 minutes on, 30 minutes off). The samples were biased at the maximum working voltage $Vmax$ per the datasheet or the calculated voltage $Vrms$,whichever was less severe:

$$Vrms = \sqrt{PR} \tag{1}$$

where P is the maximum rated power and R is the nominal DC resistance value [6]. Various parameters were monitored during the 1,000-hour Life Test such as ambient temperature and the DCR measurements were obtained at 0, 100-, 250-, 500- and 1,000-hour increments.

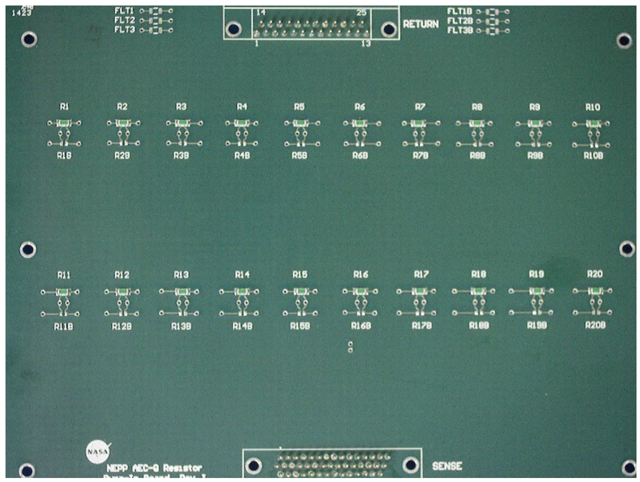

Figure 5. Life Test PCB used for Group F samples

The third test flow performed was an Accelerated Life Test. This test was performed on samples from Group E and Group I. This test flow consisted of various Life Test conditions including a test at 70°C at 0%, 70%, 120% and 150% applied power and an unbiased test at 155°C (Long-Term High Temperature Exposure Test).

A single electrical failure was observed during the Screening Test (Group A, Serial Number 51) after the thermal shock test. This sample had an out of tolerance DCR and failed per the datasheet specifications. All remaining samples passed DCR measurements per the datasheet specification limits during the Screening Tests. No electrical failures were observed during the Life Tests or Accelerated Life Tests, and all resistance drifts were within the datasheet specifications.

DEGRADATION MODELS

Film resistors have generally been found to change in resistance as a function of time and temperature according to:

$$\frac{\Delta R}{R} = \sum_i a_i t^{b_i} \, exp\left(-\frac{E_A}{kT}\right) \tag{2}$$

where a_i and b_i relate to a particular aging mechanism. [7]

The resistance data at the 0-, 100-, 250-, 500-, and 1000-hour inspection points during the Life Test were pre-processed for analysis using the following:

$$R_{shift} = 100\% \cdot \frac{R_i - R_0}{R_0} \tag{3}$$

Where R_0 is the initial resistance and R_i are the resistances at each inspection interval. This results in the data being a percent shift from initial measurements.

The models considered were assessed for their predictive power using the Mean Square Error (MSE):

$$MSE = \frac{(y_i - \hat{y_i})^2}{n} \tag{4}$$

where y_i is each measured percent resistance shift, $\hat{y}_i$ is the predicted percent resistance shift of the model and n is the number of data points. To assess the degradation model's ability to predict future resistance drifts, the measured data was separated into a training data set and a testing data set. The training data set was chosen to be the 0-, 100-, 250-, and 500-hour inspection data while the testing data was chosen to be the 1000-hour inspection data. The models were fit by regression on the testing data without having access to the 1000-hour inspection data. The various resistance degradation models were assessed against their ability to predict the 1000-hour data using the MSE as shown in Table 2. The power law model performed the best across most of the groups (lowest testing data MSE). This confirms that resistance drift found in automotive grade resistors generally conform to the power law dependance degradation model.

Table 2: Various model performance predicting the 1000th hour resistance measurements when fit to the 0 to 500-hour resistance shift data

	$f(t) = \bar{y}$		$f(t) = mt + b$		$f(t) = mt$		$f(t) = at^b$	
Group ID	**MSE training**	**MSE Testing**	**MSE training**	**MSE Testing**	**MSE training**	**MSE Testing**	**MSE training**	**MSE Testing**
A	5.62E-05	1.97E-04	3.14E-05	5.45E-05	5.00E-05	3.05E-04	1.07E-05	3.70E-05
B	1.25E-06	2.35E-06	6.84E-07	3.66E-06	9.57E-07	8.48E-06	6.85E-06	1.22E-05
C	5.50E-05	1.47E-04	1.94E-05	1.71E-04	3.26E-05	4.59E-04	2.70E-06	9.73E-06
E	9.44E-06	5.01E-05	3.26E-06	1.34E-05	5.61E-06	2.27E-05	7.53E-06	7.86E-06
F	7.20E-08	3.13E-07	4.65E-08	1.30E-07	5.15E-08	2.34E-07	1.27E-07	8.93E-08
G	9.49E-07	1.10E-05	6.42E-07	1.45E-06	6.53E-07	1.32E-06	7.07E-07	4.50E-06
Total	2.02E-05	7.62E-05	9.16E-06	3.95E-05	1.48E-05	1.30E-04	4.79E-06	1.19E-05

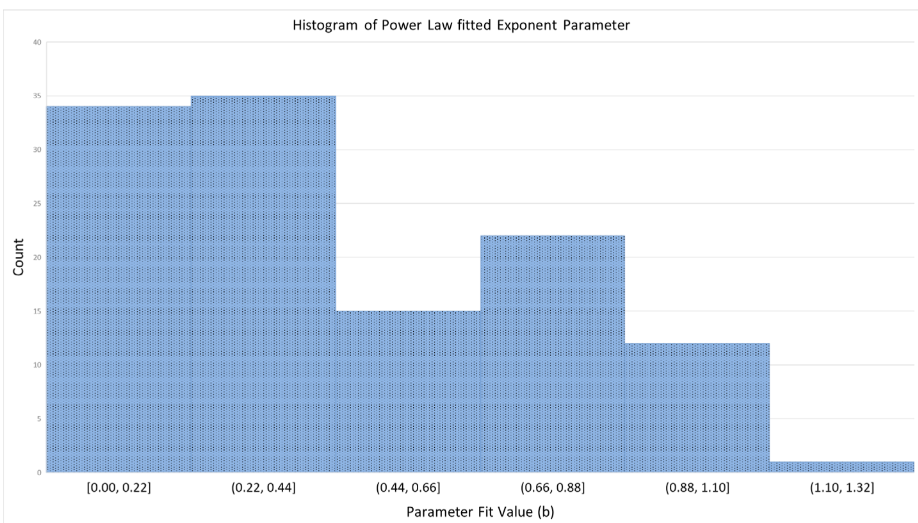

Figure 6: Histogram of the fitted power exponent for each of the 120 resistors that were life tested (Groups A, B, C, E, F, and G)

Out of 120 resistors that underwent Life Testing, only six (6) had a fit to the power law exponent greater than 1 with a maximum value of 1.12 (see Figure 6). All other 114 resistors had a fitted power law exponent less than 1. While the power law model may be better at prediction and a better fit to the data, the linear model in general is more conservative since the fitted power law exponent is less than 1 for almost all resistors in the dataset. This means that the linear model will grow more rapidly in general and reach earlier projected times to failure than the associated power law models.

MODEL PROJECTED FAILURE TIMES

Using a threshold for failure of a 1% resistance drift, we can project the degradation model forward in time until the threshold is met. These times are the projected times to failure for the resistor. Note that these are projected failure times and do not represent actual observed failures due to resistance drift. Reality in application may not conform to these laboratory test-based models. Using the linear resistance drift degradation model, we find the sudo-failure times shown in Figure 7 from our Life Test data.

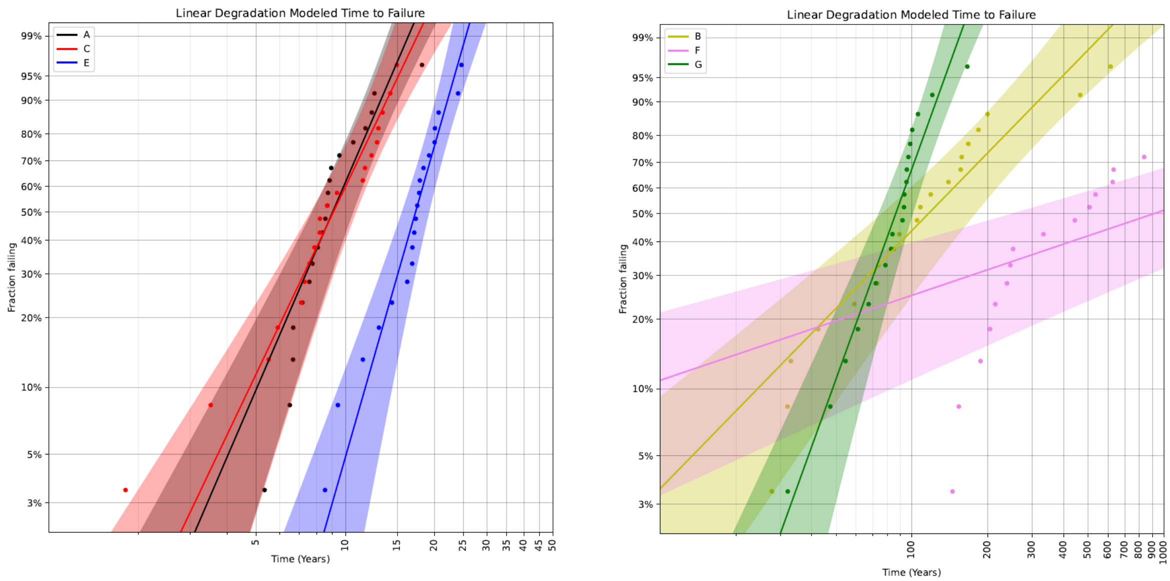

Figure 7: The projected times to failure shown on Weibull probability paper and found by extrapolating the Life Test data using the linear degradation model to a 1% resistance shift threshold. [8]

The parameters of the Weibull distribution fitted to the projected times to failure are given in Table 3.

Table 3: Weibull distribution fitted parameters to the projected times to failure using the linear degradation model.

	Scale (α)	**Shape (β)**	**Earliest Projected Failure (yrs)**	**Projected TTF 50% (yrs)**
A	10.1	3.2	5.3	9
B	157	1.2	28	116
C	10.3	2.9	1.8	9
E	18.6	4.8	8.5	17
F	2296	0.4	145	918
G	96.4	3.2	32	86

SUMMARY AND CONCLUSIONS

Rigorous stress testing of 9 different automotive grade chip resistors demonstrated their durability under thermal shock, Life and Accelerated Life Test conditions. A single electrical failure was observed during the Screening Test (Group A, Serial Number 51) after the thermal shock test, with an out of tolerance DCR per the datasheet specifications. All remaining samples passed DCR measurements per the datasheet specification limits. However, the Life Test for this group revealed no failures. Life Test based models show that some automotive grade resistors are likely to last 10 years at nominal usage conditions while others might fail earlier. The extension of Life Tests is recommended to ensure that the proposed degradation models accurately reflect real long-term operating behavior.

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