Evaluation of Automotive Grade Resistors for Space

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2024 NEPP Electronics Technology Workshop (ETW), NASA GSFC Greenbelt, MD, June 3-6, 2024.

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Background and Scope

- Global product shortages and shipping delays are still an obstacle and projects are still expected to meet deadlines that cannot take these global impacts into consideration.

- Many projects have found some alternative solutions to still meet deadlines, including the possibility of leveraging test data and requirements used in automotive grade parts.

- In addition, automotive grade parts may offer designers a wider range of parts to consider.

- A recent study conducted by NASA recommended the use of high-volume manufactured commercial components for space applications, provided they demonstrate evidence of well-monitored and tightly controlled reliability and fabrication practices [1].

- Automotive grade components have stringent qualification requirements, *but* the responsibility is on the user to assure parts compliance to datasheet specifications and to perform screening.

- *This study aims to evaluate the reliability of automotive grade chip resistors for space.*

Acronyms

- **AEC:** Automotive Electronics Council
- **AEC-Q:** Automotive Qualified
- **ALT:** Accelerated Life Test
- **COTS:** Commercial Off The Shelf
- **DC:** Direct Current
- **DUT:** Device Under Test
- **DPA:** Destructive Physical Analysis
- **EEE:** Electrical, Electronic, and Electromechanical
- **EEEE:** Electrical, Electronic, Electromechanical, and Electro-Optical
- **GSFC**: Goddard Space Flight Center
- **HAST**: Highly Accelerated Stress Test
- **HTOL**: High Temperature Operating Life
- **IPA:** Isopropyl Alcohol
- **ISO**: International Organization for Standardization
- **LAT**: Lot Acceptance Testing
- **MASCD:** Mission Assurance Standards and Capabilities Division
- **MIL**: Military
- **NEPP:** NASA Electronic Parts and Packaging Program
- **OSMA:** NASA Office of Safety and Mission Assurance
- **PDA**: Percent Defect Allowable
- **PMA**: Prohibited Material Analysis
- **PPM**: Parts Per Million

- **QML**: Qualified Manufacturers List
- **QUAL:** Qualification
- **SCRN:** Screening
- **SMD:** Surface Mount Devices
- **SPEC:** Specification
- **TCR:** Temperature Coefficient of Resistance
- **TTF:** Time to Failure

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Overview of AEC-Q200

- **AEC:** Automotive Electronics Council
- **AEC-Q:** Automotive Qualified

- **AEC-Q200:** Stress Test Qualification For Passive Components [2]

  - **Table 7** : Stress Qualifications for Resistors
  - **Table 7A** : Resistors Process Change Qualification Guidelines for the Selection of Tests
  - **Table 7B-5**: Acceptance Criteria for SMD Chip Resistors

- Not required:
  - Traditional Screening (per EEE-INST-002 or MIL-SPECs)
  - Lot Acceptance Testing
- Parts are qualified once and then remain qualified as long as manufacturing process remains the same.
- Manufacturing Process change notifications are required and re-qualification based on applicable tests.
- Other quality control processes are left up to the discretion of the manufacturer.

AEC-Q200 and EEE-INST-002

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 [3] **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) [2] **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		

[2] *Stress Test Qualification for Passive Components.* AECQ -200 Rev. E. Automotive Electronics Council. March 2023.
[3] *Instructions for EEE Parts Selection, Screening, Qualification, and Derating.* EEE-INST-002. NASA/TP—2003–212242. NASA Goddard Space Flight Center. April 2008.
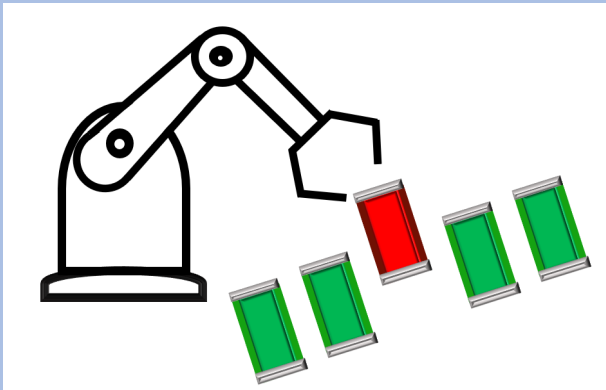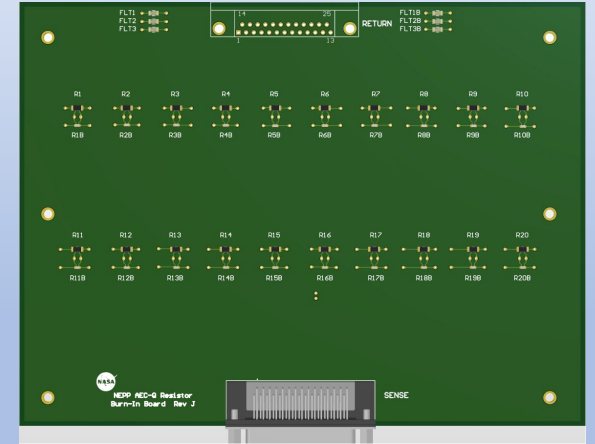
Resistor/Part Numbers Evaluated

Group ID (Part Number)	Manufacturer	Resistance (Ω)	Tolerance (%)	Wattage (W)	Chip Size	Resistor Technology	Testing Performed		
							Screening	Life	Accelerated Life
A	A	0.1	0.5%	1	2512	Metal Strip	✓	✓	✗
B	A	49.9	1%	0.25	1206	Thick Film	✓	✓	✗
C	B	49.9	1%	0.1	0603	Thick Film	✓	✓	✗
D	A	1,000	1%	0.25	1206	Thick Film	✓	✗	✗
E	B	1,000	1%	0.1	0603	Thin Film	✓	✓	✓
F	A	10,000	1%	0.25	1206	Thin Film	✓	✓	✗
G	B	10,000	1%	0.1	0603	Thin Film	✓	✓	✗
H	A	100,000	1%	0.25	1206	Thick Film	✓	✗	✗
I	C	100,000	1%	0.1	0603	Thick Film	✓	✗	✓

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Testing Performed

Screening

Life Test
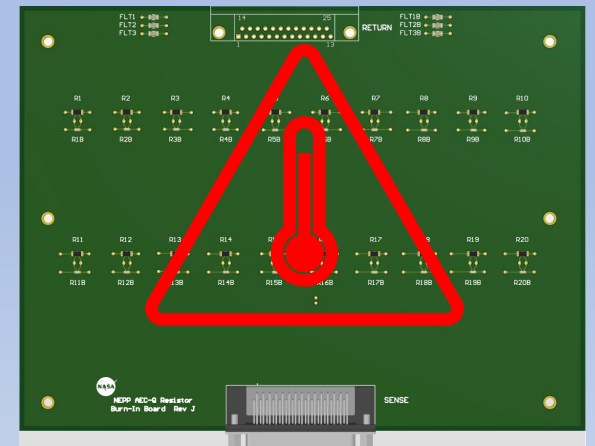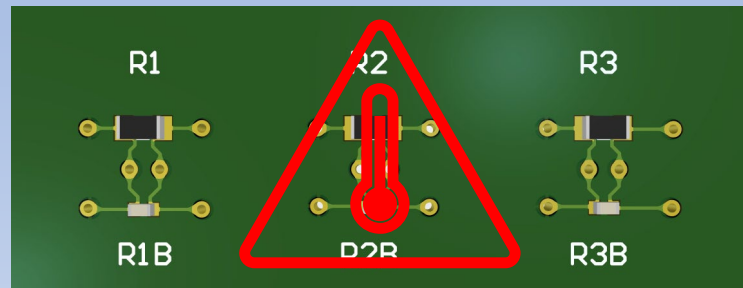
Accelerated Life Test

Screening Test Flow

Test	Test Description	Standard
[1] Initial External Visual Examination	External visual examination on 13 samples at 10X-30X.	EEE-INST-002, Table 2A MIL-PRF-55342J, para 4.8.1.1
[2] Mechanical Examination	Physical dimensions of 3 samples.	Manufacturer Drawing
[3] Prohibited Material Analysis	Prohibited Material Analysis on 3 samples.	GSFC S-311-M-70, Requirement 4.1.3
[4] Initial DC Resistance Measurements	DC Resistance at 22°C ± 3°C	MIL-STD-202, Method 303
[5] Thermal Shock	Thermal shock (100 cycles). High temperature - max. rated operating Low temperature - min. rated operating	MIL-STD-202, Method 107
[6] Final DC Resistance Measurements	DC Resistance at 22°C ± 3°C	MIL-STD-202, Method 303
[7] Final External Visual Examination	External visual examination on 13 samples 10X-30X.	EEE-INST-002, Table 2A MIL-PRF-55342J, para 4.8.1.1
[8] Percent Defective Allowable (PDA)	Level 1 : 5%	EEE-INST-002, Table 2A
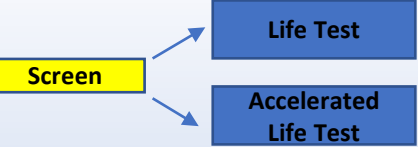
Screening Test Setup : DC Resistance

- DC Resistance Test per MIL-STD-202, Method 303 [4]

- Performed on all samples (Groups A – I)

- Measurements obtained pre and post thermal shock at room temperature

- Four-Wire Kelvin measurement method used (voltage is measured at the DUT and voltage drop in test leads is eliminated)

- Pass/Fail Criteria per datasheet specification limits
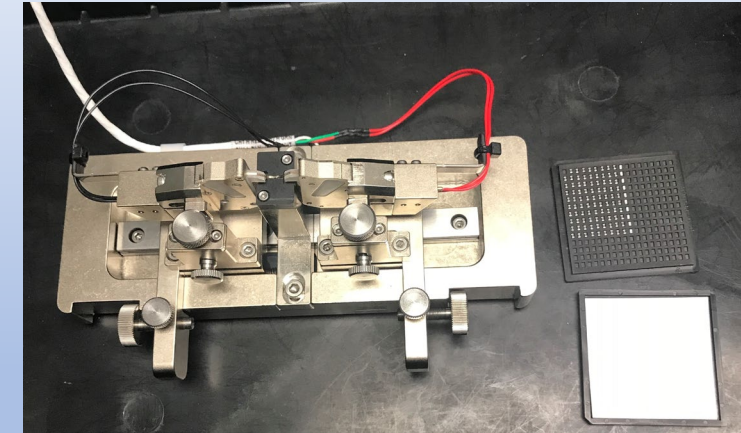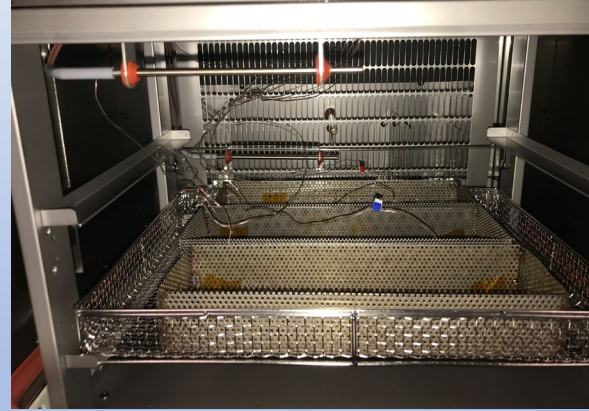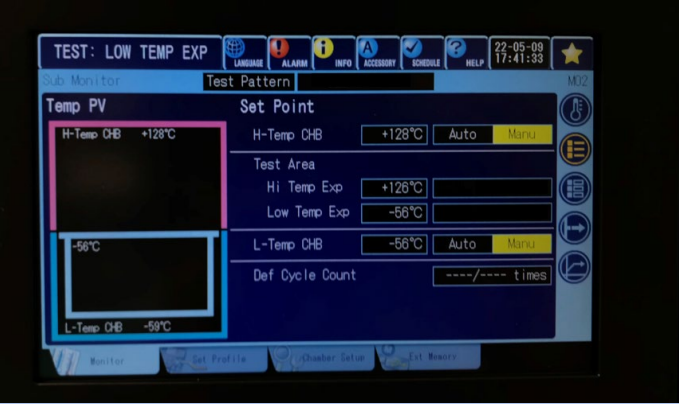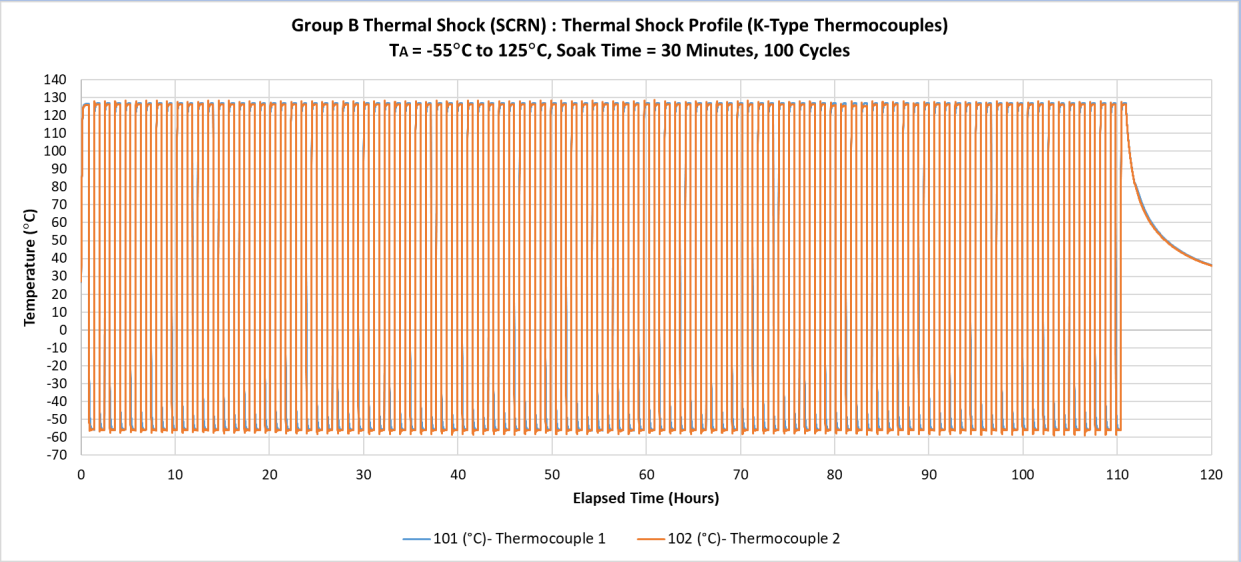

DCR Test Fixture

Device Under Test (DUT)

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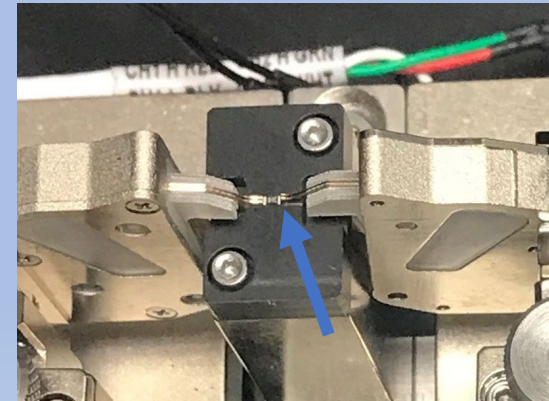
Screening Test Setup : Thermal Shock
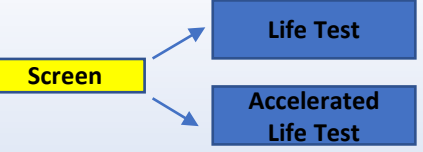
- Thermal Shock Test : per MIL-STD-202 Method 107 [5]

- Performed on all samples (Groups A – I)

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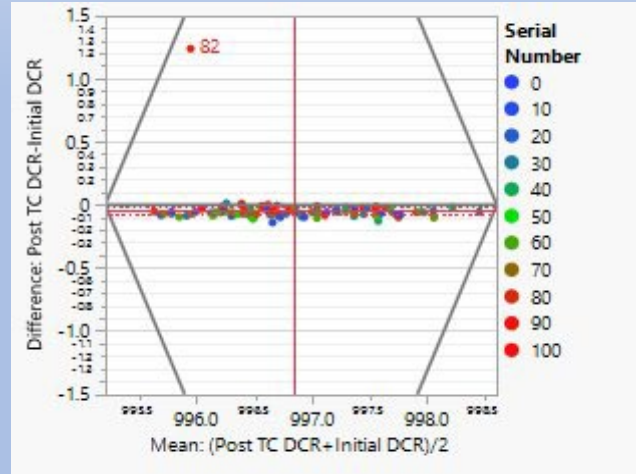

Thermal Shock Chamber

Group B Thermal Shock (SCRN) : Thermal Shock Profile (K-Type Thermocouples)
T_A = -55°C to 125°C, Soak Time = 30 Minutes, 100 Cycles

Thermal Shock Profile (Group B)

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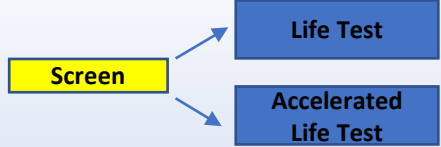
Screening Test Data/Results
DC Resistance Distribution (1k Ω) : Group D
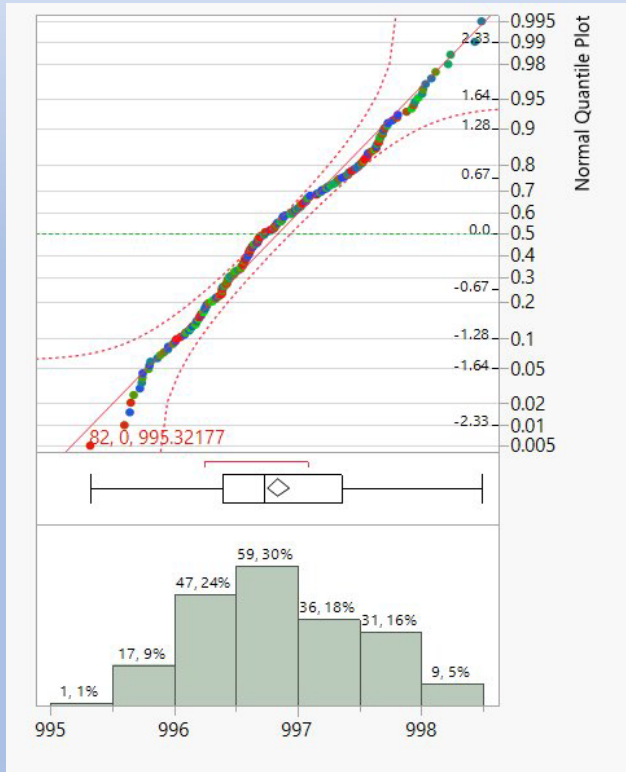
Normal Quantile Plot
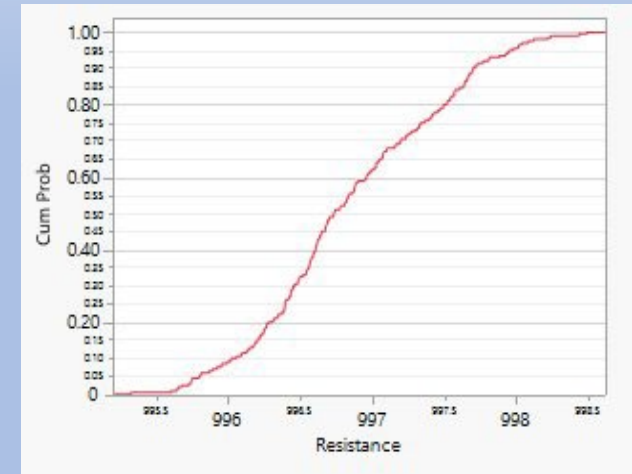
Mean Difference Plot

CDF Plot

Screening Test Data/Results
## DC Resistance Distribution (0.1 Ω) : Group A

Normal Quantile Plot

Mean Difference Plot

CDF Plot

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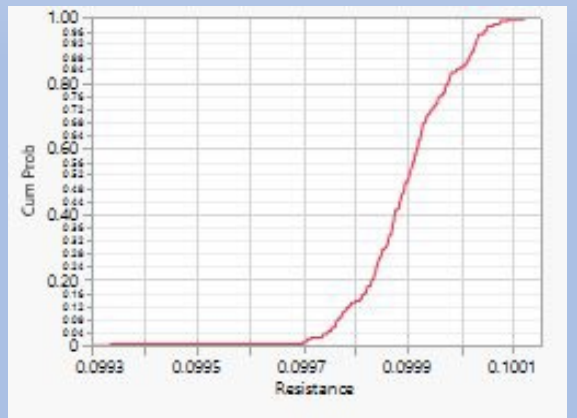
Screening Test Summary

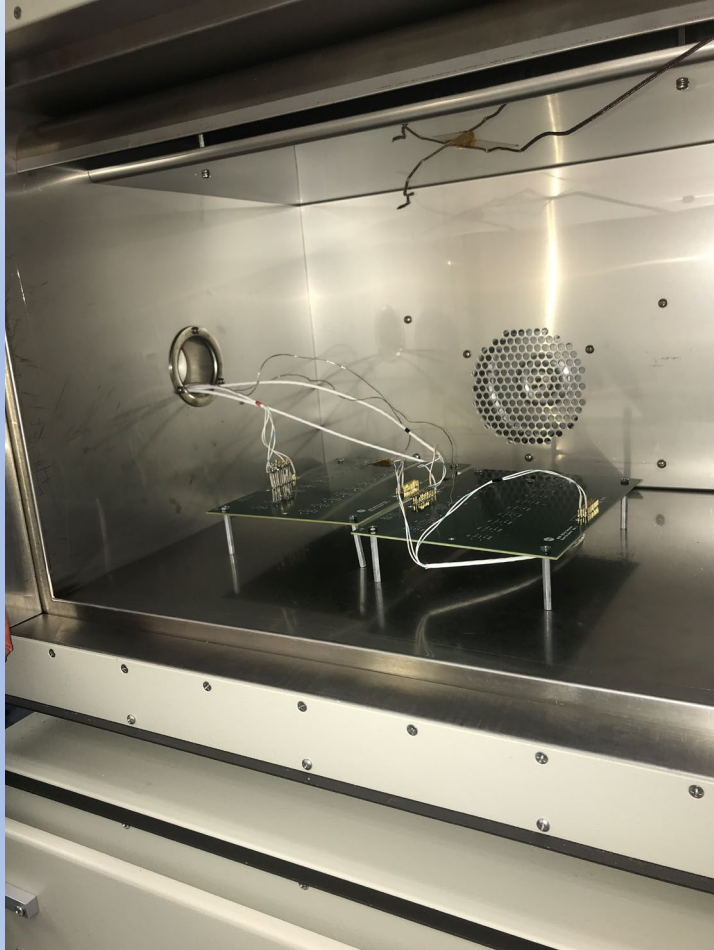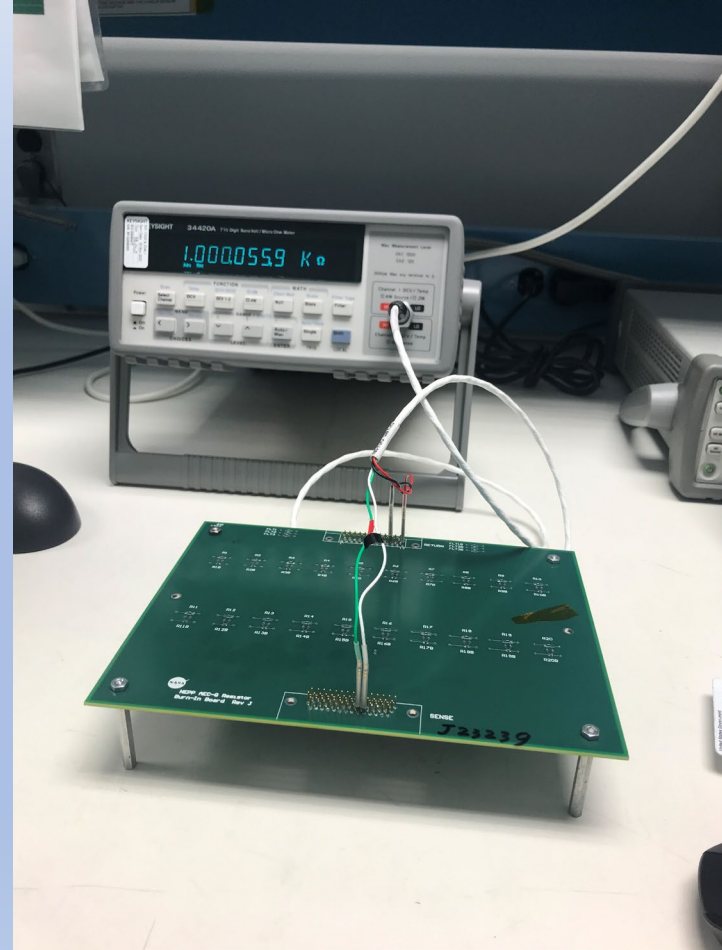| Group ID	Resistance (Ω)	Tolerance (%)	Limits (Ω)	Total Qty Submitted	Qty Pass : Initial DCR (Pre-Thermal Shock)	Qty Fail : Initial DCR (Pre-Thermal Shock)	Qty Pass : Final DCR (Post-Thermal Shock)	Qty Faill : Final DCR (Post-Thermal Shock)	Notes
A	0.1	0.5%	$0.0995\ \Omega \le R \le 0.1005\ \Omega$	*99	99	0	98	1	Serial Number 51 *failed final DCR test* (below data sheet limit, *SN 51 = 0.09934 Ω*) *Qty = 99 (shipping issues)
B	49.9	1%	$49.401\ \Omega \le R \le 50.399\ \Omega$	100	100	0	100	0	All samples passed initial and final DCR measurements per datasheet.
C	49.9	1%	$49.401\ \Omega \le R \le 50.399\ \Omega$	100	100	0	100	0	All samples passed initial and final DCR measurements per datasheet.
D	1000	1%	$990\ \Omega \le R \le 1010\ \Omega$	100	100	0	100	0	All samples passed initial and final DCR measurements per datasheet.
E	1000	1%	$990\ \Omega \le R \le 1010\ \Omega$	100	100	0	100	0	All samples passed initial and final DCR measurements per datasheet.
F	10000	1%	$9,900\ \Omega \le R \le 10,100\ \Omega$	100	100	0	100	0	All samples passed initial and final DCR measurements per datasheet.
G	10000	1%	$9,900\ \Omega \le R \le 10,100\ \Omega$	100	100	0	100	0	All samples passed initial and final DCR measurements per datasheet.
H	100000	1%	$99,000\ \Omega \le R \le 101,000\ \Omega$	*62	62	0	62	0	All samples passed initial and final DCR measurements per datasheet. *Qty = 62 (shipping issues)
I	100000	1%	$99,000\ \Omega \le R \le 101,000\ \Omega$	100	100	0	100	0	All samples passed initial and final DCR measurements per datasheet.

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Life Test Flow

| Test	Test Description	Standard
[*] Screening to EEE-INST-002, Table 2A	Screening.	EEE-INST-002, Table 2A
[1] Printed Circuit Board : Preparation/Assembly	Reflow samples onto PCB.	N/A
[2] Printed Circuit Board : Initial External Visual Examination	Verify samples were properly reflowed. External visual examination at 10X-30X.	MIL-PRF-55342J, para 4.8.1.1
[3] Initial DC Resistance Measurements *(0 Hours)*	DC Resistance at 22°C ± 3°C.	MIL-STD-202, Method 303
[4] Life Test (1,000 Hours) *DCR Measurements Obtained:* *0, 100, 250, 500 and 1,000 hours*	1,000 Hour Life Test at 70°C, 1x rated power (90 minutes ON, 30 minutes OFF). DC Resistance at 22°C ± 3°C.	MIL-STD-202, Method 108
[5] Final DC Resistance Measurements *(1,000 Hours)*	DC Resistance at 22°C ± 3°C. Delta Resistance (ΔR) per datasheet specification.	MIL-STD-202, Method 303
[6] Printed Circuit Board : Final External Visual Examination	External visual examination at 10X-30X.	MIL-PRF-55342J, para 4.8.1.1

Screen → Life Test
Screen → Accelerated Life Test
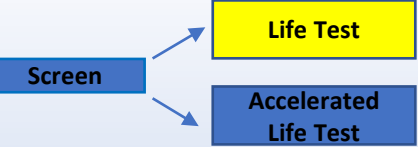
Life Test Setup

Group C and Group E samples in test chamber

Test setup for obtaining DCR measurements

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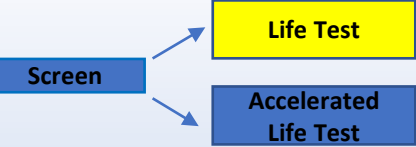
Life Test Criteria

- Applied Voltage: $V_{rms} = \sqrt{PR}$ or the maximum working voltage (V_{max}) per the datasheet whichever is less severe.
- Cyclical 90 min power ON and 30 min OFF
- Total test time: 1,000 hours
- Inspection times for room temperature DCR: 0, 100, 250, 500, and 1,000 hours
- 1,000-hour resistance shift failure criteria was tolerance on the datasheets (0.5% for Group A, 1% all other Groups).
- Degradation analysis and Time to Failure (TTF) projection:
  - Degradation Model: Linear
  - Fitted Distributions to Projected Time To Failure (TTF): Lognormal & Weibull shown on Lognormal probability paper.
  - Event Plots for Projected Time To Failure (TTF) are also shown.

Group E Life Test (LIFE) : Board Power Supply (1.5 Hours ON, 0.5 Hours OFF)

— 103 (Vdc)- PwrSupply_Group E
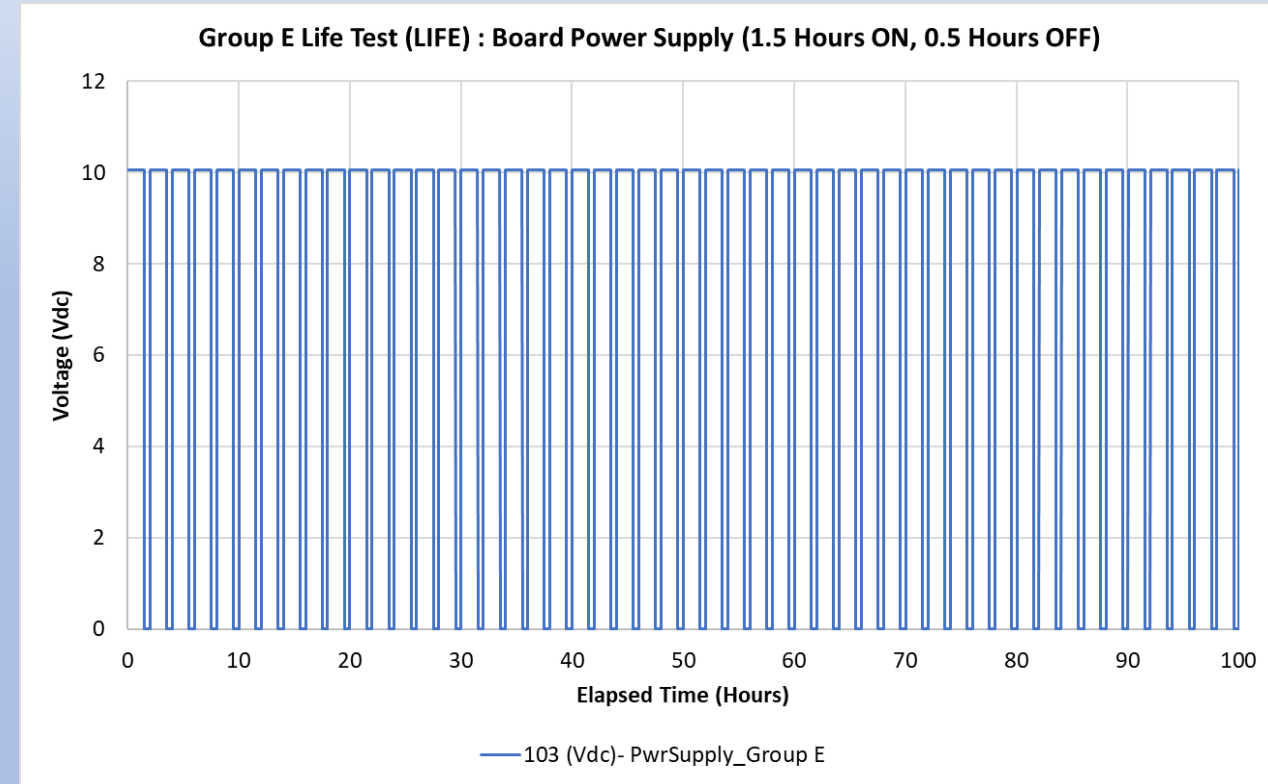
Testing and Analysis Specifications

Displaying 100 hours out of the 1,000-hour Life Test (Group E)

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Life Test Data/Results
DC Resistance Distribution (49.9 Ω) : Group B

Normal Quantile Plot

Mean Difference Plot

CDF & Event Plots

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DC Resistance Distribution (10k Ω) : Group G

Normal Quantile Plot

Mean Difference Plot

CDF & Event Plots

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Life Test Data/Results Summary

Group ID	Earliest Projected Failure (yrs)	Projected TTF 50% (yrs)
A	3.7	6
B	10	23
C	2.5	9
E	8	15
F	97	203
G	14	80

Summary of Life Test resistance shift degradation analysis. 20 resistors tested per Group.

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Accelerated Life Test Flow

Test	Test Description	Standard
[*] Screening to EEE-INST-002, Table 2A	Screening	EEE-INST-002, Table 2A
[1] Printed Circuit Board : Preparation/Assembly	Reflow samples onto PCB.	N/A
[2] Printed Circuit Board : Initial External Visual Examination	Verify samples were properly reflowed. External visual examination at 10X-30X.	MIL-PRF-55342J, para 4.8.1.1
[3] Initial DC Resistance Measurements *(0 Hours)*	DC Resistance at 22°C ± 3°C.	MIL-STD-202, Method 303

[4] Life Testing (500 Hours)
 	
DCR Measurements Obtained:
0, 100, 250 and 500
	Various life tests were performed:
	    @ 70°C: 0%, 70%, 120% and 150% applied power.
	    @ 155°C: No applied power.
	Each Life Test had 15 resistor samples.
		Modified MIL-STD-202, Method 108

[5] Final DC Resistance Measurements *(500 Hours)*	DC Resistance at 22°C ± 3°C.	MIL-STD-202, Method 303
[6] Printed Circuit Board : Final External Visual Examination	External visual examination at 10X-30X.	MIL-PRF-55342J, para 4.8.1.1

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Accelerated Life Temperature Models

Arrhenius based model put forth by R. W. Kuehl [9]:

$$\ln \frac{\Delta R}{R[\text{ppm}]} = f(t) R[\text{ppm} * K] * \frac{1}{T} + \ln\left(\frac{\Delta R}{R}\right)_{\text{pot}} (t)[\text{ppm}]$$

Arrhenius with temperature dependent power law degradation.

$$\ln(\Delta R \ / \ R\,[\text{ppm}]) = (B * \ln(t) + C)\frac{1}{T} + D * \ln t + F$$

$$\longrightarrow \qquad \frac{\Delta R}{R} = F_1 t^{\left(\frac{B}{T}+D\right)} \cdot e^{\frac{-E_a}{K_B T}}$$

$$\frac{\Delta R}{R} = \frac{t}{t_0} \cdot 2^{\frac{T_1 - T_0}{30K}} \cdot \frac{\Delta R}{R_{t_0, T_0}}$$

$$\longrightarrow \qquad \frac{\Delta R}{R} \propto t, \text{ Linear degradation}$$

$$\frac{\Delta R}{R} = A \frac{t}{t_0} \cdot e^{\frac{-E_a}{K_B}\left(\frac{1}{T_0}-\frac{1}{T_1}\right)} \cdot \frac{\Delta R}{R_{t_0, T_0}}$$

$$\longrightarrow \qquad \frac{\Delta R}{R} \propto t, \text{ Linear with Arrhenius temperature dependance.}$$

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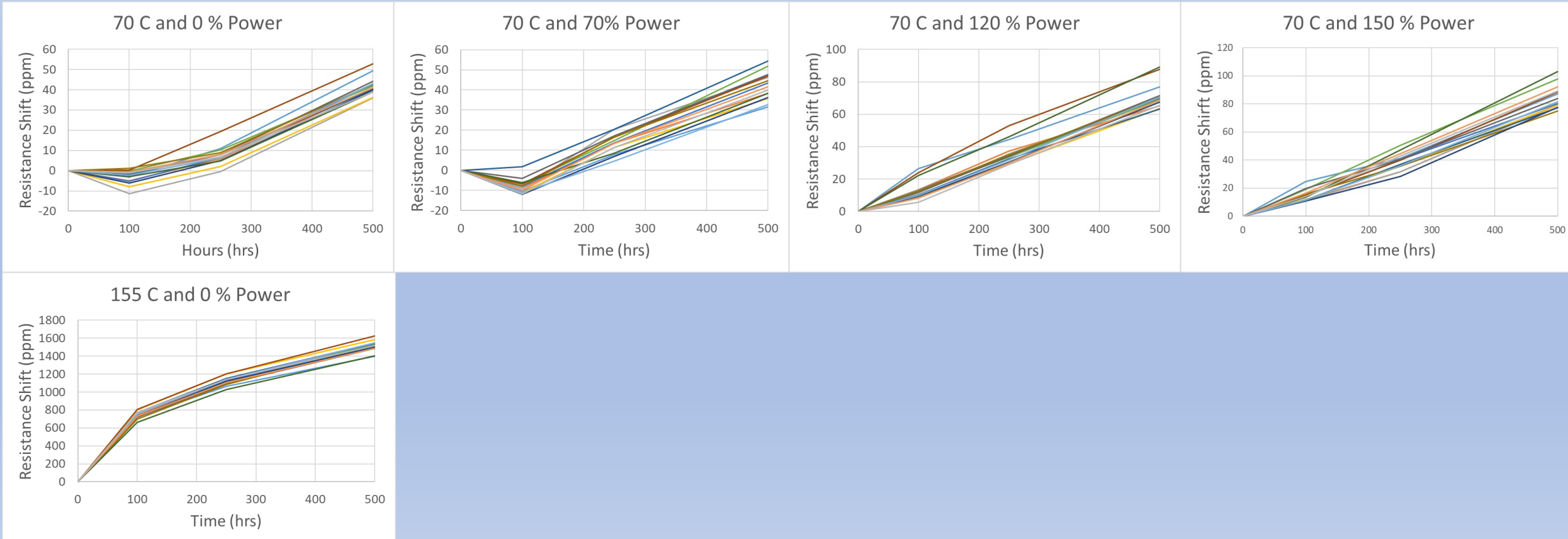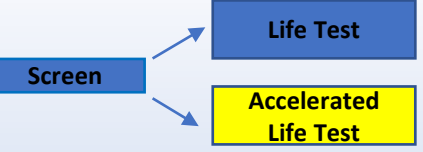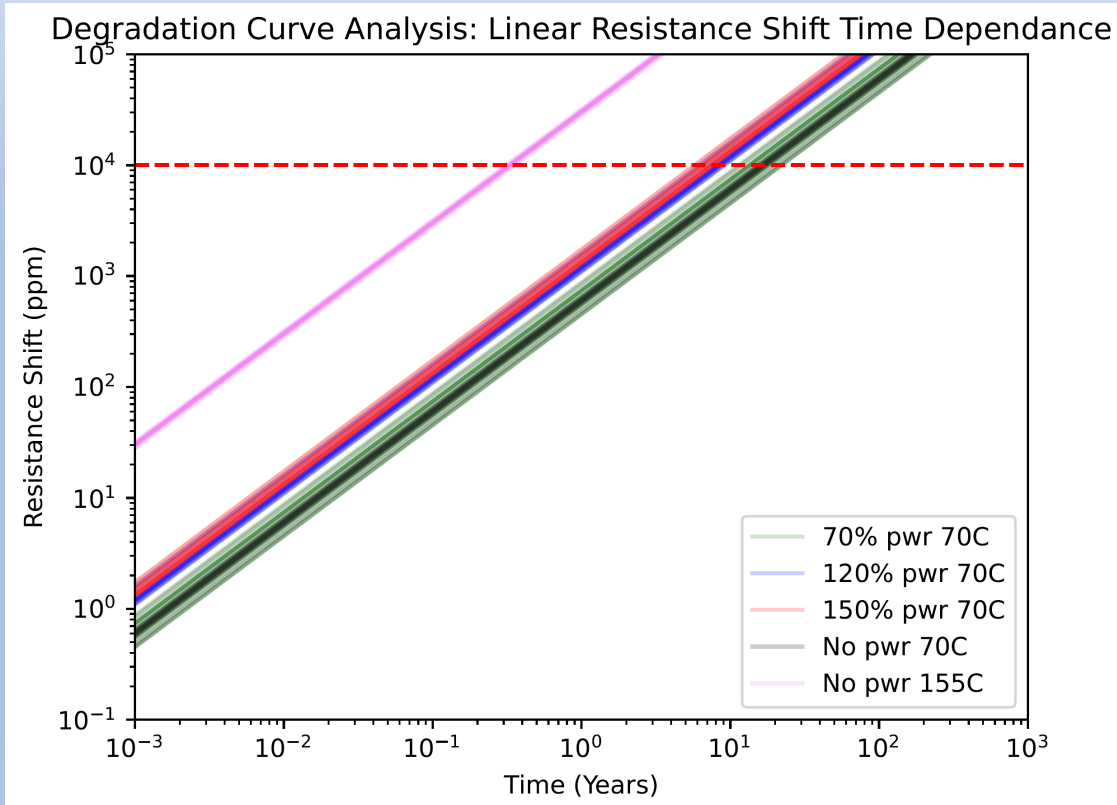
Accelerated Life Test Data/Results : Group E

Resistance data has been corrected for ambient lab temperature using the measured Temperature Coefficient of Resistance (TCR) close to room temperature.
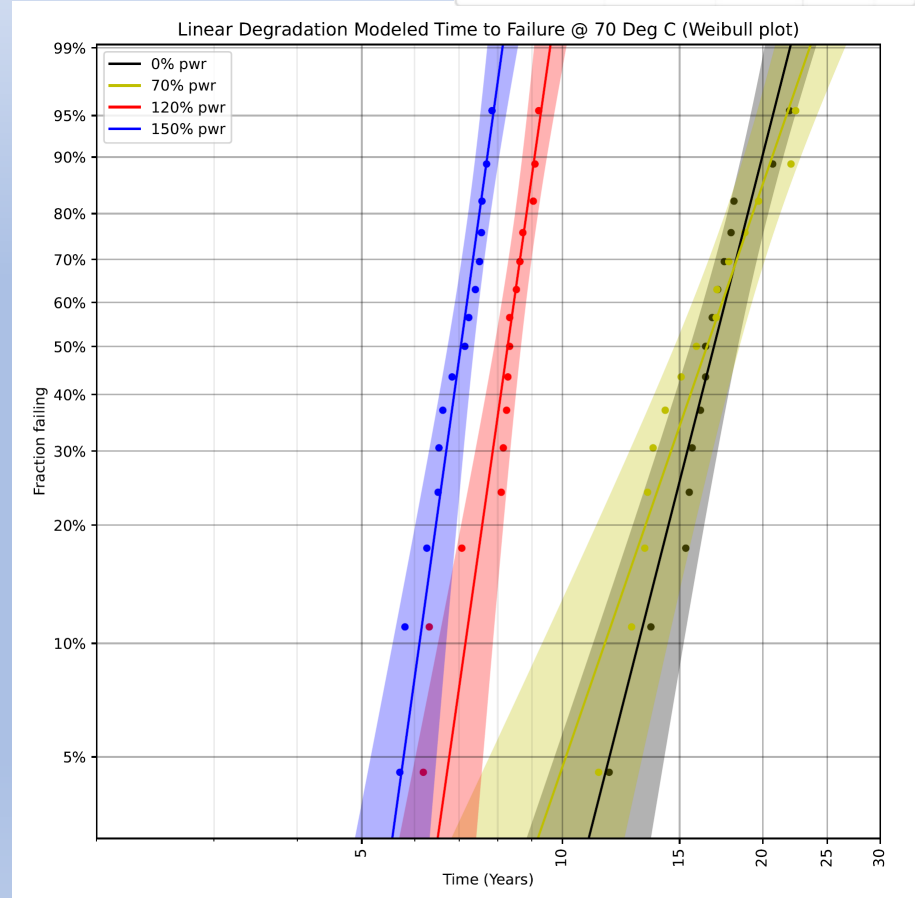

70 C and 0 % Power

70 C and 70% Power

70 C and 120 % Power

70 C and 150 % Power

155 C and 0 % Power

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Accelerated Life Test Data/Results : Group E

Projected failure times are from where degradation curves meet the 1% shift failure threshold.

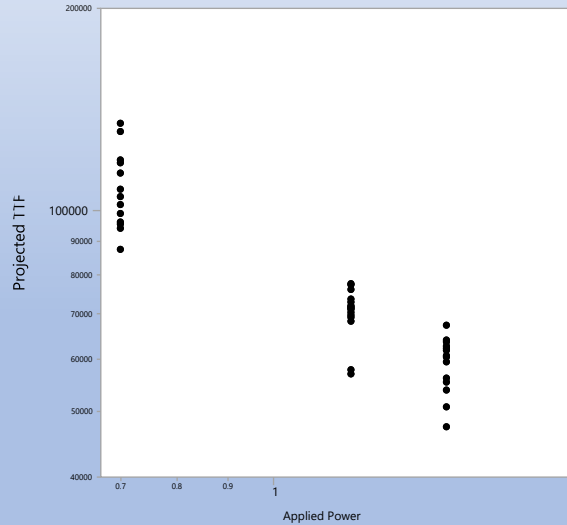Projected failure times fit to Weibull distributions and plotted on probability paper. [8]

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Accelerated Life Test Power Dependance : Group E

Data Scatter Plot

Acceleration Factor Plot

Cox-Snell Residual P-P Plot

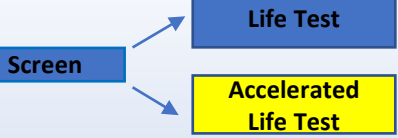$$\text{TTF}_{50\%} = e^{\beta_0} P^{\beta_1} = 80740 \cdot P^{-0.77}$$
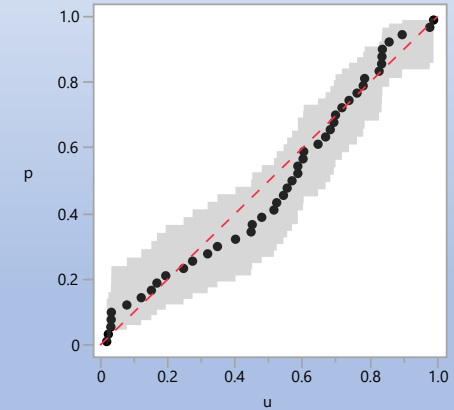
$$R(t) = 1 - \Phi\left(\frac{\ln t - \mu}{\sigma}\right)$$

Inverse Power Law Model Estimates

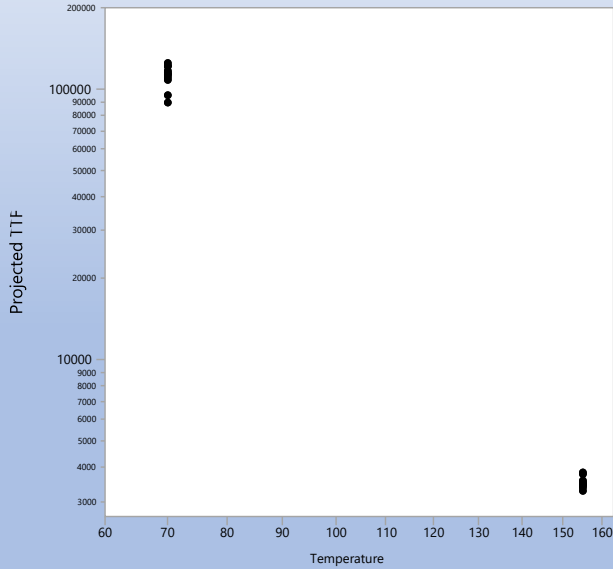| Parameter	Estimate	Std Error	95% Confidence Interval (Wald) Lower	95% Confidence Interval (Wald) Upper
β_0	11.29873	0.01613825	11.26710	11.33036
β_1	-0.77079	0.04904206	-0.86691	-0.67467
σ	0.10525	0.01109435	0.08351	0.12699

$$\mu = 11.29873 - 0.7707909 \cdot \text{Log}(\text{Applied Power})$$

Accelerated Life Test Basic Arrhenius Temperature Dependance : Group E

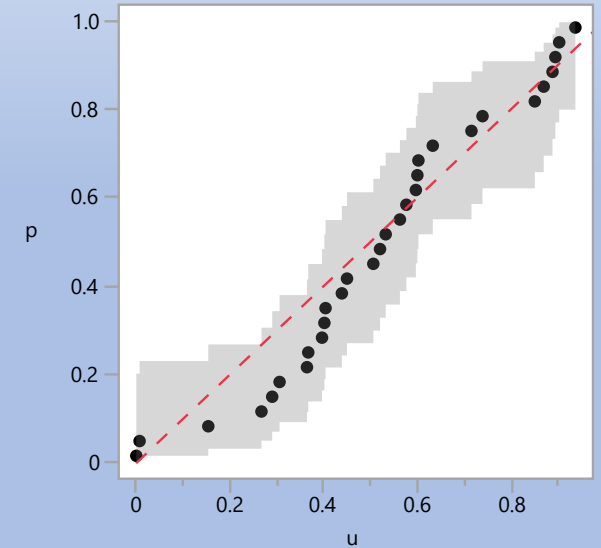**Life Test**

Screen

Accelerated Life Test

Data Scatter Plot

Acceleration Factor Plot

6.84317

112.5

Temperature

Cox-Snell Residual P-P Plot

Arrhenius Celsius Law Model Estimates

	95% Confidence Interval (Wald)			
Parameter	Estimate	Std Error	Lower	Upper
β0	-5.821685	0.11521687	-6.047506	-5.595864
β1	0.516057	0.00375971	0.508688	0.523425
σ	0.069128	0.00892432	0.051636	0.086619

$$\mu = -5.821685 + \left(\frac{0.5160565 \cdot 11604.518122}{\left(\text{Temperature} + 273.15 \right)} \right)$$

$$\text{TTF}_{50\%} = e^{\beta_0} e^{\frac{\beta_1}{K_B T}}$$
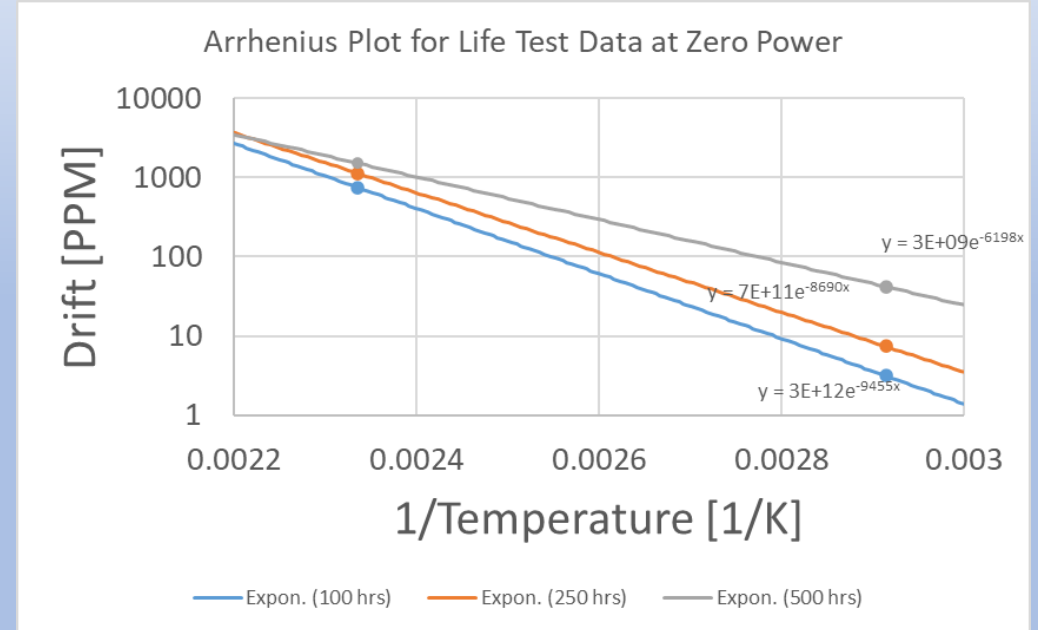
$$R(t) = 1 - \Phi\left(\frac{\ln t - \mu}{\sigma} \right)$$

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Modified Arrhenius Temperature Dependance Model[9]: Group E

Avg. Resistance Shift [ppm]	100 hrs	250 hrs	500 hrs
70 Deg C	-3.140	7.376	41.917
155 Deg C	745.7	1125.6	1512.9

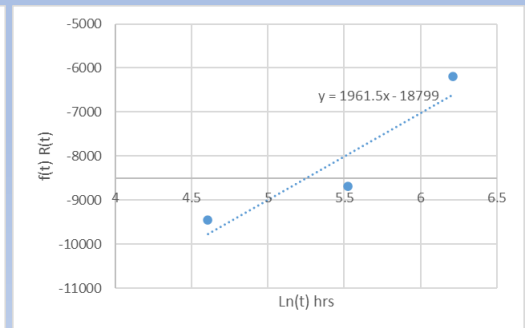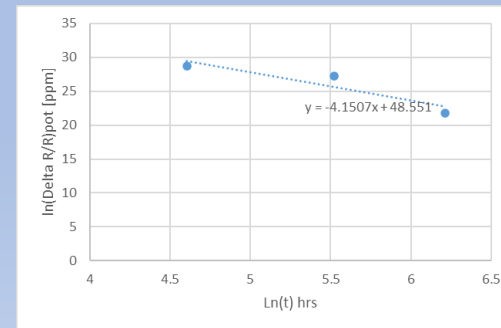$$\ln\frac{\Delta R}{R}[ppm] = f(t)R[ppm*K] * \frac{1}{T} + \ln\left(\frac{\Delta R}{R}\right)_{pot}(t)[ppm]$$

$$\ln(\Delta R/R)_{pot}(t) = D * \ln(t) + F = -4.151\ln(t) + 48.55$$

$$f(t)R(t) = B * \ln(t) + C = 1961.5\ln(t) - 18799$$

yields

$$\ln\frac{\Delta R}{R}[ppm] = (1961.5\ln(t) - 18799) * \frac{1}{T} - 4.151\ln(t) + 48.55$$

Arrhenius Plot for Life Test Data at Zero Power

$y = 3E+09e^{-6198x}$
$y = 7E+11e^{-8690x}$
$y = 3E+12e^{-9455x}$

Expon. (100 hrs) — Expon. (250 hrs) — Expon. (500 hrs)

$y = -4.1507x + 48.551$

$y = 1961.5x - 18799$

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Summary and Future Work

- A single electrical failure was observed during the Screening Test (Group A, Serial Number 51) after the thermal shock test, with a out of tolerance DC resistance per the datasheet specifications. All remaining samples passed DC resistance measurements per the datasheet specification limits.

- Life Test based models show that some automotive resistors are likely to last 10 years at nominal usage conditions while others might fail earlier. The earliest projected time to failure in our data set is 2.5 years for the Group C samples, another early projected failing group are Group A samples with the earliest failure of 3.7 years.

- Extending of Life Tests is recommended to ensure that the proposed degradation models accurately reflect real long-term operating behavior.

- *Future Work*--> European Space Agency (ESA) Space Passive Component Days (SPCD) 2024 Conference
  - Abstract accepted, drafting final paper and presentation.

- *Future Work*--> Accelerated Life Test: Hot spot analysis on boards and resistors. Finishing accelerated life tests and analysis. 85 ℃ and 125 ℃ Life Tests can help confirm temperature dependance acceleration models. Combining Power and Temperature stress models for the Group E resistor. Finish Group I accelerated testing and analysis.

- *Future Work*--> Life Test: Extend Life Tests of resistors and perform construction analysis on selected thin film and thick film automotive resistors to compare against MIL-STD equivalents.

- *Future Work* --> Screening: Pulsed Power Screening tests of automotive resistors with thermal imaging.

Acknowledgements

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https://ntrs.nasa.gov/api/citations/20220018183/downloads/20220018183.pdf

[2] *Stress Test Qualification for Passive Components.* AECQ -200 Rev. E. Automotive Electronics Council. March 2023.

[3] *Instructions for EEE Parts Selection, Screening, Qualification, and Derating*. EEE-INST-002*. NASA/TP—2003–212242. NASA Goddard Space Flight Center. April 2008.

[4] *Department of Defense Test Method Standard, Method 303, DC Resistance*. MIL-STD-202-303 Rev. H. Defense Logistics Agency. April 2015.

[5] *Department of Defense Test Method Standard, Method 107, Thermal Shock.* MIL-STD-202-107 Rev. H. Defense Logistics Agency. April 2015.

[6] *General Specification for Resistor, Chip, Fixed, Film, No established Reliability, Established Reliability, Space Level.*
  MIL-PRF-55342 Rev. J. Defense Logistics Agency. May 2021.

[7] *Specification for the Performance of Destructive Physical Analyses*. S-311-M-70 Rev. D. NASA Goddard Space Flight Center. June 2015.

[8] Reid, M. (2022). Reliability – a Python library for reliability engineering (Version 0.8.2) [Computer software]. Zenodo.
https://doi.org/10.5281/ZENODO.3938000

[9] R. W. Kuehl, *"Stability of thin film resistors - Prediction and differences base on time-dependent Arrhenius law,"* Microelectronics Reliability 49, pp. 51-58, 2009.

[10] T. Epp Schmidt et al, *"Long-Term Tin Whisker Risk Mitigation using a Conformal Coating."* NASA Goddard Space Flight Center NEPP Electronics Technology Workshop. June 2023.
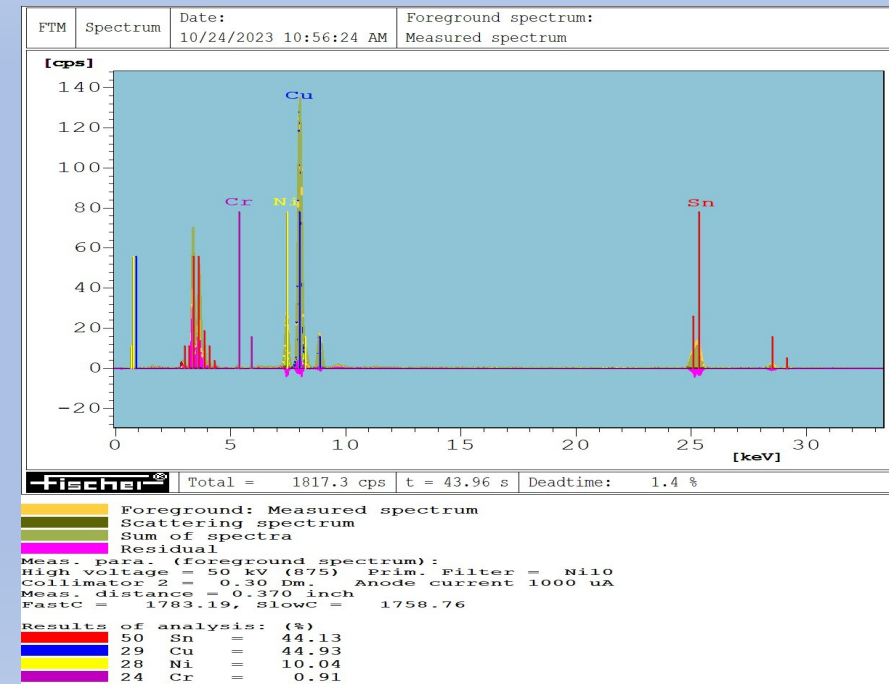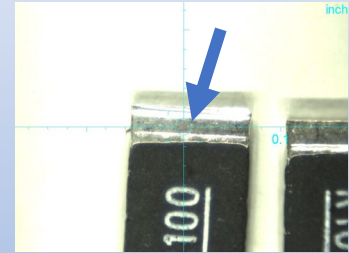
Backup

Backup – Screening Test Data/Results: Prohibited Material Analysis
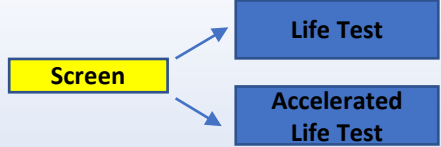
• Prohibited Material Analysis (PMA) was performed on 3 samples per part number/group.

• Pure Tin (Sn) plating was observed on the terminations of various part numbers.

• Due to the possibility of tin whisker growth on pure tin-plated surfaces, pure tin plating on terminations has been prohibited historically from use in space applications. However, pure Tin coated terminations are standard for automotive and commercial grade parts.

• While GSFC S-311-M-70 [7] considers the use of Tin (Sn) finishes containing < 3 % wt. Lead (Pb) as a failure, the use of conformal coating is an accepted technique by NASA for whisker growth mitigation and has been shown effective at capturing long-term whisker growth. [10]

• EEE parts such as these with pure tin terminations can be used in NASA applications with appropriate whisker mitigation practices are used.
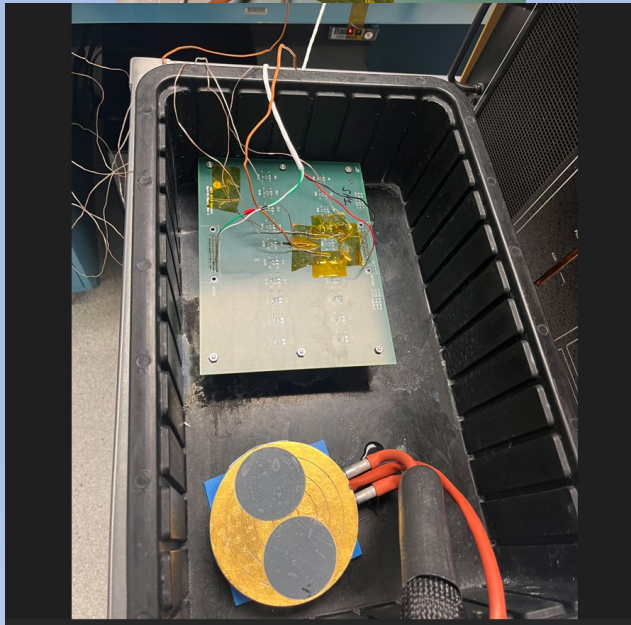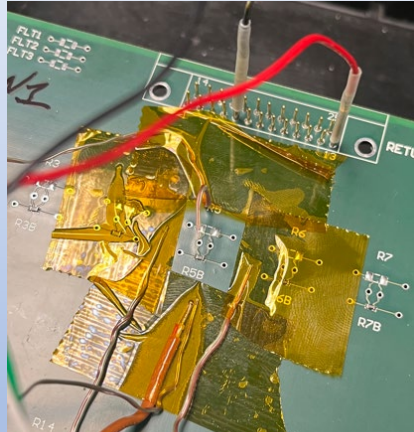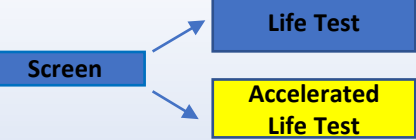

PMA on terminations of a Group A sample

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Backup – Life Test Criteria : Delta R

Group ID	Delta R
A	± (1.0 % + 0.0005 Ω)
B	± (1 % R + 0.05 Ω)
C	± (1.0%+0.05Ω)
D	± (0.5 % R + 0.05 Ω)
E	± (0.1%+0.05Ω)
F	± (0.05 % R + 0.01 Ω)
G	± (0.1%+0.05Ω)
H	± (1 % R + 0.05 Ω)
I	±3 %

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Backup – Group E, TCR

Screen → Life Test / Accelerated Life Test

TCR Measurement Setup

Group E, SN 5

$$y = -0.006x + 999.93$$
$$R^2 = 0.9098$$

Resistance (Ω) vs Temperature (°C)

Group E, SN 6

$$y = -0.006x + 1000.5$$
$$R^2 = 0.8961$$

Resistance (Ω) vs Temperature (°C)

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