Evaluation of Feed-Through Polymer Tantalum Capacitors for Space Applications

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Abstract

In 2023 AVX developed a new technology of feed-through capacitors that can be used for high (up to GHz range) frequency signal filtering for FPGA, microswitches or micro-DC-DC converters as a replacement for the currently used MLCCs. This part is a Low Inductance Bulk Capacitor (LIBC). It has low ESR and insertion loss values and is manufactured using technology similar to chip polymer tantalum capacitors and have.

The purpose of this work is to evaluate the design and performance of the parts using engineering samples from AVX, address potential reliability issues, and suggest screening and lot acceptance procedures necessary to use these capacitors in space projects.

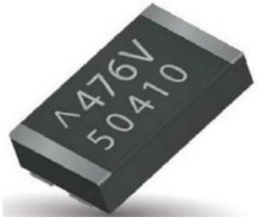
List of Acronyms

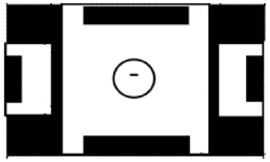
3D	three-dimensional	**HTS**	high temperature storage
AC	alternative current	**IM**	infant mortality
ACC	anomalous charging current	**LIBC**	low inductance bulk capacitor
AF	acceleration factor	**PST**	power surge test
BI	burn-in	**PWB**	printed wiring board
CA	construction analysis	**SS**	sample size
CCS	constant current stress	**TC**	temperature cycling
DC	direct current	**TPC**	tantalum polymer capacitor
DCL	DC leakage	**TTF**	time to failure
DF	dissipation factor	**UL**	useful life
EDS	energy dispersive spectroscopy	**VBR**	voltage breakdown
ESR	equivalent series resistance	**VR**	voltage rating
HALT	highly accelerated life testing	**WO**	wear-out
HP	Hewlett Packard		

Outline

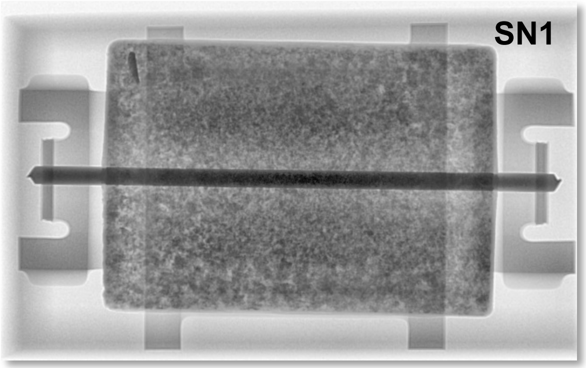
- Construction analysis
- Insertion losses
- AC characteristics
- Leakage and absorption currents
- Reliability assessments using HALT
- Breakdown voltages
- Anomalous charging currents
- Assessments of Maximum Direct Current
- Suggestions for screening and lot acceptance testing

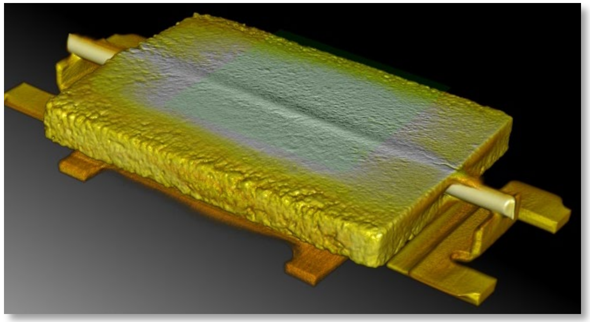
CA: Radiography

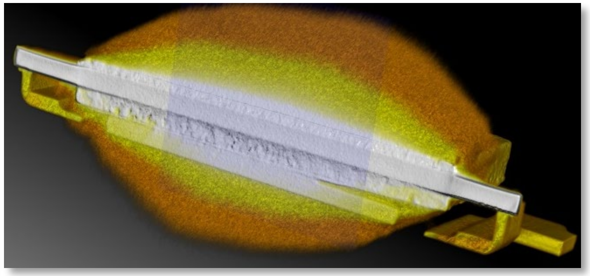


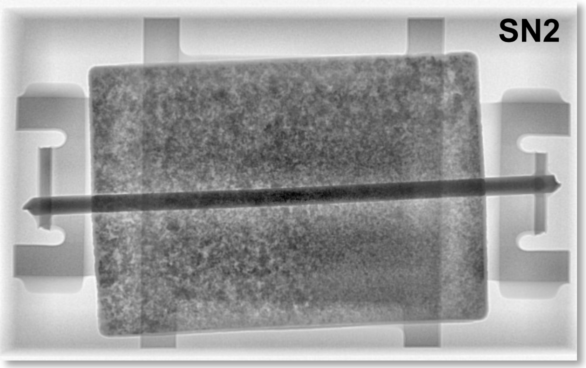


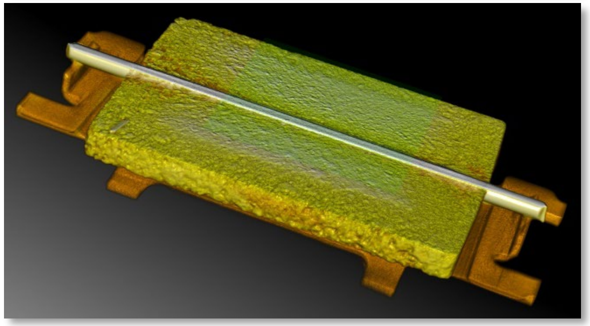
- CA was carried out using two samples and included radiography, 3D X-ray, cross-sectional examinations and EDS

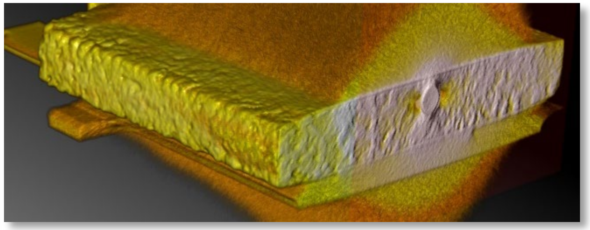






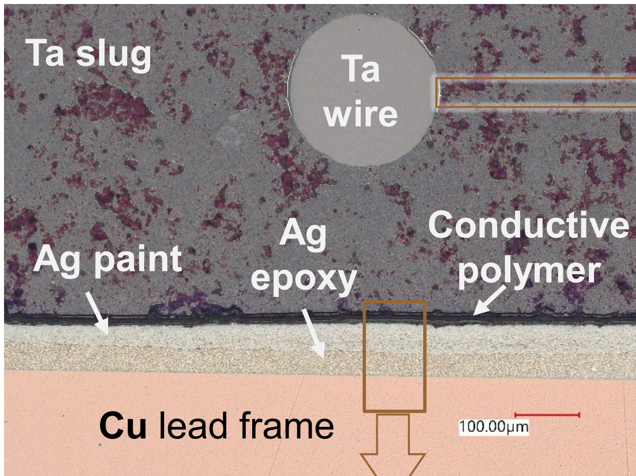


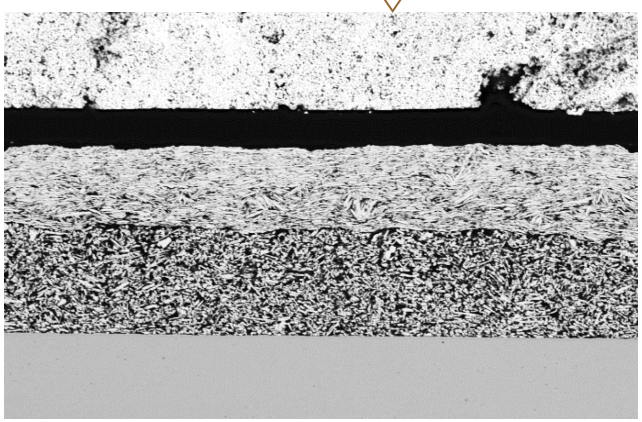


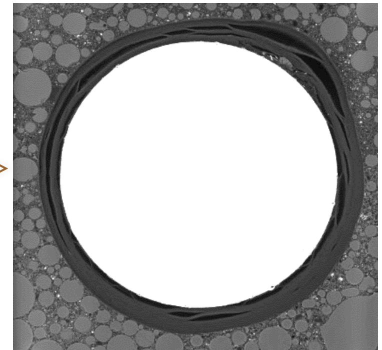


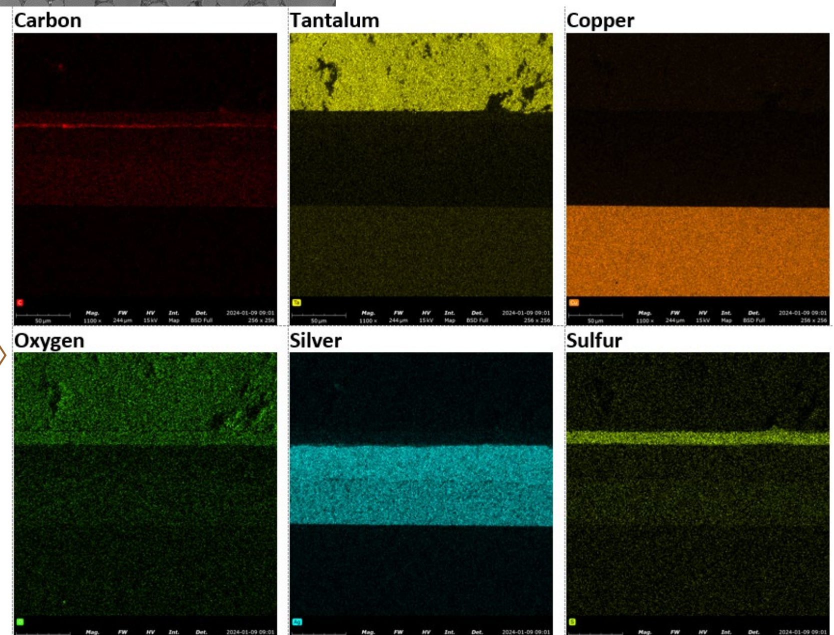
✓ No anomalies except for some misalignment of the through wire in SN2

CA: Cross-Sectioning

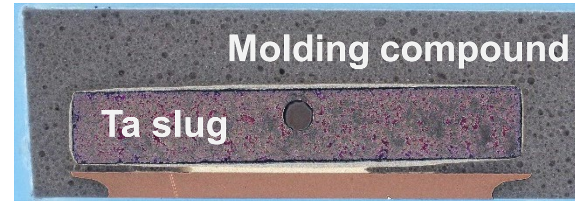








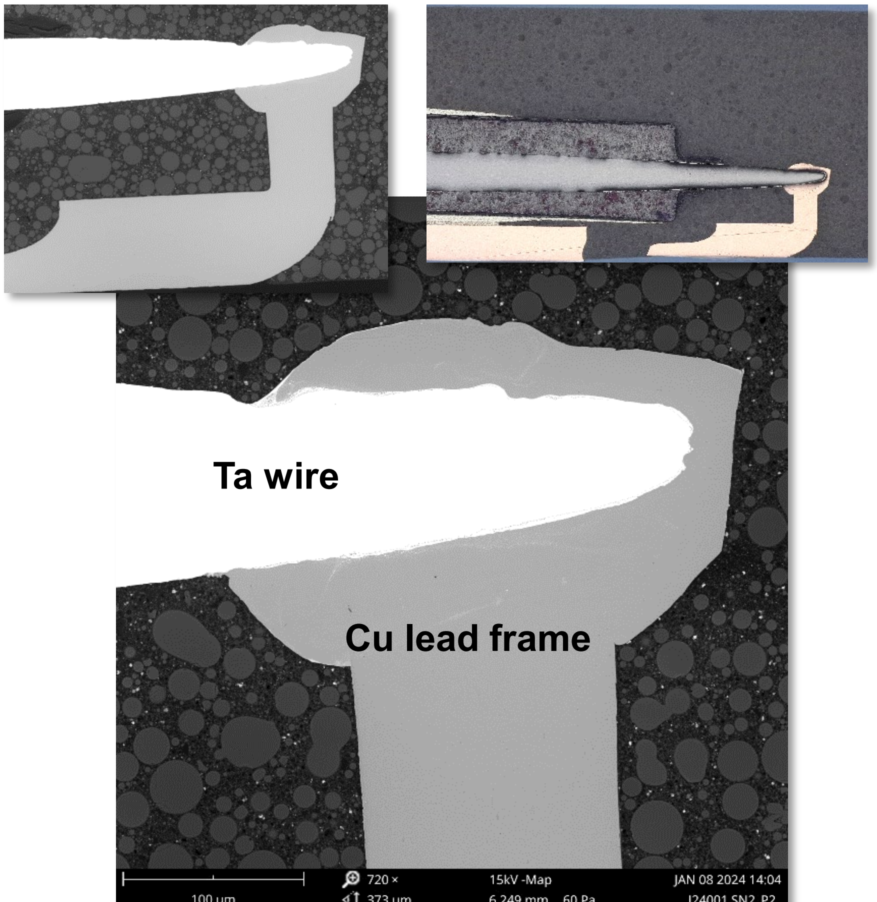
Across the leads

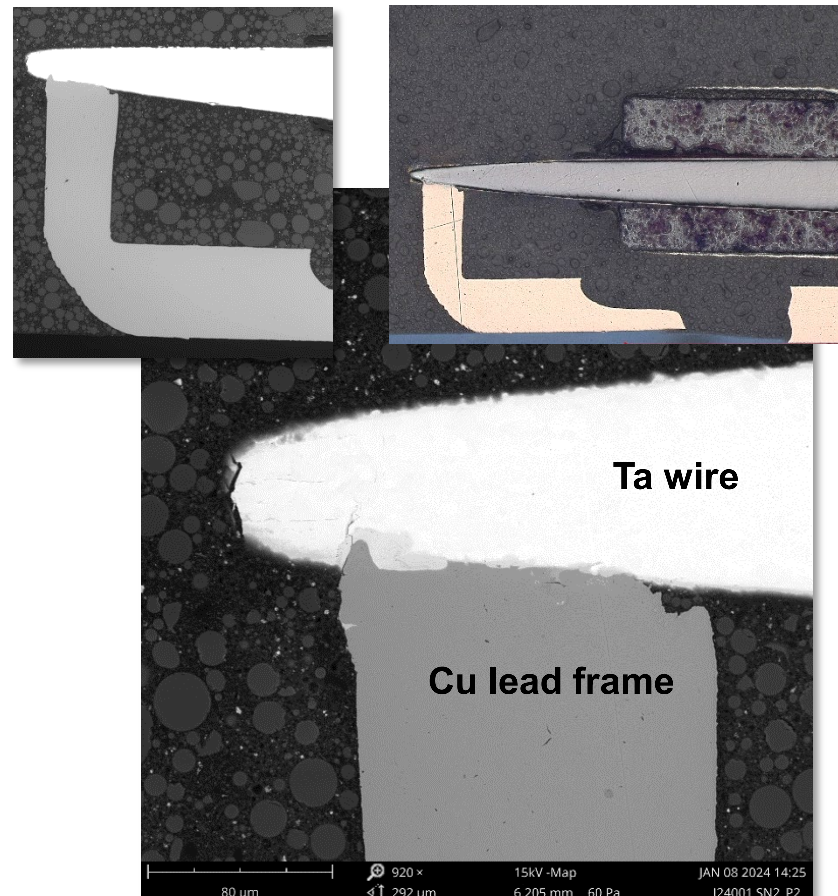


Along the leads

- ✓ Tantalum wire length is 6.5 mm and diameter 0.24 mm
- ✓ Separation between layers of conductive polymer cathode that is also typical for PTCs
- ✓ A thin carbon layer separated silver paint and conductive polymer

CA: Wire Welding

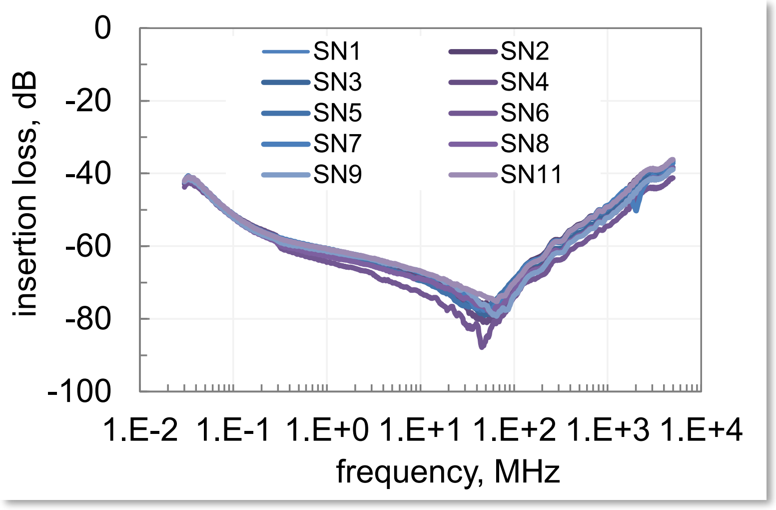


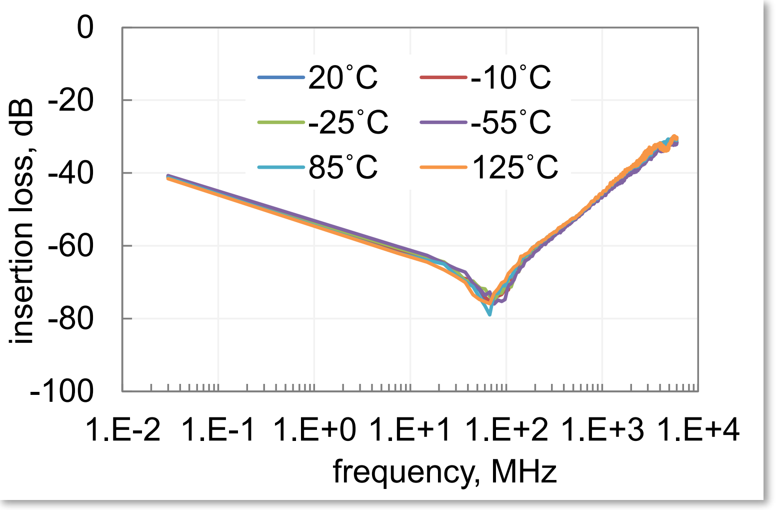


✓ Adequate welding between tantalum wire and copper lead frame

Insertion Losses

- The losses were measured in the frequency range from 30 kHz to 6 GHz using an HP vector network analyzer VNA 8753E

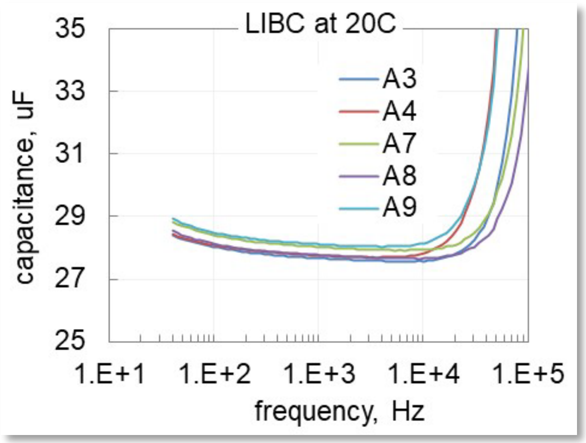


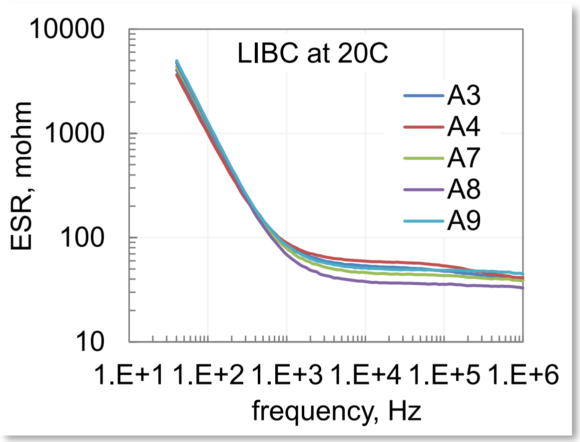


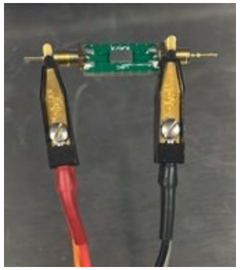
- ✓ Insertion losses are reproducible from sample to sample
- ✓ Forward power transmission S21 does not change significantly with temperature in the range from -55 °C to +125 °C

AC Characteristics

- Frequency dependencies of capacitance and ESR were measured using Agilent impedance analyzer 4294A





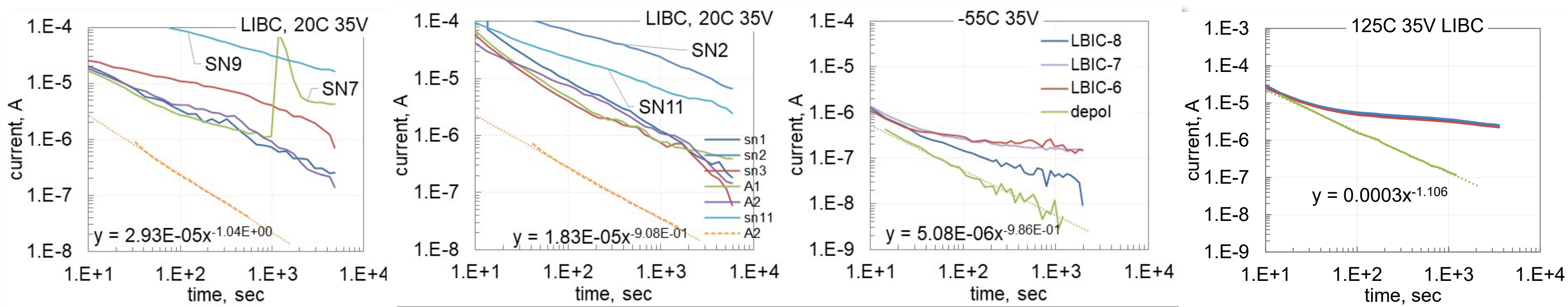


- ✓ Capacitance and DF at 120Hz were 29.7 ±0.2 uF and 2.85 ±0.2%. ESR at 100 kHz was 45 ±15 mOhm
- ✓ One-week bake at 100 °C reduced capacitance by 4.8 ±0.4%, but DF and ESR did not change significantly

Leakage Currents

- Twelve parts were mounted onto test PWB and baked for 10 days at 100 °C
- Relaxation of currents was monitored at room conditions for 1 hour at 35 V and for 20 min during depolarization at 0 V

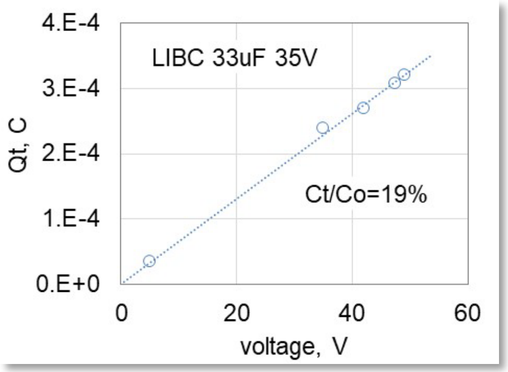
Polarization (solid lines) and absorption (approximated with a power function) currents

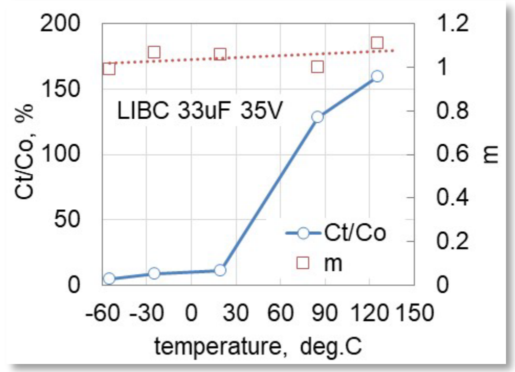


- ✓ DCL was within the specified limits; however, three out of 12 parts had out-of-family samples with currents increased by more than an order of magnitude
- ✓ Leakage currents exceed absorption currents even at -55 °C
- ✓ One sample, SN7, had a scintillation event after ~ 15 min at 35 V, 20 °C

Absorption Capacitance

- Polarization and depolarization currents were measured with time at temperatures from -55 to +125 °C
- Depolarization currents follow Curie–von Schweidler law, $I(t) = I_0 \times t^{-m}$, $m \sim 1$
- Absorption capacitance was calculated at different polarization voltages V and temperatures as: $C_t = \frac{Q_t}{V} = \frac{I_0}{[V(1-m)]} t^{(1-m)} \Big|_{1E0}^{1E4}$



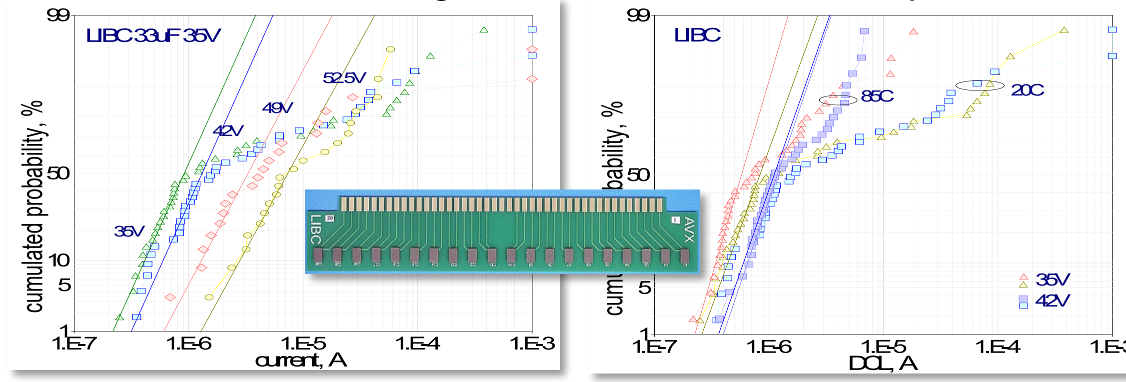


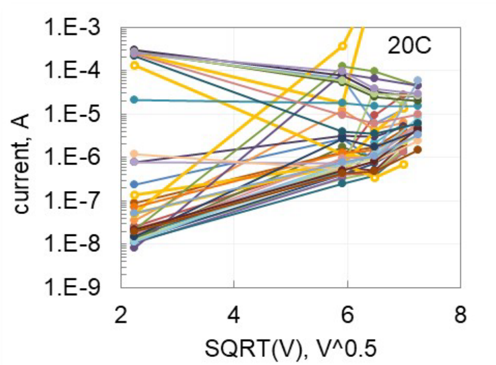
- ✓ At 20 °C, Q_t increases linearly with voltage resulting in $C_t \approx 0.2C_o$
- ✓ Absorption currents increased substantially at HT. This resulted in increasing of the absorption capacitance from ~5% to more than 120% of C_o at T > 85 °C.
- ✓ The exponent *m* does not change substantially with temperature indicating that the distribution of traps remains stable

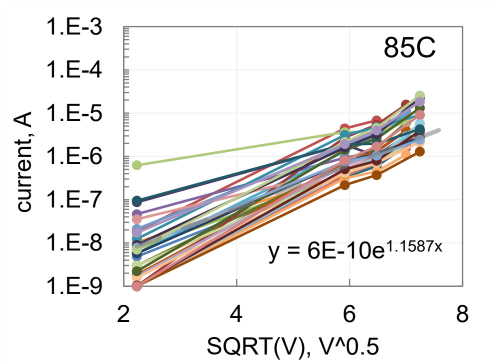
Effect of Voltage and Temperature on DCL

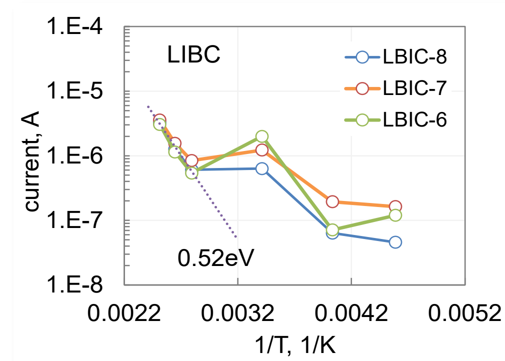
- ❑ Leakage currents were measured after reflow soldering onto test PWBs
- ❑ Assuming DCL_{max} = 0.1CV = 115 μA, ~ 10% of the lot failed at 20°C

Effect of voltage *Effect of temperature*





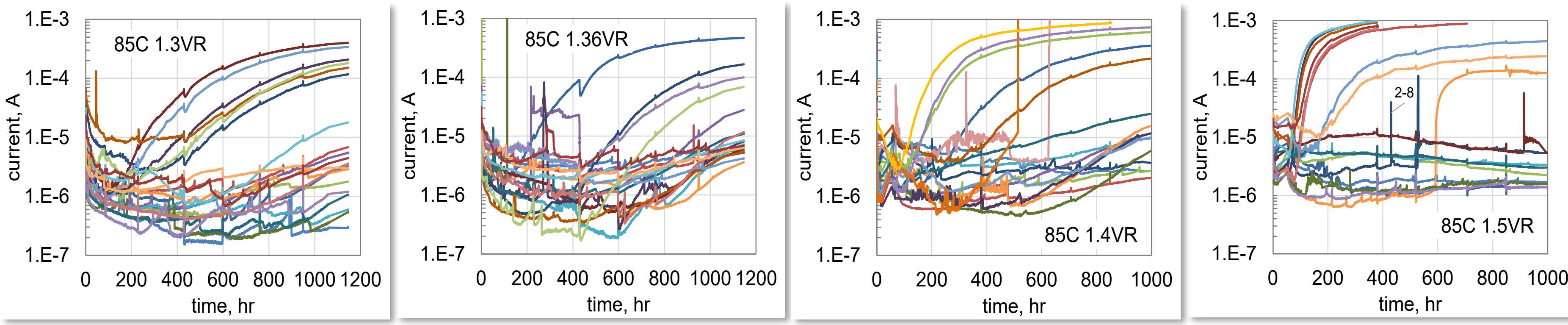




- ✓ The spread of leakage currents indicates insufficient control during manufacturing
- ✓ Leakage currents at 85 °C were less than at 20 °C due to of anomalous transients
- ✓ Voltage dependence of leakage currents indicates Schottky mechanism of conduction
- ✓ Based on measurements of leakage currents in the range from 85 to 125 °C E_a = 0.52 eV, which is between E_a for 10V (~0.2eV) and 60V (~0.8eV) for PTCs

HALT

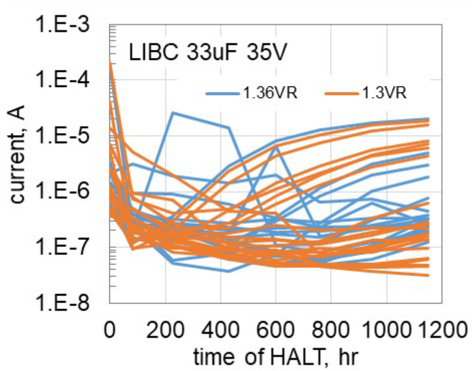
- HALT at 85 °C was carried out by monitoring leakage currents at voltages $u = V_{stress}/VR$ = 1.3, 1.36, 1.4, 1.5, and 1.7 using 20 samples soldered onto a test PWBs.
- The increase of currents was limited by the current sense resistors (10 kohm)

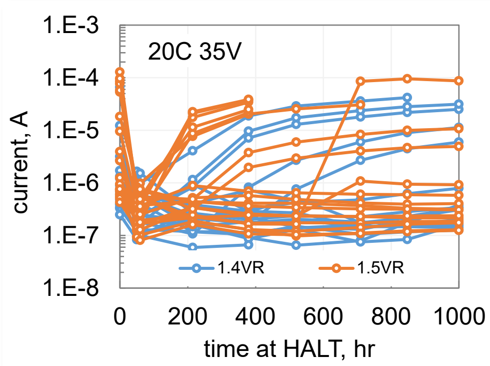


- ✓ At *u* < 1.7 only 4 catastrophic failures were observed: 2 during *u* = 1.36 (at 1 and 113 hr) and 2 at *u* = 1.4 (at 514 and 626 hr). There were 11 catastrophic failures at *u* = 1.7 that occur before 136 hours.
- ✓ In many cases, currents were unstable and had spikes caused by scintillation breakdowns.
- ✓ Most of the parts (up to 90%) had a tendency of gradual increasing of currents with time.

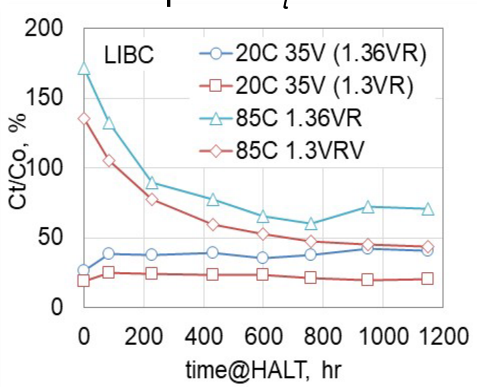
Effect of HALT on DCL

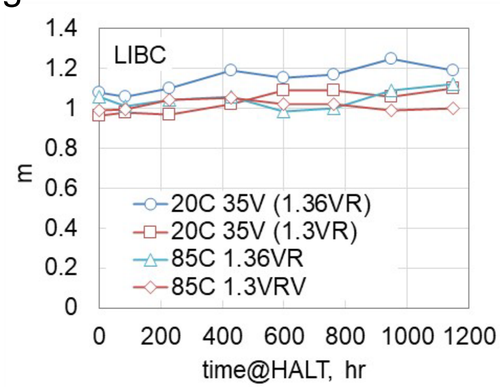
- ❑ Polarization and depolarization currents were measured at 20°C and 35V periodically during HALT.
- ❑ Bias for 5 samples was set to 0V after 400 hours of HALT due to high level of currents.





Absorption C_t and *m* during HALT at *u* = 1.3 and 1.36

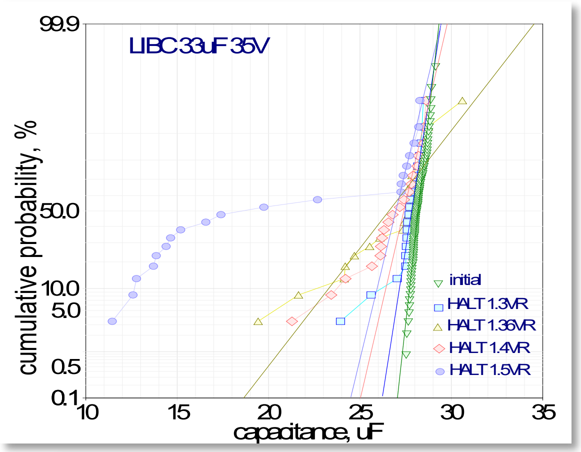


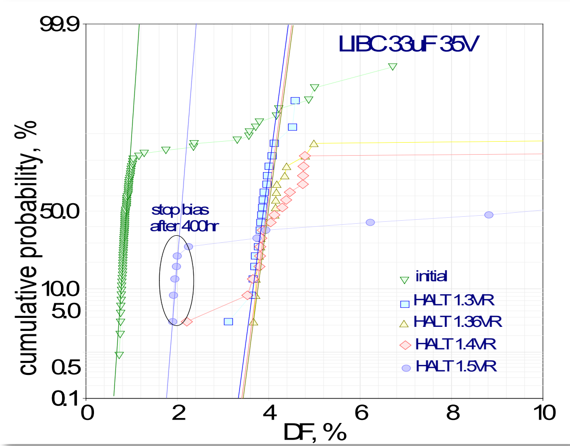


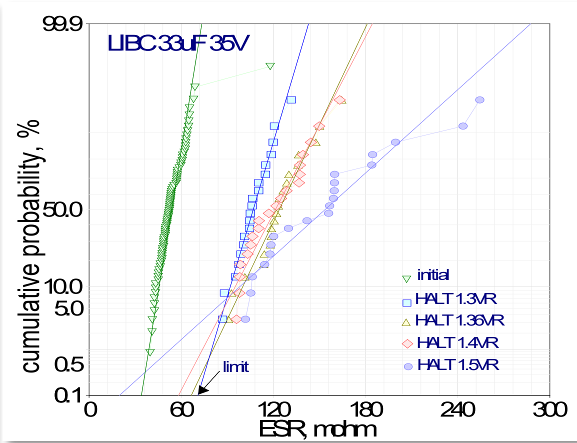
- ✓ Degradation of currents measured at room temperature was similar to degradation during HALT
- ✓ The 5 samples that were biased for 400 hours only, reduced DCL ~100 times after bake at 85C for 600 hours. This indicates that DCL degradation was reversible and was likely due to excessive concentration of oxygen vacancies in Ta2O5
- ✓ Absorption capacitance at 85 °C decreased by ~3 times during HALT, but did not change significantly at 20 °C
- ✓ The slope of absorption currents, *m*, remained stable

Effect of HALT on AC Characteristics

- Capacitance, DF, and ESR were measured before and after HALT on parts soldered onto test PWBs.



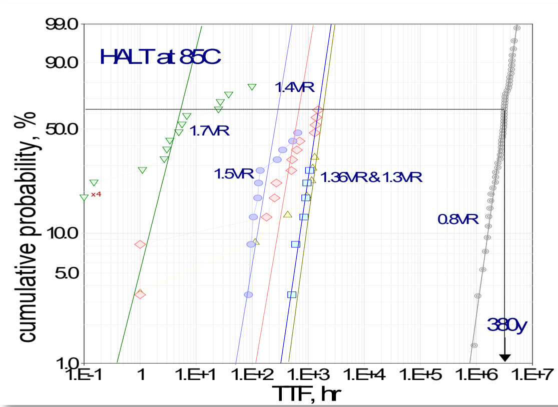


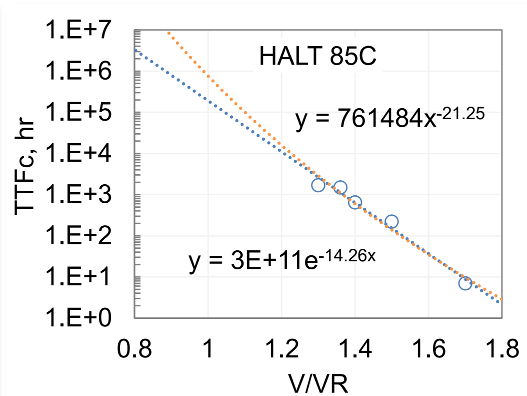


- ✓ Halt resulted in significant degradation of AC characteristics. However, there was no correlation between degradation of AC and DC characteristics
- ✓ The higher the voltage stress during HALT, the larger the proportion of parts with decreased capacitance. ~40% of samples had *C* < 15uF after HALT at 59.5V
- ✓ Approximately 15% of the parts had out-of-family DF values initially. HALT did not cause DF failures at 1.3VR, but 15% failed at 1.4VR and 50% failed at 1.5VR
- ✓ Samples that were baked after 400 hours at 1.5VR had normal DF values
- ✓ HALT resulted in increasing of ESR more than 2 times. Degradation was more significant at 1.5VR

Acceleration Factor and Useful Life

- Times-to-failure, TTF, for each part were determined as times to reach 0.1 mA
- Similar to distributions of TTF for PTCs, Weibull distributions of TTF for the feed-through capacitors indicated the presence of IM, WO and anti-WO failures
- Characteristic times of WO failures, TTF_c, were determined at each stress voltage and were approximated with power, $TTF_c \sim u^n$, and exponential, $TTF_c \sim exp[B \times u]$, functions that allowed for optimistic and conservative predictions, respectively





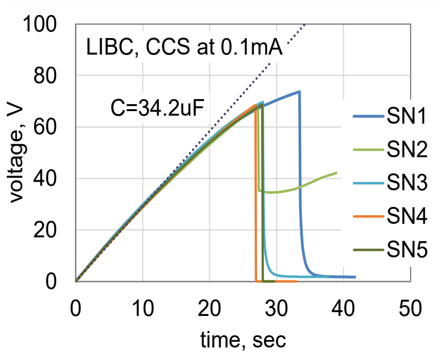
Useful Life (*UL*) was calculated as a time to failure inception (probability of WO failures = 0.1%) based on the slope of Weibull distributions, β and *TTF$_c$*:

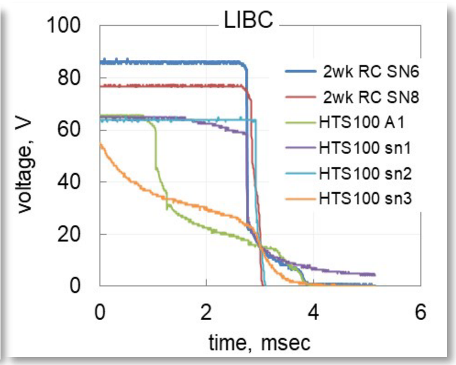
$$UL = TTFc(V,T) \times [-\ln(0.999)]^{1/\beta}$$

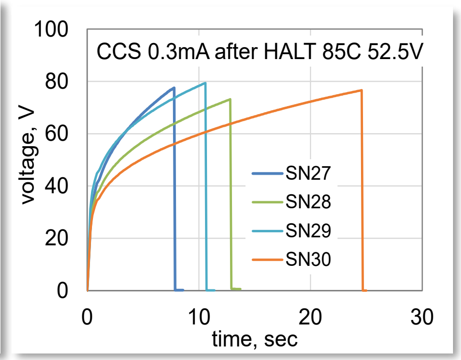
- ✓ Approximations of the $TTF_c(V)$ dependence yielded voltage acceleration constants of *B* = 14.2 and *n* = 21.2 for the exponential and power models
- ✓ Assuming β = 3.1 for WO failures at *u* = 0.8, *UL* = 41 years for the exponential and more than 1000 years for the power approximations
- ✓ Larger SS for HALT should be used to get more accurate assessments of *AF* and *UL*
- ✓ The presence of IM failures indicates the need for BI screening

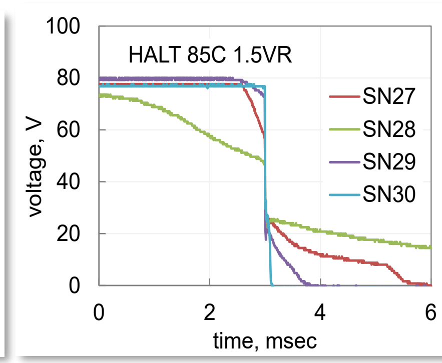
Breakdown Voltages

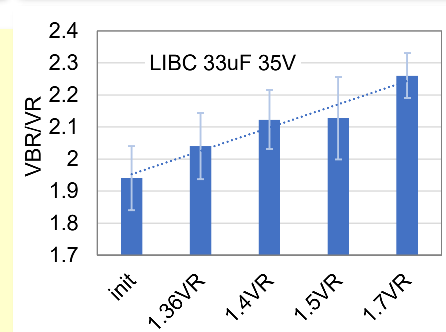
- VBR was determined using CCS testing at currents in the range from 0.1 to 1 mA.







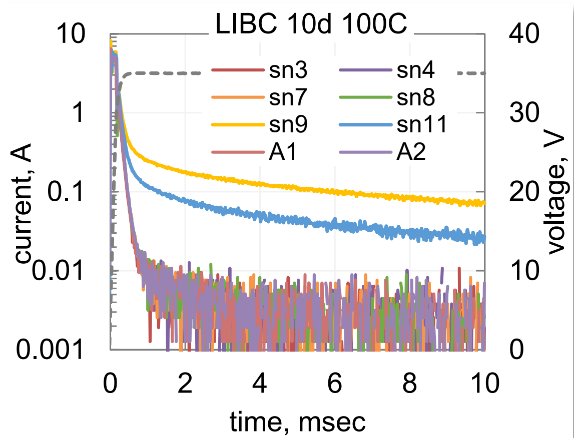


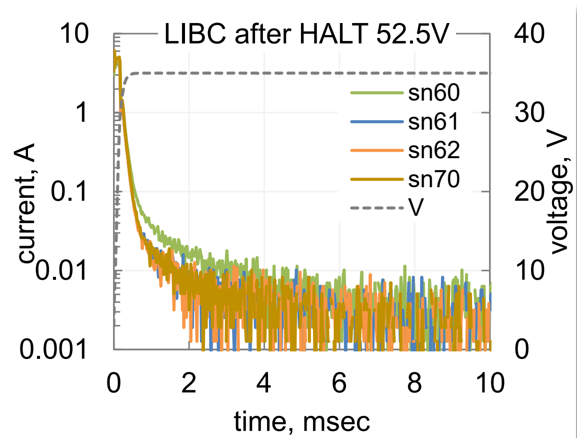


- ✓ Virgin parts had u_{BR} = *VBR/VR* = 1.94 ±0.1 and dry capacitors (after bake at 100 °C) had u_{BR} = 1.85 ±0.05 (moisture effect)
- ✓ HALT at 85 °C increased VBR. The higher the stress voltage, the greater is the rise of VBR (16% at u_{BR_HALT} = 1.7). This explains the presence of anti-WO failures
- ✓ VBR for LIBC are somewhat less than for 35V PTCs that had u_{BR} ≈ *2.2 ±0.2*
- ✓ Resistance of the parts after breakdown was in the range from units to hundreds of ohms
- ✓ Scintillations had fast and slow self-healing processes with times from 0.1 msec and up to more than 6 msec

Anomalous Charging Currents

- The level of ACC was characterized by PST and calculation of the transfer charge, Q_d, and discharge energy, U_d, using 21 samples after drying at 100 °C for 10 days and 10 samples after 1000 hours HALT at 85 °C
- For comparison, theoretical values were calculated as $Q = CV$ and $U = CV^2/2$.

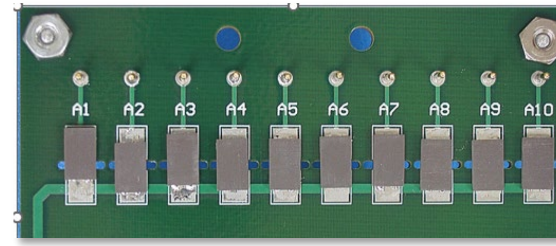




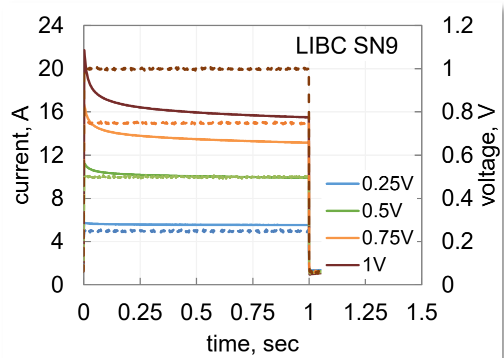
	Calculated	No ACC	Low ACC	Post HALT 52.5V
Q_d, C	1.20E-03	1.1E-3 ±2E-5	(1.7-2.6)E-3	1.05E-3 ±7.5E-5
U_d, J	2.02E-2	2.1E-2 ±8E-4	(4.2-7.4)E-2	2.2E-2 ±8.5E-4
QTY		17	4	10

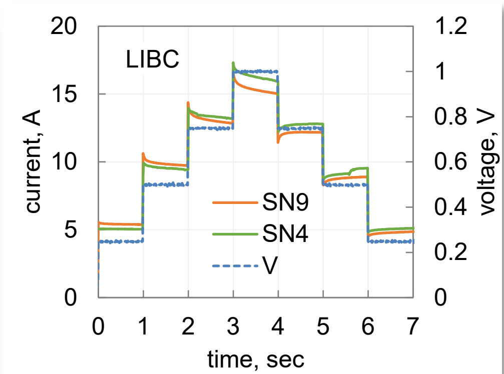
- ✓ The values of Q_d and U_d for 17 out of 21 (81%) samples were close to the theoretical values indicating no ACC
- ✓ Four samples had ACC with U_d < 0.1 J that can be characterized as a low ACC level
- ✓ Samples after HALT had no ACC

Effect of Direct Current

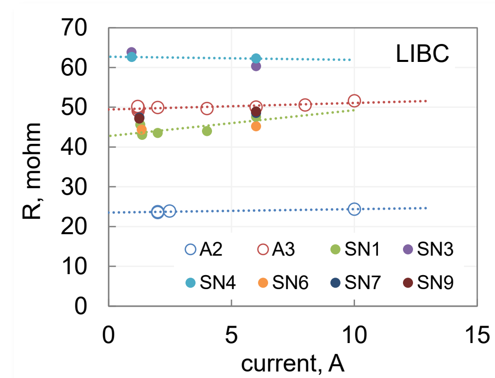


- Samples soldered onto a PWB were stressed by 1 sec voltage pulses while their currents were measured with time
- One sample failed after overstress by a 30 A pulse

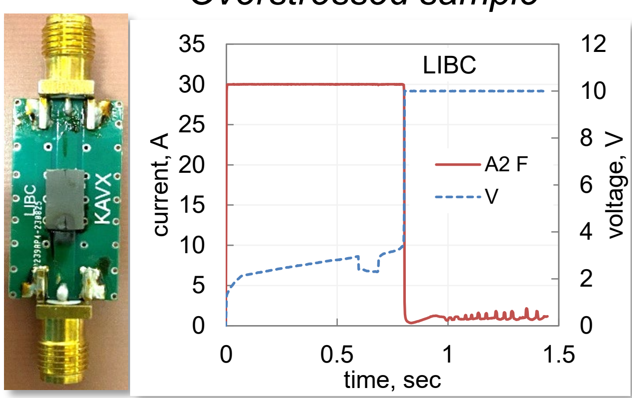




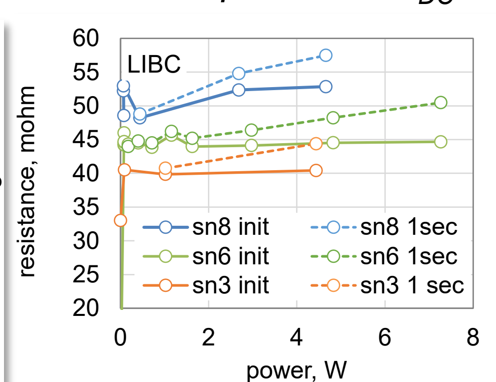
Effect of test current on R_{DC}



Overstressed sample



Initial and post 1sec R_{DC}

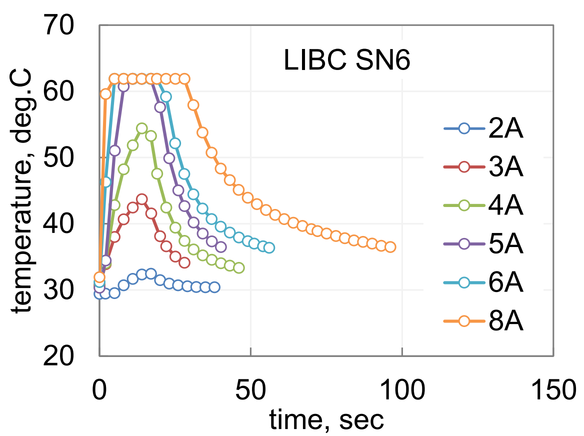


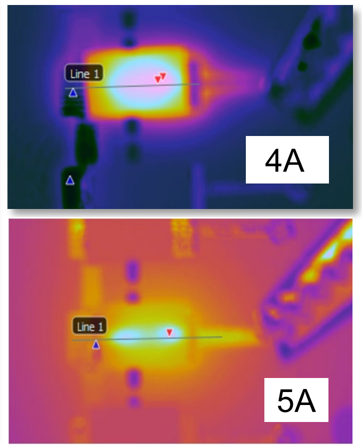
- ✓ At voltages above 0.2 V, the current exceeded 5 A and decreased with time due to self-heating of the wire
- ✓ The parts can sustain ~15 A for 1 sec, but this results in substantial overheating

Effect of Direct Current, Cont'd

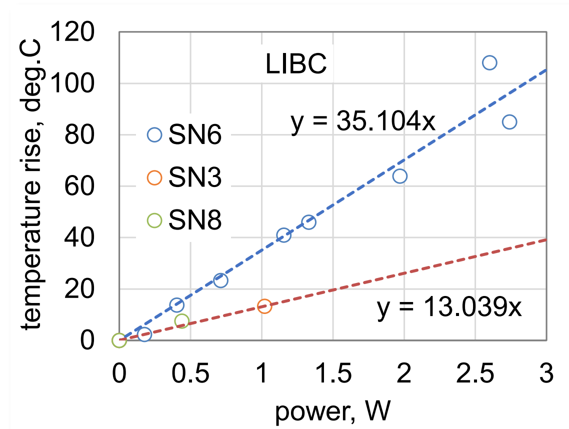
- Temperature rise during DC testing was measured with IR camera and with a Minco temperature sensor

20 sec ON/OFF power pulses, IR camera (T_{max}= 61°C)

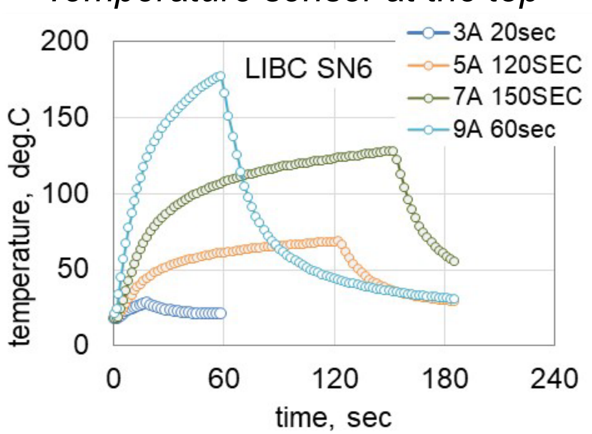




Temperature rise vs. pulse power and R_{th}

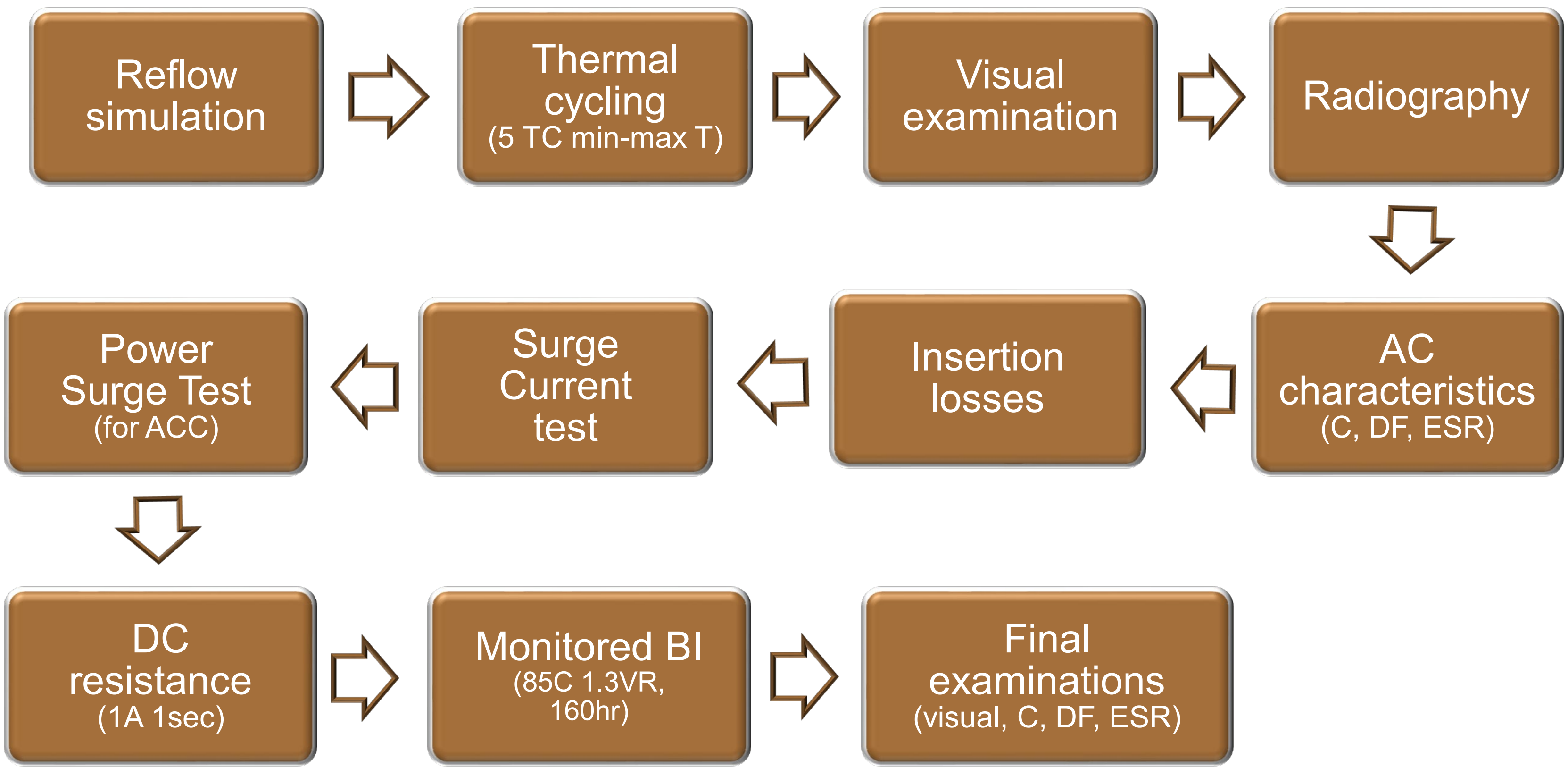


Temperature sensor at the top

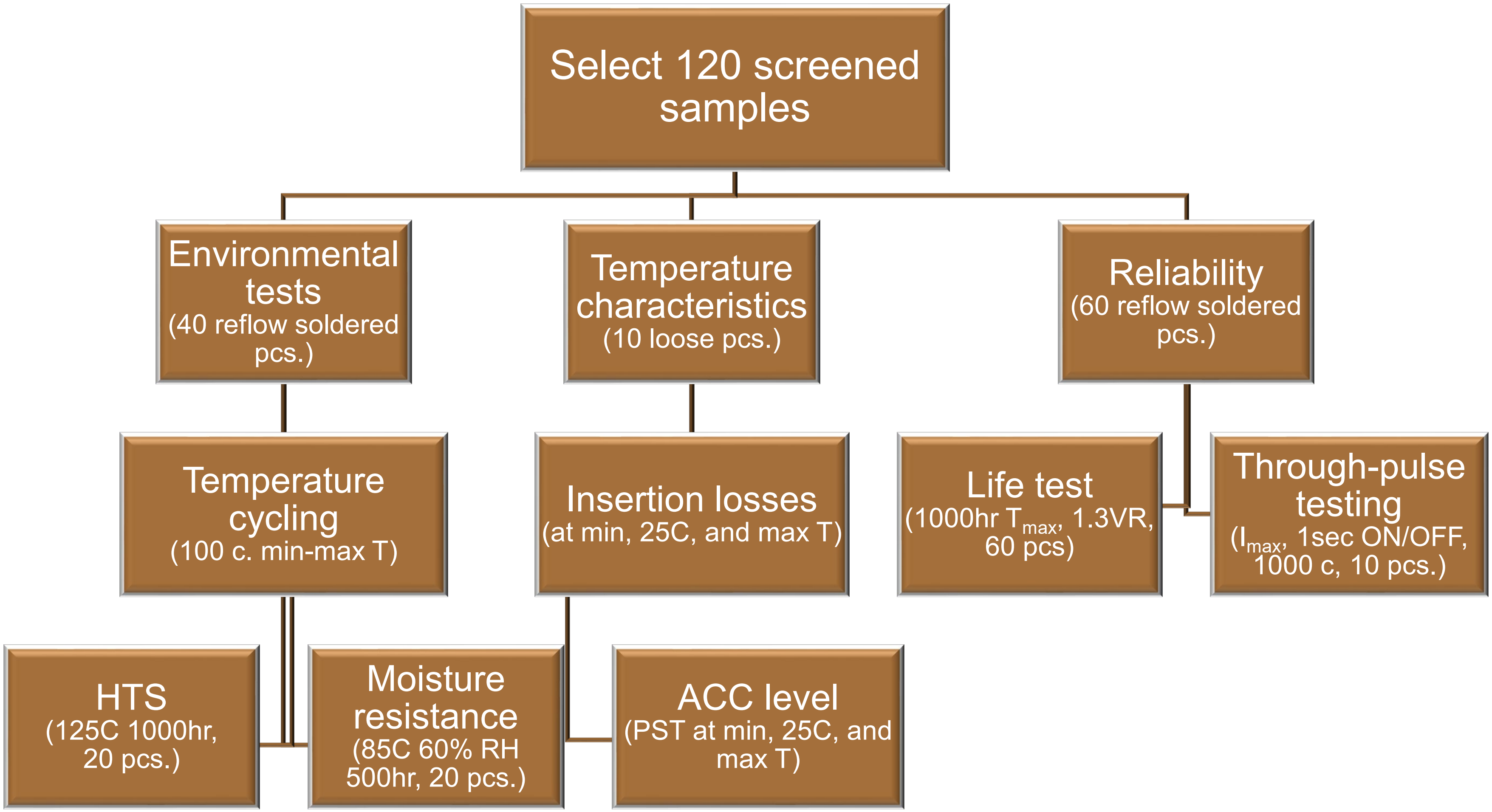


- ✓ Initially, the hottest area is at the wire welding
- ✓ The thermal resistance, R_{th}, is in the range from 13 to 35 K/W
- ✓ Most likely, the part can operate reliably at currents ≤ 3 A

Suggestions for Screening



Suggestions for LAT



Conclusion

- Engineering samples of AVX Low Inductance Bulk Capacitors (LIBC) had reproducible HF characteristics and the forward transmission, S21, in the range from 30kHz to 6 GHz is below -40 dB, which exceeds characteristics of ceramic feedthrough capacitors
- The parts have a low level of ACC even after 620 hours of storage at 100C
- Breakdown voltages of the parts are 1.85 ±0.05 VR that increase after HALT (up to 2.25VR at 1.7VR). This explains the presence of anti-WO failures
- The parts can operate reliably at the through currents up to 3 A
- Preliminary HALT results show that at 85 °C the voltage acceleration constants are B = 14.2 and n = 21.2 for the exponential and power models and the expected useful life at 85 °C and 0.8VR exceeds 40 years
- With a proper screening and lot acceptance testing the part can be used for space applications