High-Temperature Reliability of Flexible Printed Circuits on Biodegradable Substrates With Water-Based Inks and Room-Temperature Adhesives

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InterPACK 2025: 174747

Motivation

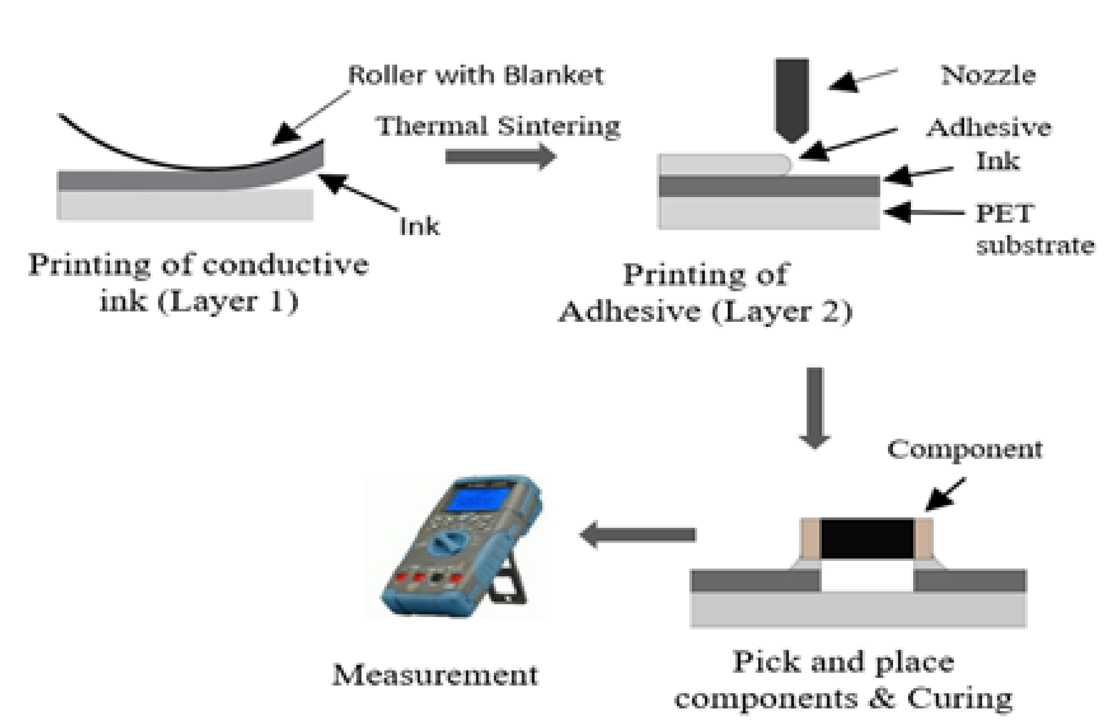
- The rising demand for sustainable and eco-friendly electronics calls for manufacturing techniques that minimize environmental impact.
- Conventional fabrication processes rely on high temperatures and non-biodegradable materials, leading to excessive energy consumption and waste generation.
- Water-based conductive inks, biodegradable polymer substrates, and room-temperature curable ECAs provide a pathway toward energy-efficient and low-impact electronic manufacturing.
- Evaluating thermal cycling reliability and sustained high-temperature performance is critical to ensure device durability in automotive and harsh-environment applications.
- Investigating electrical and material degradation mechanisms under cyclic and thermal stresses supports the development of robust flexible circuits.
- Bridging the knowledge gap in sustainable flexible electronics promotes the transition toward reliable, eco-conscious technologies for next-generation systems.

Objectives

- Investigate the feasibility of gravure offset printing for sustainable flexible circuits on biodegradable BPET substrates.
- Evaluate the thermal cycling reliability of water-based silver nanoparticle inks and room-temperature curable ECAs.
- Perform thermal cycling and high-temperature exposure tests to assess circuit durability and reliability under harsh conditions.
- Demonstrate the electrical functionality of an inverting Schmitt Trigger circuit after prolonged thermal cycling and elevated temperature operation.
- Compare experimental and simulated results to validate electrical behavior, switching stability, and degradation mechanisms.
- Provide insights to promote the adoption of eco-friendly printed electronics in automotive and harsh-environment applications.

Methodology

Work Flow Diagram

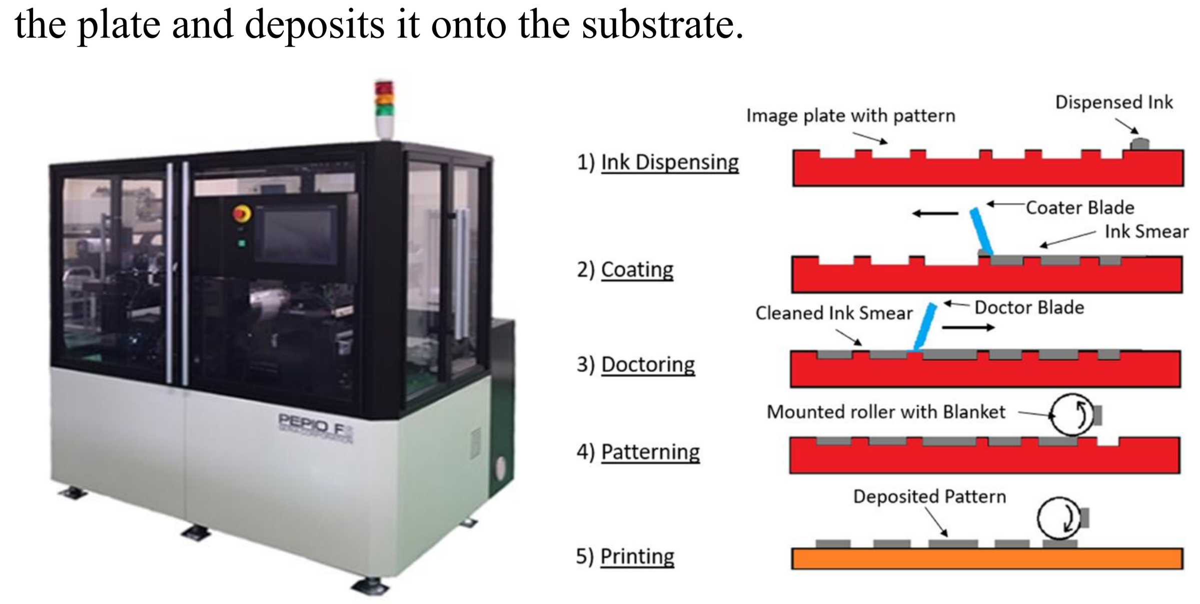


Material Properties

Water-based Ink Properties	
Color	Silver Grey
Solid Content	85 wt%
Sintering Temperature	80°C for 60 min
Electrically Conductive Adhesive (ECA)	
Material	Silver Paste
Color	Silver
Reactive solids contents	100%
Sintering Temperature	24 hrs. @ Room Temperature
Resistivity	10^{-4} Ω-cm
Substrate	
Material	BPET(biodegradable Polyethylene Terephthalate)
Yield MPa	288
Thickness(mm)	0.02
Elongation at break (%)	100
Tensile Strength at break(kpsi)	31

Printing Technology

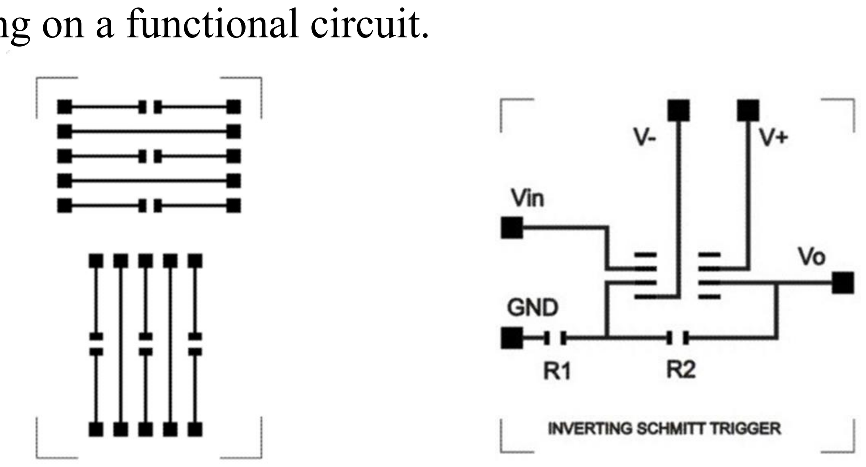
- Gravure printing is a roll-to-roll printing technique which uses a roller and an etched plate.
- The ink is first dispensed on the plate, and the coater plate spread the ink over the plate while the doctor plate remove the ink smear over the plate.
- The roller, equipped with a mounted blanket, picks up the ink from the plate and deposits it onto the substrate.



Gravure Offset Printer — Gravure Offset Printing Schematic

Material Properties

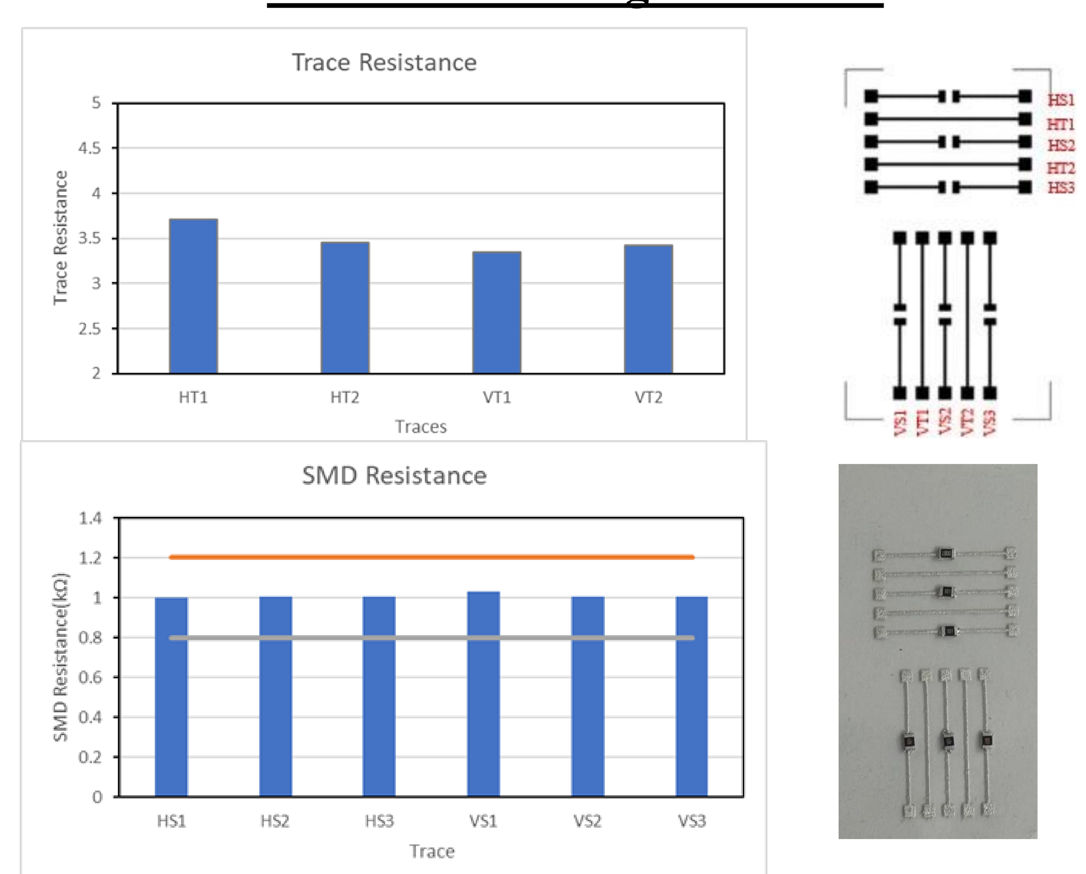
- Test Vehicle Design 1 is used to study the effect of thermal cycling on traces and SMDs with interconnects.
- Test Vehicle Design 2 is used to understand the effect of thermal cycling on a functional circuit.



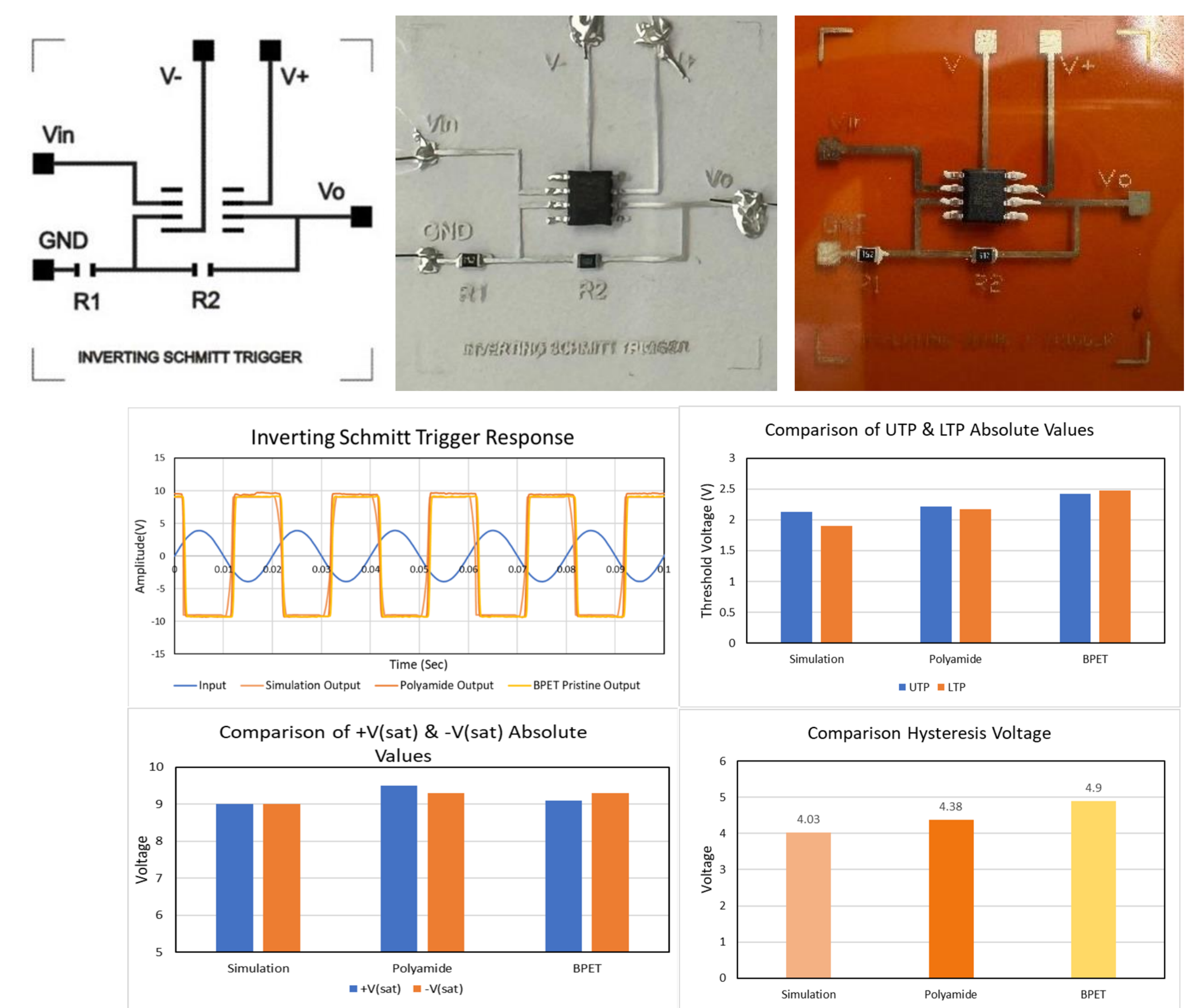
Test Vehicle - 1 — Test Vehicle - 2

Results

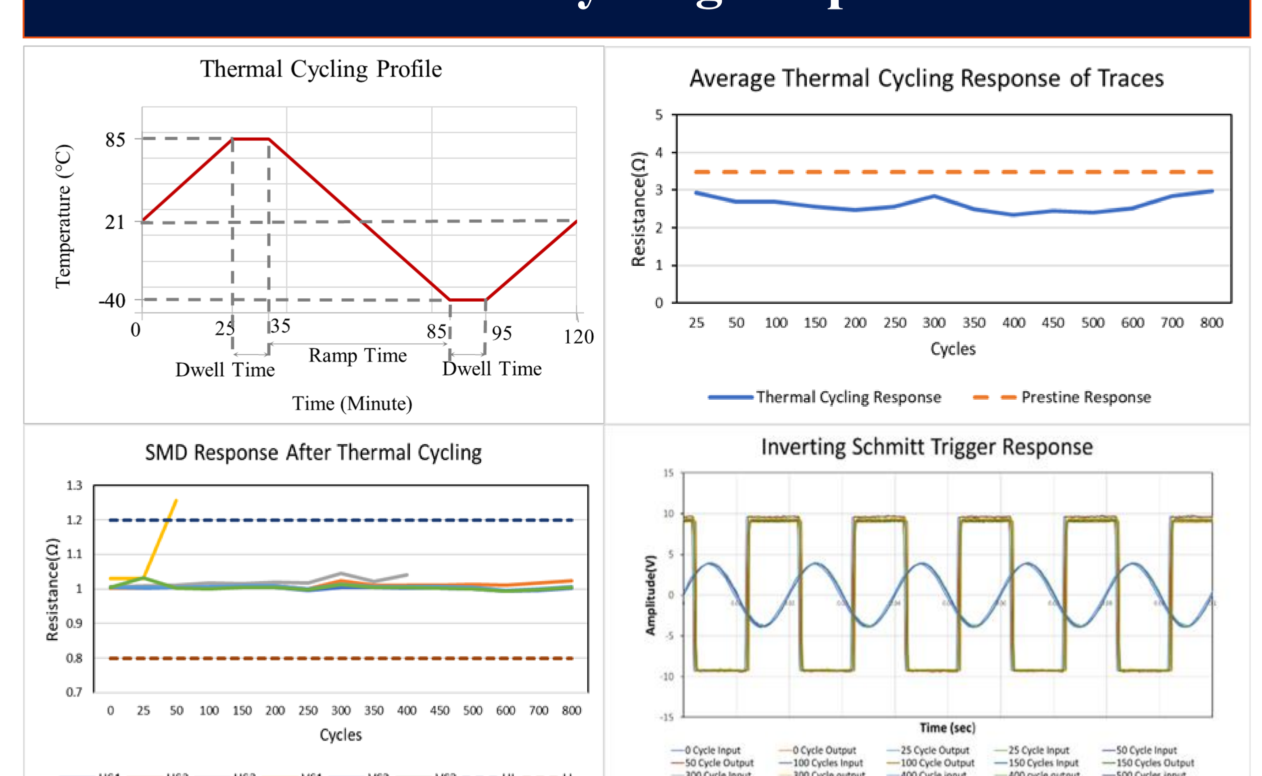
Test Vehicle Design 1 Results



Test Vehicle Design 2 Results

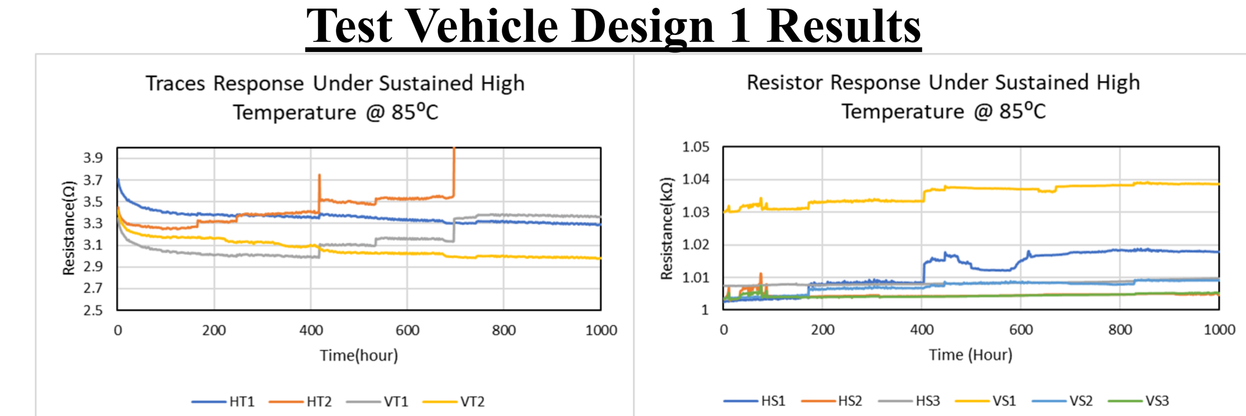


Thermal Cycling Response

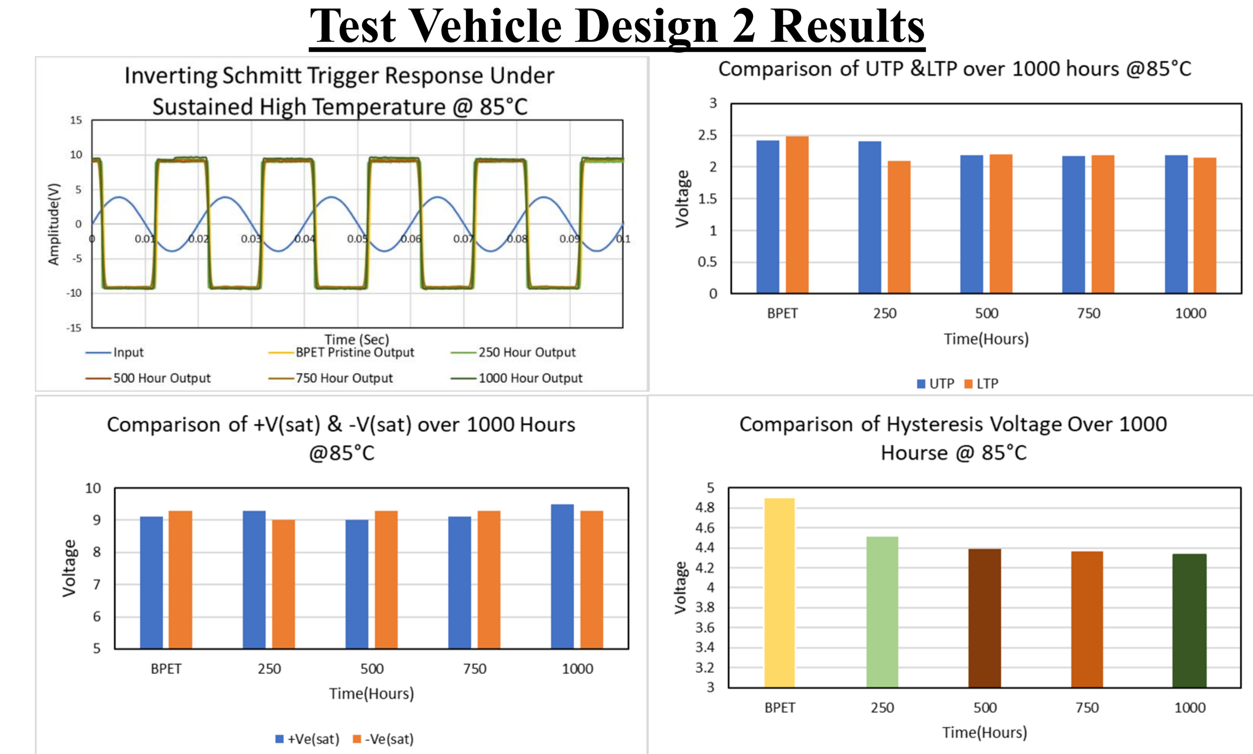


Sustained High Response

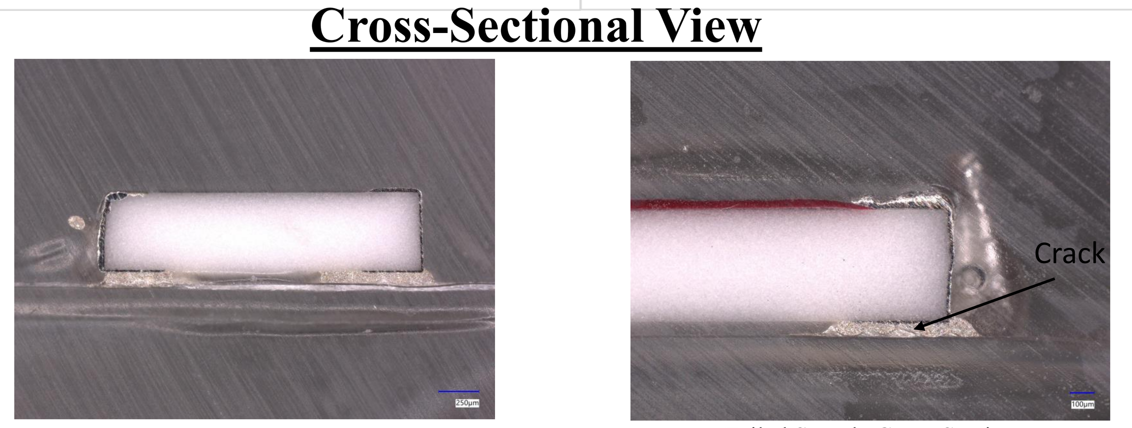
Test Vehicle Design 1 Results



Test Vehicle Design 2 Results



Cross-Sectional View



Pristine Sample Cross-Section — Failed Sample Cross-Section

Conclusions

- Demonstrated the viability of sustainable materials (water-based silver ink, BPET substrate, and room-temperature curable ECA) for flexible printed circuits.
- Printed traces and SMD interconnects showed stable resistance within IPC-9701A limits over 1000 h at 85 °C and 800 cycles from -45°C to 85°C.
- Vertical trace orientations (VT1, VT2) exhibited superior thermal reliability compared to horizontal traces.
- SMD interconnects (e.g., VS2, VS3) maintained minimal resistance drift, confirming robust adhesion and conductivity.
- Schmitt Trigger circuits on BPET retained sharp switching and stable hysteresis behavior despite long-term and cyclic thermal exposure.
- Results validate that eco-friendly additive electronics can meet automotive-grade reliability, supporting sustainable adoption in harsh environments

Results

The project was sponsored by the NextFlex Manufacturing Institute under PC8.5 Project titled – Biodegradable Substrates Low-Temperature Cure Water-Based Inks Room Temperature Cure Interconnects and Rework for Sustainable Additively Printed Electronics. This material is based, in part, on research sponsored by Air Force Research Laboratory under agreement number FA8650-20-2-5506, as conducted through the flexible hybrid electronics manufacturing innovation institute, NextFlex. The US Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation thereon. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of Air Force Research Laboratory or the US Government.