
*Integrity ★ Service ★ Excellence*

# SHOCK TESTING OF 3D PRINTED MULTI-MATERIAL CIRCUITS

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# Outline

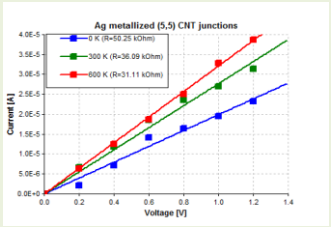
1. USAF AM-Enabled Electronics
2. Integrating Traditional PCB Production with Printing
3. High-*g* Survivable 'Resilient' Electronic Materials
4. Hybridized printed Circuit Boards
5. Potting Replacements for High-g Resiliency
6. High-g Survivable Printed Electronics
7. Conclusions & Future Work

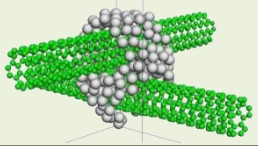
# USAF AM-Enabled Electronics

## *Mechanical Resilience in High-g Environment*

### Materials & Design

**AFOSR ICE³ (RX/RW)**

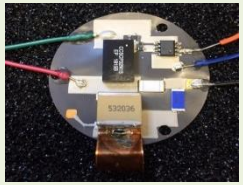


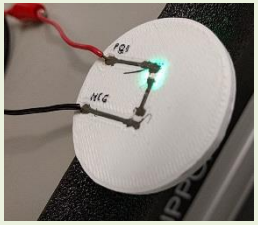
Novel materials that are flexible with superior adhesion

### Hybridized Systems

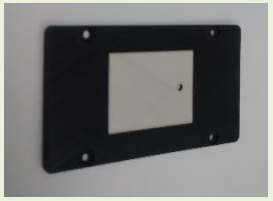
**FLEGOMAN CRDF (RW, RX, RY)**



High voltage circuits



Functional circuits

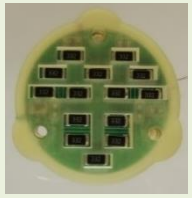


Printed Antennas

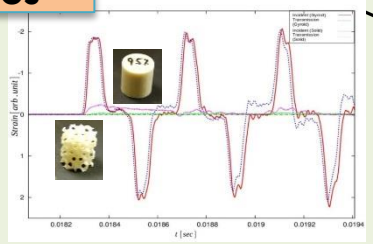
**In-house Proof of Concept Studies**

### Innovative Packaging

**JFTP 3D Packaging (AFRL, ARDEC, NSWC)**



Printed PCB supports

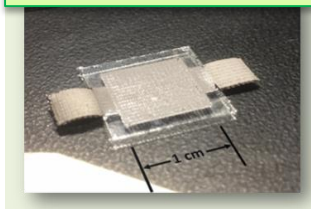


Cellular designs

High G Survivability

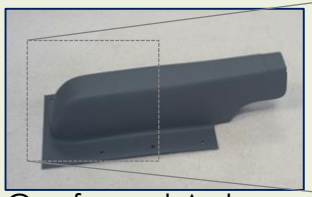
### Fully Printed Devices

**FLEGOMAN CRDF (RW, RX, RY)**

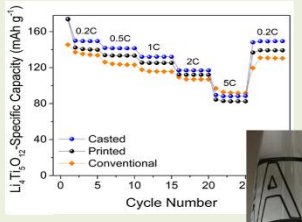



Capacitor

RFID on flex




Conformal Antenna



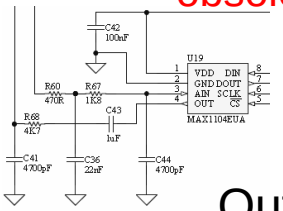

Printed flexible batteries


Sun et al., 2013. Adv. Matls 25: 4539-4543

# Integrating Traditional PCB Production with Printing

Programmatic impact: in-house expertise, customization, obsolescence

Altium Circuit Board Designer

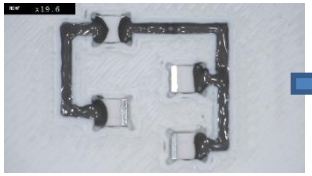



Output

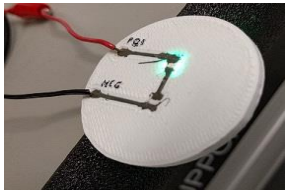
Solidworks

IR curing oven

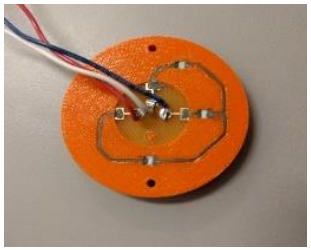
Makerbot



ABS/Ag/TPU

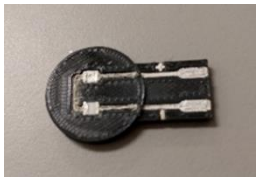


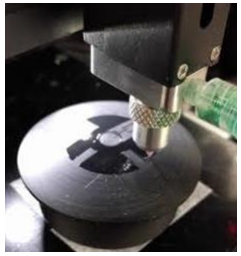
Embedded design

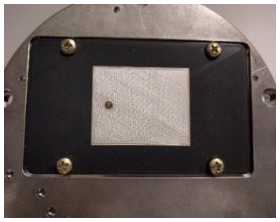


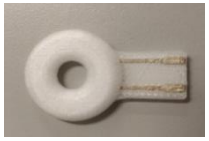
Fortus 250MC

Voxel8





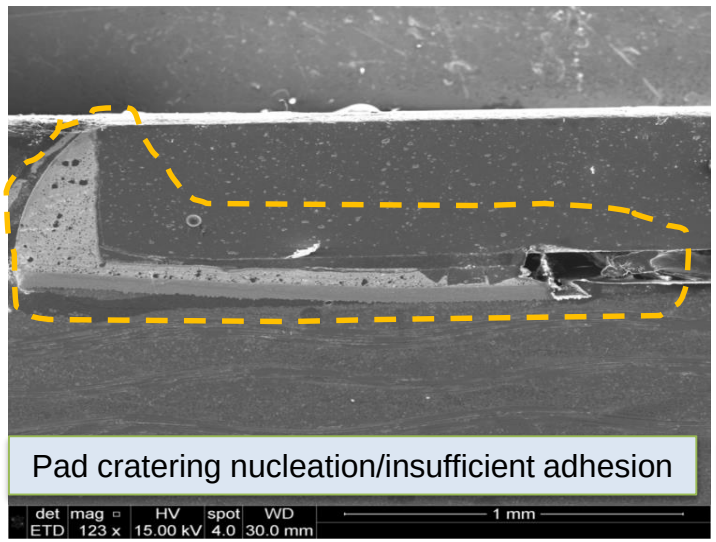
USB (5V) power

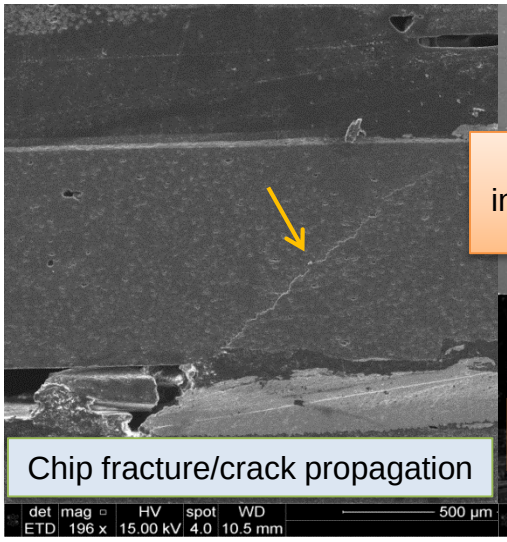
# The Challenge:
## High-*g* Survivable 'Resilient' Electronic Materials

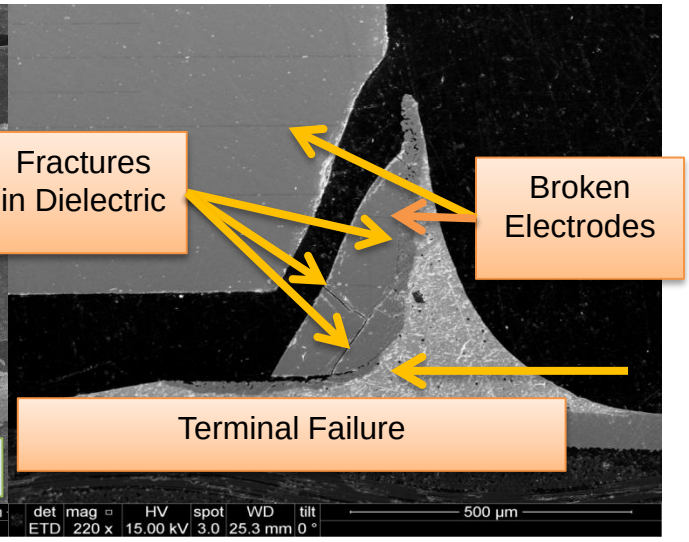
## 1. AFOSR Integrated Circuits for Electronics in Extreme Environments-ICE$^3$

**Objective:** **Develop and assess "resilient" multi-functional electronic materials** designed to survive and operate well beyond commercially available technologies in a High-*g* Environment.

- Potential replacements for conventional (consumer, batch-processed) electronic interconnects (ie. traces and Sn-Pb solders) for harsh mechanical and vibration-specific requirements (ie. strain resiliency)

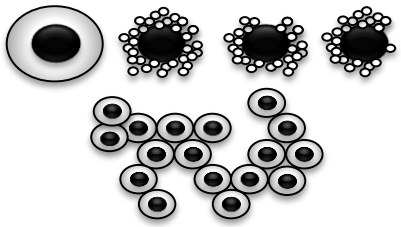


# Synthesis of Ag-CB/PU Nanocomposites

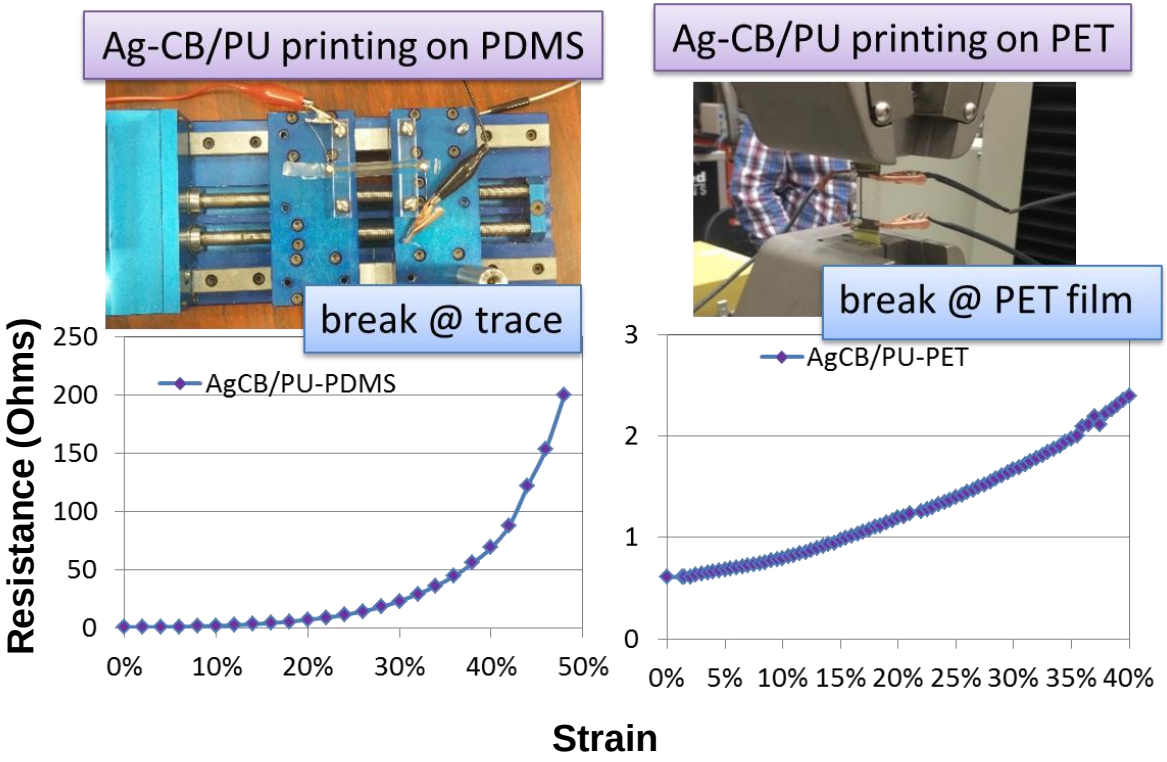
## 1. AFOSR Integrated Circuits for Electronics in Extreme Environments-ICE$^3$



-**Up to 47k S/cm** electrical conductivity @ 88 wt% (***comparable to pure Ag electrical conductivity of 600k S/cm)***

***Note:** High vol% to generate CB network vs. CNTs (1-2vol% predicted due to physical CNT networking)

**Substrate variability to minimize printed trace resistance change under strain**

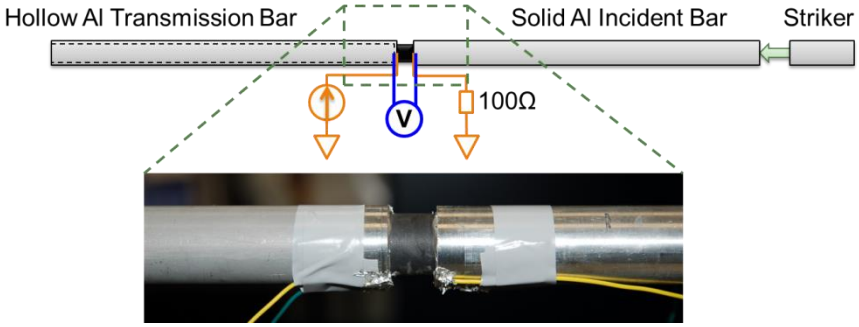


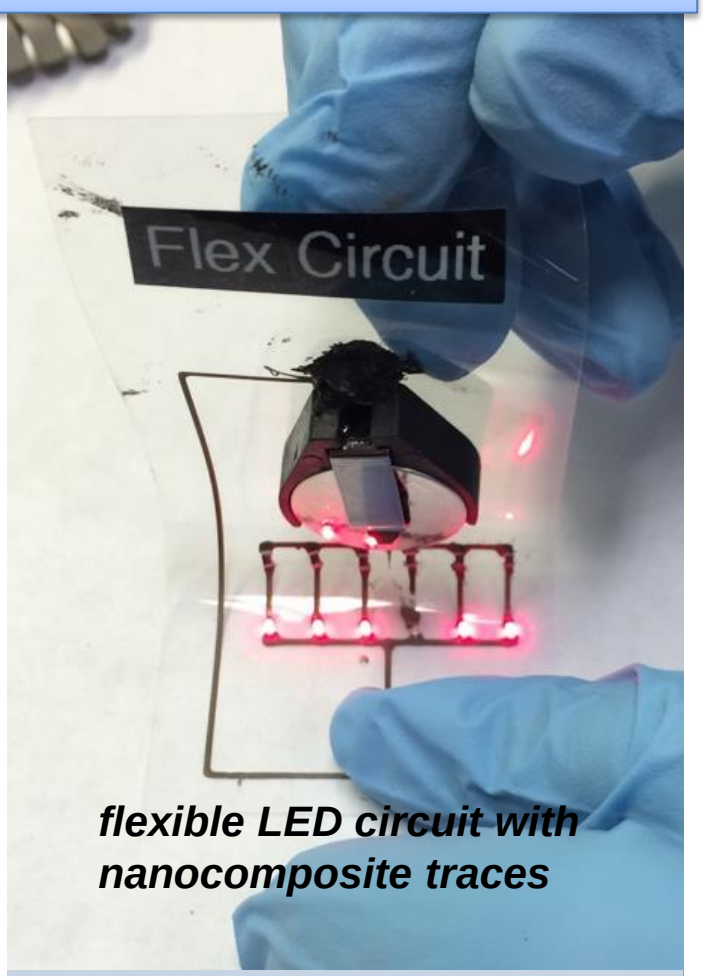

*Chen et al., 2015 MRS Advances, Dec 2015 pp. 1-6*

# Some Key Discoveries

## 1. AFOSR Integrated Circuits for Electronics in Extreme Environments-ICE$^3$

- Polymer matrix *and* nanoparticle fillers can be optimized for strain resiliency & tailored to application area
  - Epon 828/D2000 initially selected due to low Tg (application for solders undergoing shear-mode failure)
  - Polyurethane (PU) matrices (application for traces undergoing in-plane strain-mode failure)
  - Ag-coated CB imparts electrical conductivity while saving cost and density compared to solid Ag nanoparticles
  - SHPB high strain rate testing- nanocomposite compression leads to contact loss
  - Materials continue to be printed/tested in-house…



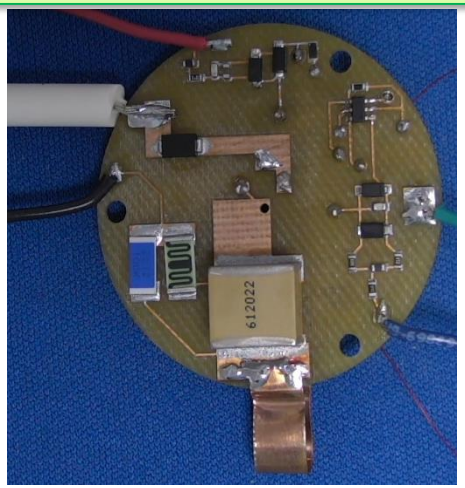

***flexible LED circuit with nanocomposite traces***

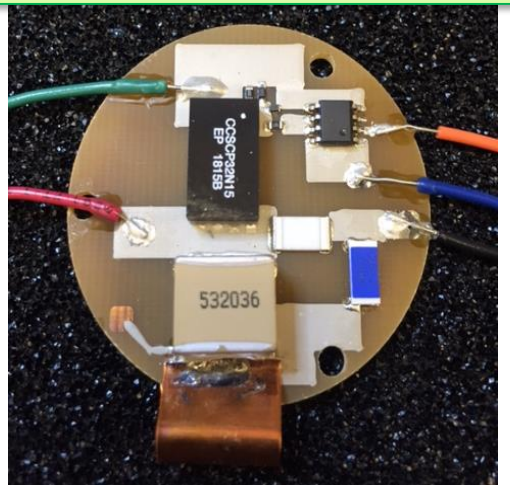
*Chen et al., 2015 MRS Advances, Dec 2015 pp. 1-6*

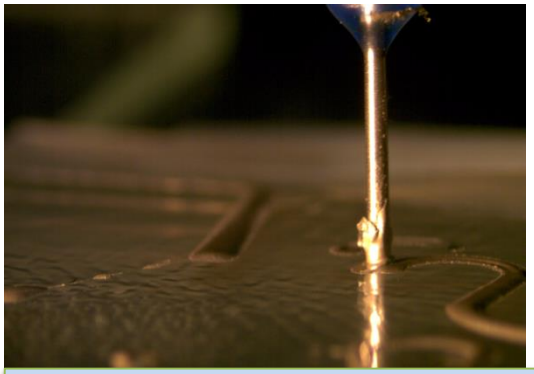
# Hybridized Printed Circuit Boards

## 2. Flexible Electronics & General Ordnance Manufacturing-FLEGOMAN

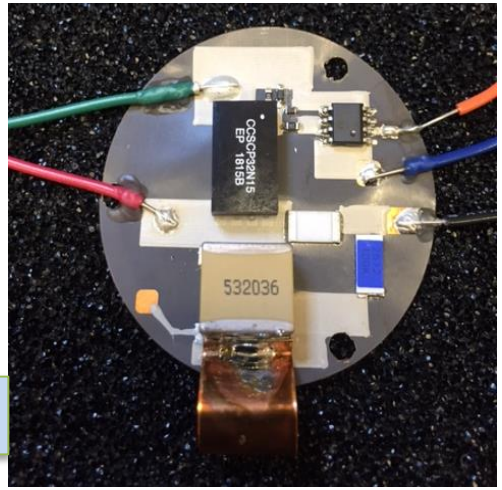
- Printed capacitor and thinned switch were unable to withstand test conditions
- Printed <u>conductive traces</u> to withstand 3000 Amps over 100 ns; populated w/ COTS components
  - Printed on both FR4 and polyimide (flexible substrate)



Ag/TPU conductive ink



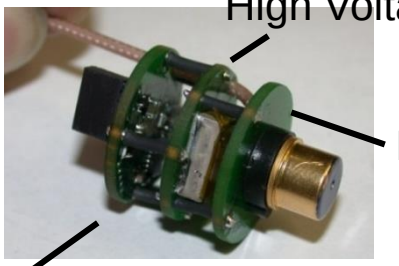
# The Challenge:
## Potting Replacements for High-*g* Resiliency

### 3. JFTP Electronics Packaging

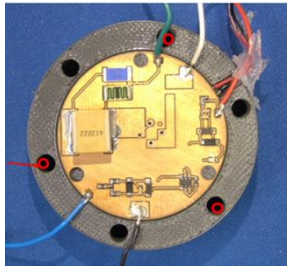
**Objective:** **Develop packaging technologies** for a fuze fireset to improve the survivability (strain reduction) and reliability (re-work) during a high-*g* accelerations.

- Broad transition potential for hard target fuzes used in penetrators, gun launched munitions, precursor weapons, etc. via encapsulant-free design using Additive Manufacturing (AM)

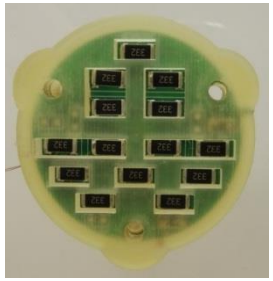
**Candidate Packaging Schemes**



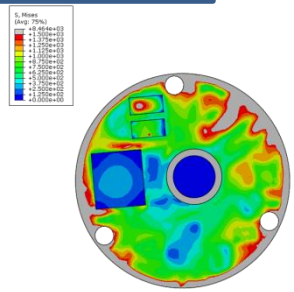

**Optimization of AM Fireset Supports**



Design



Materials characterization



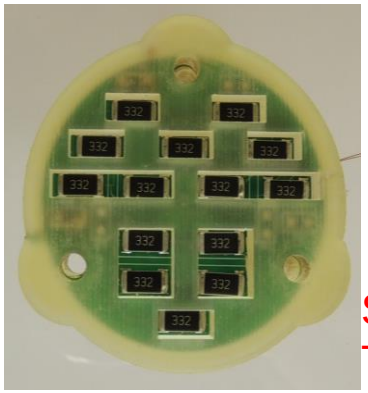
Modeling & simulation

# Supports for High-g Acceleration

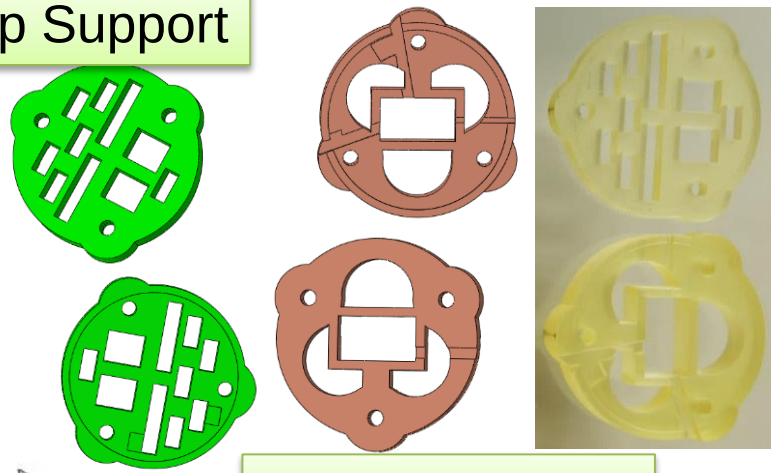
## 3. JFTP Electronics Packaging

- Supports designed around components of resistor bridge PCB
- Required to be compatible with existing fixtures and clearance for triaxial accelerometer, strain gage, cabling

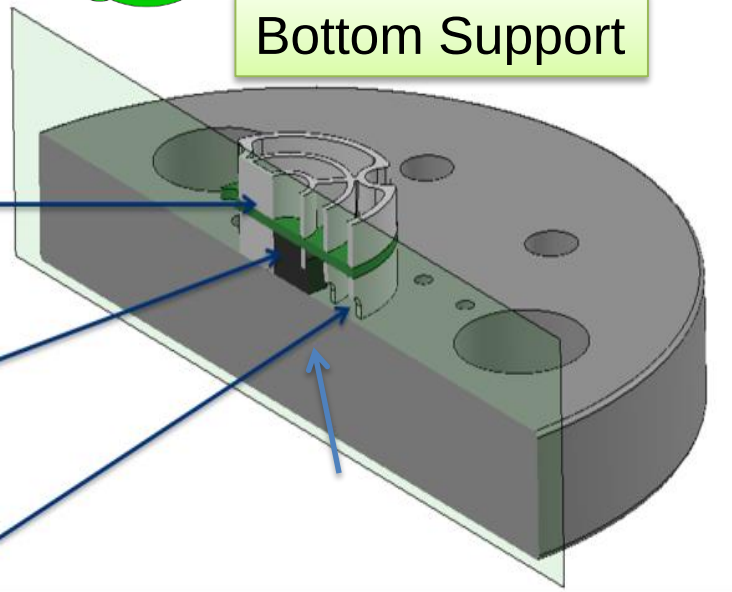
Material: Full Cure 720 (Acrylic)
Printer: Objet Eden 260



Top Support

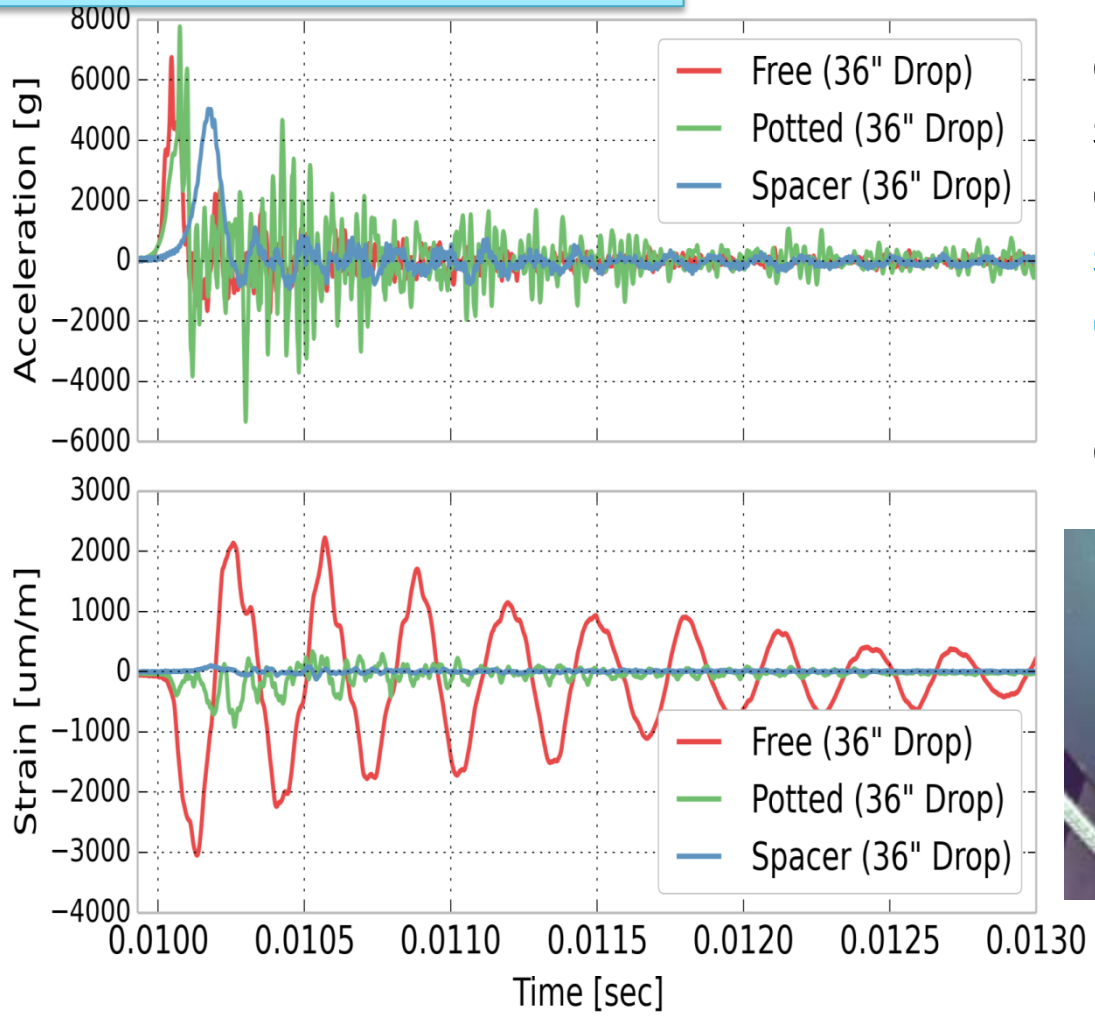


Bottom Support

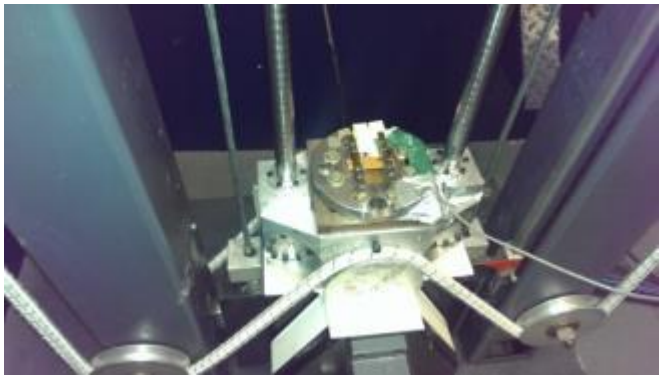


# Board-level strain lower than free and potted

## 3. JFTP Electronics Packaging



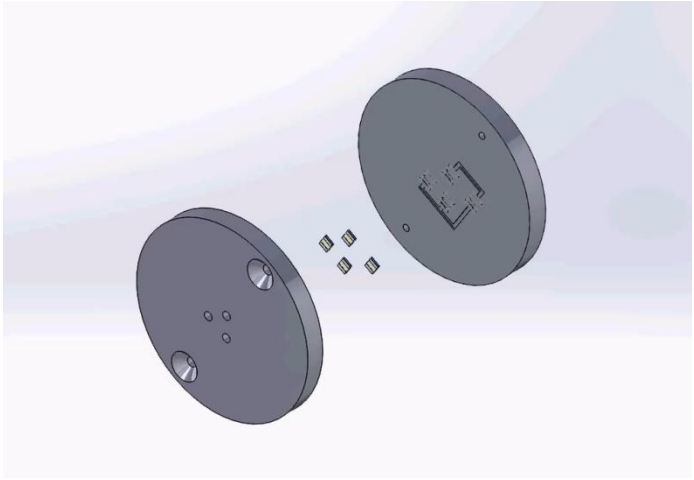

Demonstrated proof-of-concept that printed supports (pseudo-potting) do excellent job suppressing board deflection/reducing strain in drop test simulations & experiments



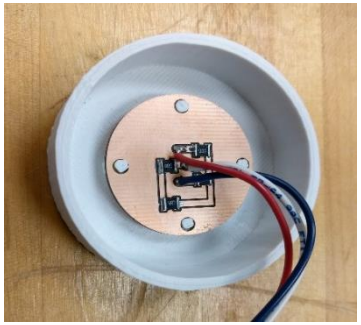
# High-*g* Survivable Printed Circuits

**Proof of Concept Studies**

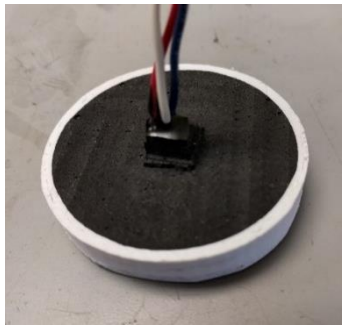
- ***AM embedded circuit design same dimensions as previous work…***
- AM printed substrate (Makerbot/ABS) and syringe-printed traces (Ag-CB/TPU) w/ manually placed COTS components
- Multi-materials printer (Voxel8) with PLA/proprietary Ag ink



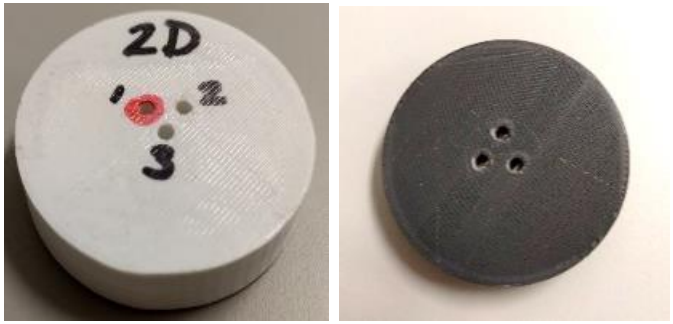
Printed mold; Traditional PCB (FR-4)



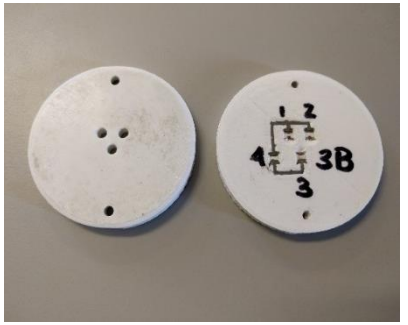
Potting: Stycast 1090SI



Fully embedded design



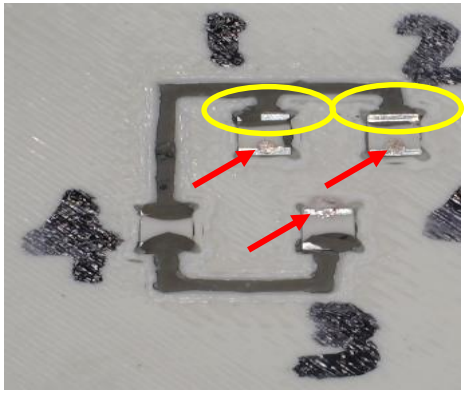

2 piece design



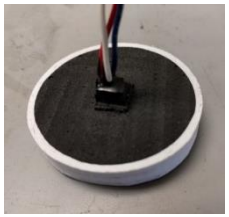
# Drop Test Results
# Potted vs. Printed

**Proof of Concept Studies**

Analysis of trace connecting resistors <u>1 and 2 (simplest case)</u>



*Some evidence of damage*



Potted (45k*g*)

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1 pc design ABS slurry (3/3 to 45k*g*)

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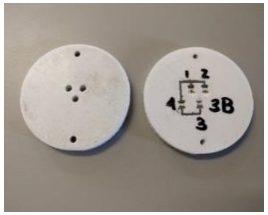


2 pc design Epoxy (2/3 to 45kg) (1/3 to 15kg)

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1 pc design Epoxy (1/2 to 35kg) (1/2 to 15 kg)

>

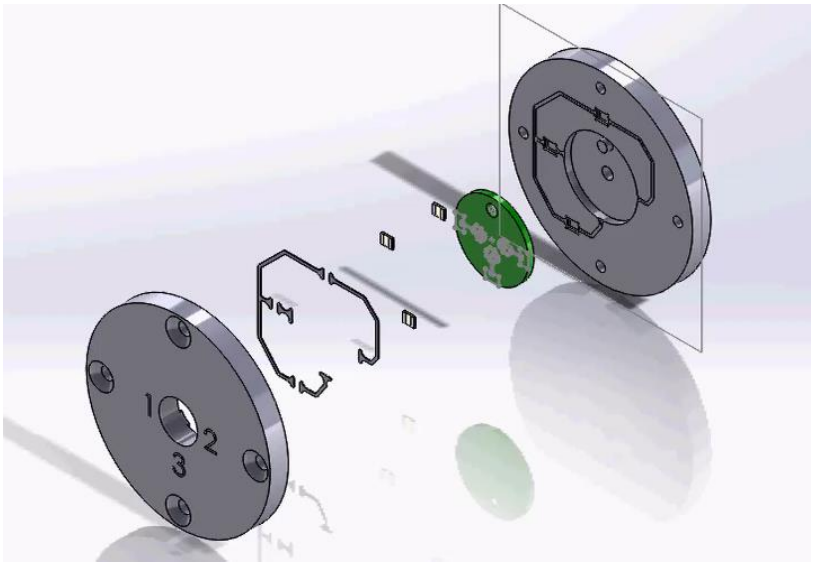
Voxel 8 (Fail @ 15kg)

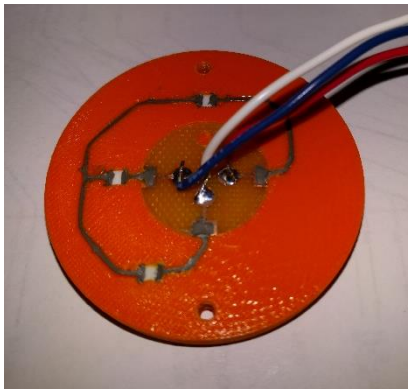
- Proof of concept that ABS/CB-Ag/TPU samples can survive high-g drops up to 45k*g* (in the simplest case of a single connecting trace @ points 1-to-2)
- Other measurements taken at points 1-to-3 (1 resistor in path) and 2-to-3 (2 resistors in path)
- 2/3 measurements suggest that 1pc sample w/ ABS slurry provides better component adhesion for survivability at greater k*g* than 1pc sample w/ epoxy
- *Materials irregularities due to syringe printing and gluing components by hand likely to play a role in data variability*
- Voxel8 materials (PLA/proprietary Ag ink) not high-*g* resilient

# Continuing Design Iteration

**Proof of Concept Studies**

- Incorporate mini-FR4 board and solder leads for improved static/dynamic measurements
- Improve trace design by eliminating sharp corners and creating wider, stronger “bridges”
- Future considerations: Tailor component support/recess, examine more complex electrical designs, how to solder printed connection points

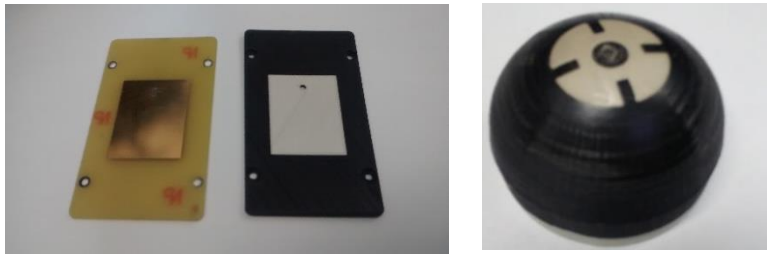


Material: ABS, Printer: Fortus 250 (better quality part)

# Conclusions & Future Work

- Tailoring designs and materials plays a fundamental role in developing printed electronics for munitions (high G/high strain environments)
- Commercial and novel inks continue to be developed and are currently selected in an empirical fashion
- Hybridization of COTS/printed electronics is the current state-of-the art
- NextFlex ($45M in total projects, 17 projects awarded in PC2.0; Printing on Complex Surfaces, Flex-Hybrid Array Antenna)



Printed antennas

Cross TD FY17-19 CRDF: Develop and demonstrate multi-layer additive manufactured conformal arrays on an in-theatre platform; demo conformal antenna

# THANK YOU

# QUESTIONS?

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