NASA SIBatt-3D

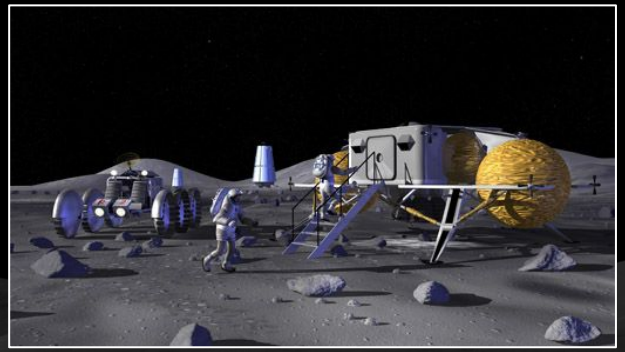
In-Space and On-Surface 3D Printing Sodium-Ion Batteries from ISRU Materials

Presented by Cameroun Sherrard

The Inspiration

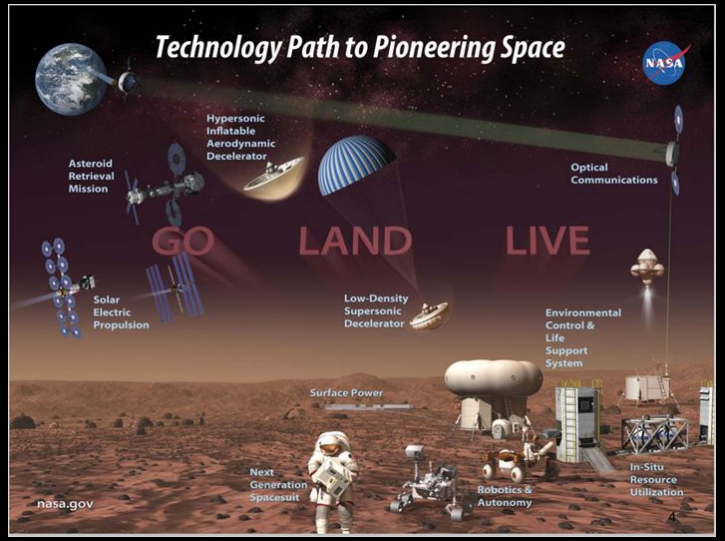
- ★ Resupply/Replenish Power Storage Devices on Extended Space Mission
  - Build new batteries as needed to suit different requirements to reduce the variety brought from earth
  - Using versatile multi-use feedstocks to bring less material and save mass on extended missions
- ★ Provide a sustainable Power Sources for Surface Missions on the Moon and Mars
  - Use materials found in martian and lunar regolith to provide a sustainable power source and reduce required resupply payloads
  - Develop scalable techniques that can eventually be used power large scale systems such as habitats


The Soyuz TMA-15M spacecraft



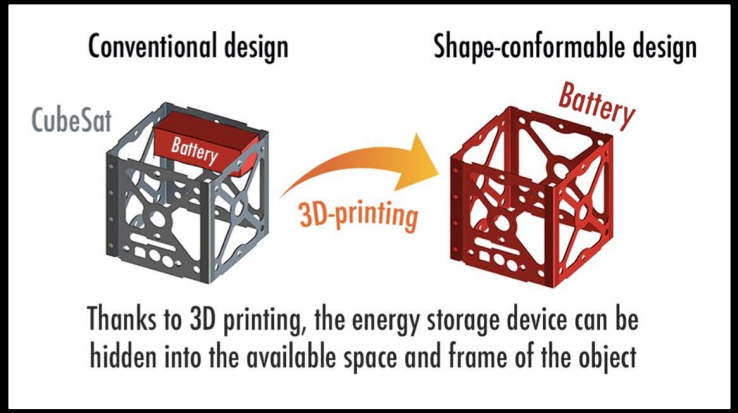
NASA Mission Alignment

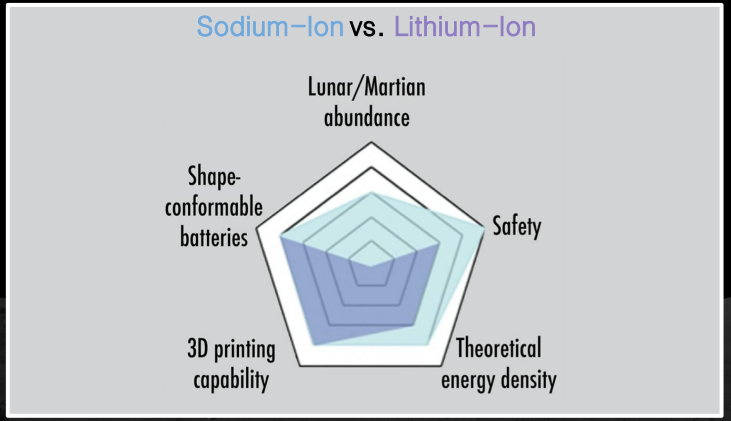
- ★ Space Technology Mission Directorate
  - Technology research and development for in-space and lunar/martian surface applications
- ★ In-Space Manufacturing
  - Development of manufacturing and recycling systems and processes - “Make it Don’t Take It”
- ★ On-Demand Manufacturing of Electronics
  - Additive manufacturing of metals, electronics, and sensors in microgravity



The SIBatt-3D Solution

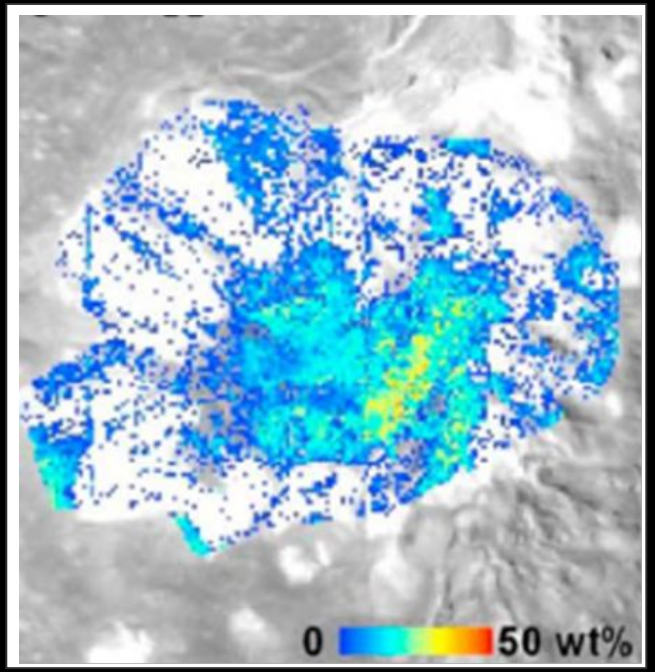
- ★ 3D printing
  - Versatile manufacturing technique
    - On-demand prints
    - Reduced waste
  - Shape-conformable printing
    - Reduce dead volume
    - Potentially act as structures
- ★ Sodium-Ion Chemistry
  - Relative abundance of active materials on the moon and mars
  - Improved safety and sustainability over other chemistries





The SIBatt-3D Solution

- ★ ISRU
  - Use materials found on the moon and mars for sustainable power on extended missions
  - Reduce cost reducing shipments to replenish material
- ★ Supporting Systems
  - Print supporting electrical and ceramic components using the same system for easy integration of batteries into other systems



Mineral mapping result for Jackson Crater for clinopyroxene taken from Lemelin [1]

Terrestrial Applications

- ★ Sustainability
  - Better for the environment than Lithium and Cobalt mining
  - Additive manufacturing processes are generally less wasteful
- ★ Safety
  - Sodium-ion chemistries are less prone to overheating and catching fire
  - Solid electrolytes
- ★ Shape-Conformability
  - Allow for device miniaturization
  - Potentially act as structures
- ★ On-Demand Manufacturing
  - Create batteries for different applications as needed

Material Identification

Possible ISRU Materials for SIBs							
Negative Electrode Materials							
$Na_3V_2(PO_4)_2F_2$	$Na_3V_2(POg_4)_3$	V_2O_5	$NaFePO_4$	$NaFe(SO_4)_2$	$NaMnO_2$	$NaFeO_2$	$Na_{0.44}MnO_2$
Positive Electrode Materials							
$FeTiO_3$	Hard carbon	TiO_2	TiS_2	FeS_2	$Na_2Ti_3O_7$		
Separator for gel electrolyte or Solid electrolyte							
Filler for separator and/or solid polymer electrolyte		Salt for solid or gel polymer electrolyte		Polymer matrix for solid polymer electrolyte	Ceramic electrolyte		
$Nano\ SiO_2$	TiO_2	$NaPF_6$	$NaClO_4$	Polyethylene oxide	$Na_3Zr_2Si_2PO_{12}$ (NASICON)	Na_3PS_4	

Regolith | Potential Regolith | Recycling Only | Cold Volatile

Material Properties and Extraction

	Positive electrode candidates		Negative electrode candidates	
Material	$NaFeO_2$	$Na_{0.44}MnO_2$	Hard carbon	TiO_2
Voltage (vs. Na/Na^+)	3.1 V	2.5-3.5 V	0.2 V	1.0 V
Theoretical capacity (mAh/g)	241.8	121	300	335
Practical?	Yes	Yes	Yes	Yes

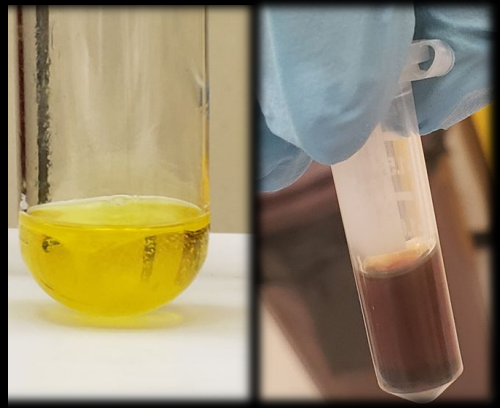


Image of ionic liquid trihexyltetradecylphosphonium pentachloride (P_{66614} Cl_5) before (left) and after (right) Ilmenite digestion

Print Technologies

Material Extrusion - Direct Ink Write

A form of material extrusion printing that uses thick film inks as feedstocks

High TRL - Well understood technology that has been tested in microgravity

Integrated part of the Advanced Toolplate multi-material 3D printer built for NASA ISM

Difficult to achieve high resolution and high loading

Print Technologies

Vat Photopolymerization - Digital Light Processing
Printing using a photopolymer that hardens when exposed to light

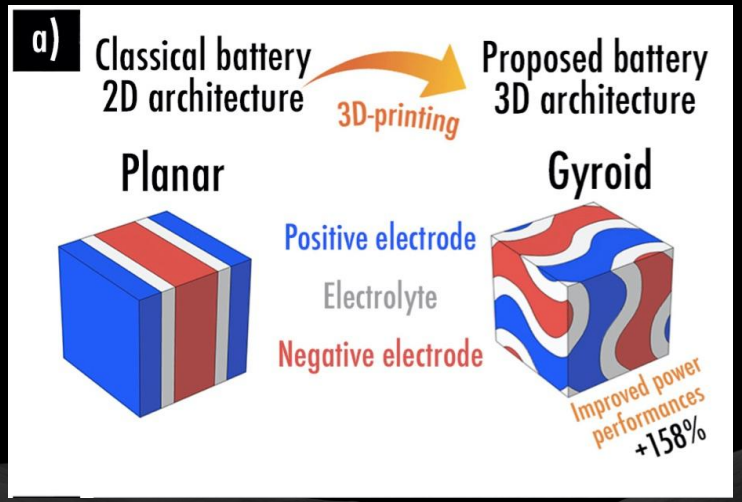
High TRL - Well understood technology that has been tested in microgravity

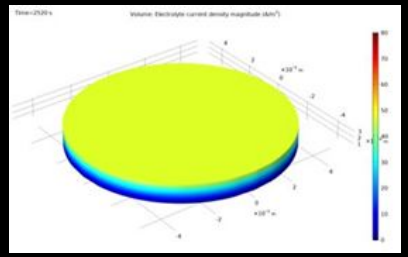
High Resolution - enhances complex geometries

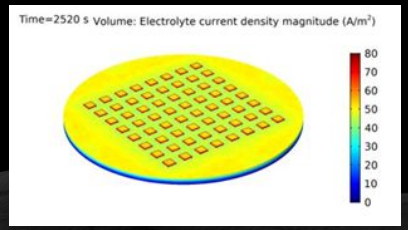
Complex and energy intense post processing steps and issues with loaded materials mean the a special printer is required

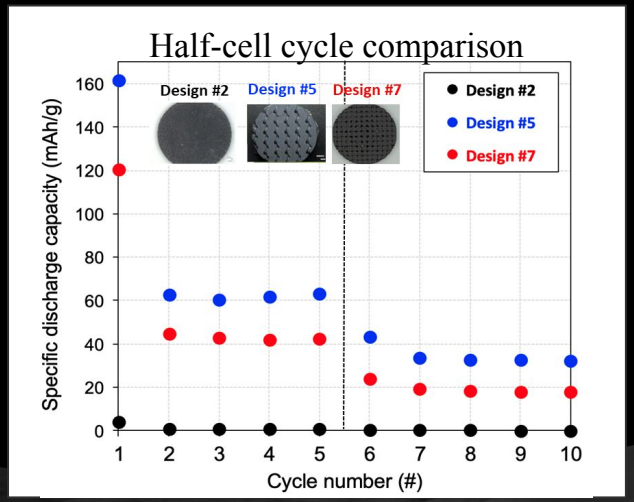
Electrode Design

Complex 3d electrode designs have been shown to improve performance and can help compensate for the losses generally associated with 3d printed electronics



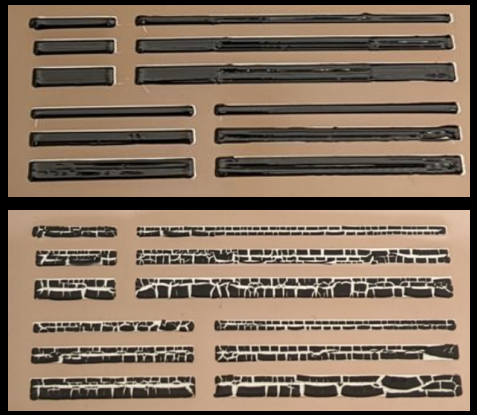




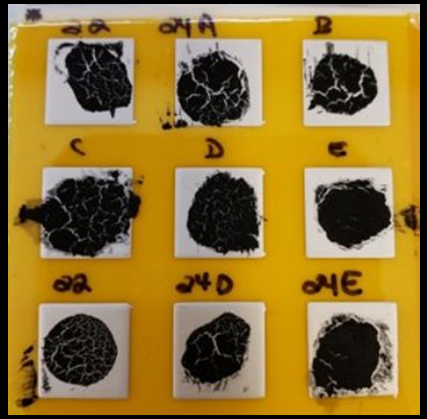


Direct Ink Write Prints

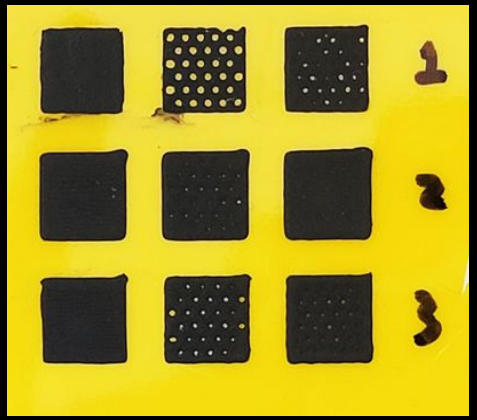
Custom inks were developed for each battery component. Inks are tested for an acceptable level of printability and adhesion while maintaining a high percentage of active material

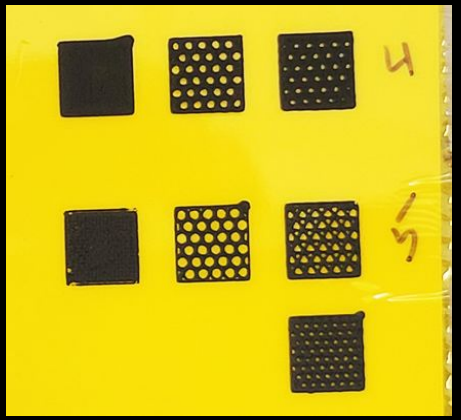


Hard Carbon ink tests on printed silver



Tests of different solvents in hard carbon inks to reduce cracking

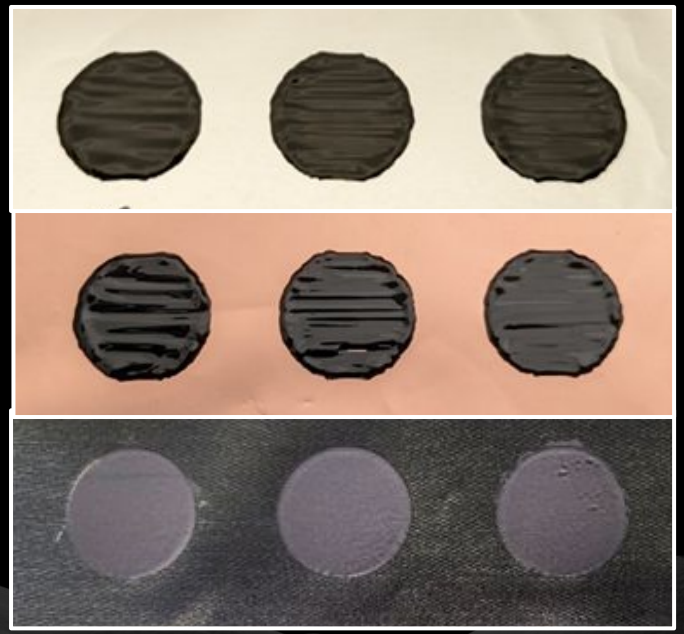




Testing Na0.44MnO2 ink formulations to in 1cm squares with different infill percentages to improve printability, formulation 5 was selected

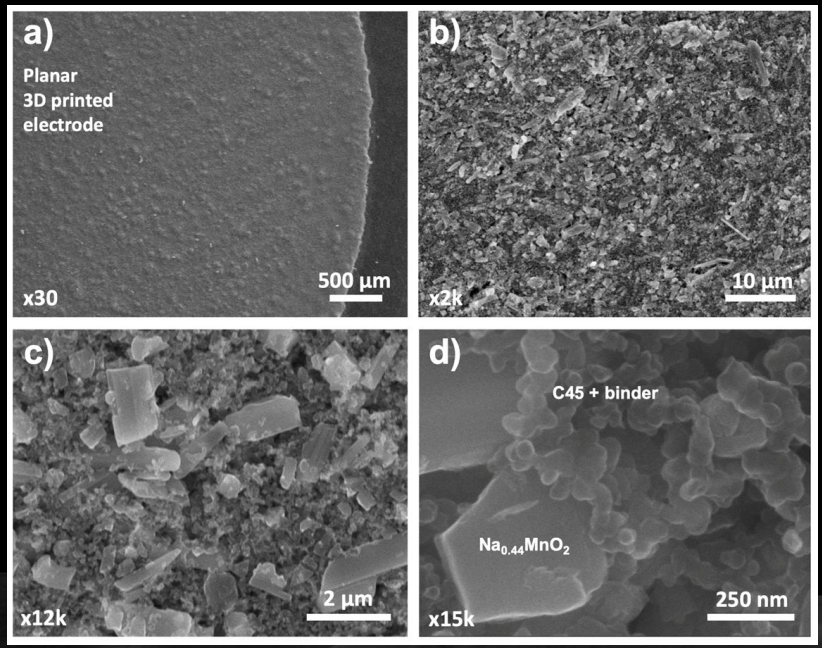
Direct Ink Write Prints

DIW Printed Electrodes for Coin Cell Tests



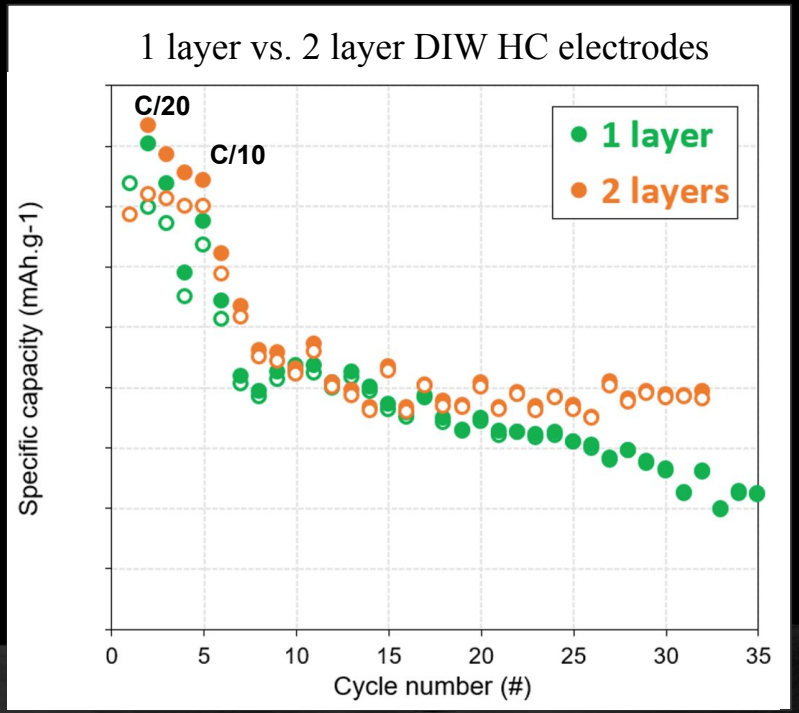
Printed Na0.44MnO2 electrodes on different foil substrates (Aluminium, Copper, Carbon Coated Al

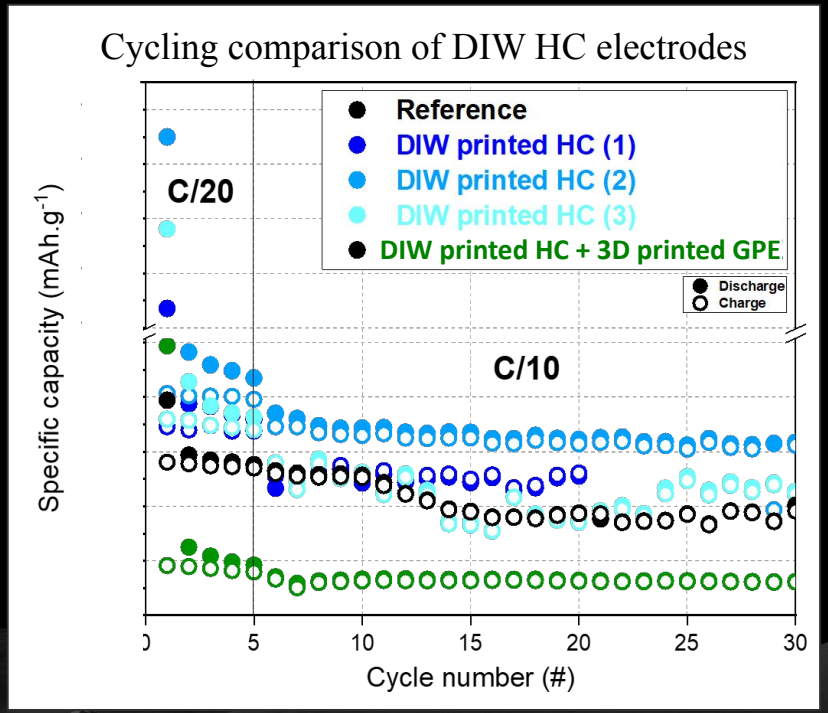
SEM observation of a 3D printed $Na_{0.44}MnO_2$ electrode



$Na_{0.44}MnO_2$ electrode printed at MSFC, very homogeneous, good dispersion of components considerable microporosity

Direct Ink Write Electrode Tests



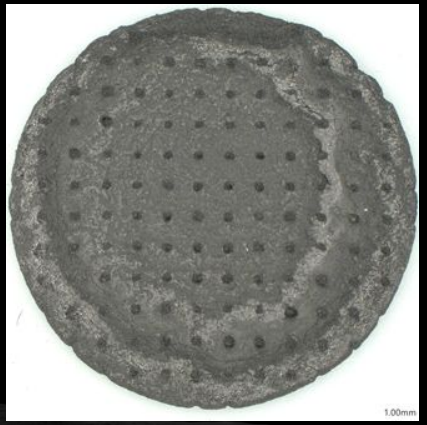


Vat Photopolymerization Prints

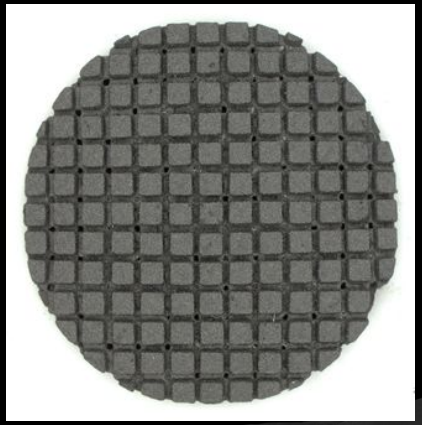
Custom resins were developed for each battery component. Different formulations of base resin, active material and conductive additives were tested along with a variety of print parameters and sintering and debinding processes

Solid TiO2 Electrode (Design 1)

Gyroid TiO2 Electrode (Design 5)

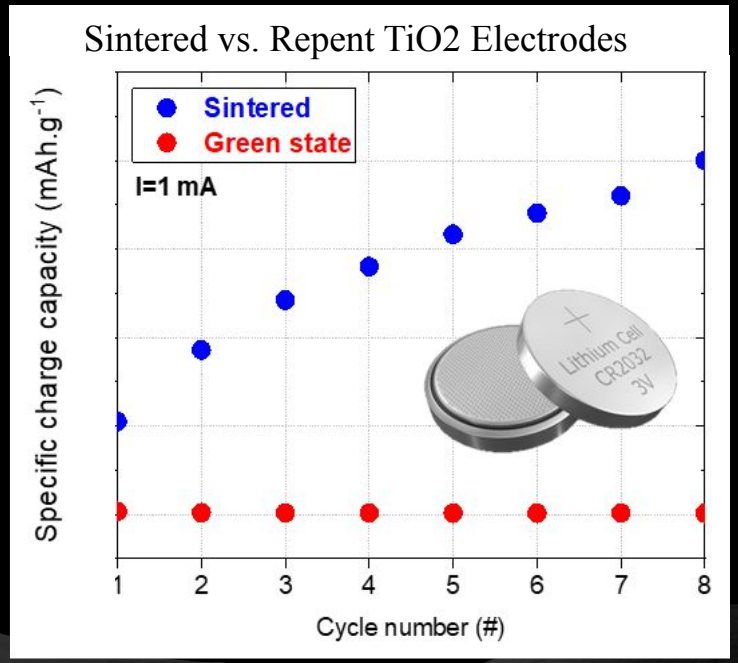


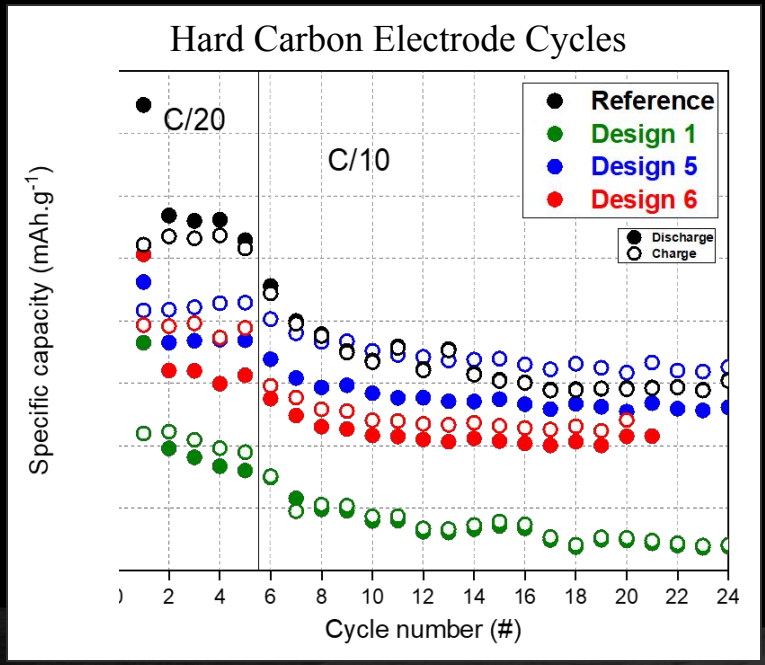
Grid TiO2 Electrode (Design 6)



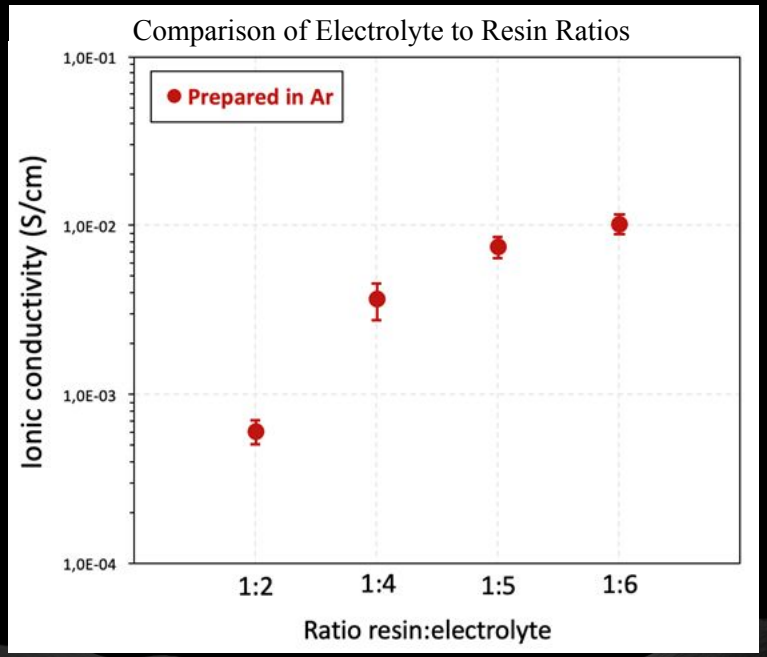
Grid TiO2 Electrode (Design 7)

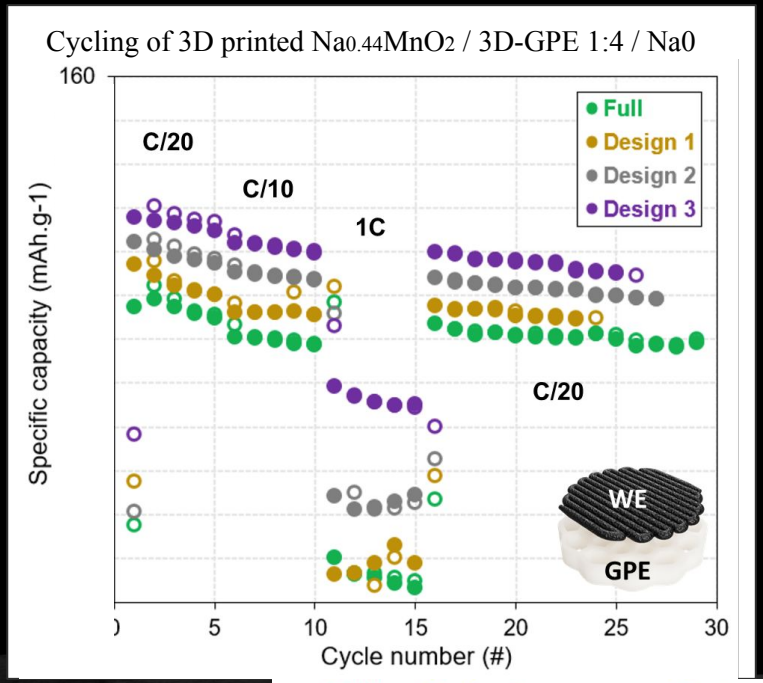
Vat Photopolymerization Electrode Tests



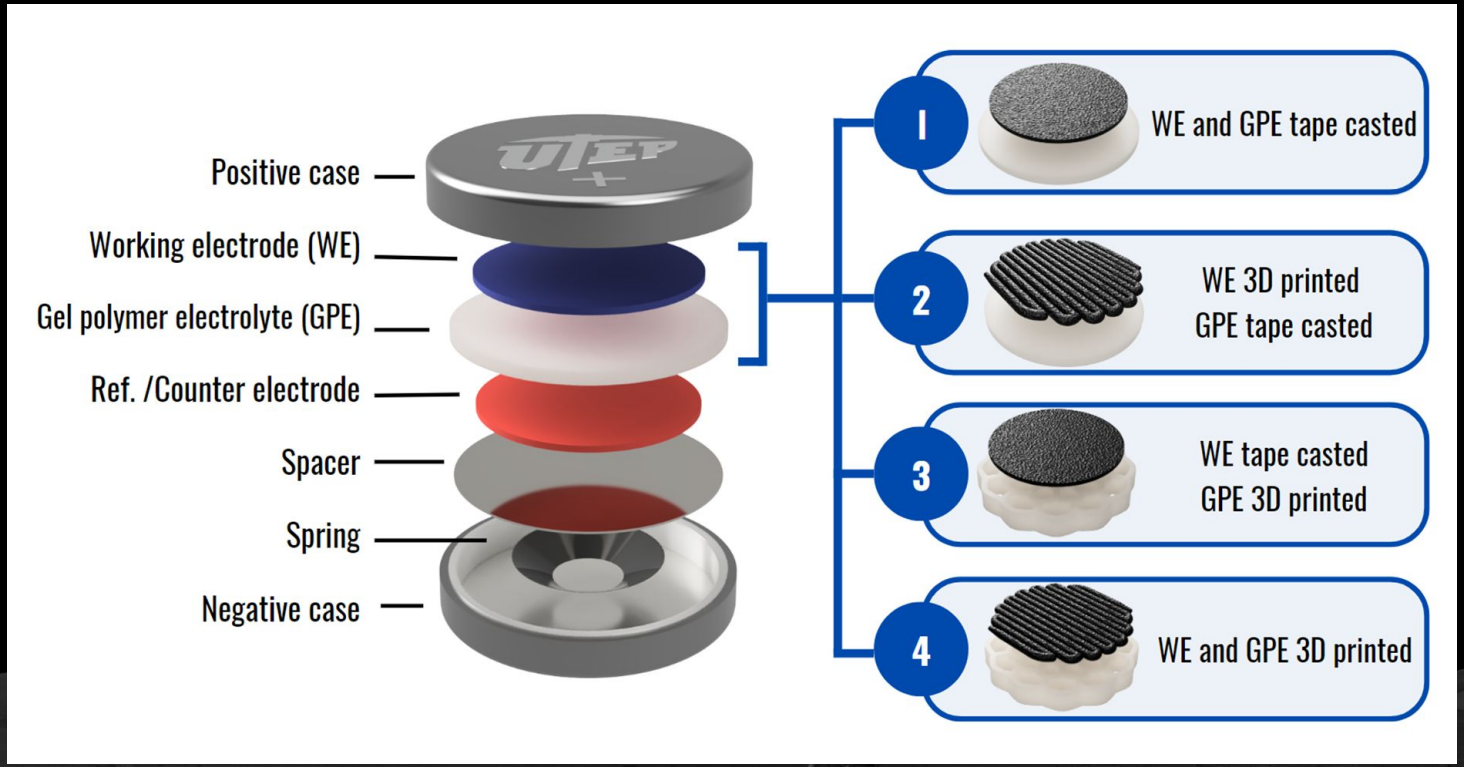


Printed Electrolytes

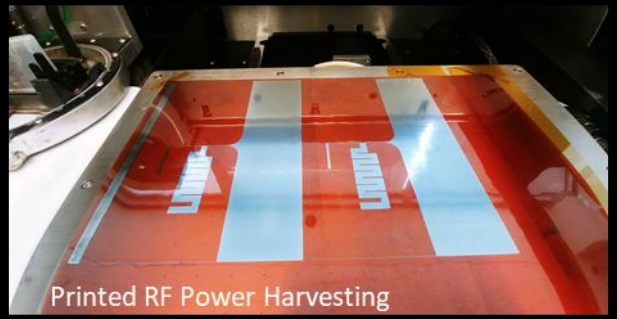


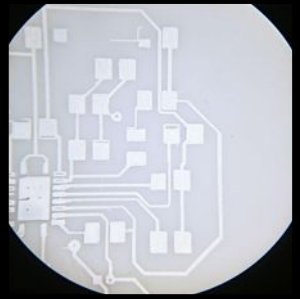


Complete Printed Cells

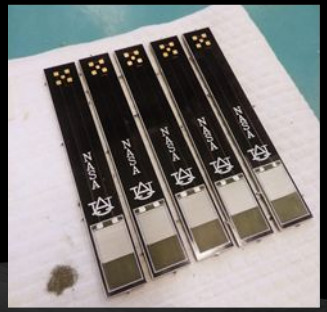


Printed Supporting Elements (ODME)

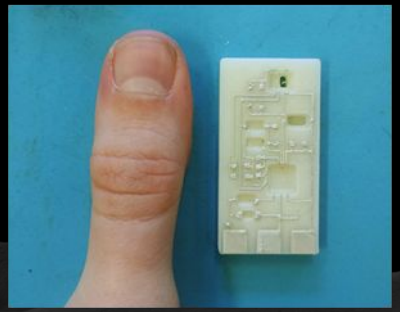


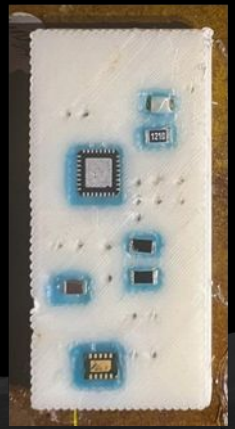


Printed BLE
Arduino Board



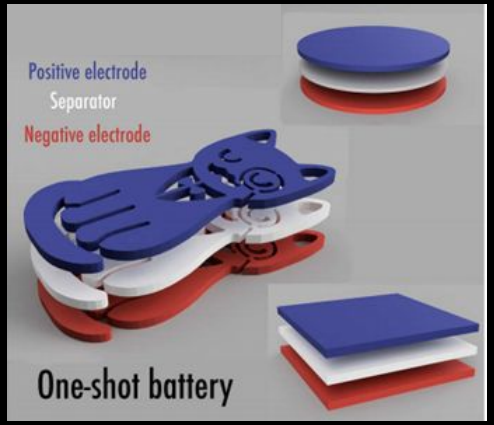
Printed multilayer CO2 Sensor

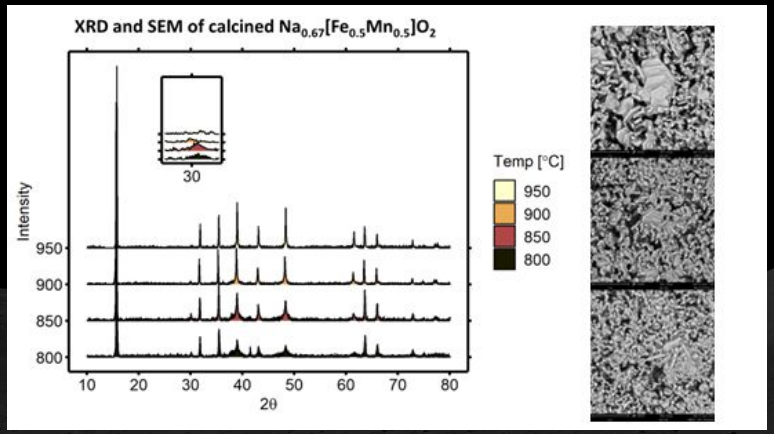




Next Steps

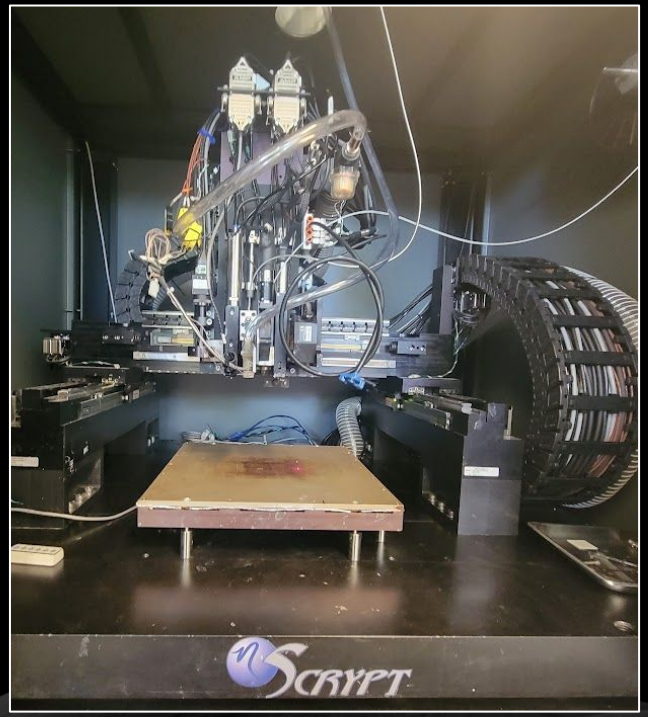
- ★ Test full battery cells
- ★ Demonstrate a shape conformable battery
- ★ Single shot complete battery prints
- ★ Solid electrolyte development
- ★ Improve ISRU and material recycling

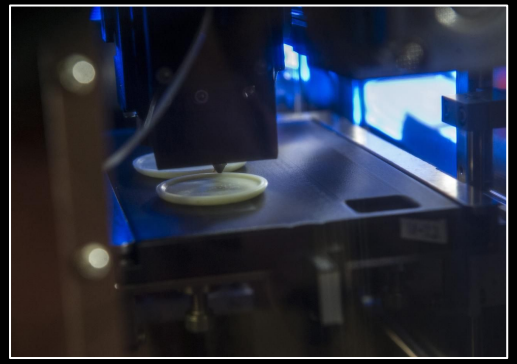




Infusion Paths

- ★ Further Raise the TRL by printing in a relevant environment
- ★ Integrate with Advanced Toolplate multi-material printer
- ★ Embed a printed battery in a printed structure.





Publications

IEEE Access – Towards High Resolution 3D Printing of Shape-Conformable Batteries via Vat Photopolymerization: Review and Perspective

Perspective: What would battery manufacturing on the Moon and Mars look like?

Upcoming:

Creation of a carbon coated TiO2 with dual functionality facilitates 3D printing and improved electrochemical performances of the electrode

Gel Polymer Electrolyte Article

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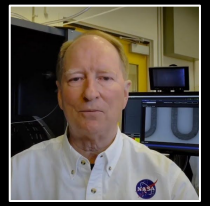
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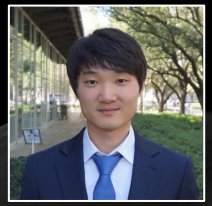
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Questions?

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References and Permissions

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Slide 5: Nasa Graphic

Slide 6. Image from NASA graphic from Recycling Symbol - Download the Original Recycle Logo

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Slide 18: Graphic provided by UTEP

Slide 19: Nasa Images

Slide 20: Graphic provided by UTEP Chart created by NASA

Slide 21: Images provided by NASA

Slide 23: Team images used with approval

What is SIBatt-3D?

★ Developing additively manufactured battery cells and supporting systems

- In-Space/On-Surface
- Sodium Ion Chemistry
- ISRU Feedstocks
- Integrated printed supporting elements