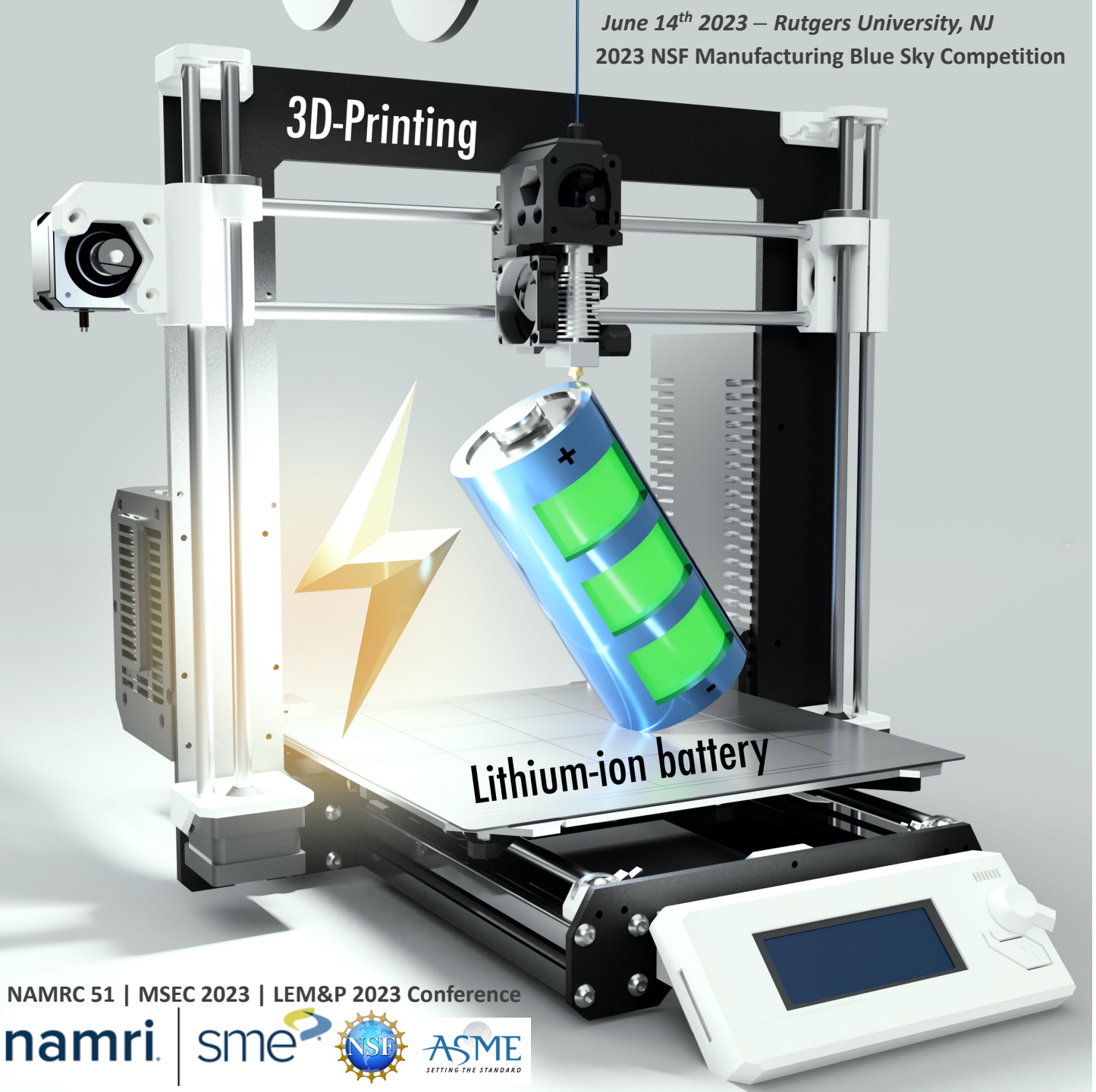
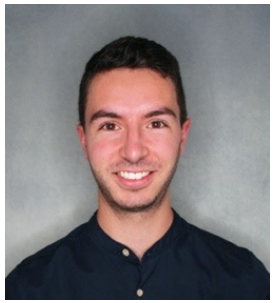
June 14th 2023 – Rutgers University, NJ

2023 NSF Manufacturing Blue Sky Competition



NAMRC 51 | MSEC 2023 | LEM&P 2023 Conference

3D PRINTING OF SHAPE-CONFORMABLE AND STRUCTURAL BATTERIES



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UTEP

FULBRIGHT France

ESTRELLA

ENERGY STORAGE AND ELECTRONICS 3D PRINTING LABORATORY

In collaboration with

OAK RIDGE National Laboratory

INL Idaho National Laboratory

NASA

YOUNGSTOWN STATE UNIVERSITY

UNIVERSITÉ de Picardie Jules Verne

Sandia National Laboratories

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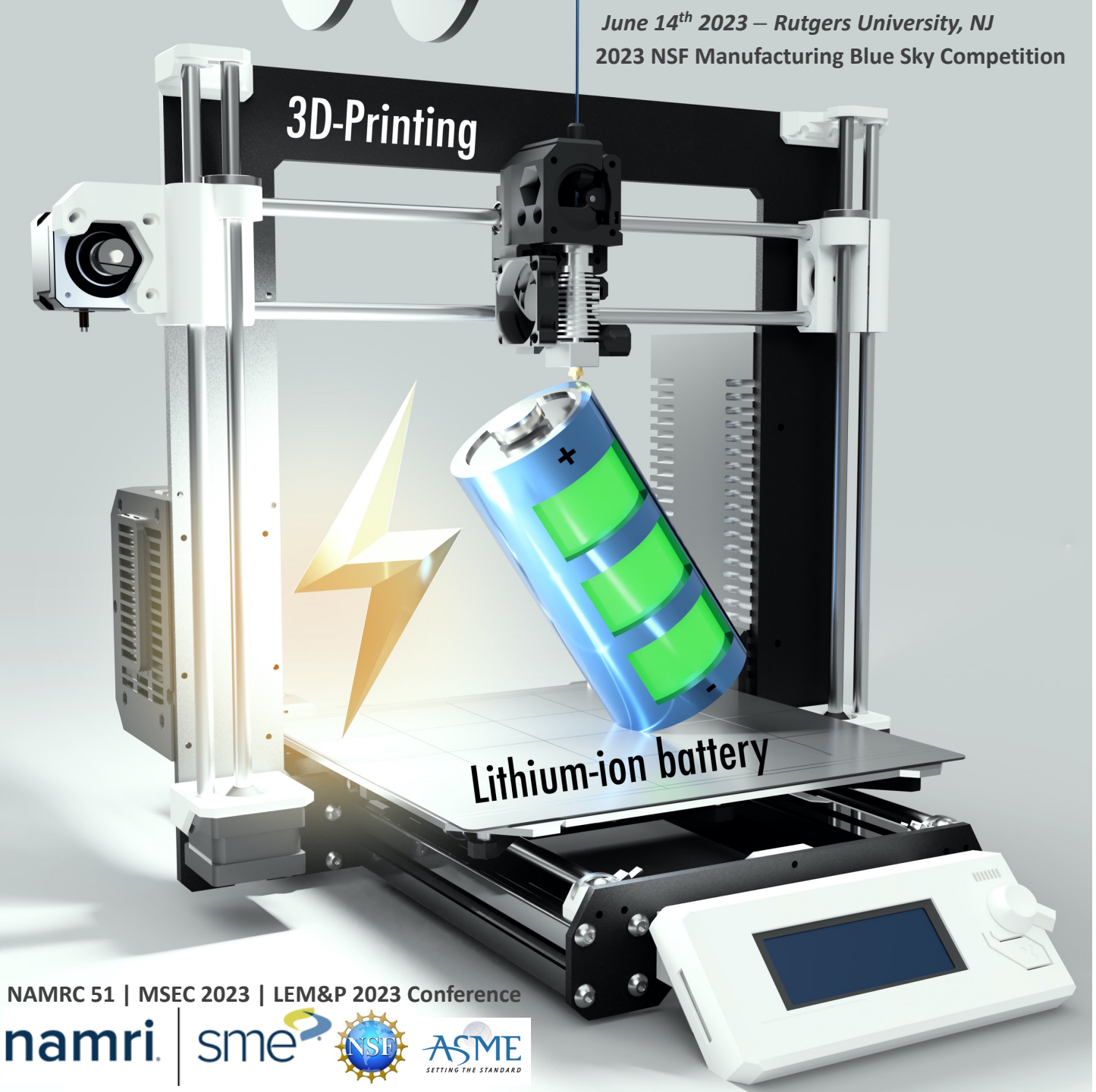

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Battery Manufacturing Challenges:

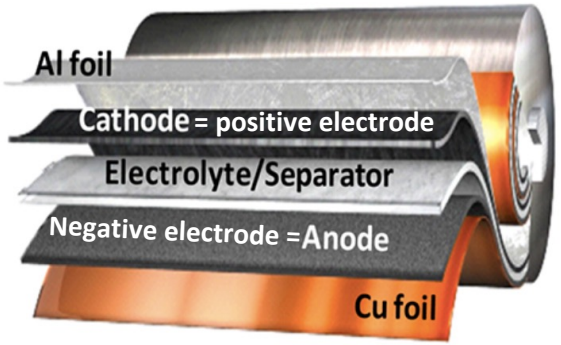
- Battery performance (capacity, power) and safety
- Battery design (restricted to planar only)
- Structural battery with load-bearing capability

Outline of the presentation

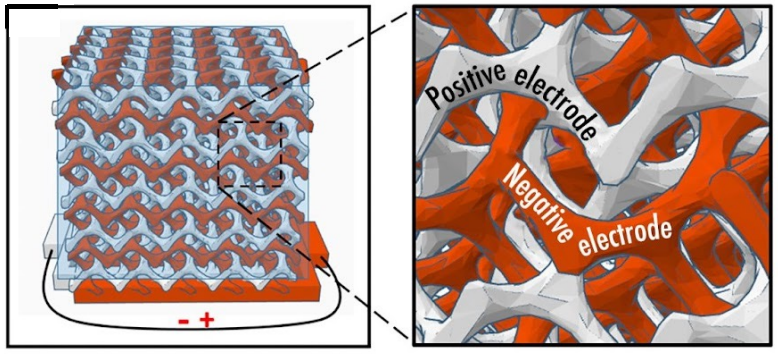
1. WHY 3D PRINTING OF BATTERIES?
2. FILAMENT EXTRUSION
3. POWDER BED FUSION
4. VAT PHOTOPOLYMERIZATION
5. CONCLUSIONS & PERSPECTIVES

1. WHY 3D PRINTING OF BATTERIES?

From 2D to 3D electrodes



3D PRINTING



Surface area

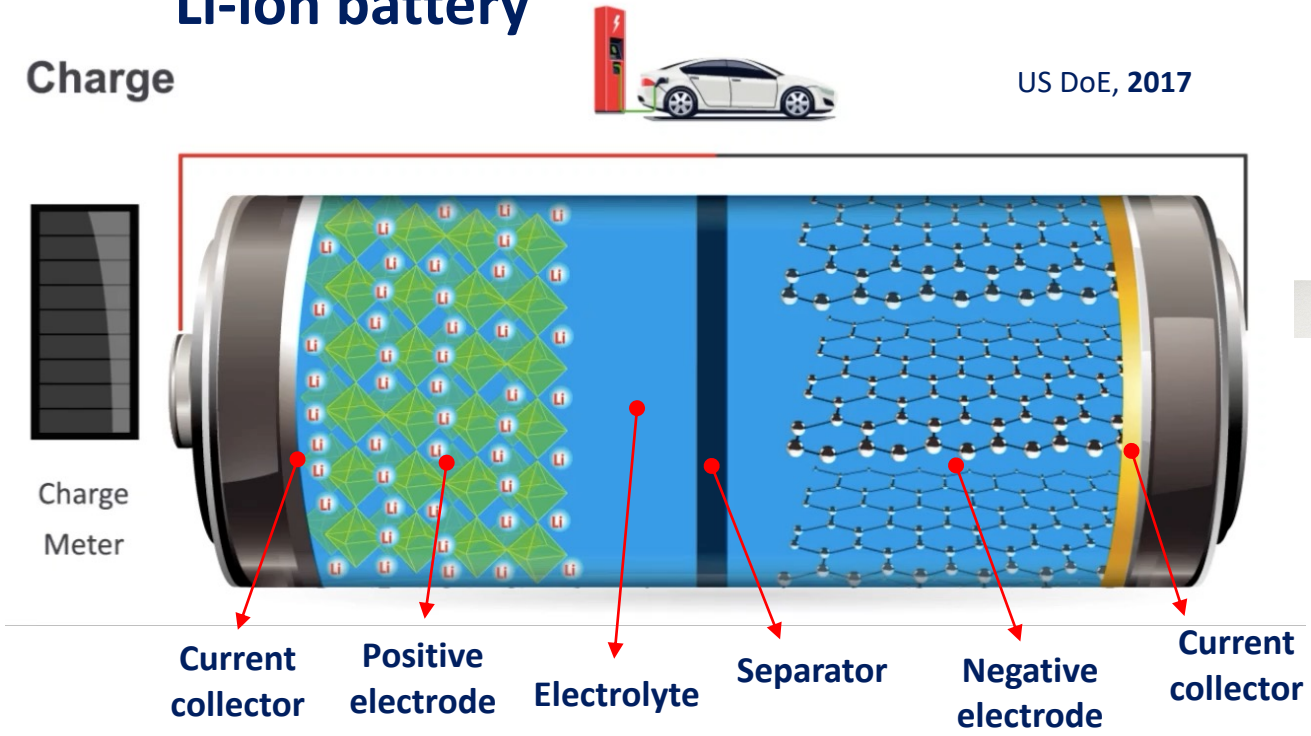
Li⁺ diffusion

Power Performances

Maurel et al., *Additive Manufacturing*, **2021**.

Park et al., *Mater. Des.*, **2020**. Singh et al., *Sci Rep* **2012**

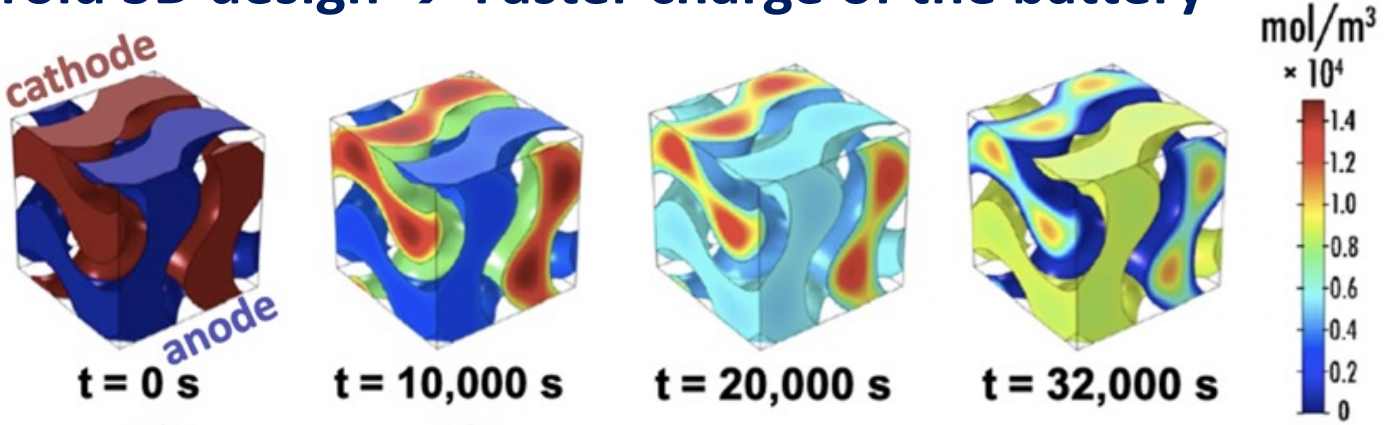
Li-ion battery



US DoE, **2017**

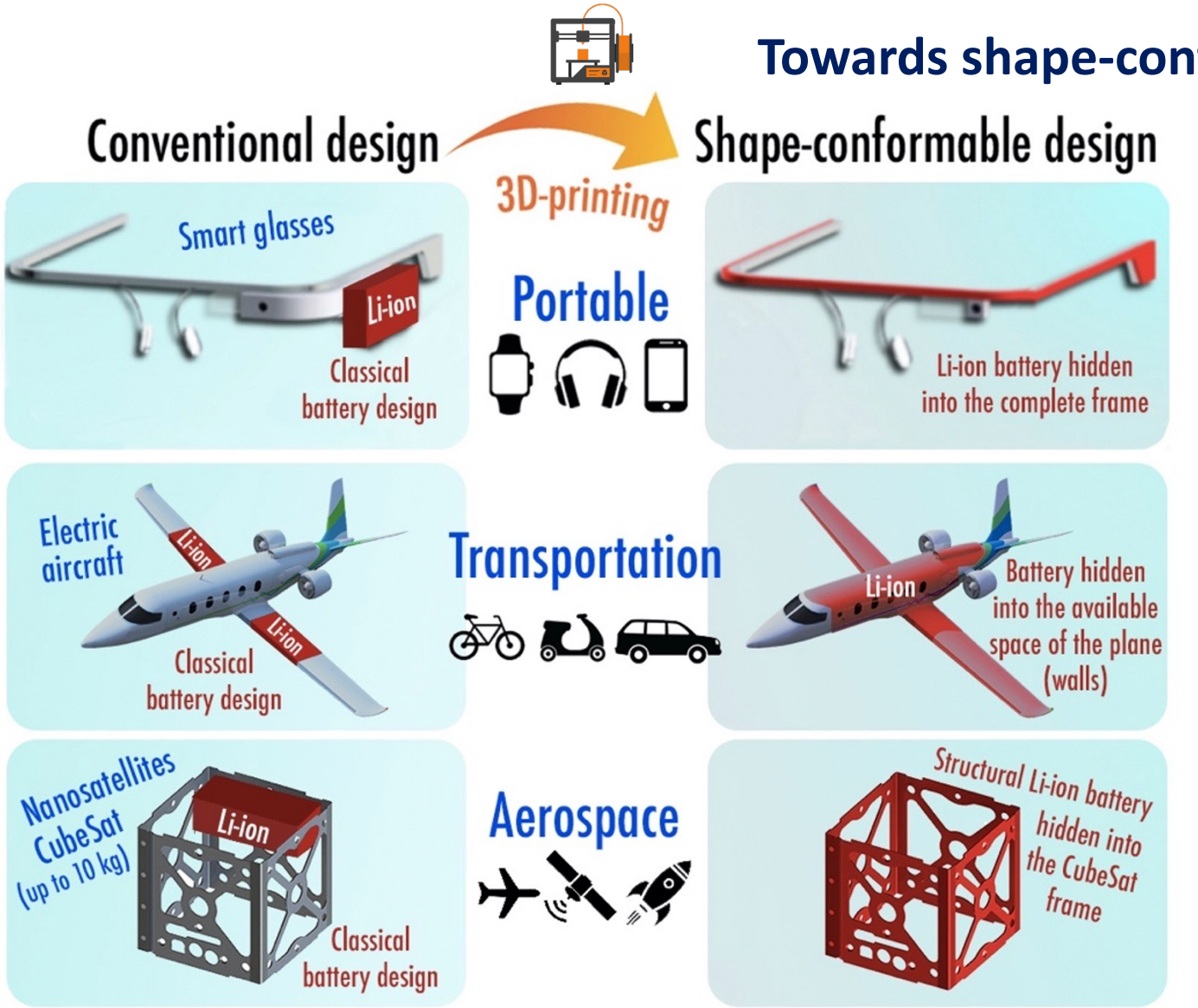
THE NOBEL PRIZE IN CHEMISTRY 2019

Gyroid 3D design → Faster charge of the battery

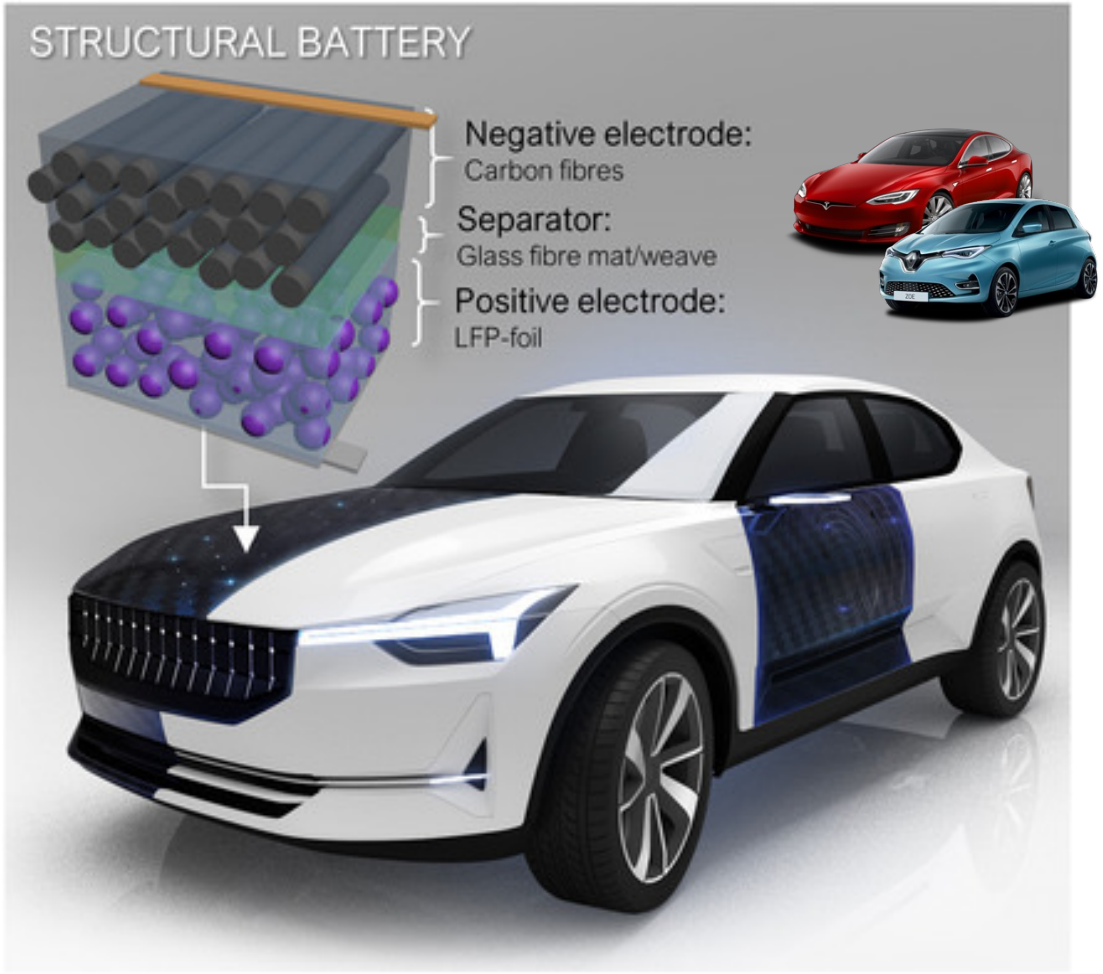


1. WHY 3D PRINTING OF BATTERIES ?

Towards shape-conformable battery / Structural battery



Kim et al., *Nano Letters* **2015**, 15, 5168.
Maurel et al., *Additive Manufacturing*, **2021**.



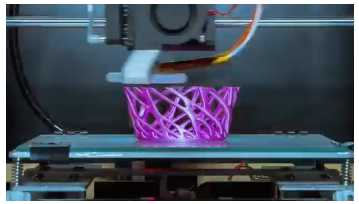
→ **Improved volumetric capacity**

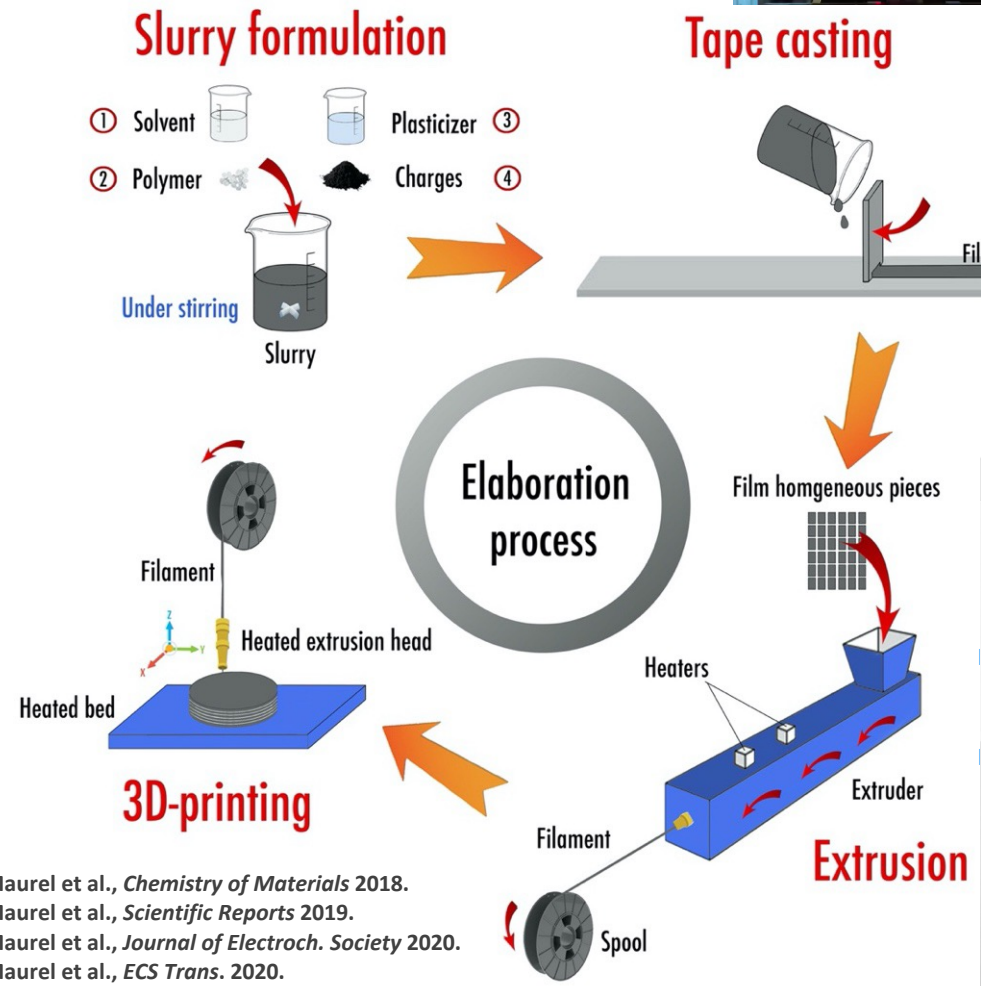
Asp et al., *Advanced Energy and Sustainability Research* **2021.**

2. FILAMENT EXTRUSION 3D PRINTING OF BATTERIES

Filament extrusion

Thermoplastic filament as material feedstock



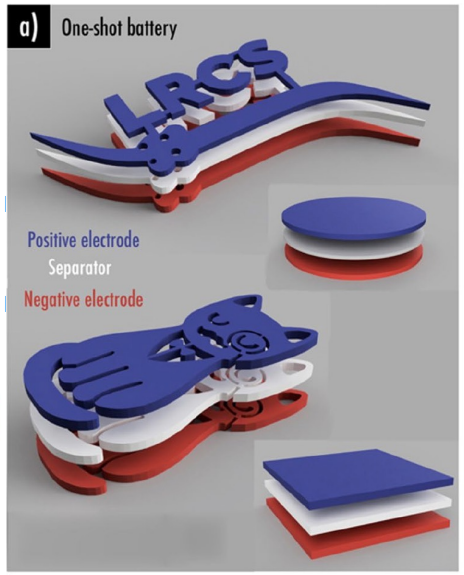


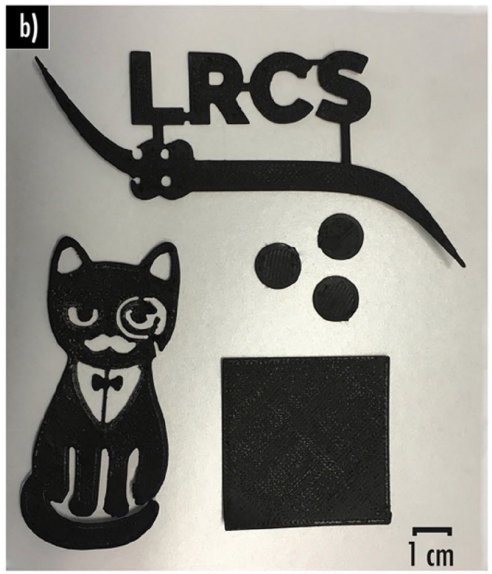
Maurel et al., *Chemistry of Materials* 2018.
Maurel et al., *Scientific Reports* 2019.
Maurel et al., *Journal of Electroch. Society* 2020.
Maurel et al., *ECS Trans*. 2020.
Maurel et al., *Additive Manufacturing* 2021.
Maurel et al. *ECS Journ. Sol. State. Sci. & Tech* 2021.
Maurel et al., *Frontiers Energy Research* 2021.

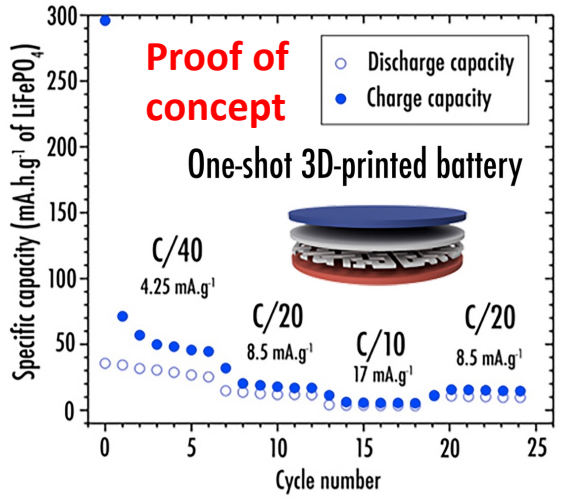
UNIVERSITÉ de Picardie Jules Verne

Development of composite filaments loaded with lithium-ion battery active materials

3D printing of a functional complete battery in a single print





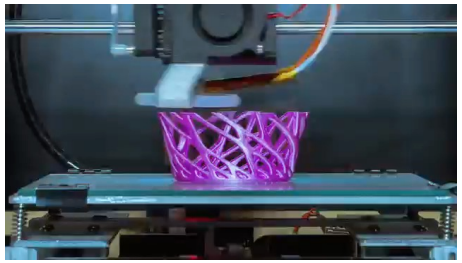


3. POWDER BED FUSION 3D PRINTING OF BATTERIES

Development of composite positive electrodes → Polypropylene (PP) polymer matrix loaded with $LiFePO_4$ (LFP) as lithium-ion battery active material and black carbon (C45) as conductive additive

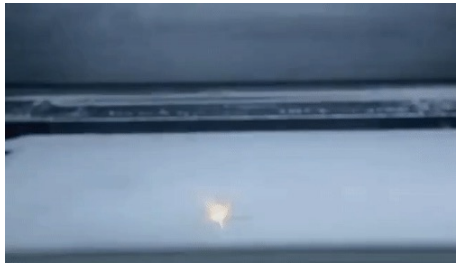
Filament material extrusion (ME)

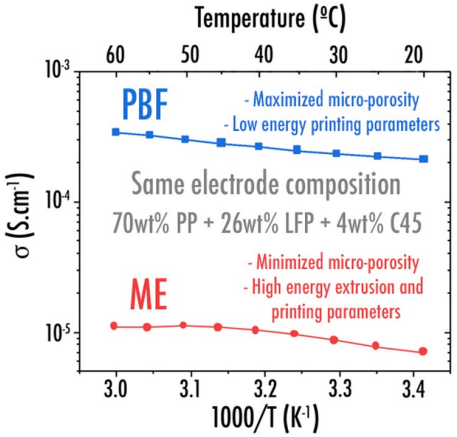
Thermoplastic filament as material feedstock

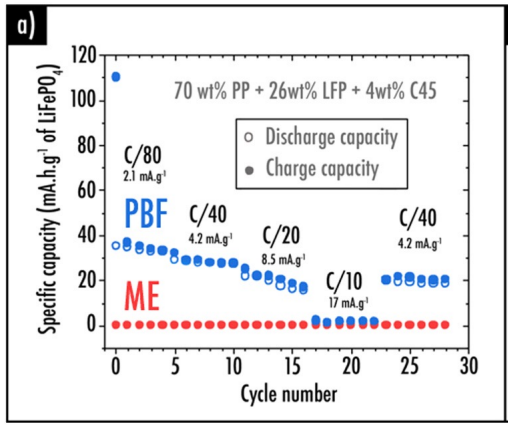


Powder Bed Fusion (PBF)

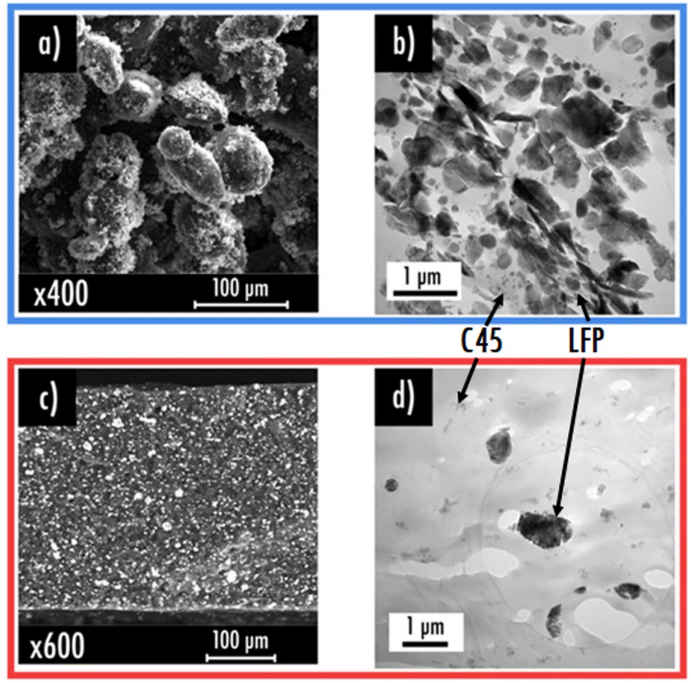
Powder as material feedstock







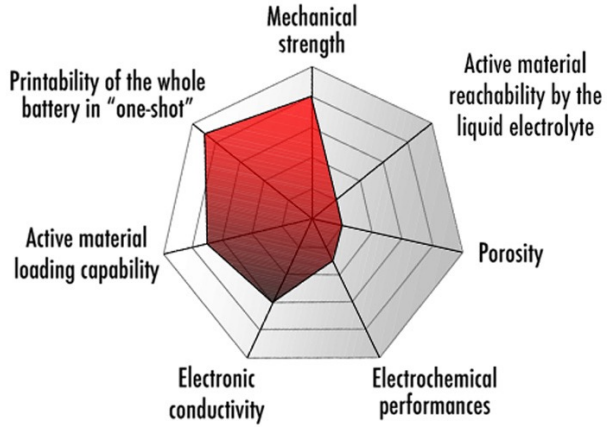
Same electrode composition
70wt% PP + 26wt% LFP + 4wt% C45



Maurel et al., *Additive Manufacturing* 2021.

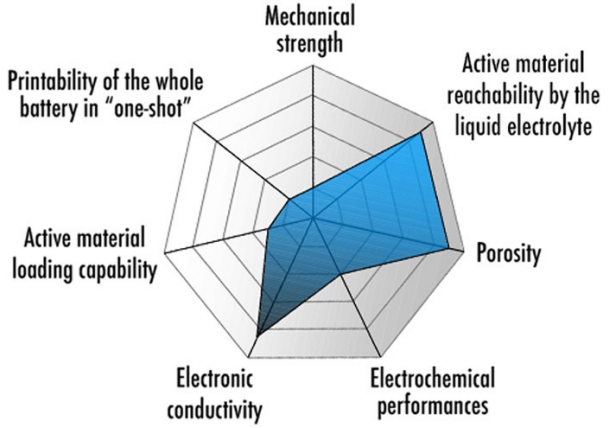
ME

(High energy extrusion and printing parameters)



PBF

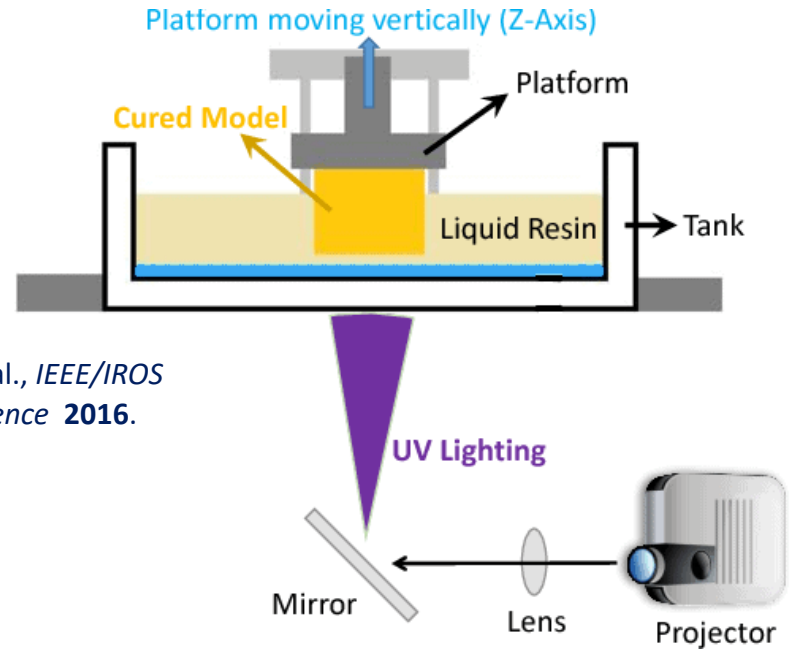
(Low energy printing parameters)



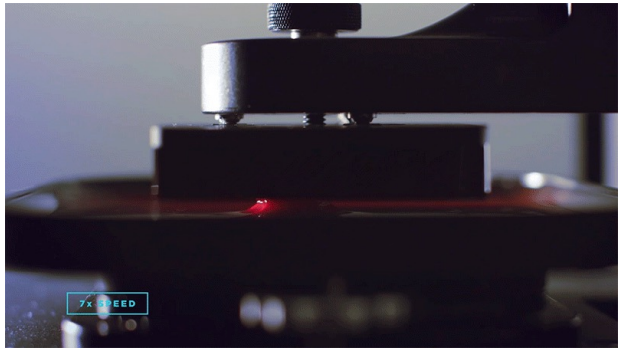
4. VAT PHOTOPOLYMERIZATION 3D PRINTING OF BATTERIES

Vat Photopolymerization

Photocurable resin as material feedstock



Wu et al., *IEEE/IROS Conference* **2016**.



www.carbon3d.com

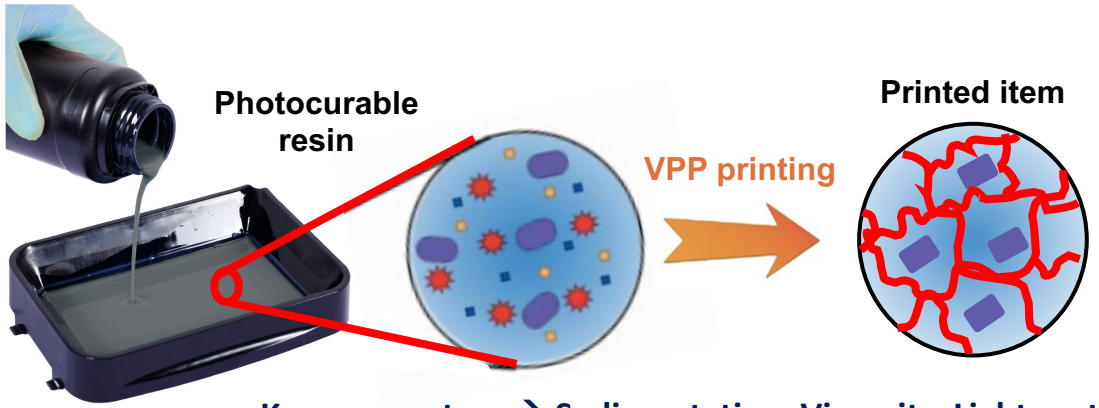
Choi et al., *Int. J. Adv. Manuf. Technol.*, **2010**.

Composite resins formulation

for each component of a classical **lithium-ion** or **sodium-ion battery**

Printability
Monomers, oligomers, photo-initiator

Electrochemical performances
Active materials + Conductive additives
< 40 wt.%



Key parameters → Sedimentation, Viscosity, Light-scattering

Note: The introduction of solid particles limits the printing resolution

Maurel et al. IEEE Access, 2021.

4. VAT PHOTOPOLYMERIZATION 3D PRINTING OF BATTERIES

2023 NSF Manufacturing Blue Sky Competition
3D PRINTING OF SHAPE-CONFORMABLE AND STRUCTURAL BATTERIES - Dr. Alexis Maurel

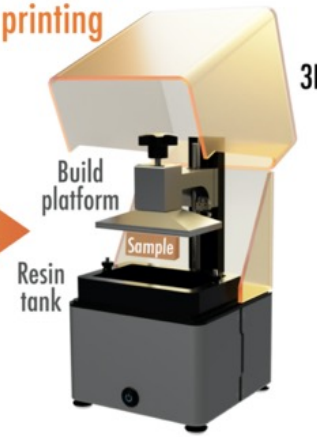
a) Precursor approach

Composite resin formulation

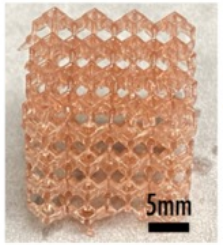
1. Polymer matrix
2. Photoinitiator
3. Deionized water
4. Metal precursors salts

The absence of solid particles prevents the UV light-scattering during printing

Vat photopolymerization 3D printing

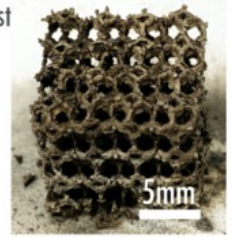


3D printed lattices containing the metal precursors



Thermal post-processing (debinding + sintering)

Battery material
$Li_{1.05}Ni_{0.33}Mn_{0.33}Co_{0.33}O_2$
(NMC111) 3D structure



Optimization between

Electrochemical performances

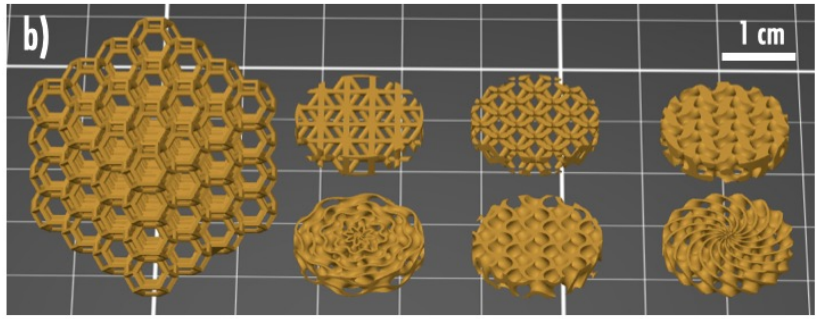
vs.

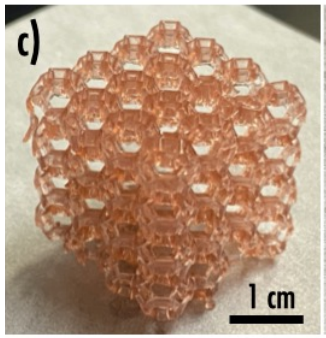
Mechanical integrity

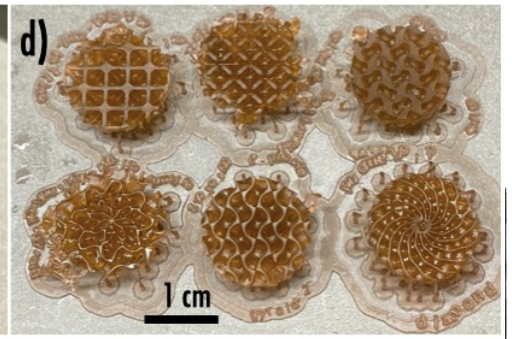
Sandia National Laboratories

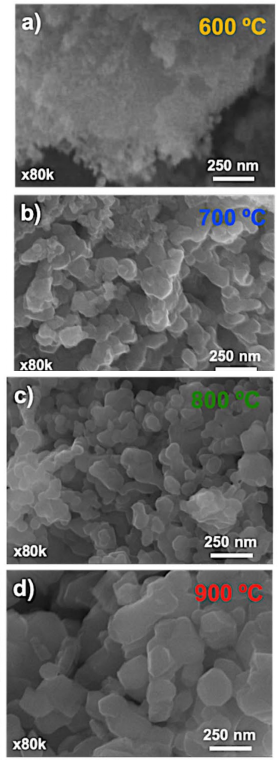
OAK RIDGE National Laboratory

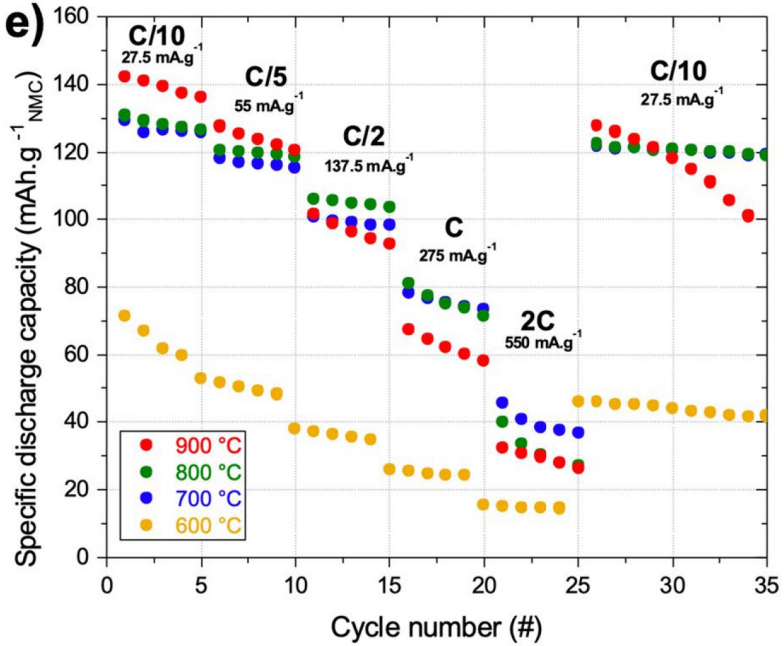
YOUNGSTOWN STATE UNIVERSITY

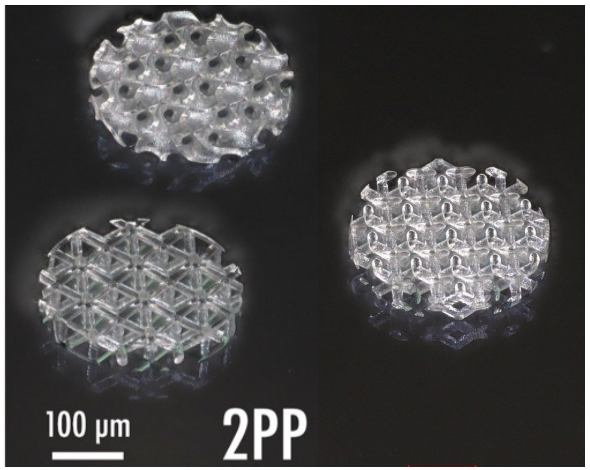






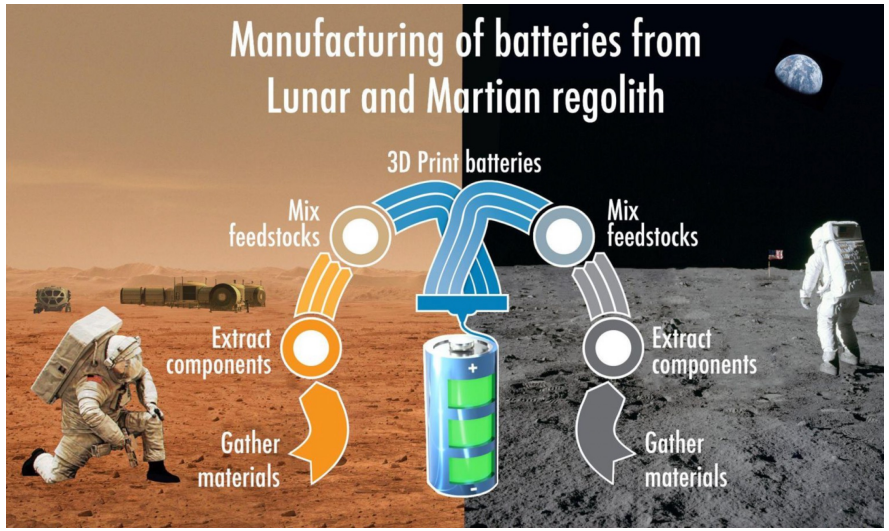






Martinez et al. Sci. Rep, 2022.

4. VAT PHOTOPOLYMERIZATION 3D PRINTING OF BATTERIES



ACS Energy Letters

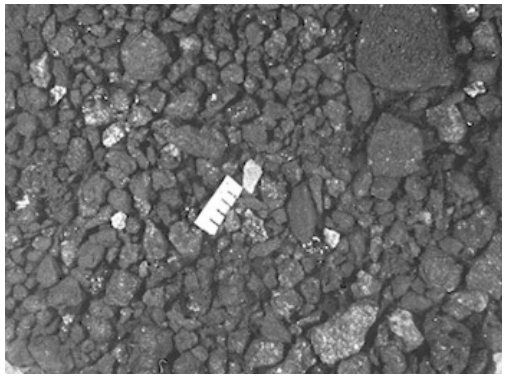
http://pubs.acs.org/journal/aelccp

What Would Battery Manufacturing Look Like on the Moon and Mars?

Cite This: *ACS Energy Lett.* 2023, 8, 1042−1049 Read Online

Maurel et al. ACS Energy Letters 2023.

In-situ resources utilization



Regolith

Packaging & waste materials

What battery chemistry?

→ Sodium-ion battery

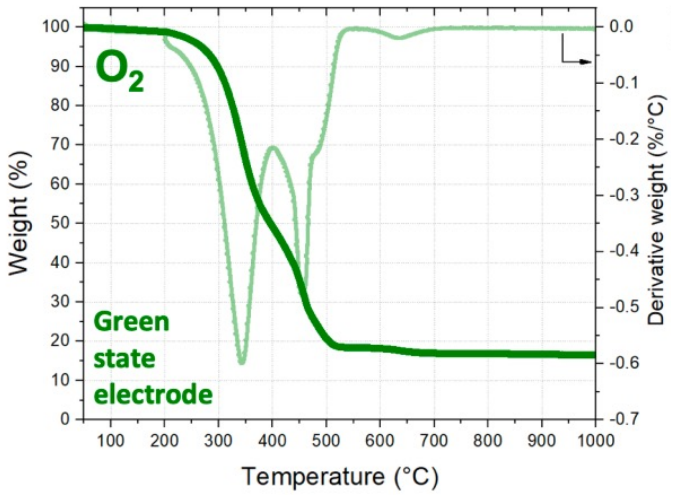
Table 1. Bulk Composition of Lunar, Martian, and Terrestrial Soil[a]

Element	Moon (refs 17−19)	Mars (refs 20, 21, 24)	Earth (refs 25, 26)
Li (ppm)	10	1.8−3	18
Na (ppm)	2000−3000 (average); 5000 (Maria region)	5770	23 600
K (ppm)	1000	309	21 400
F (ppm)	70	20−30	525
Cl (ppm)	50	30	472
P (ppm)	800	675	757
V (ppm)	130	130	98
Mg (wt%)	5.5	18.5	2.2
Ca (wt%)	10 (highland); 8 (Maria Region)	1.7	3.9
Fe (wt%)	6 (highland); 15 (Maria region)	14.1	4.3
Mn (ppm)	200 (highland); 2000 (Maria region)	2250	716
Al (wt%)	13 (highland); 5 (Maria region)	1.6	8.0
Cu (ppm)	8	2	25
Si (wt%)	21	20.5	28.8
Ni (ppm)	200	330	56
Co (ppm)	40	71	24
Ti	1 wt% (average); 5 wt% (Maria region)	832 ppm	4010 ppm (0.4 wt%)

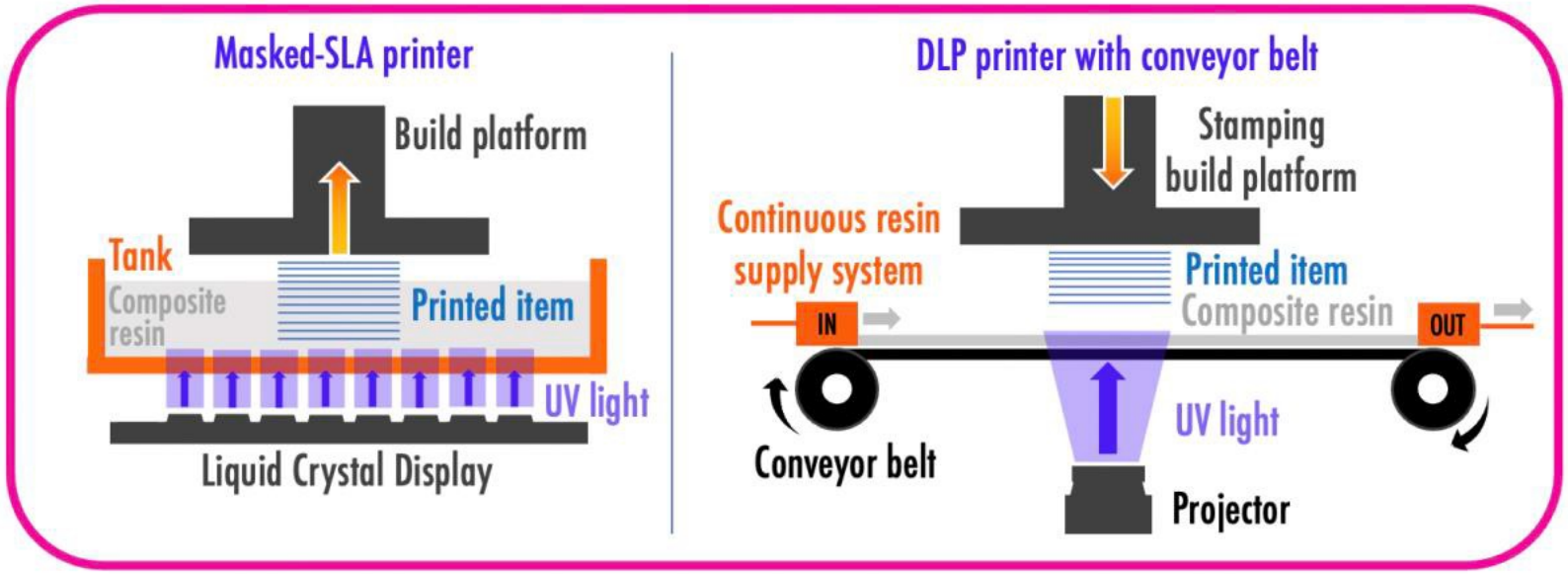
4. VAT PHOTOPOLYMERIZATION 3D PRINTING OF BATTERIES

1 Composite resin formulation

TiO_2 : C : Polymer
18 : 1.5 : 80.5 wt%



2 Vat photopolymerization 3D printing of Li-ion and Na-ion battery electrodes



✗ **Not suitable to print highly-loaded composite resins**

- Sedimentation
- Light-scattering

✓ **Suitable to print highly-loaded composite resins**

- Continuous resin supply system → no sedimentation
- Thin resin film

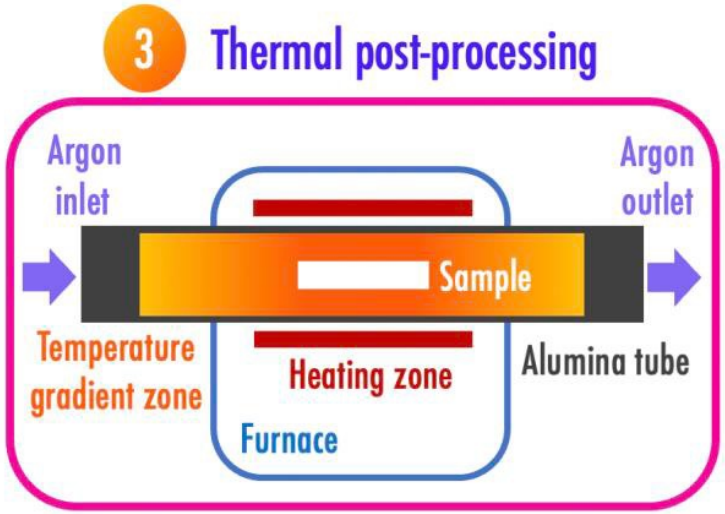
Maurel et al. (under review)

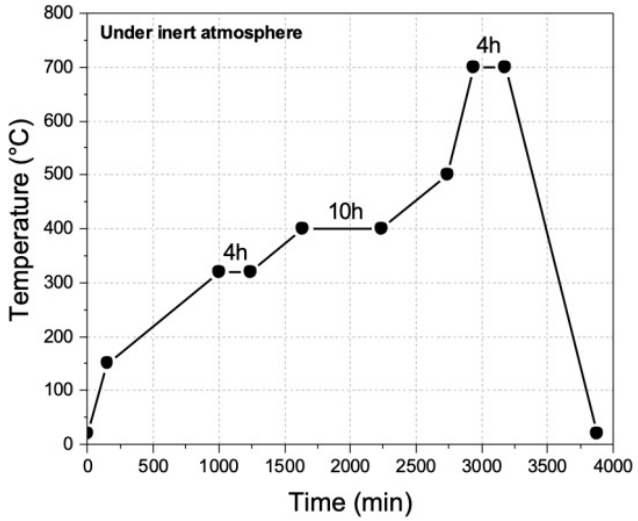
4. VAT PHOTOPOLYMERIZATION 3D PRINTING OF BATTERIES

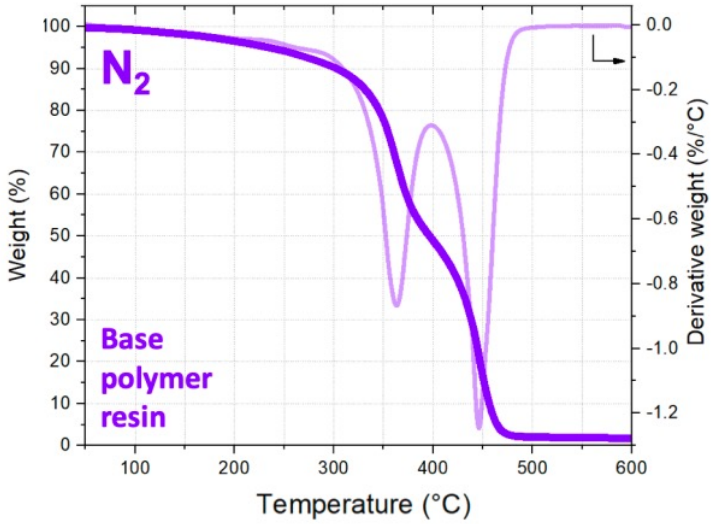
Maurel et al. (under review)

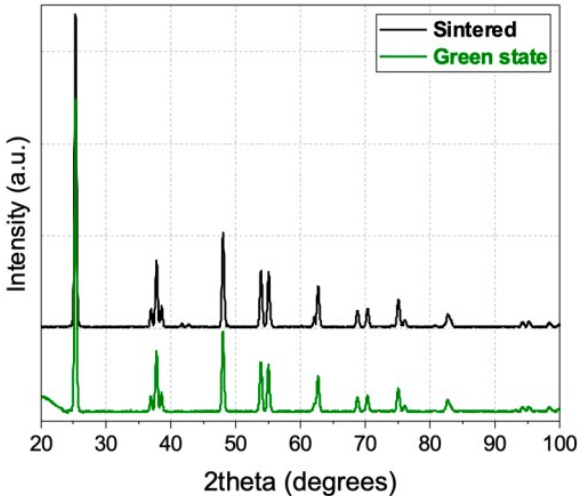
TiO_2-based electrodes for sodium-ion battery negative electrode

Impact of an additional thermal post-processing step?

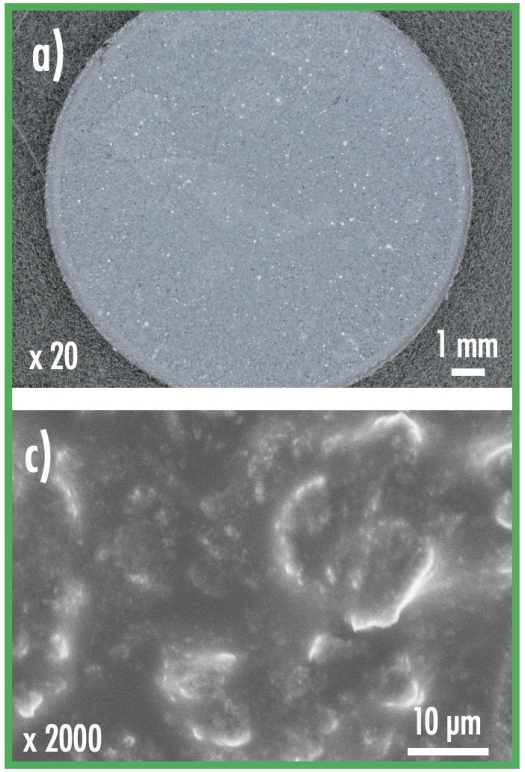




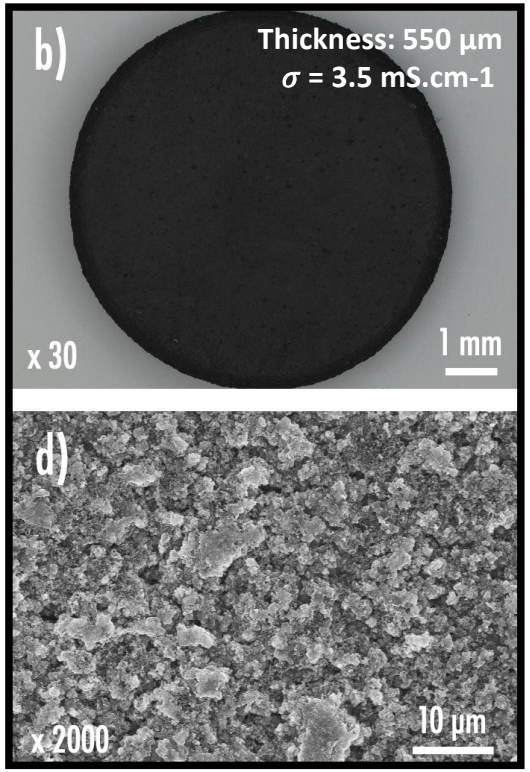




Solid green state



Solid sintered



Diameter and thickness → 40% shrinkage upon thermal post-processing

Polymer removal during debinding → Increased micro-porosity and Improved electrolyte impregnation

Poor electrochemical performances upon cycling

4. CONCLUSIONS AND PERSPECTIVES

- ✓ Multidisciplinary work → Engineering / Electrochemistry / Materials Science
- ✓ 3D printing as an innovative and modular tool to print rechargeable batteries
- ✓ Manufacturing of shape-conformable / structural / flexible batteries (dual functionality: energy storage and load bearing)
- ✓ Improved volumetric capacity and power performances
- ✓ Solid state batteries with enhanced safety relevant to federal agencies and industry

- Develop adequate composite material feedstock (filament, ink, powder, resin) for each component of the battery (electrodes, separator, electrolyte, current collectors)
- High resolution multi-material printing options are needed to manufacture the complete battery in a single step
- Targeting a wide range of applications → portable electronics, automotive, naval, aerospace, defense, and biomedical

6. ACKNOWLEGEMENTS

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3D PRINTING OF SHAPE-CONFORMABLE
AND STRUCTURAL BATTERIES - Dr. Alexis Maurel

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blue sky COMPETITION
David Dornfeld Manufacturing Vision Award

National Science Foundation

North American Manufacturing Research Institution of Society of Manufacturing Engineers and The American Society of Mechanical Engineers

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INL Idaho National Laboratory

Sandia National Laboratories

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June 14th 2023 – Rutgers University, NJ
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THANK YOU
Questions?

FULBRIGHT France
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