US ARMY RDECOM U.S. Army Research, Development and Engineering Command

# Energy-Storing Structures: Composite Capacitors and Batteries

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.


**Dr. Danny O'Brien**

**Composite and Hybrid Materials Branch**

daniel.j.obrien58.civ@mail.mil 410-306-0851

Army Research Laboratory

RDRL-WMM-A

Aberdeen Proving Ground, MD 21005


2nd Multifunctional Materials for Defense Workshop

Arlington, VA

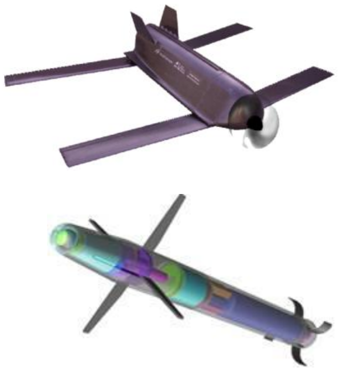
30 July 2012

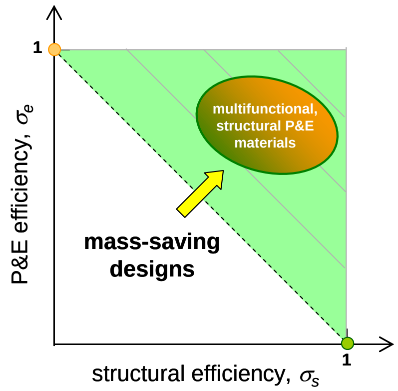
| **Report Documentation Page** | | | | | *Form Approved*<br>*OMB No. 0704-0188* |
|---|---|---|---|---|---|
| Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. | | | | | |
| 1. REPORT DATE<br>**30 JUL 2012** | | 2. REPORT TYPE | | | 3. DATES COVERED<br>**00-00-2012 to 00-00-2012** |
| 4. TITLE AND SUBTITLE<br>**Energy-Storing Structures: Composite Capacitors and Batteries** | | | | | 5a. CONTRACT NUMBER |
| | | | | | 5b. GRANT NUMBER |
| | | | | | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | | | | | 5d. PROJECT NUMBER |
| | | | | | 5e. TASK NUMBER |
| | | | | | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**U.S. Army Research Laboratory,RDRL-WMM-A,Aberdeen Proving Ground,MD,21005** | | | | | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | | | | | 10. SPONSOR/MONITOR’S ACRONYM(S) |
| | | | | | 11. SPONSOR/MONITOR’S REPORT NUMBER(S) |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT<br>**Approved for public release; distribution unlimited** | | | | | |
| 13. SUPPLEMENTARY NOTES<br>**Presented at the 2nd Multifunctional Materials for Defense Workshop in conjunction with the 2012 Annual Grantees’/Contractors’ Meeting for AFOSR Program on Mechanics of Multifunctional Materials & Microsystems Held 30 July - 3 August 2012 in Arlington, VA. Sponsored by AFRL, AFOSR, ARO, NRL, ONR, and ARL.** | | | | | |
| 14. ABSTRACT | | | | | |
| 15. SUBJECT TERMS | | | | | |
| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
| a. REPORT<br>**unclassified** | b. ABSTRACT<br>**unclassified** | c. THIS PAGE<br>**unclassified** | **Same as Report (SAR)** | **29** | |

**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std Z39-18

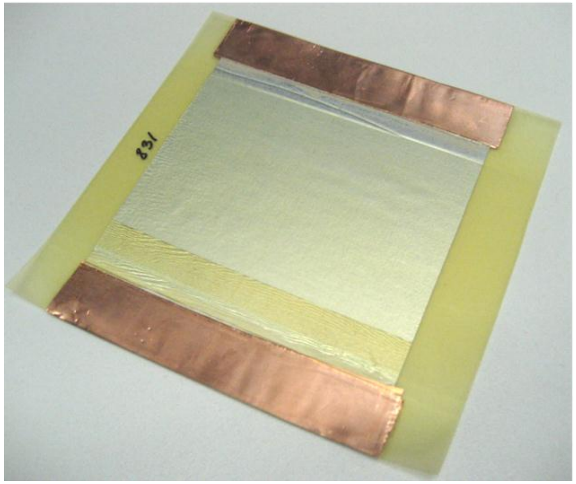
# Outline

## Motivation and Approach

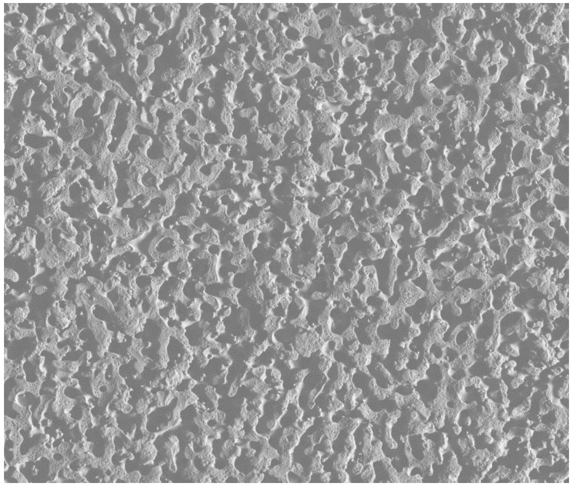





## Structural Capacitors




## Structural Batteries



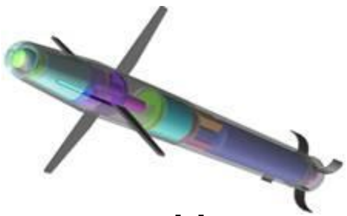
*ARL research team: Eric Wetzel Jim Snyder, Danny O'Brien,*
*Dan Baechle, Eddie Geinger, Oleg Yurchak, Wai Chin, Kris Behler*

# U.S. Army Power and Energy

## Batteries

UAV propulsion

night vision goggles, radios



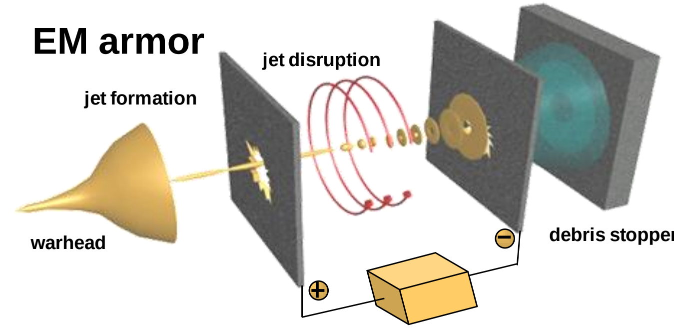
smart munition sensing, control, computation

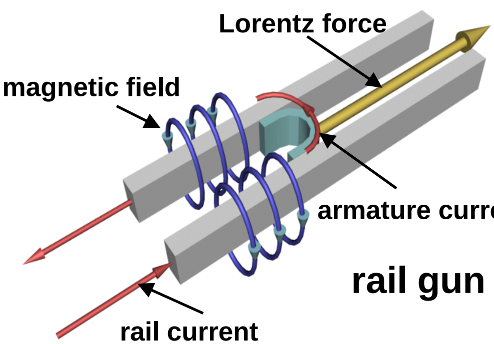
hybrid electic-combustion powerplants

## Capacitors

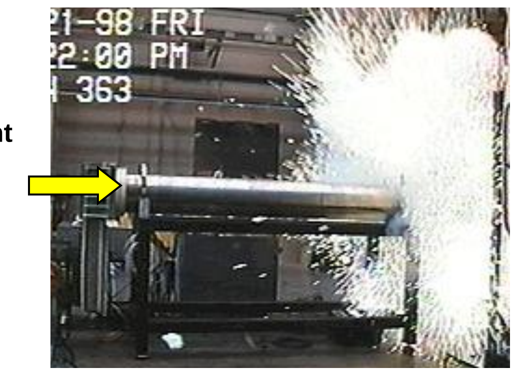
*pulsed power applications*

EM armor



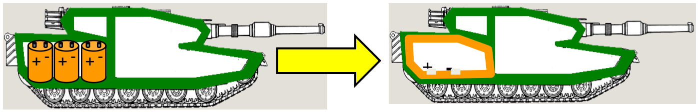

rail gun

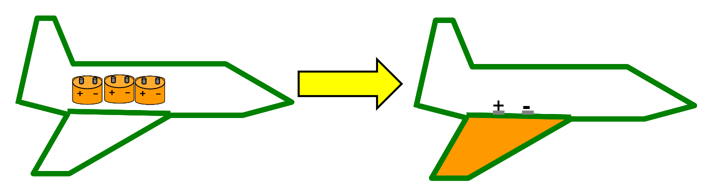


## Objective

**Reduce system mass (or volume) by creating batteries and capacitors that can carry mechanical loads.**

**Batteries / capacitors serve as structural or armor elements.**





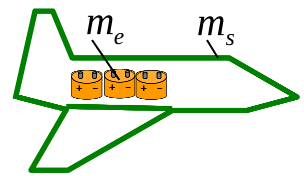
# Mass Savings through Multifunctionality

$\sigma_e \rightarrow$ mass-normalized P&E efficiency
$\sigma_s \rightarrow$ mass-normalized structural efficiency

$$\sigma_e = \frac{\overline{E}_{se}}{\overline{E}_e}$$

$$\sigma_s = \frac{\overline{S}_{se}}{\overline{S}_s}$$

## Conventional design




$$M = m_s + m_e$$

system mass [kg]; structure mass [kg]; P&E mass [kg]

## Multifunctional design

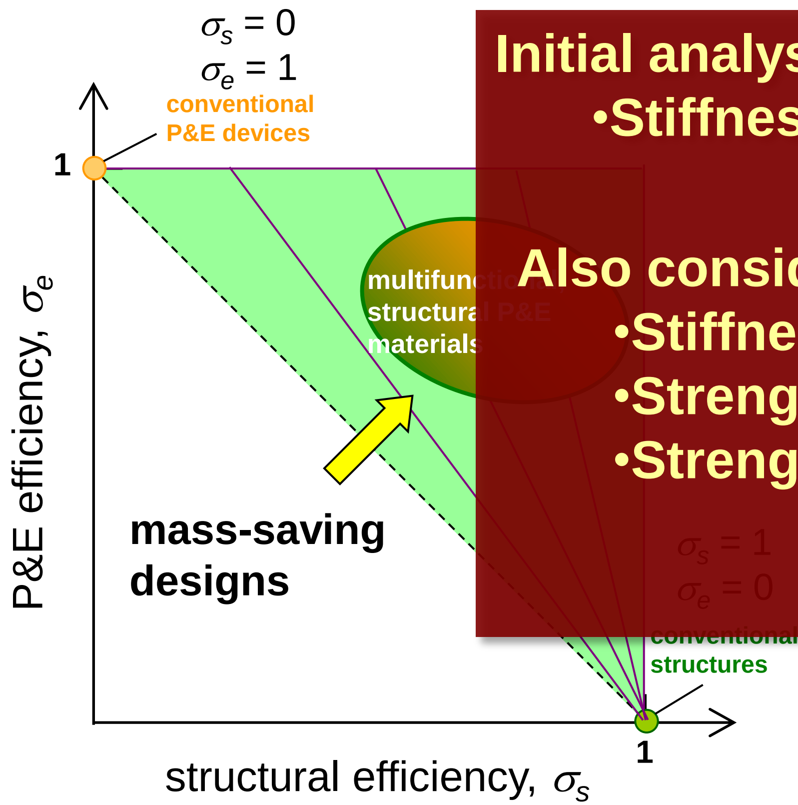
$$M^* = m_s^* + m_e^* + m_{se}^*$$
$$= \left(m_s - \sigma_s m_{se}^*\right) + \left(m_e - \sigma_e m_{se}^*\right) + m_{se}^*$$
$$= \left(m_s + m_e\right) + \left(1 - \sigma_s - \sigma_e\right) m_{se}^*$$

structural P&E mass [kg]

$$\left(M - M^*\right) = \left(\sigma_s + \sigma_e - 1\right) m_{se}^*$$

mass-savings can be achieved if:

$$\sigma_{mf} \equiv \sigma_e + \sigma_s > 1$$




**Initial analysis driven by:**
- **Stiffness / Mass**

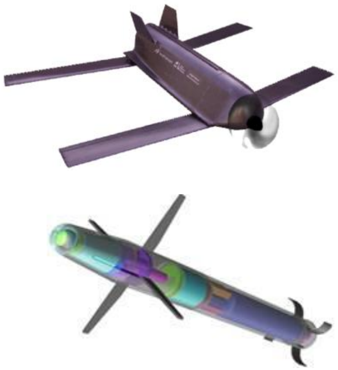
**Also consider:**
- **Stiffness / Volume**
- **Strength / Mass**
- **Strength / Volume**

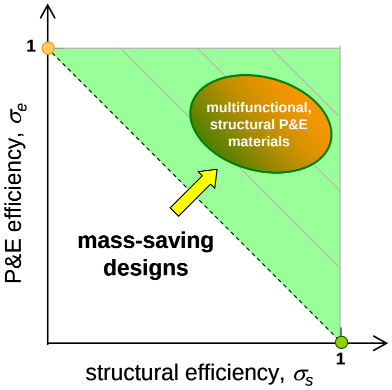
**Mass savings possible even if multifunctional material performs individual functions less efficiently than monofunctional materials.**

# Outline

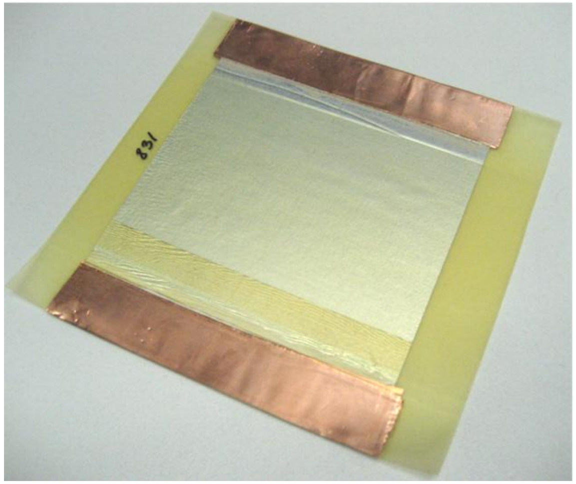


## Motivation and Approach

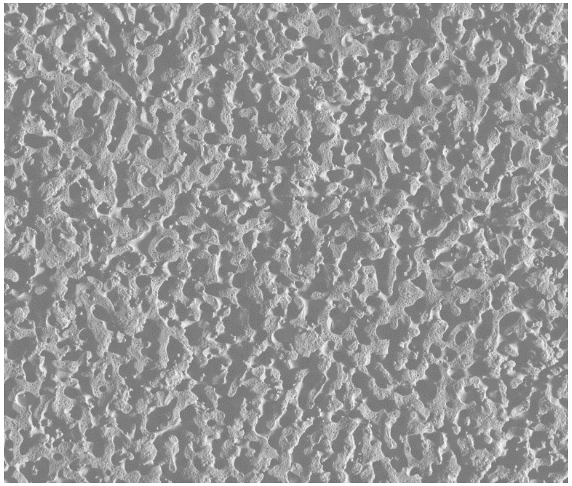





## Structural Capacitors



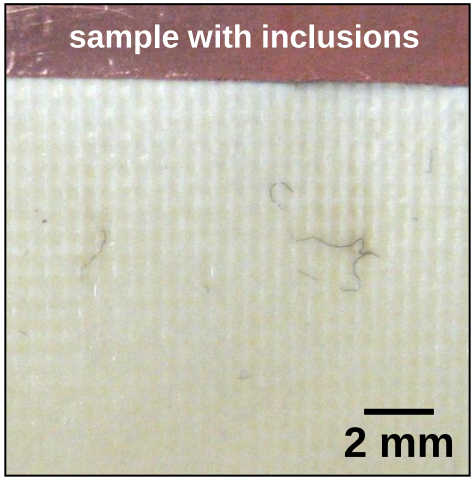

## Structural Batteries

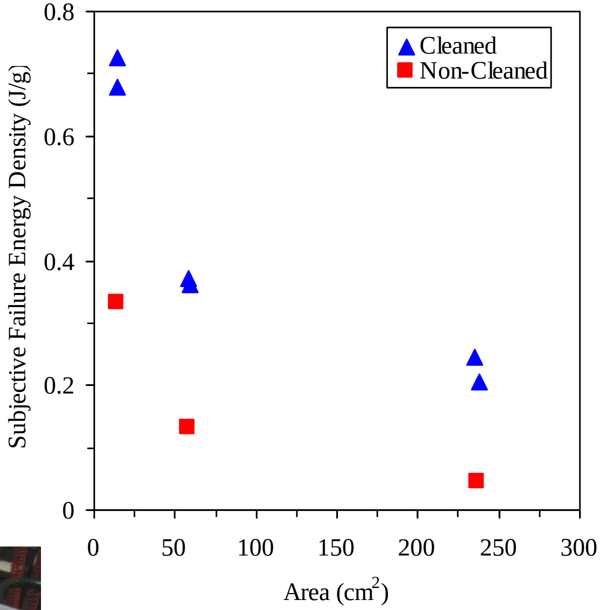


# Clean Processing Required



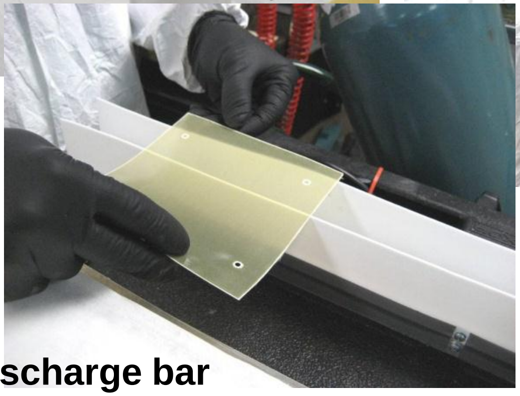
laminar flow room




solvent wipe

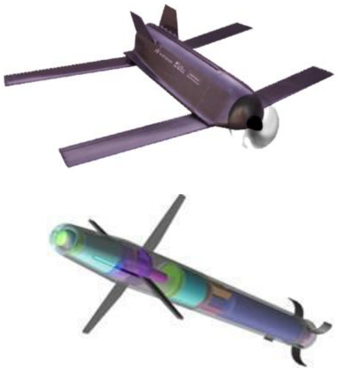
dry nitrogen

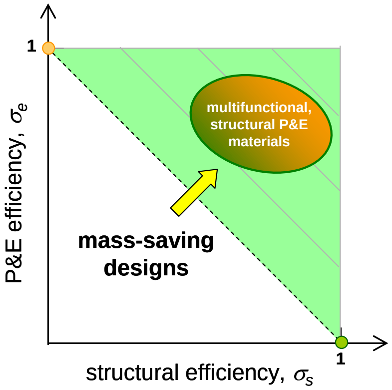


static discharge bar

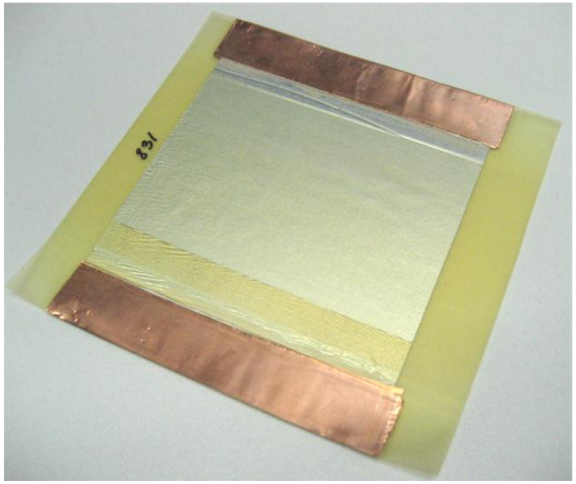
# Outline

## Motivation and Approach

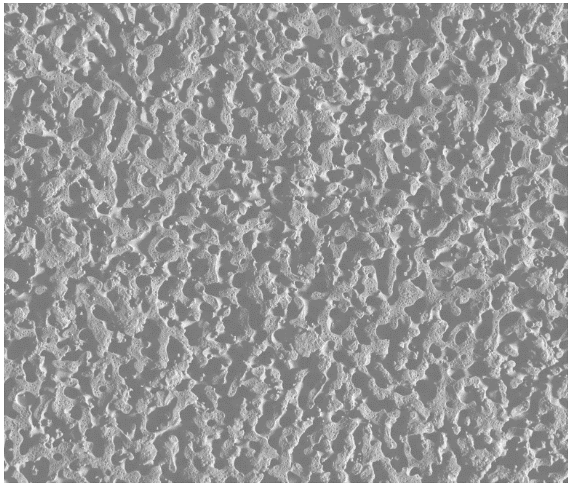





## Structural Capacitors

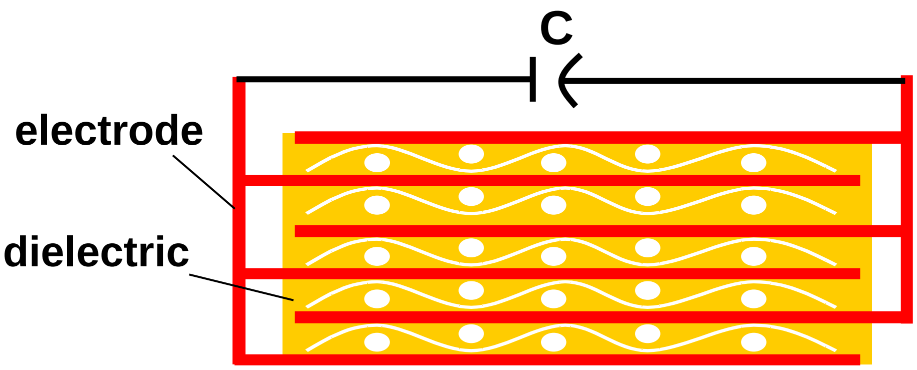


## Structural Batteries

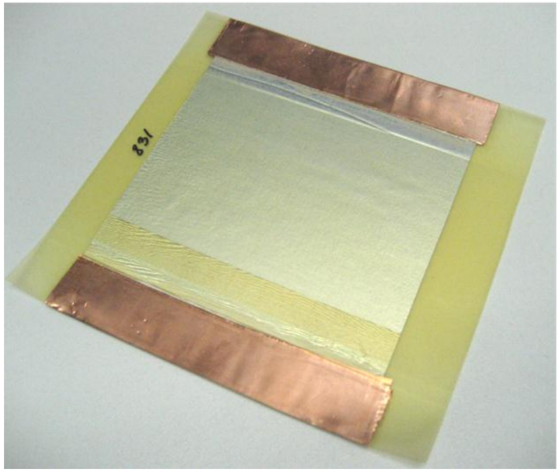


# Anatomy of a Structural Capacitor

## Electrodes
- Metallized films and papers
- Examples: 100 nm Al on Kapton film, 20 nm Al on Kraft paper

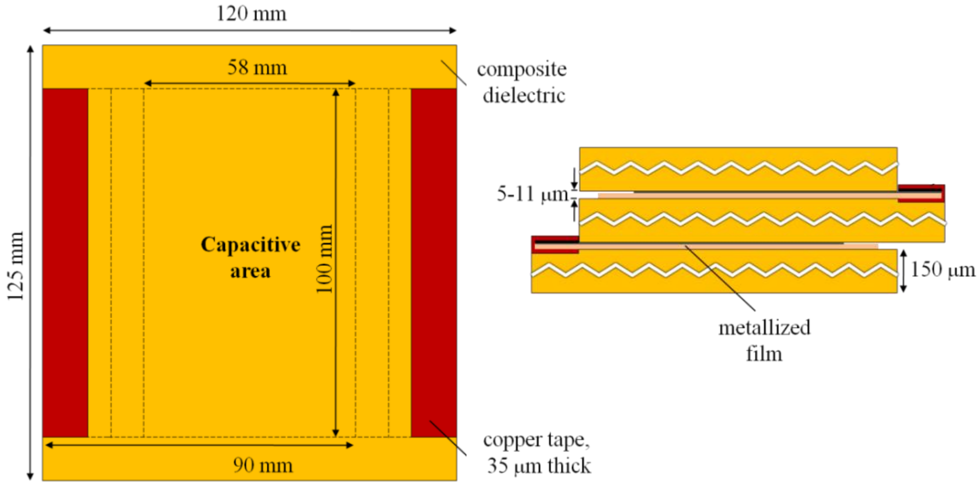



## Composite dielectric
- Glass fiber-reinforced polymers
- Example: Nelcote printed circuit board (PCB) prepreg

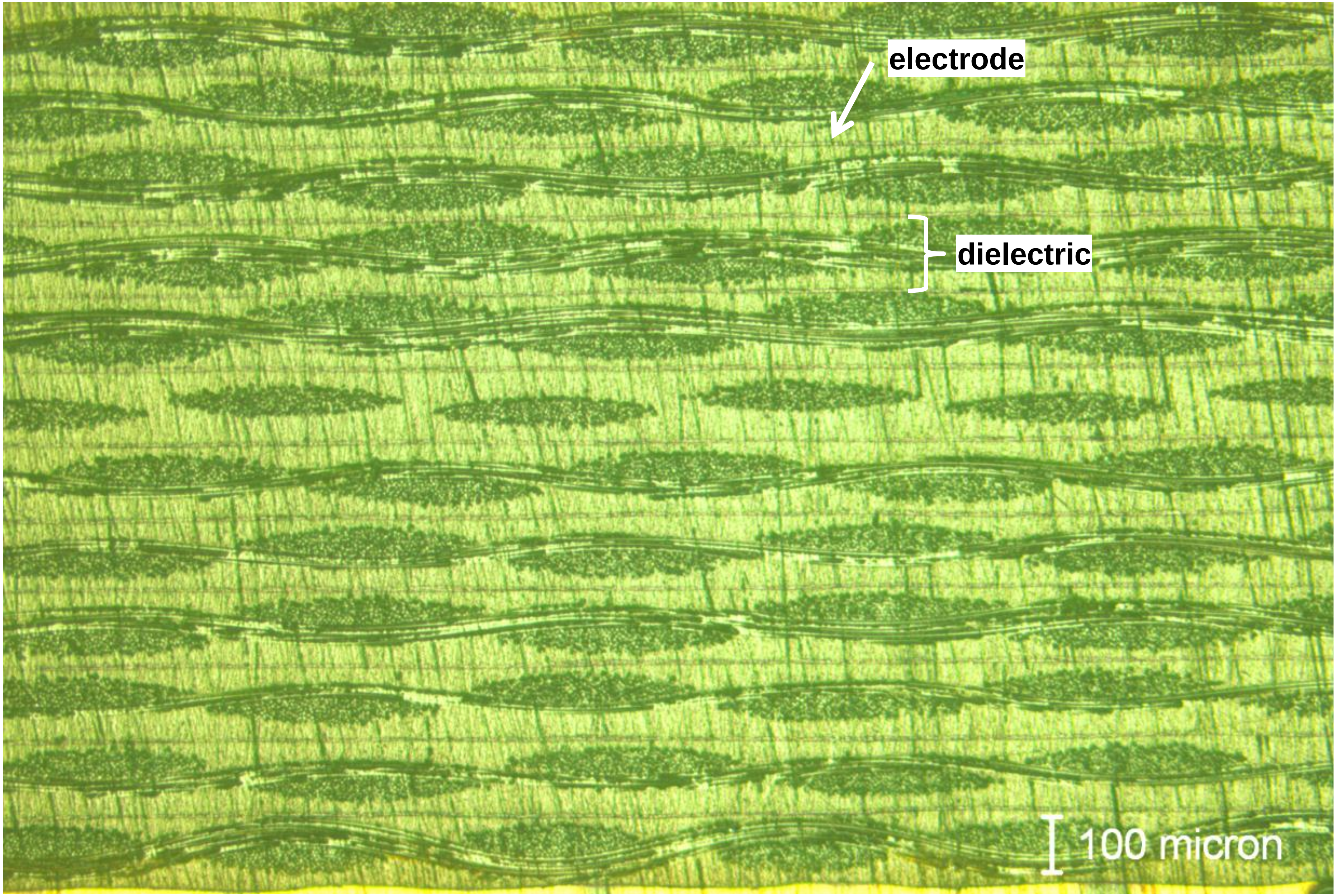


Autoclave-processed structural capacitor

- **Objective: High energy density, scalable structural capacitor**
  - High energy density
    - Vanishingly thin electrodes
    - Low void content
  - Scaling
    - Clean processing
    - Self-clearing electrodes
    - Scalable assembly

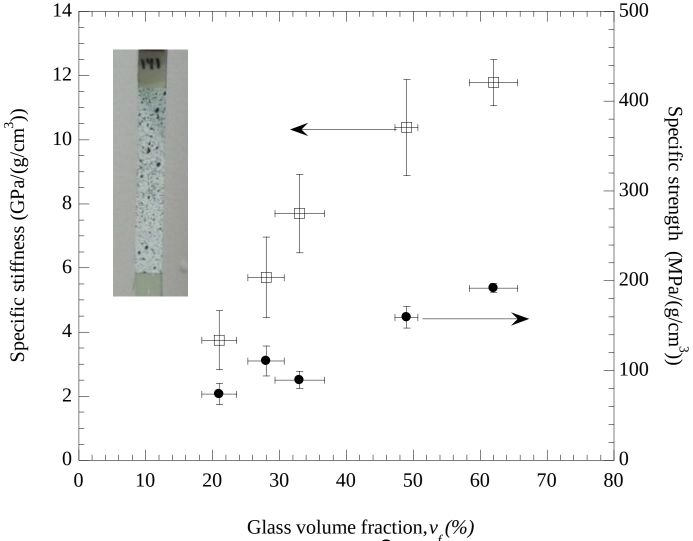


# Cross-Section of Structural Capacitor

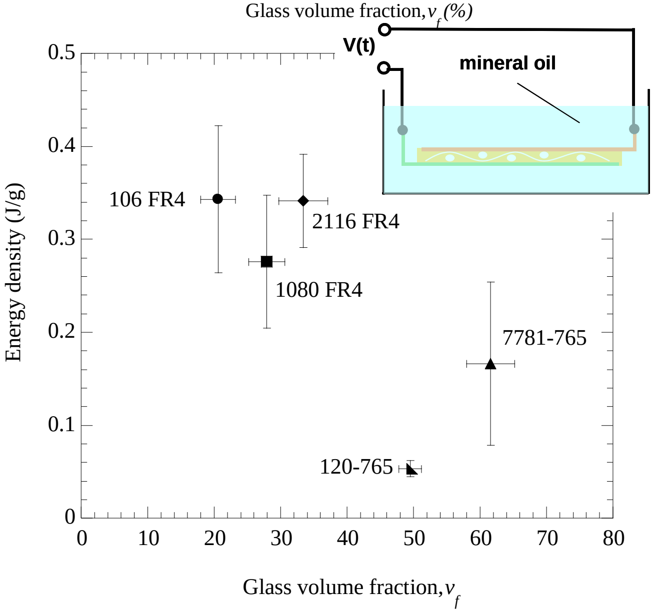


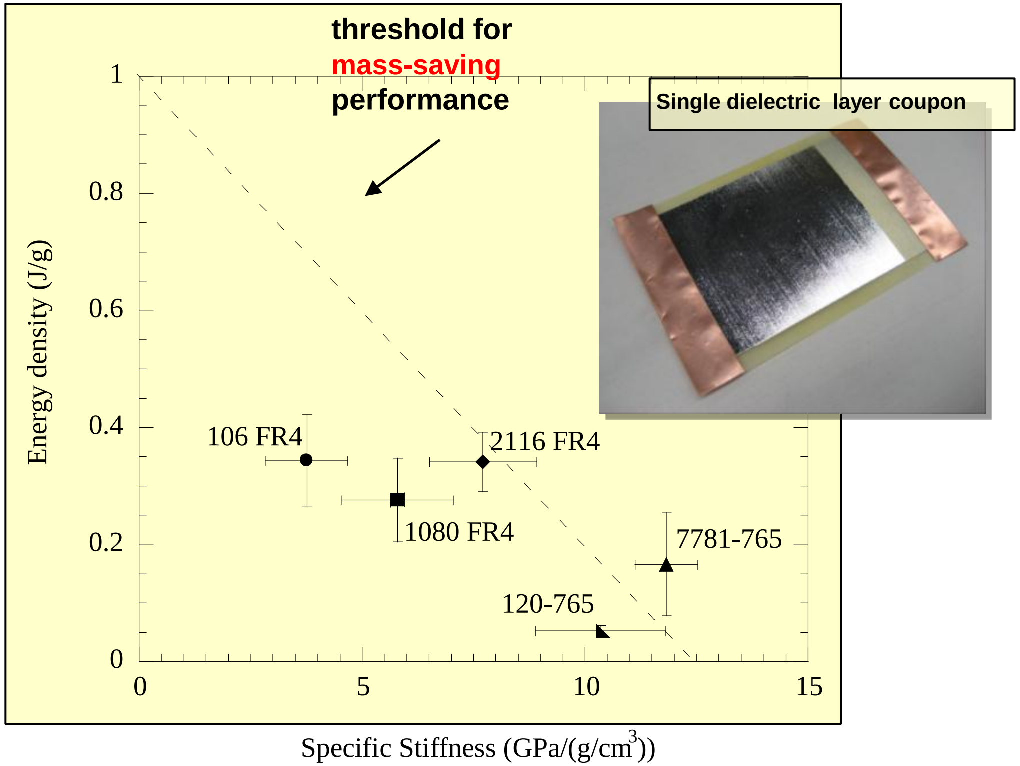
# Coupon Level Experiments
## Fiber Volume Fraction Effects

**Fiber volume fraction study showed that good multifunctional performance is obtained at high fiber volume fractions.**



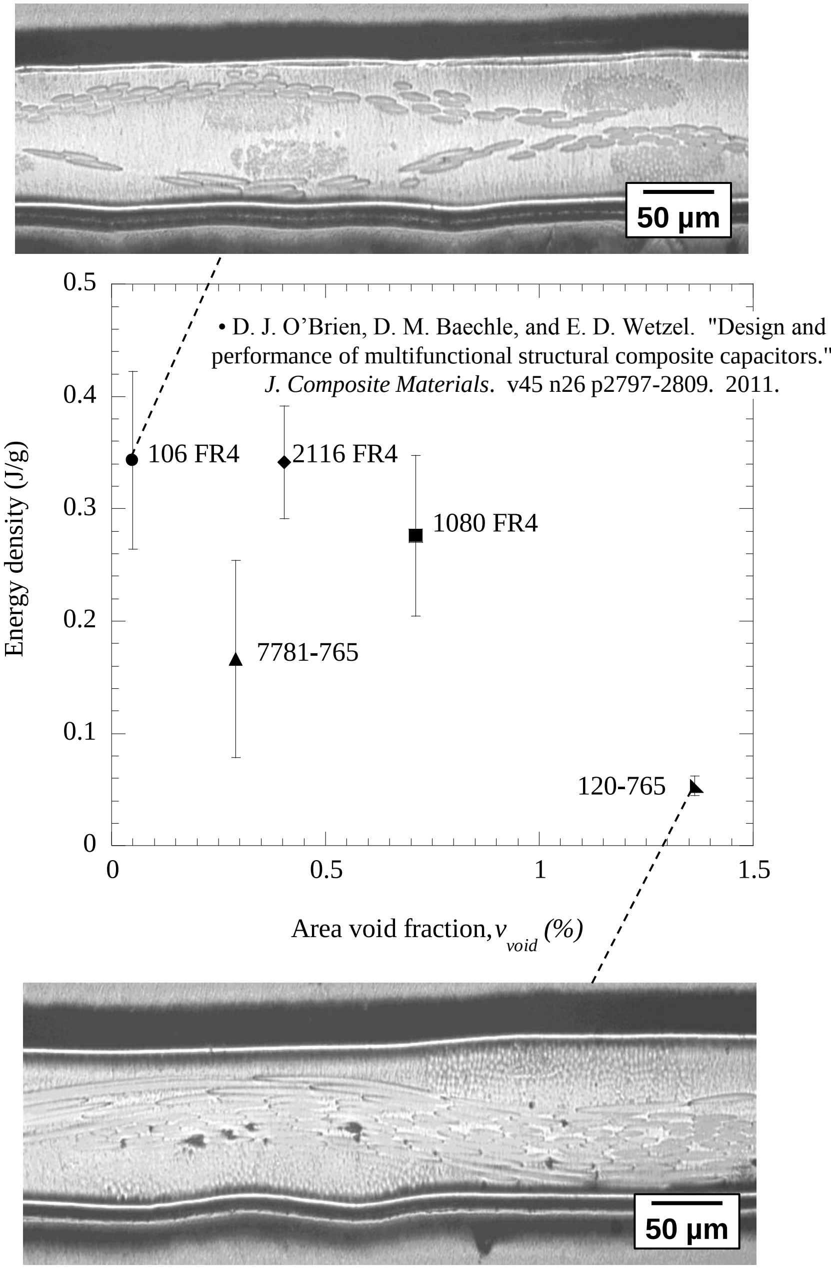

| Group | Fabric type | Matrix type | Weave type | Fabric thickness (mm) | Areal density (g/m²) |
|---|---|---|---|---|---|
| 1 | 106 | FR4 (PCB) | Plain | 0.04 | 25 |
| 2 | 1080 | FR4 (PCB) | Plain | 0.06 | 49 |
| 3 | 2116 | FR4 (PCB) | Plain | 0.10 | 109 |
| 4 | 120 | 765 (struct) | 4H Satin | 0.09 | 107 |
| 5 | 7781 | 765 (struct) | 8H Satin | 0.22 | 299 |



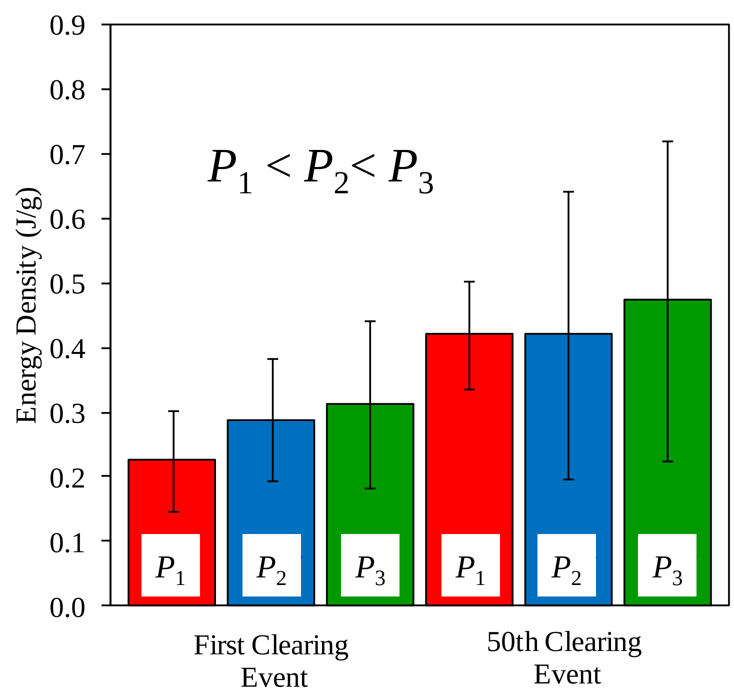

O'Brien et al. *J Comp Mat.*, 45(26) 2011.

# Void Fraction Effects



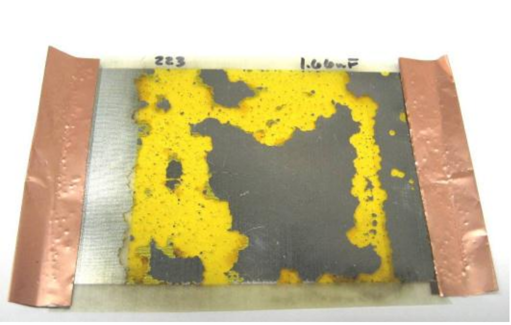

• D. J. O'Brien, D. M. Baechle, and E. D. Wetzel. "Design and performance of multifunctional structural composite capacitors." *J. Composite Materials*. v45 n26 p2797-2809. 2011.

- **Energy density decreases with increasing void fraction**
  - **Voids concentrate electric fields and reduce local dielectric strength**
- **Processing needs to be optimized to minimize void generation, growth, and persistence**
  - **High pressure processing**
  - **Minimize volatilization**

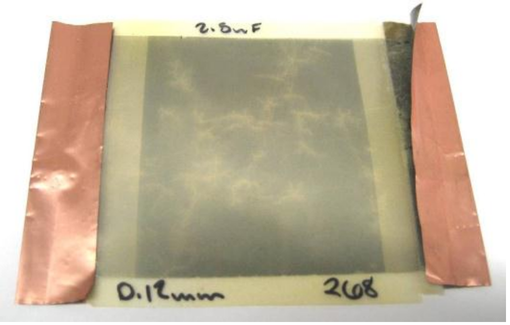


# Electrode Selection and Performance

## Self-clearing electrodes to enhance flaw tolerance

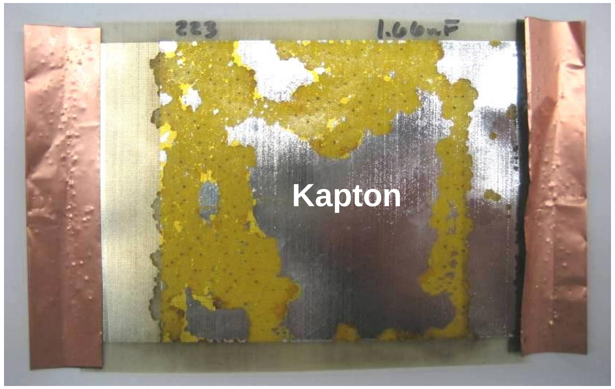


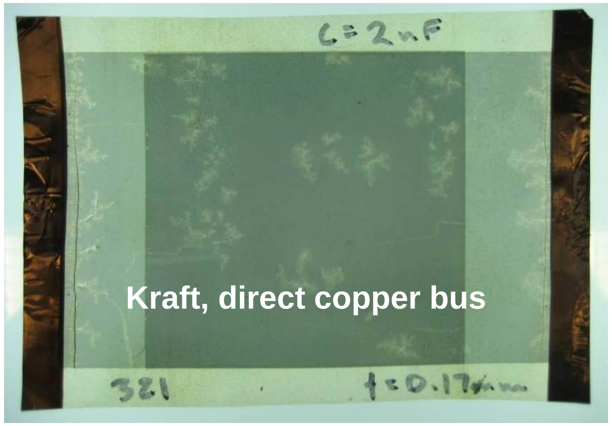

**Kapton electrode**




**Kraft paper electrode**

## Electrode connectorization

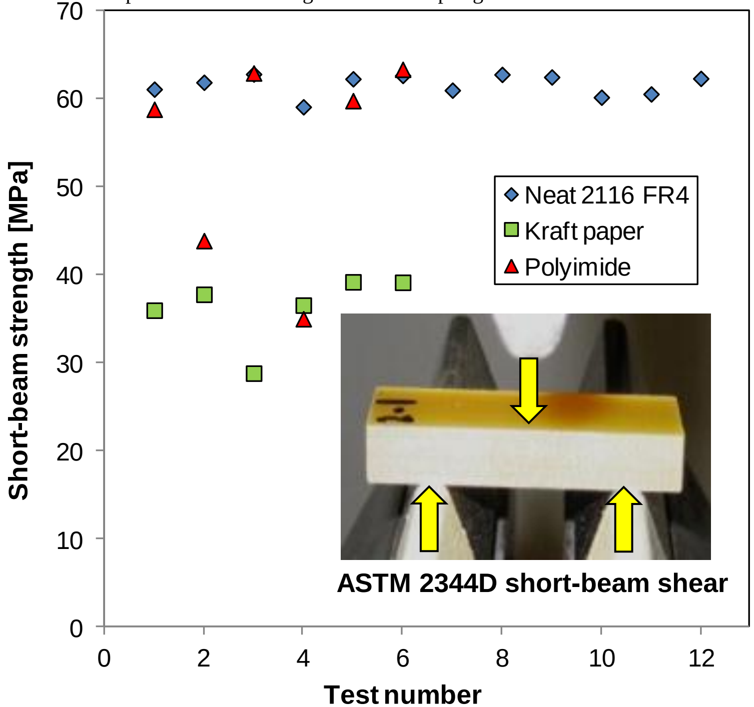


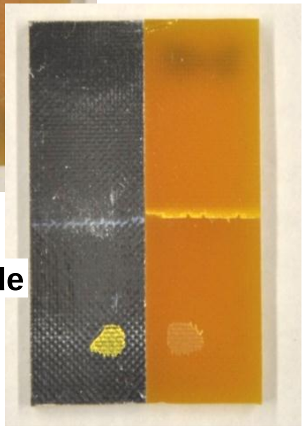


## Mechanical performance

- O.B. Yurchak, D. J. O'Brien, D. M. Baechle, and E. D. Wetzel. "Shear properties of multifunctional structural capacitors." Proceedings of SAMPE Spring Technical Conference. Baltimore, MD. May 21-24, 2012.



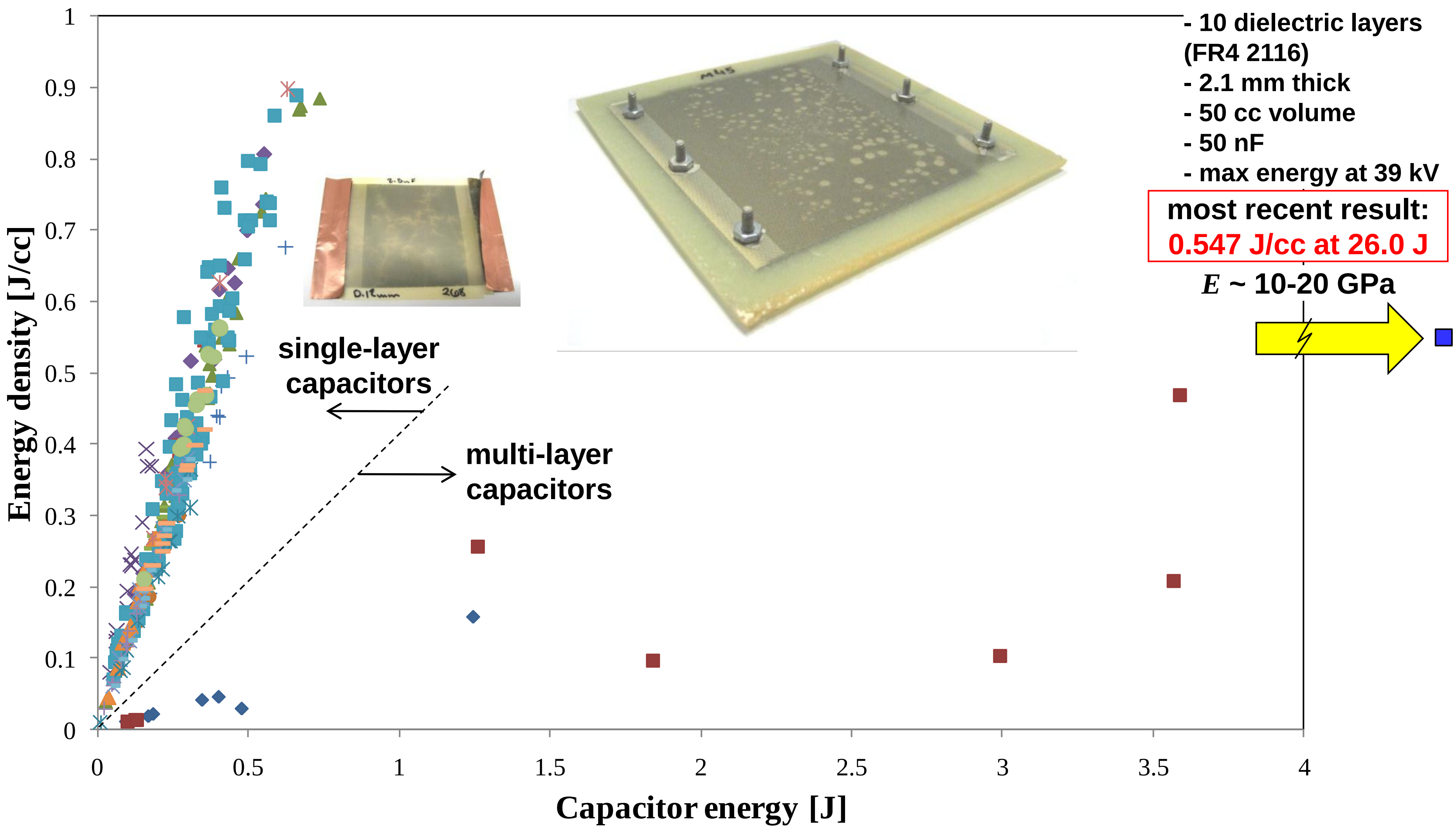

**Kraft paper**



**polyimide**

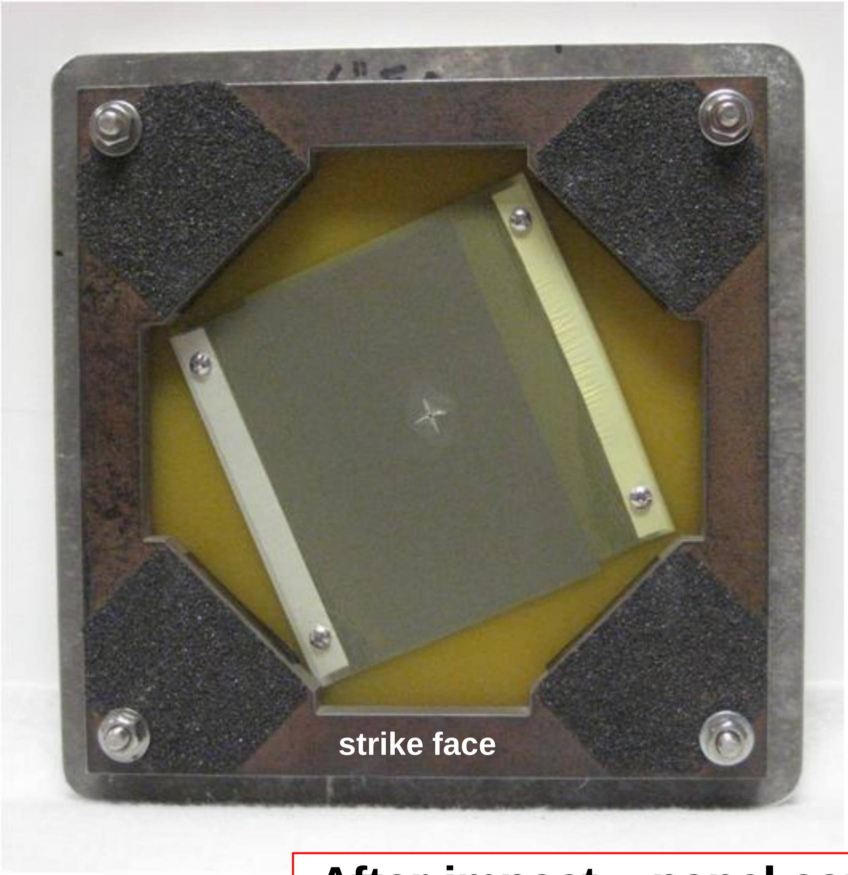
# Scaled Assembly and Performance

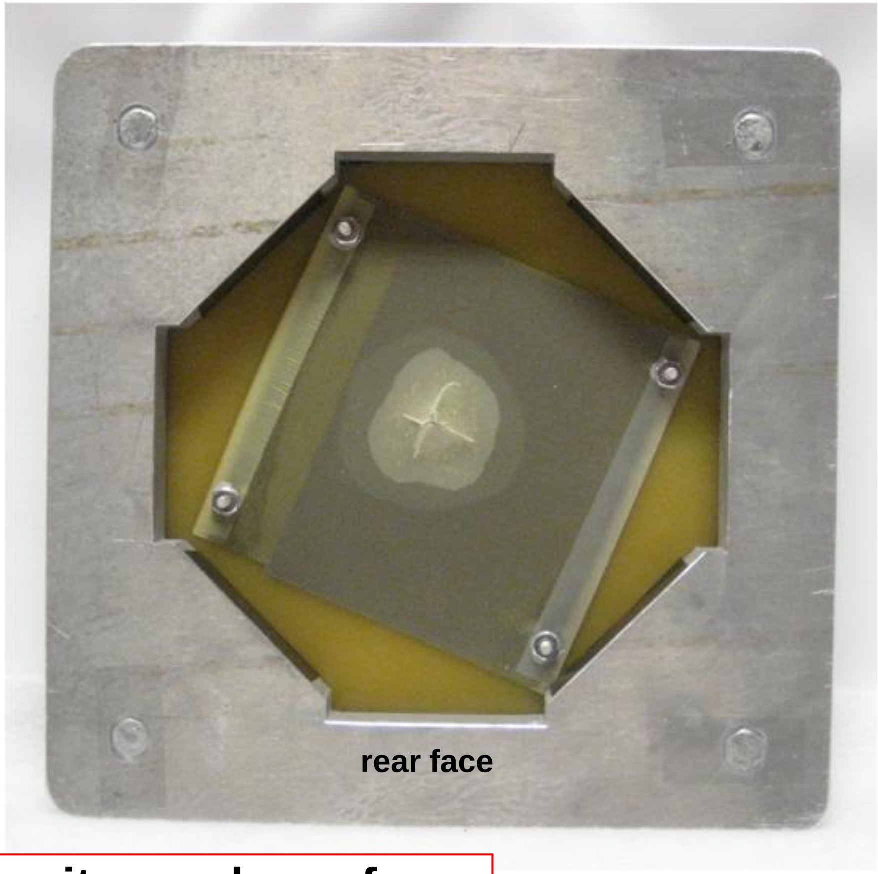
- Developed scalable assembly technique for efficient stacking of many (dozens) electrode, dielectric, and bus layers
- Maintaining excellent energy density up to high energies (volume)



# Impact Performance of Structural Capacitors

- Ballistically impact 4-dielectic layer, FR4-2116 composite panel while energized at 15 kV
  - 203 x 203 x 2 mm panels
  - Impacted with 0.22 cal steel sphere at 667 fps (penetration)

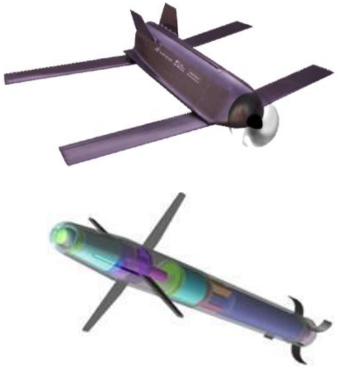


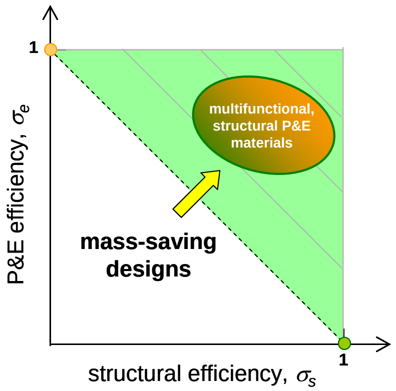




**After impact... panel capacitance drops from 16.7 nF to 13.5 nF, but still holds 15 kV.**

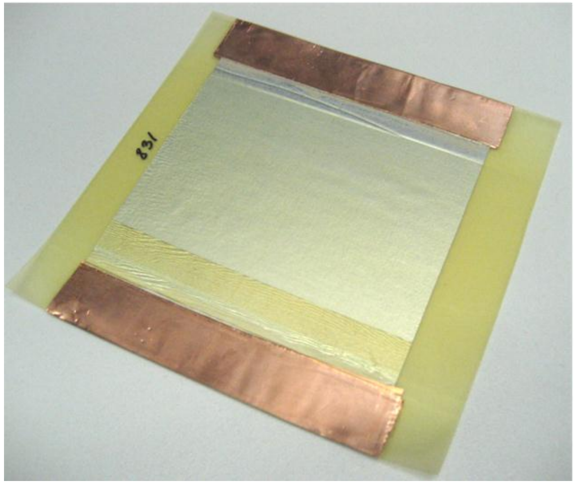
# Outline

## Motivation and Approach

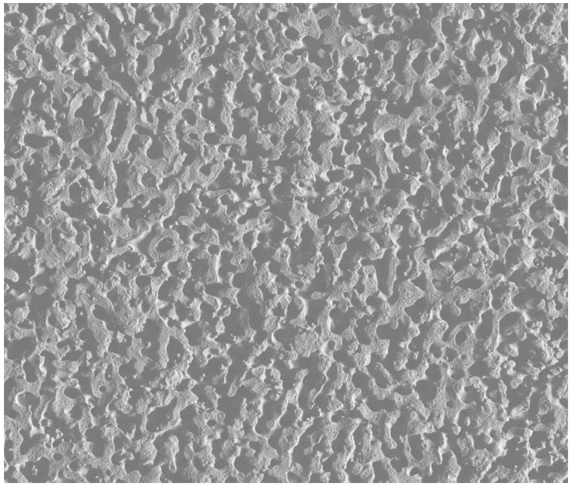





## Structural Capacitors



## Structural Batteries

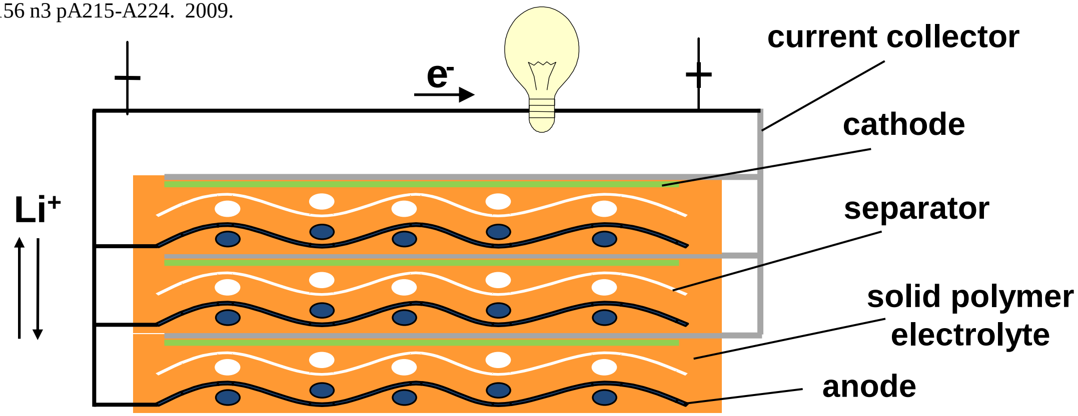


# Anatomy of a Structural Battery

## Anodes
- Intercalates Li ions and provides structural reinforcement
- Example: T-300 PAN-based carbon fiber fabric

J. F. Snyder, E. L. Wong, and C. W. Hubbard. "Evaluation of commercially available carbon fibers, fabrics, and papers for potential use in multifunctional energy storage applications." *J. Electrochem Soc.* v156 n3 pA215-A224. 2009.

## Separator
- Provides electrical insulation while permeable to electrolyte and ions
- Examples: glass veil cloth, Celgard® porous polypropylene




## Cathode
- Comprised of current collector + active cathode material
- Reacts with Li ions, busses electrons, and provides structural reinforcement
- Example: Perforated stainless steel foil coated with $LiFePO_4$ + acetylene black + binder

## Electrolyte
- Solid polymer electrolyte → provides balance of mechanical properties and ion conductivity

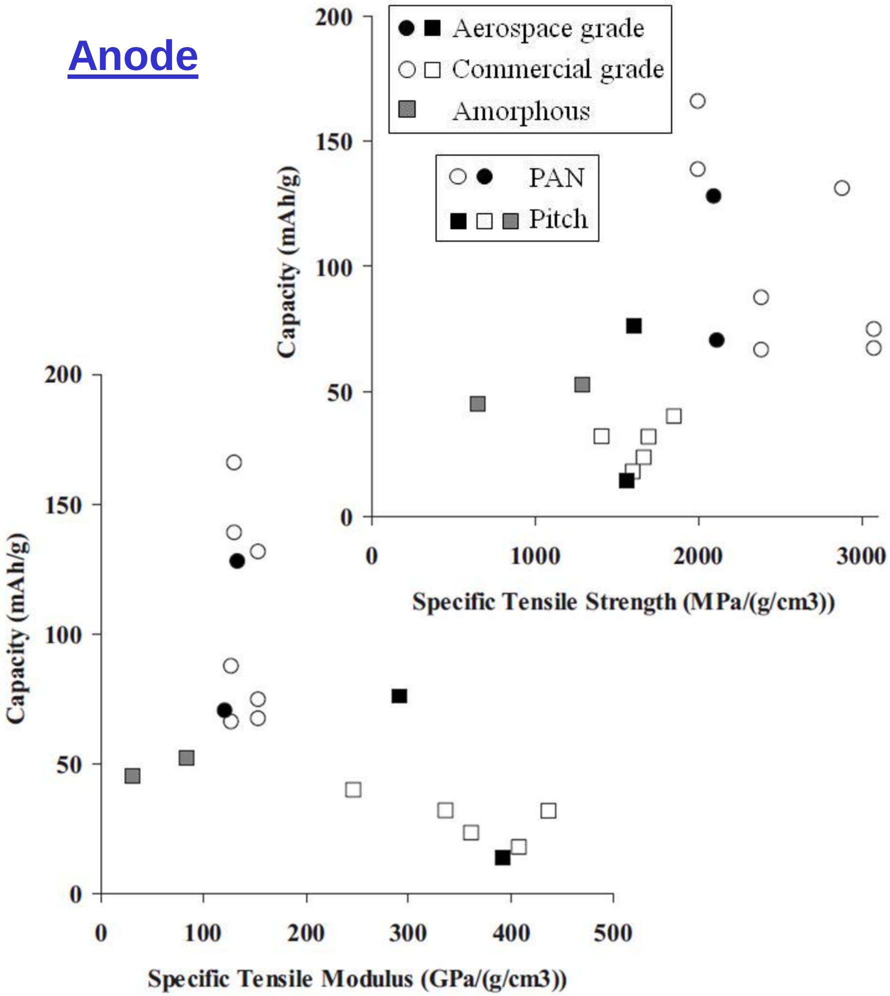
**Most critical technical / scientific challenge**

• E.B. Gienger, J.F. Snyder, E.D. Wetzel, and K. Xu. "Multifunctional structural composite supercapacitor development and evaluation." Proceedings of SAMPE Spring Technical Conference. Baltimore, MD. May 21-24, 2012.

(these electrolytes are also needed for structural supercapacitors)

# Anode and Cathode Design

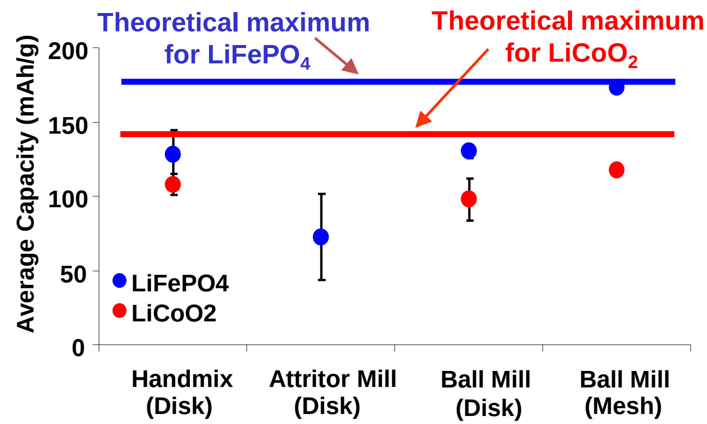
## Anode

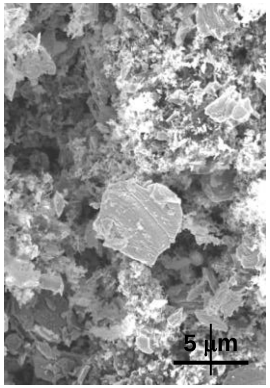


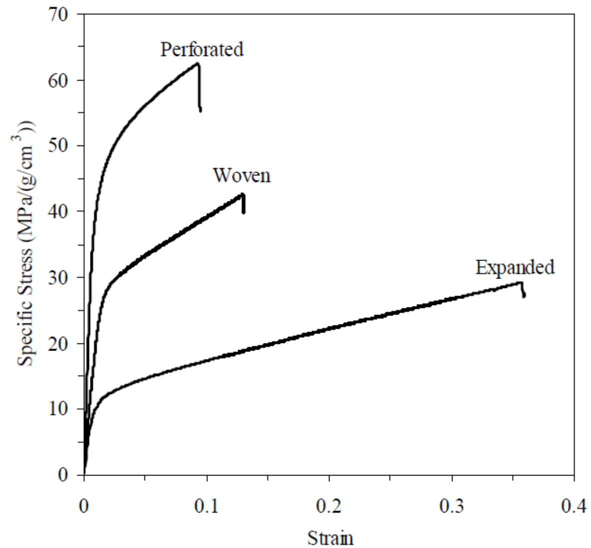

**Traditional structural carbon fiber reinforcement should provide excellent anodic functionality.**


J. F. Snyder, E. L. Wong, and C. W. Hubbard. "Evaluation of commercially available carbon fibers, fabrics, and papers for potential use in multifunctional energy storage applications." *J. Electrochem Soc*. v156 n3 pA215-A224. 2009.


## Cathode





**Cathode and current collector components provide good performance… but challenging to integrate.**

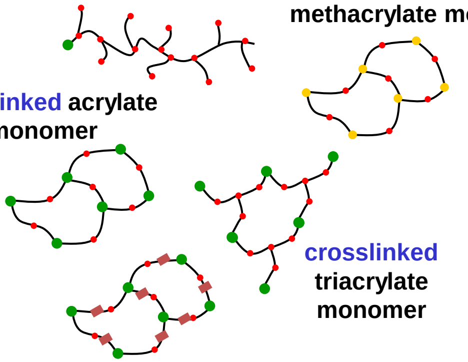
# Structural Electrolyte Architectures

## Homopolymers

comb monomer

crosslinked methacrylate monomer

crosslinked acrylate monomer

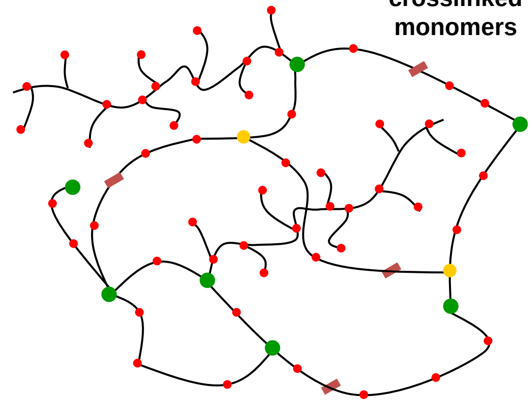


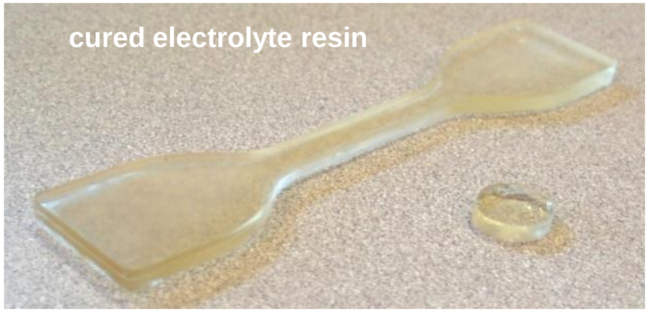
crosslinked triacrylate monomer

crosslinked monomer with additional backbone functional groups

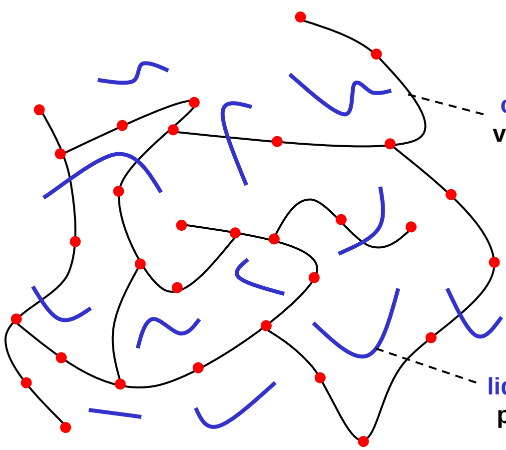
## Copolymers

copolymer of comb monomers and crosslinked monomers






## Gels



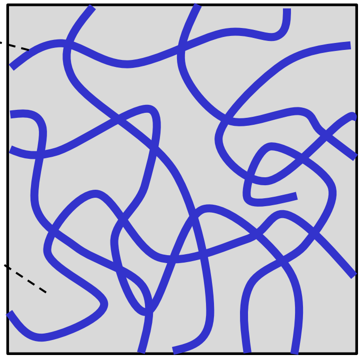
crosslinked vinyl ester or epoxy

liquid (PEG) plasticizer

## Micro-foams

liquid electrolyte

crosslinked structural polymer

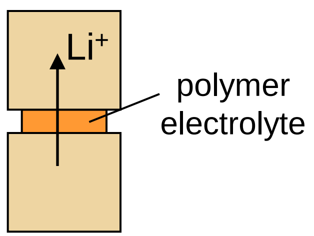


1-100 µm

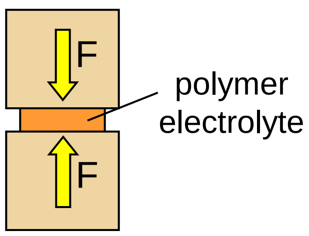
# Multifunctional Properties of Homopolymer / Copolymer Electrolytes


• J. F. Snyder, R. H. Carter, E. D. Wetzel. "Electrochemical and mechanical behavior in mechanically robust solid polymer electrolytes for use in multifunctional structural batteries." *Chem. Mater.* v19 n15 p3793-3801. 2007.
• J. F. Snyder, C. Watson, and E. D. Wetzel. "Improving multifunctional behavior in structural electrolytes through copolymerization of structure- and conductivity-promoting monomers." *Polymer*. v50 p4906-4916. 2009.

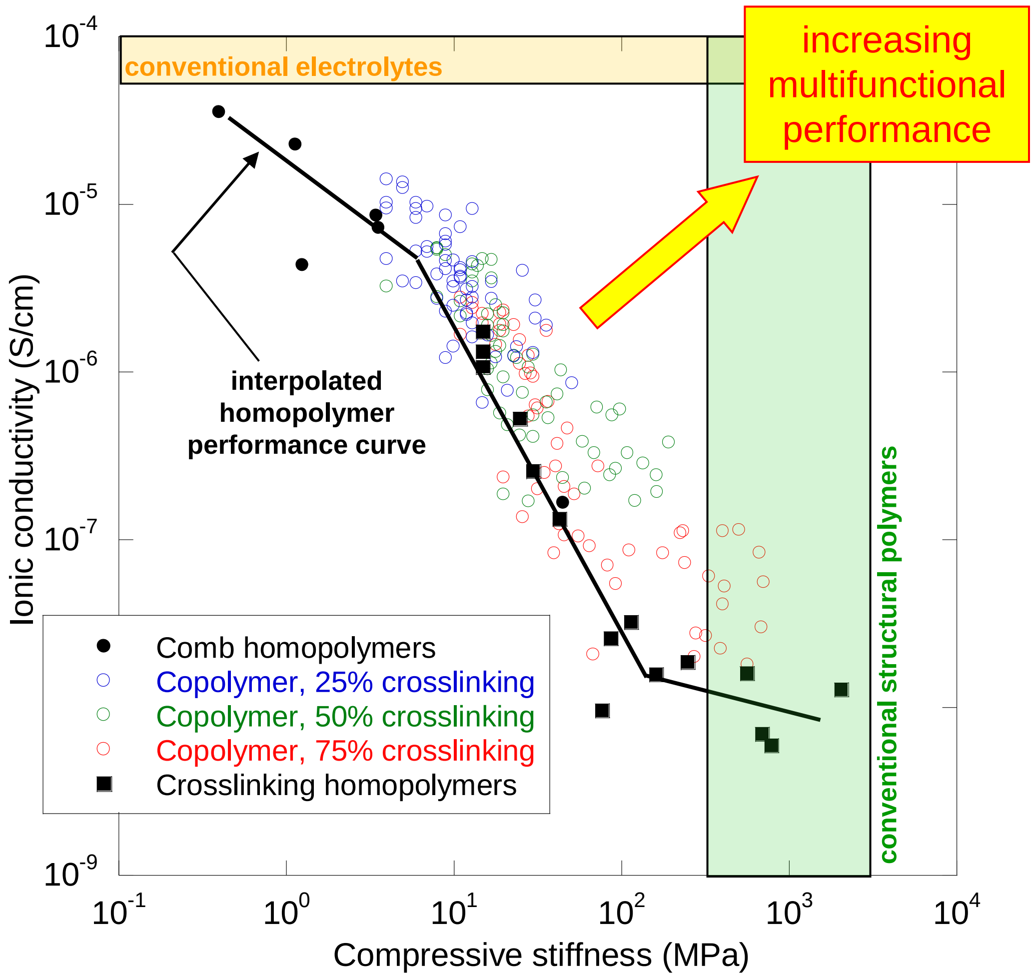

- Vinyl ester backbones
- PEG combs / plasticizers
- Variations in
  - Nature, number of reactive groups
  - PEG length and concentration
  - Endgroups (combs)
  - Crosslinking groups (networks)
- Polymers complexed with lithium triflate for ionic conductivity



Ion conductivity measurement



Compressive stiffness measurement



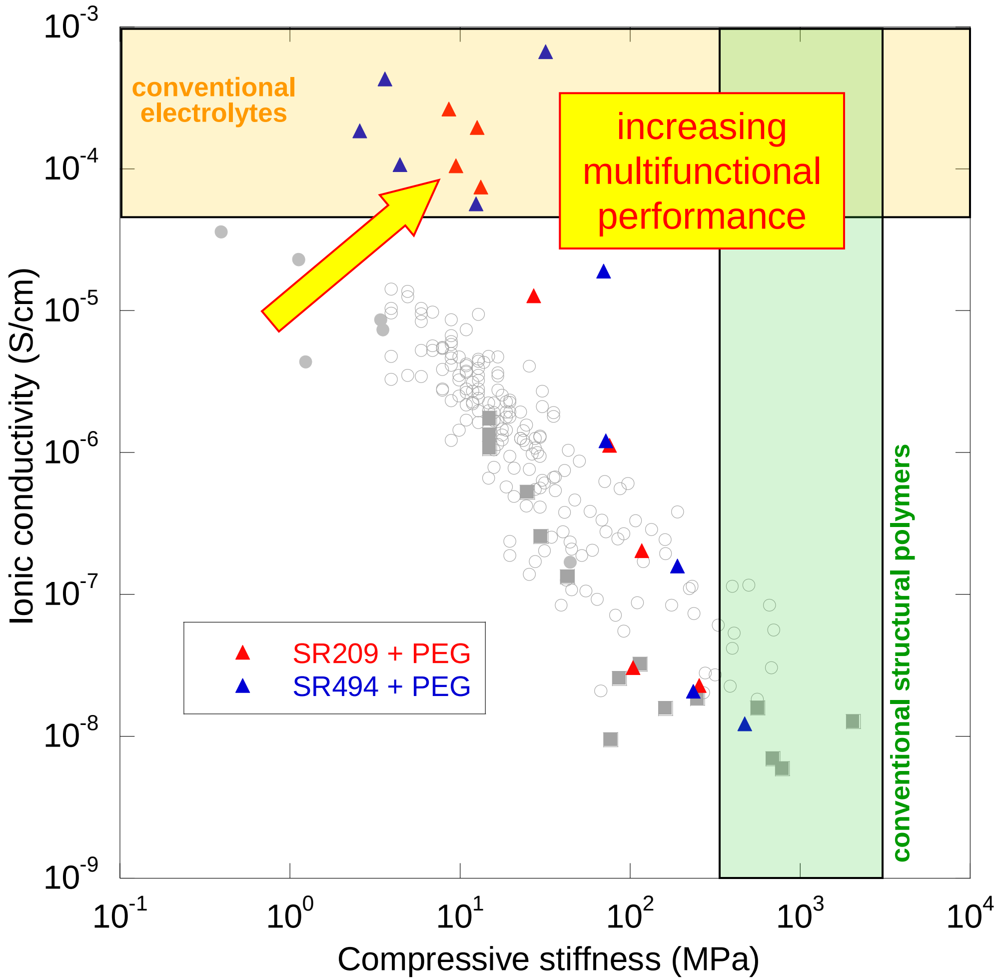

- **Clear inverse correlation between mechanical properties and conductivity**
  - **Copolymers show improved multifunctionality versus homopolymers**

# Multifunctional Properties of Gel Electrolytes



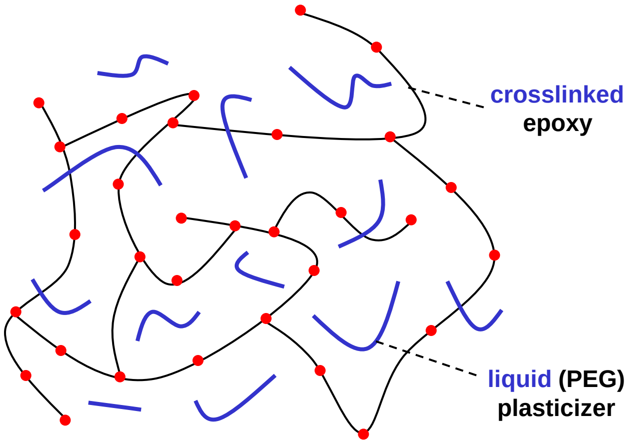
P. T. Nguyen and J. F. Snyder. "Multifunctional properties of structural gel electrolytes." *ECS Transactions.* v11 n32. 2007.

- Gel electrolytes provide greatly **enhanced multifunctional performance**




**Gel electrolytes provide good balance of mechanical performance and ion conductivity**

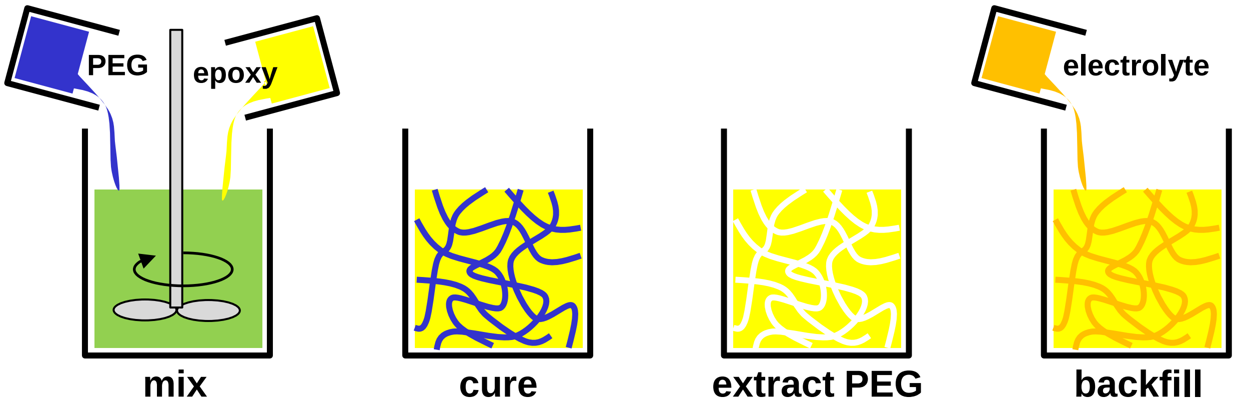
**Example epoxy-based electrolyte:**
**EPON 828 epoxy plasticized with 80% liquid electrolyte**
**($C_2HF_6NO_4S_2$ dissolved in 50:50 ethylene carbonate and dimethyl carbonate)**



# Polymer MicroFoam Electrolytes



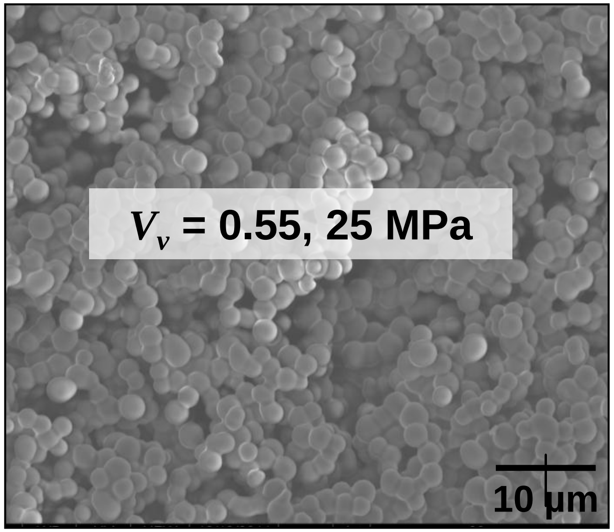
- Processing approach
  - PEG (e.g. 70% v/v) mixed with epoxy pre-polymer (e.g. 30%v/v)
  - System cured → phase-separates, leaving micro-sized epoxy/PEG interpenetrating network
  - Sonicate in water, dry in oven to remove PEG
  - Soak in liquid electrolyte to back-fill pores



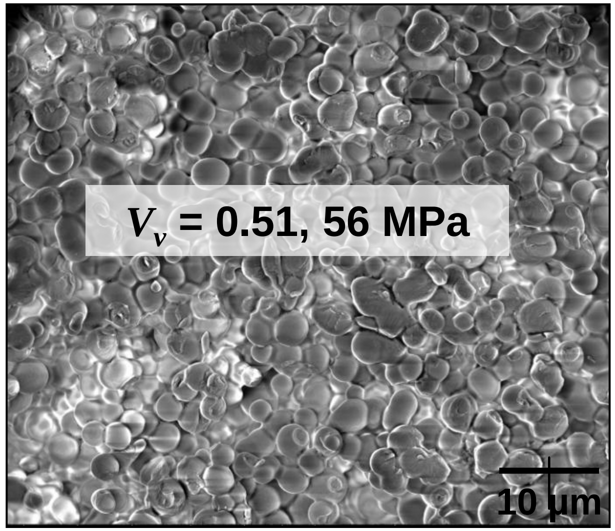

- Tailorable microstructure → PEG/epoxy ratio, cure temperature, surfactant
- Advantages relative to gel electrolytes
  - Process base resin without electrolyte
    - Avoid salt contamination effects
    - Prevent evaporation of electrolyte during vacuum / heating
  - Independent selection / engineering of liquid porogen and liquid electrolyte → more design / processing flexibility
  - Minimize likelihood of plasticization of structural polymer

# MicroFoam Performance

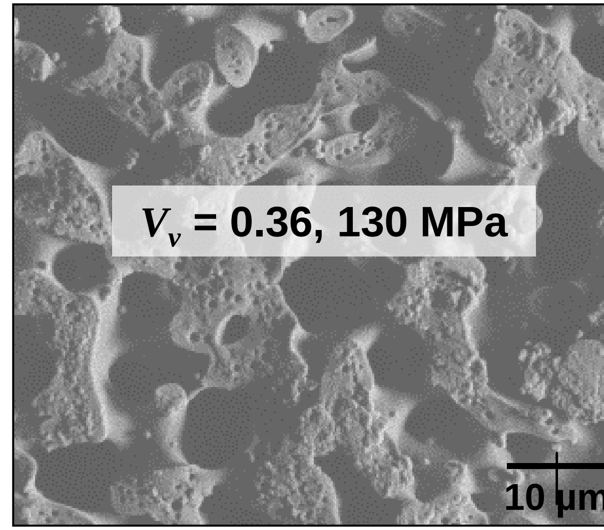





**25% epoxy + 75% PEG**




**30% epoxy + 70% PEG**



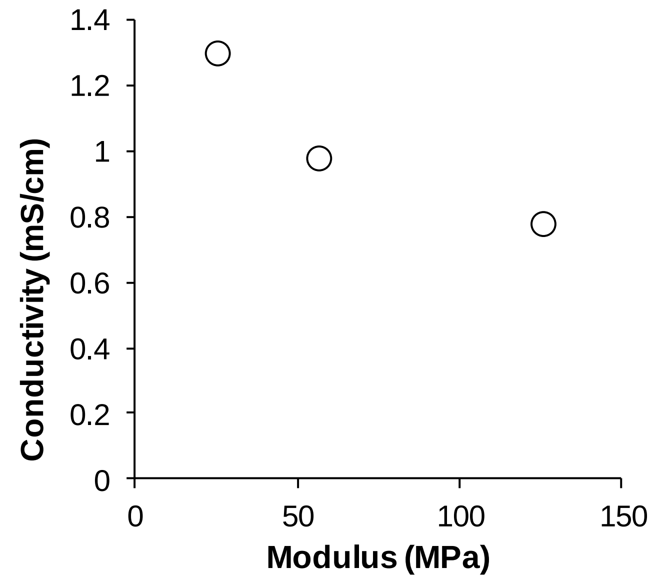

**35% epoxy + 65% PEG**

**(all samples: Epon 828 + PACM, 160C cure, 5% PEG-PPG-PEG surfactant, backfilled with 1 M LiTFSI / propylene carbonate electrolyte)**

| % Epoxy (original mixture) | Void volume fraction | Electrolyte uptake | Conductivity (mS/cm) | Compressive modulus (MPa) |
|---|---|---|---|---|
| **25%** | 55% | 128% | 1.3 | 25.3 |
| **30%** | 51% | 105% | 0.98 | 56.5 |
| **35%** | 36% | 60% | 0.78 | 125.6 |

**Co-continuous structure (e.g. 35% epoxy) provides best multifunctional performance.**

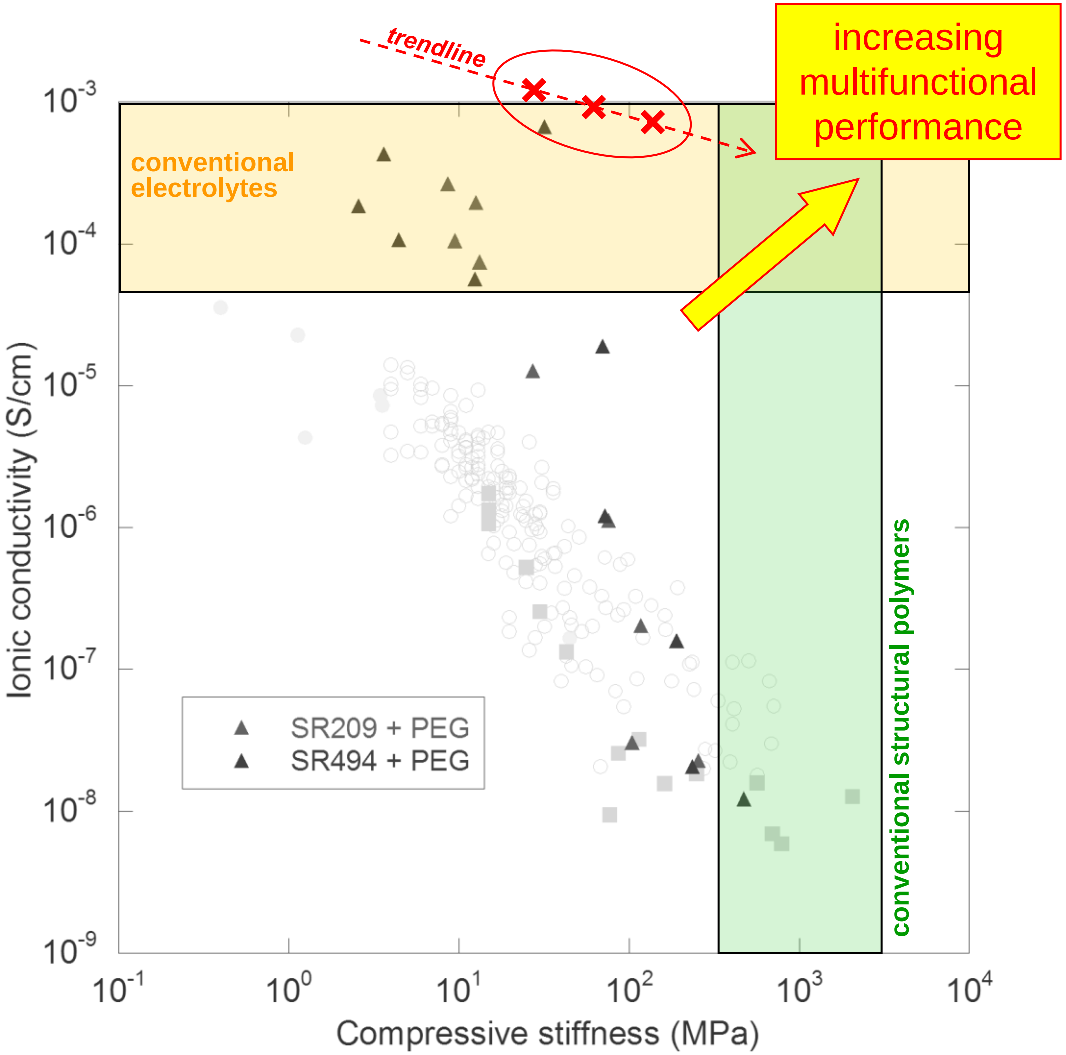
Co-continous structured postulated as idealized multifunctional structures by e.g. Torquato et al. *J. App. Phys.* v94 n9 p5748. 2003.



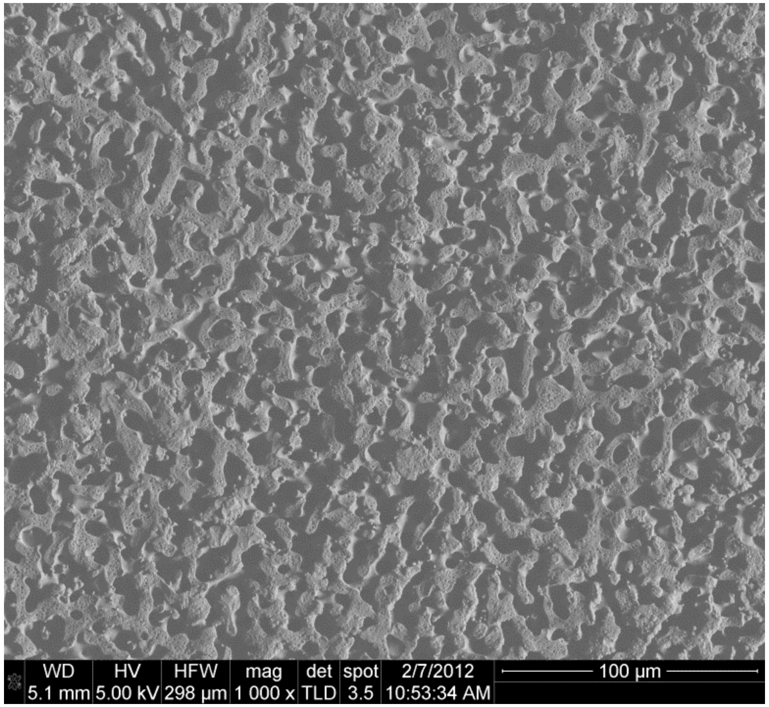
# Multifunctional Properties of MicroFoam Electrolytes



- Microfoam electrolytes provide best multifunctional performance to date → a leading candidate for structural batteries




- Additional processing advantages of microfoam electrolytes are also attractive
- Next challenge → Controlling microstructure near surfaces / interfaces



# Conclusions

**Technical community is converging towards practical, mass-saving structural power and energy composites.**

## Continuing Work

- **Capacitors**
  - Continued scaling (lab safety limit → 100 J)
  - Beyond commercial FR4 prepreg → high dielectric additives, super-clean prepregging
- **Batteries**
  - Further exploration of polymer foam electrolytes
    - Achieve goal of 1 GPa and 0.1 mS/cm
    - Designed, self-assembling electrolyte-electrode interfaces
    - Scaled fabrication
  - Highly structural cathodes
  - Integrated packaging

# Effect of Electrode Thickness on Capacitance and Energy Density

$\varepsilon_0 \rightarrow$ permittivity of free space
$\kappa \rightarrow$ matrix relative dielectric constant
$d \rightarrow$ electrode spacing
$h \rightarrow$ electrode waviness amplitude
$l, w \rightarrow$ length, width of unit cell
$C \rightarrow$ capacitance
$\overline{C} \rightarrow$ volume-normalized capacitance
$V \rightarrow$ voltage
$S \rightarrow$ matrix dielectric strength

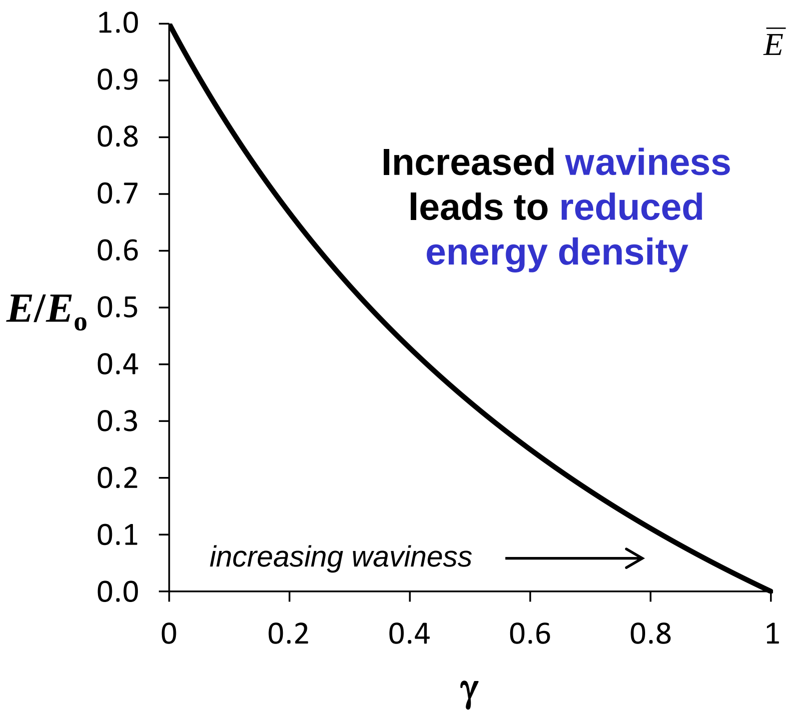
## Thin, Flat Electrode

**(e.g. metallized film)**


$$C_o = \varepsilon_0 \kappa \frac{lw}{d} \qquad \overline{C}_o = \frac{C_o}{Vol} \rightarrow \boxed{\overline{C}_o = \frac{\varepsilon_0 \kappa}{d^2}}$$

$$\overline{E}_o = \frac{1}{2}\overline{C}_o V^2 = \frac{1}{2}\overline{C}_o (S \cdot d)^2 = \frac{1}{2}\frac{\varepsilon_0 \kappa}{d^2}(S \cdot d)^2$$

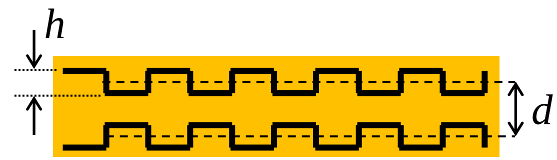
$$\boxed{\overline{E}_o = \frac{1}{2}\varepsilon_0 \kappa S^2}$$




**Increased waviness leads to reduced energy density**

## Wavy Electrode

**(e.g. carbon fabric electrode)**




$$\gamma \equiv \frac{h}{d}$$

$$C = \varepsilon_0 \kappa l w \left( \frac{1}{2}\frac{1}{d+h} + \frac{1}{2}\frac{1}{d-h} \right) \qquad \overline{C} = \frac{C}{Vol} = \frac{\varepsilon_0 \kappa}{d^2}\frac{1}{(1-\gamma^2)} \rightarrow \boxed{\overline{C} = \overline{C}_o \frac{1}{(1-\gamma^2)}}$$

$$\overline{E} = \frac{1}{2}\overline{C}V^2 = \frac{1}{2}\overline{C}(S \cdot (d-h))^2 = \frac{1}{2}\frac{\varepsilon_0 \kappa}{d^2}\frac{1}{(1-\gamma^2)}(S \cdot (d-h))^2$$

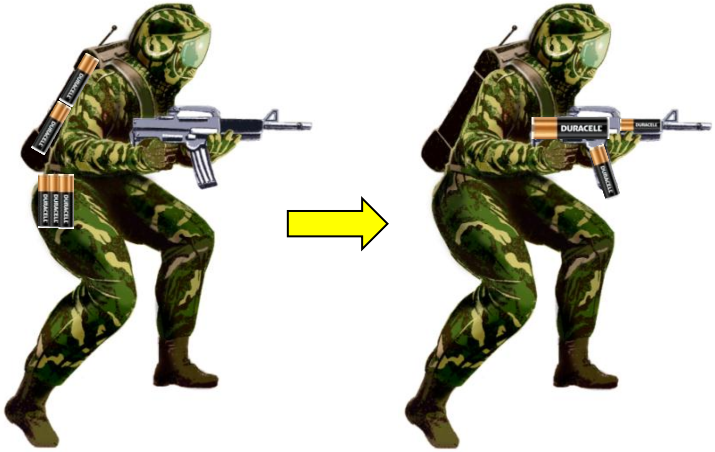
$$\overline{E} = \frac{1}{2}\varepsilon_0 \kappa S^2 \frac{(1-\gamma)}{(1+\gamma)} \rightarrow \boxed{\overline{E} = \overline{E}_o \frac{(1-\gamma)}{(1+\gamma)}}$$

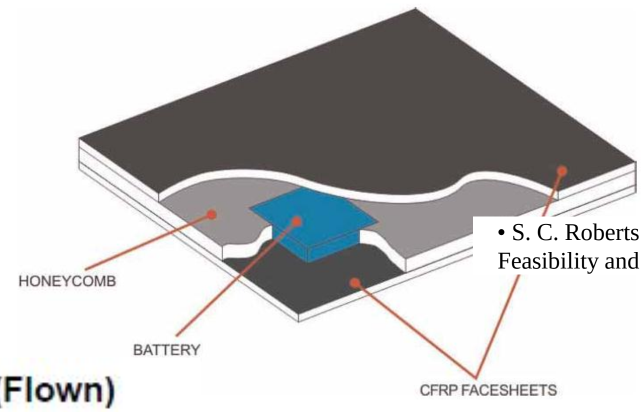
**Thin, flat electrodes should be used to achieve maximum energy density.**

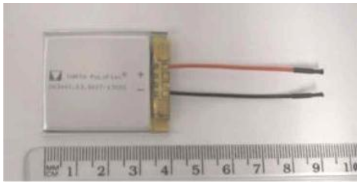
- **In dielectric capacitor, electrodes bus power, but do not store energy → therefore their mass should be minimized**
- **The dielectric body possesses maximum energy when uniformly polarized at limiting dielectric strength → flat electrodes provide uniform electric fields**

# One Approach: Embedded Devices

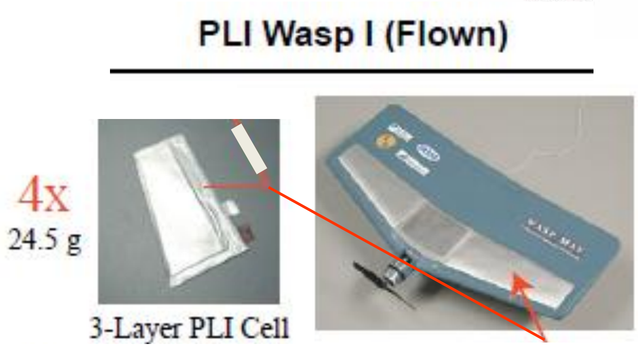
- Battery **packaging used as structure**, or structure used as packaging to **protect / ruggedize battery**
  - **Active battery elements** see **negligible mechanical loads**
- Typical: **embed COTS batteries** into composite structures



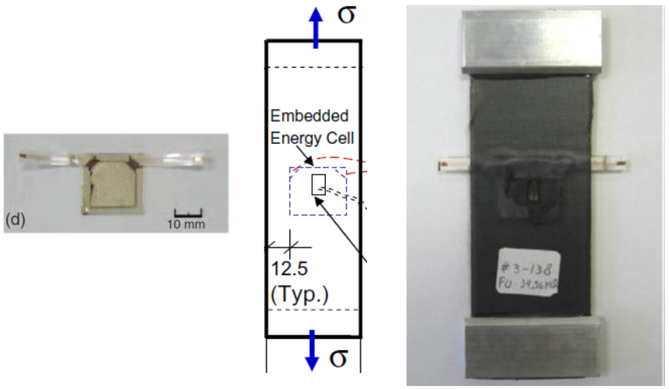


• S. C. Roberts and G. S. Aglietti. "Satellite multifunctional power structure: Feasibility and mass savings." Proc. IMechE. Part G. v222 n1 p41-51. 2008.




• J. P. Thomas and M. A. Qidwai. "The design and application of multifunctional structure-battery materials systems." JOM. v57 n3 p18-24. 2005.

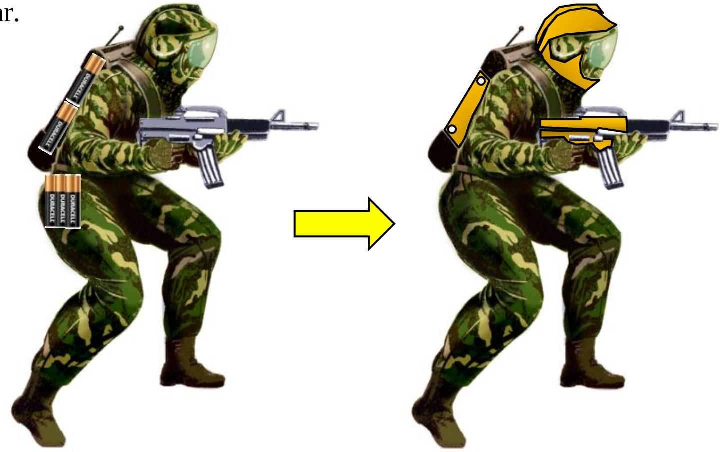


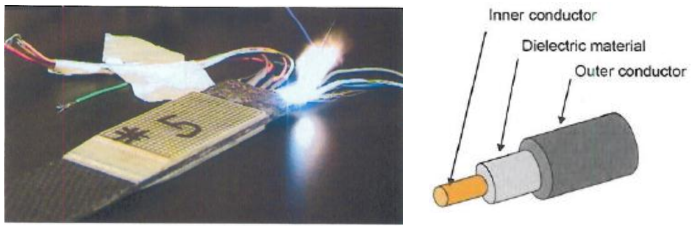

• T. Pereira, Z. Guo, S. Nieh, J. Arias, and H. T. Hahn. "Embedding thin-film lithium energy cells in structural composites." Comp. Sci. Tech. v68 p1935–1941. 2008.

# Multifunctional Approach: Structural Devices

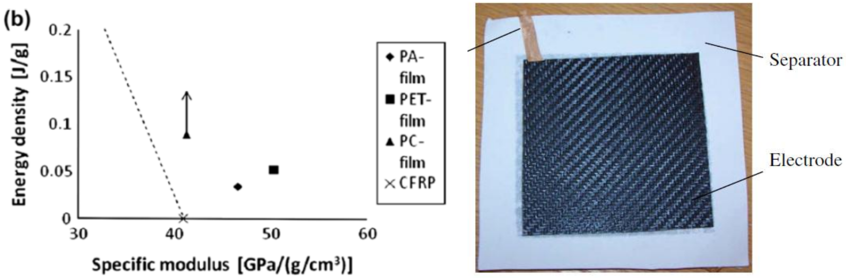
J. F. Snyder, D. J. O'Brien, and E. D. Wetzel. "Structural batteries, capacitors, and supercapacitors." Handbook of Solid State Batteries & Capacitors. Eds: N. Dudney, W. West, J. Nanda. To appear.

- **Active energy-storing materials directly bear mechanical loads**
  - **Requires development of structural electrolytes, dielectric, electrodes, separators, etc.**
- **Structural capacitors more advanced than structural batteries**

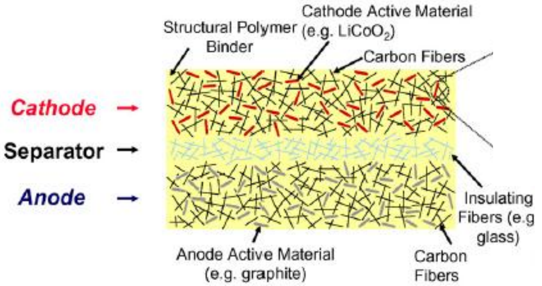




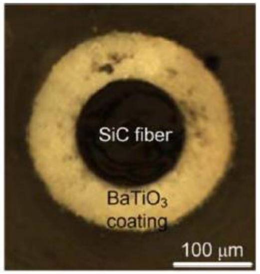

• W. Baron and D. Zeppettella. "Multifunctional airframe structure for energy storage using load bearing coaxial capacitor." Proc. of ASME-SMASIS. SMASIS08-435. 2008.



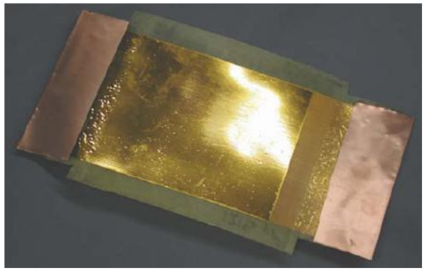

• T. Carlson, D. Ordeus, Maciej Wysocki, and L. E. Asp. "Structural capacitor materials made from carbon fibre epoxy composites." Comp. Sci. Tech. v70 n7 p1135. 2010.




• P. Liu, E. Sherman, and A. Jacobsen. "Design and fabrication of multifunctional structural batteries." J. Power Sources. v189 p646. 2009.



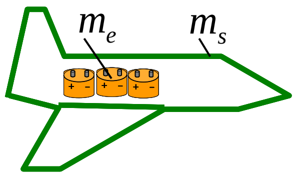

• Y. Lin and H. A. Sodano. "Characterization of multifunctional structural capacitors for embedded energy storage." J. App. Phys. v106 n114108. 2009.



• J. F. Snyder et al. "Structural composite capacitors, supercapacitors, and batteries for U.S. Army applications." Proc. of ASME-SMASIS. SMASIS08-315. 2008.

# Mass Savings through Multifunctionality

## Conventional design



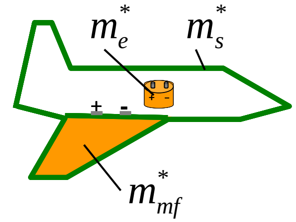

system mass [kg] — P&E mass [kg] — structure mass [kg]

$$M = m_e + m_s$$

*(mass balance)*

$\bar{\Gamma} m_e$ *(total system energy capacity)*

$\bar{E} m_s$ *(total system structural capacity)*




## Multifunctional design

$$M^* = m_e^* + m_s^* + m_{mf}^*$$

structural P&E mass [kg]

*(mass balance)*

$$\bar{\Gamma} m_e^* + \bar{\Gamma}_{mf} m_{mf}^* = \bar{\Gamma} m_e$$

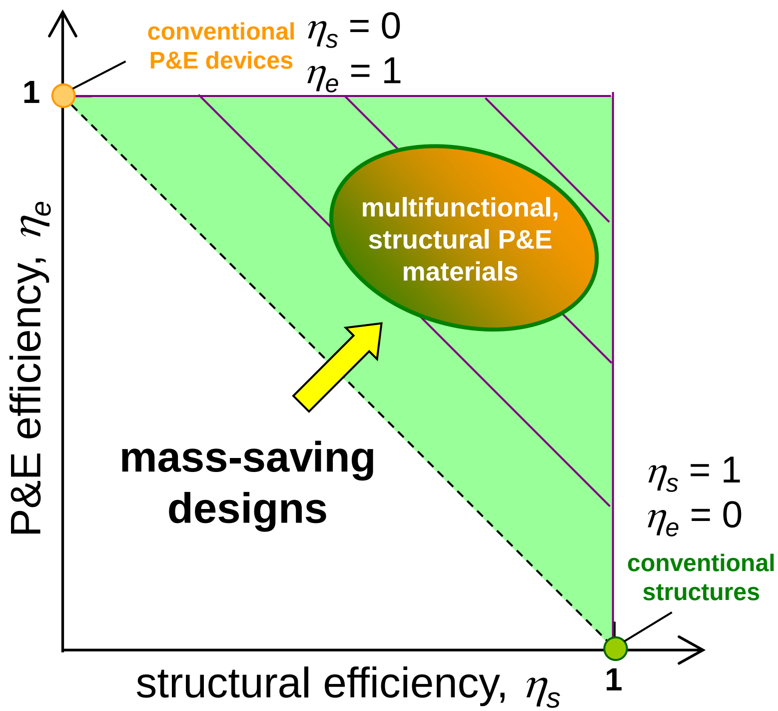
*(maintain total system energy capacity)*

$$\bar{E} m_s^* + \bar{E}_{mf} m_{mf}^* = \bar{E} m_s$$

*(maintain total system structural capacity)*

$$\left(M - M^*\right) = \left(\frac{\bar{\Gamma}_{mf}}{\bar{\Gamma}} + \frac{\bar{E}_{mf}}{\bar{E}} - 1\right) m_{mf}^*$$

• D. J. O'Brien, D. M. Baechle, and E. D. Wetzel. "Design and performance of multifunctional structural composite capacitors." *J. Composite Materials*. v45 n26 p2797-2809. 2011.




**mass-savings can be achieved if $M^* < M$:**

$$\therefore \quad \frac{\bar{\Gamma}_{mf}}{\bar{\Gamma}} + \frac{\bar{E}_{mf}}{\bar{E}} > 1 \quad \Rightarrow \quad \eta_{mf} \equiv \eta_e + \eta_s > 1$$

$$\eta_e = \frac{\bar{\Gamma}_{mf}}{\bar{\Gamma}} = \frac{\text{energy density of multifunctional structure}}{\text{energy density of conventional P\&E}}$$

$$\eta_s = \frac{\bar{E}_{mf}}{\bar{E}} = \frac{\text{specific stiffness of multifunctional structure}}{\text{specific stiffness of conventional structure}}$$

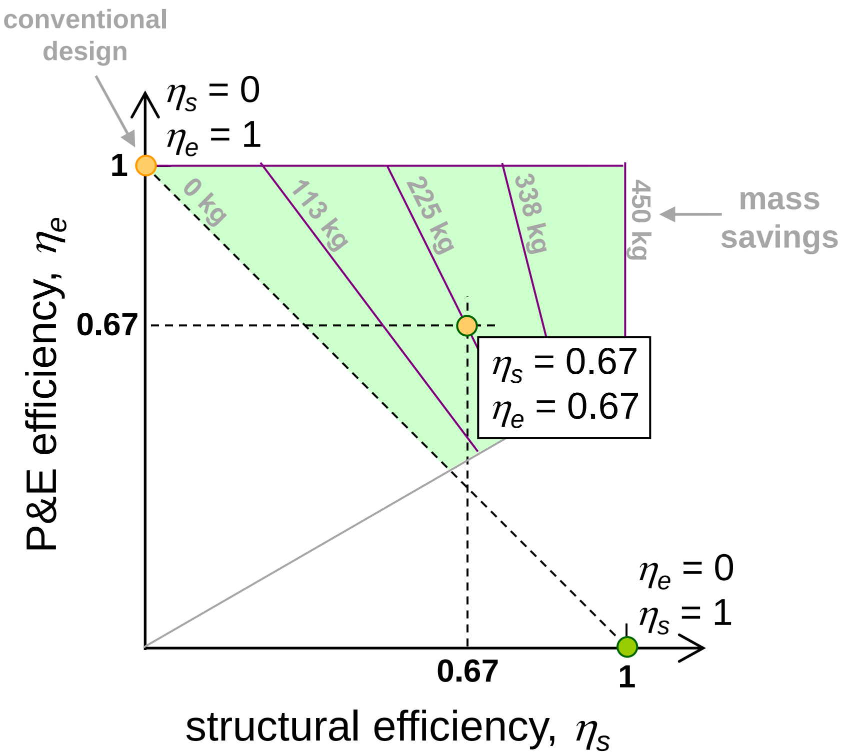
**Mass savings possible even if multifunctional material performs individual functions less efficiently than monofunctional materials.**

# Example: Commercial Electric Automobile



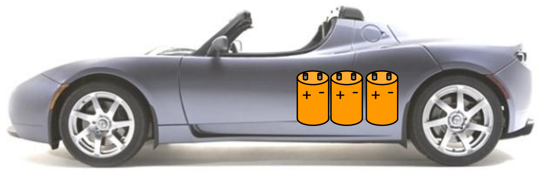
**Prius : 21 kW, 202V, 45kg NiMH battery pack, 1300 kg curb weight**

**Tesla Roadster: 215 kW, 375 V, 450 kg Li-ion battery pack, 1220 kg curb weight**




## Conventional design

| | |
|---|---|
| 770 kg structure | ($\eta_e = 0$, $\eta_s = 1$) |
| + 450 kg battery | ($\eta_e = 1$, $\eta_s = 0$) |
| 1220 kg total system weight | |



## Multifunctional design

| | |
|---|---|
| 320 kg structure | ($\eta_e = 0$, $\eta_s = 1$) |
| + 675 kg structural battery | ($\eta_e = 0.67$, $\eta_s = 0.67$) |
| 995 kg total system weight | |

**System weight reduced by 18%**


**Underside of the Tesla Roadster's carbon fiber rear panel.**

**Tesla roadster uses RTM-ed, epoxy carbon fiber composite body panels with a glass fiber / polypropylene interlayer.**