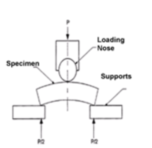


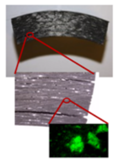

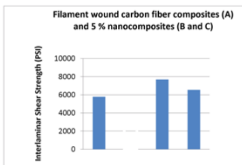


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*Exceptional service in the national interest*

# Improved Properties of Nanocomposites for Flywheel Applications

*September 2012*


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U.S. DEPARTMENT OF ENERGY NNSA

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# **Project:** Improved Flywheel Materials

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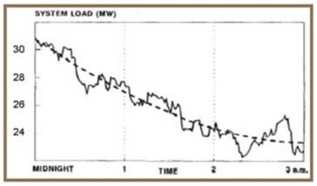
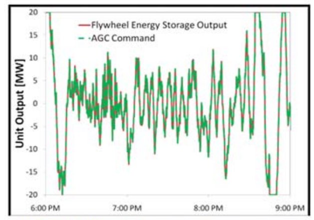



**Problem:** Small changes in the AC grid energy levels necessitates rapid and exact changes in the demand/surplus requirements to ensure energy leveling. Gas powered generators are lacking.

**Approach:** Flywheels are a clean and efficient method that can meet the energy leveling demands. To store more energy, flywheels need to spin faster, which requires stronger rims. Focused on the materials (C-fiber, glass fiber, resin) of composite flywheels. No major changes to basic design, processing parameters, and/or cost can be incurred.




A 20 MW flywheel energy storage resource accurately following a signal


**Stationary Energy Storage Impact:** The economics of flywheel-based energy storage might potentially be improved by a factor of 3 or more. The increased storage/supply will be necessary to meet expected future complications expected as alternative energies (i.e., solar, wind, etc.) are introduced.



The Need for Speed Kills

# Goal: to explore nanocomposites as the rim material to produce improved flywheel performance.

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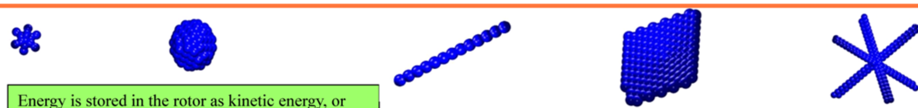
Low load levels of nanoparticle fillers have lead to dramatic property changes

| Loading (wt %): | | | | |
|---|---|---|---|---|
| | 4 | $Al_2Si_2O_5(OH)_4$: | *23%* | *storage, 113% flexural strength,*[1] |
| | 3 | $Al_2O_3$: | *75%* | *tensile strength,*[2] |
| | 2 | $SiO_2$: | *3%* | *hardness, 57% impact, 65 % flex, 88 % tensile strength,*[3] |
| | 2 | ZrP: | *52%* | *Youngs Modulus, 14% tensile strength 6 %, fracture toughness,*[4] |
| | 0.4% CNT-2% | ZrP: | *41%* | *Youngs Modulus, 55% tensile strength.*[5] |



Energy is stored in the rotor as kinetic energy, or more specifically, rotational energy:

$$E_k = ½ \cdot I \cdot \omega^2$$

ω = angular velocity, I = moment of inertia of the mass about the center of rotation

The amount of energy that can be stored is dependent on:

$$s_t = \rho \cdot r^2 \cdot \omega^2$$

$s_t$ = tensile stress on the rim, ρ = density, r is the radius, ω is the angular velocity of the cylinder.

Polym Res (2008)
hem (2006)
*al* J. App Polym Sci
olym Sci B: Polymer
em Mater (2010)

Small % changes in the flywheel spin speed leads to magnified energy storage

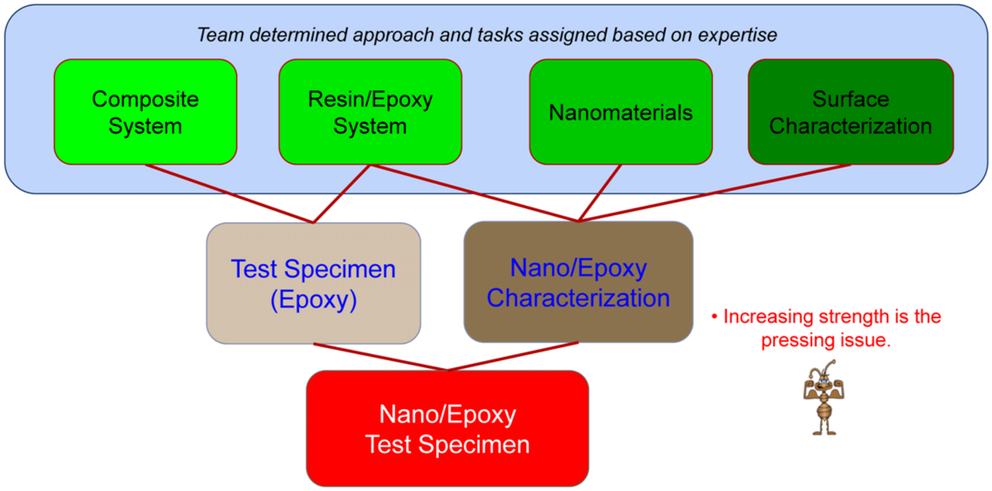
*16,000 rpm ⟶ 20,000 rpm*
*25 kWh ⟶ 39 kWh*
*of extractable energy*

25 kWh/100 kW per unit = 21 kg TNT

# **FY12 Overall Objectives:** defining nanoparticle fillers effects on the 'state-of-the-art' system



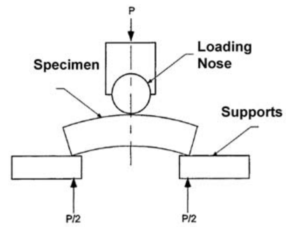
• Flywheel applications are interested in increasing the strength of the resin/C-fiber interaction to allow for faster spin speeds.




• Incorporation of suggested nanomaterials or resins will represent verification of our approach

# Interlaminar strength of composite test specimens for different resin systems indicated that the….

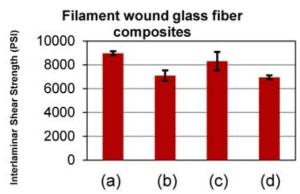
Filament wound glass and carbon fiber composite tubes

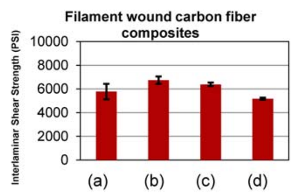



Arc 3-point bend specimens

**Resin Systems**

(a) Standard: epoxy anhydride /catalyst
(b) Epoxy anhydride/catalyst
(c) Epoxy anhydride/catalysts/modifier
(d) Epoxy amine



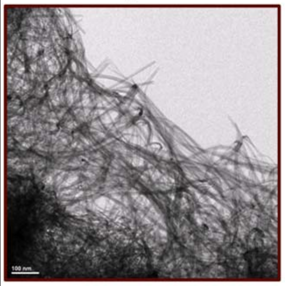




(i) system is good model to 'real-world materials' and allows for interpretation of NW additives

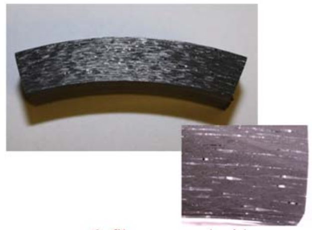
(ii) C-fiber/resin interaction needs increased

# Nanocomposites show a < 30% increase in measured strength of C-fiber wound test specimen!

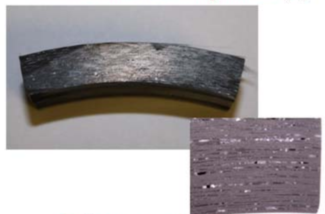
hybrid



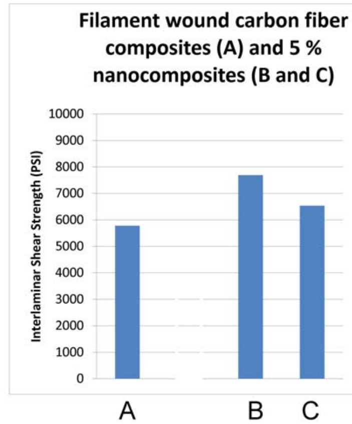
Large scale preparation of nanowires available



C-fibers wound with unfunctionalized nanoparticles (B)



C-fibers wound with functionalized nanoparticles (C)




(i) Sarwar et al. *J. Sol-Gel Sci Tech*. (**2007**) 44, 4.
(ii) Adler-Abramovich et al. Angewandte Chemie (**2010**) 49, 1-5.
(iii) Kane et al. J Appl. Cryst. (**2009**) 42, 925.
(iv) Sumfleth et al *Polymer* (**2008**) 49, 5105.
(v) Sangermano et al. Macromol. Mater. Eng. (**2006**) 291 517.

# Increased shear and interlaminar-fracture strength of flywheel carbon fiber-epoxy composite by 30%, may enable 20-30% reduction in flywheel energy storage cost ($/kW-h).

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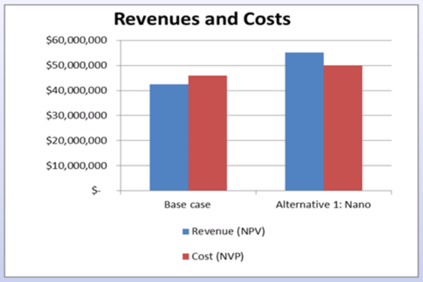
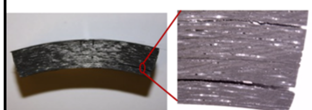
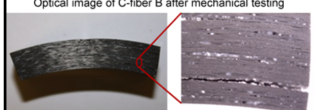


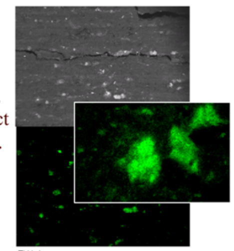

Case Study: 20-MW Beacon Power Facility (NY)

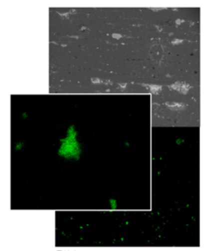
- Technology increases power capacity to 26 MW and energy capacity to 7.5 MW-service hours.
- Decreases average energy storage costs to $1500/kW and $6000/kW-h.
- After accounting for new-technology and additional production costs, return on improved-nanocomposite investment is 4%-6% per year over 20-year service life.


Optical image of C-fiber B after mechanical testing


Optical image of C-fiber C after mechanical testing

Poor distribution of nanomaterial observed, implies a minimal impact for the load levels used.



# C-fiber resin interaction requires improvement, so functionalization of the C-fiber undertaken.

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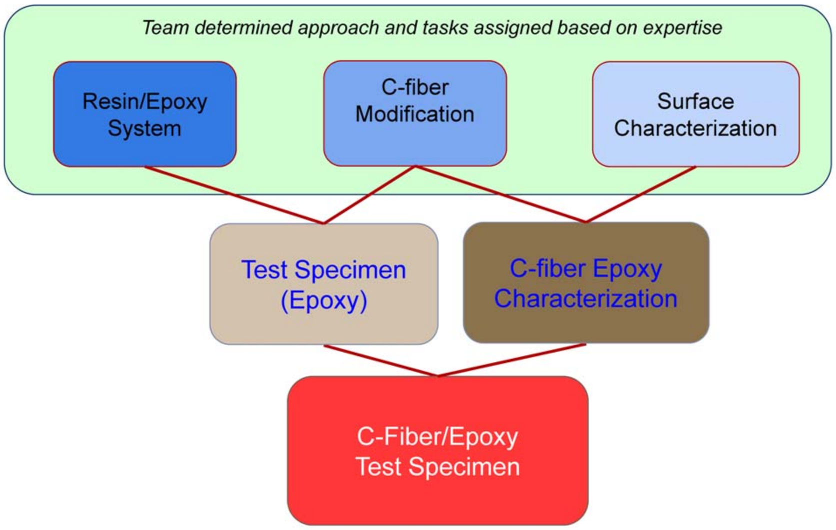
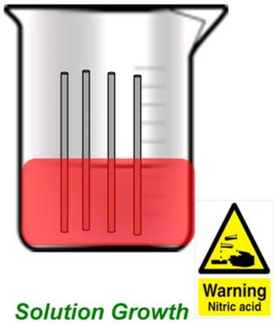
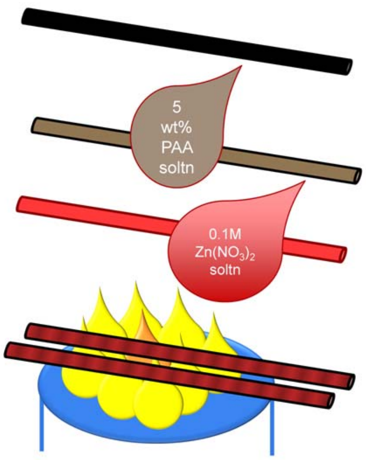


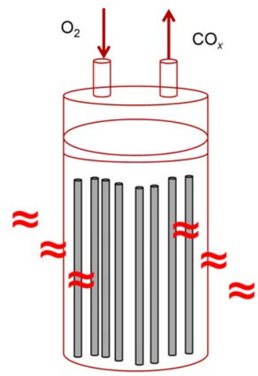
# Several approaches to functionalize C-fibers were undertaken




*Solution Growth*




*Rapid Thermal Decomposition*:




*Thermal oxidation*

# C-fiber modification results promising

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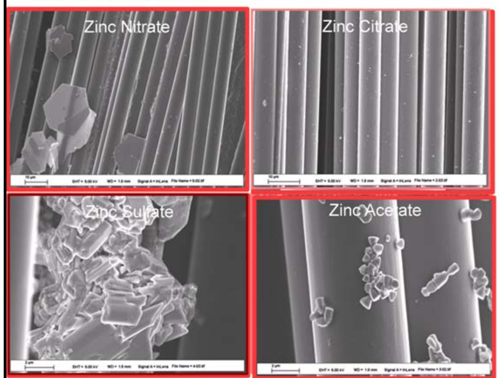
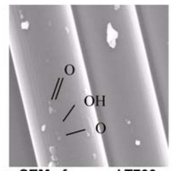
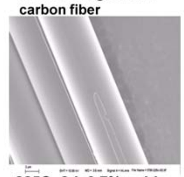
## Solution Growth



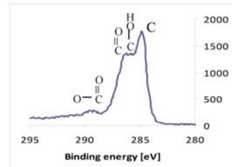

## Thermal Oxidation



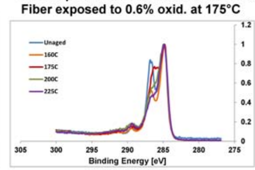

SEM of unaged T700 carbon fiber



225C, 2d, 0.7% oxid.




XPS to probe surface oxidation of carbon Fiber exposed to 0.6% oxid. at 175°C

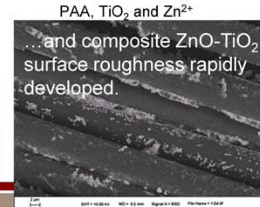



## Rapid Thermal Decomposition

PAA-$Zn^{2+}$ solution


Pechini formulation


PAA, $TiO_2$ and $Zn^{2+}$



## Summary/Conclusions

- Test Specimen Model identified:

(i) **good indicator of 'real world' properties,**

- Introduction of $TiO_2$ nanowires led to a 30 % increase in tested strength
- Economically correlates to a 20 % reduction in cost
- Better properties expected upon better distribution of poorly distributed nanowires in matrix.

(ii) **C-fiber/resin interaction needs increased.**

C-fiber modification underway:

(a) solution growth,
- surface modification shown with control indicated by anion

(b) thermal oxidation
- $CO_x$ gas observed without substantial decomposition of C-fiber

(c) rapid thermal decomposition.
- rapid surface modification noted with bonding between fibers.

# Future Tasks: Milestones for FY13

- Retest resin at higher load levels consistent with test specimen.
- Functionalize/characterize $TiO_2$ nanowires for improved distribution.

- Re-evaluate distributed functionalized $TiO_2$ nanowires in test specimen.

- Optimize surface modification of C-fiber with ceramic nanomaterials.

- Determine interaction strength of C-fiber and ceramic NM.
- Introduction of optimized modified C-fiber into test specimen model system.

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