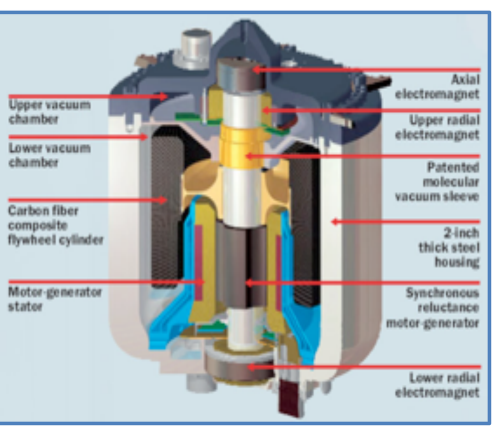
SAND2016-7761D

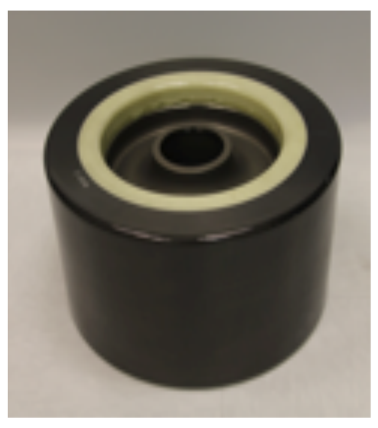
Improved Materials for Flywheel Energy Storage Applications

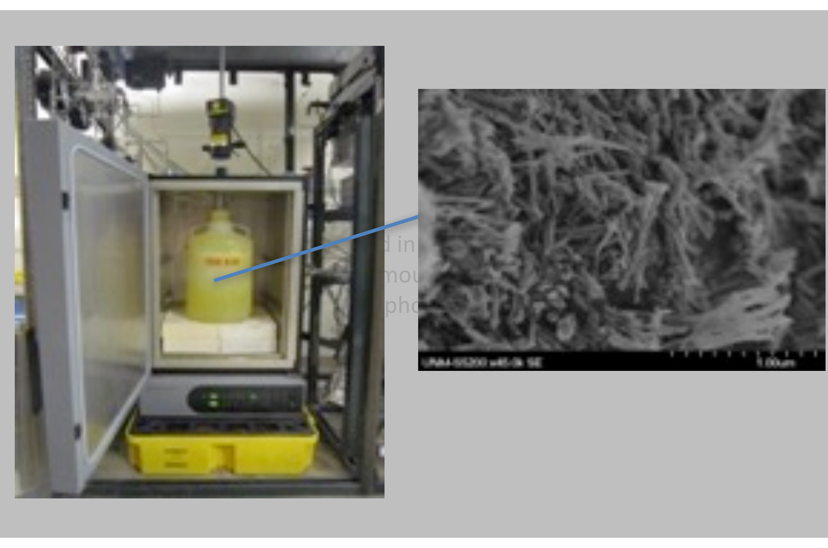
Timothy J. Boyle, Timothy N. Lambert, Nelson S. Bell, William K. Miller

Sandia National Laboratories, Advanced Materials Laboratory, 1001 University Boulevard, SE, Albuquerque, New Mexico 87106

Ph. (505)272-7625 or tjboyle@Sanida.gov

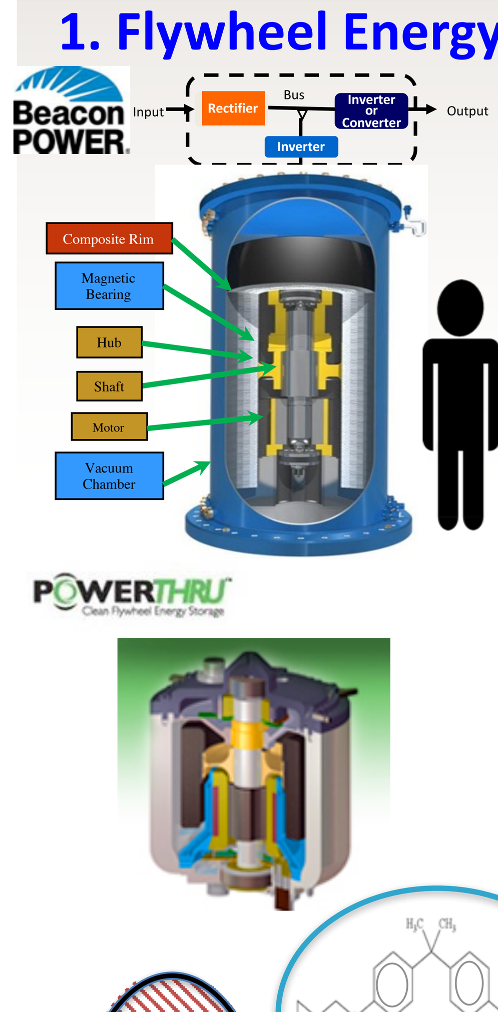






Exceptional service in the national interest

1. Flywheel Energy Storage Systems



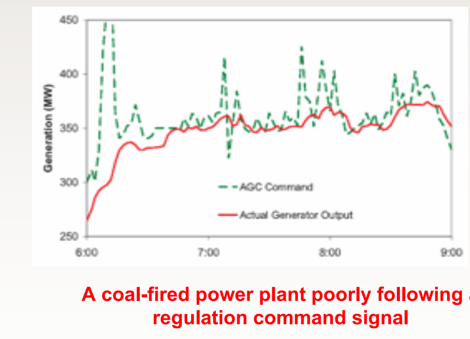
Problem: Flywheels that are used to level the AC grid need to spin faster, which requires stronger rims. Focused on the material (C-fiber, glass fiber, resin) properties of composite flywheels.

No major changes to basic design, processing parameters, and/or cost can be incurred.

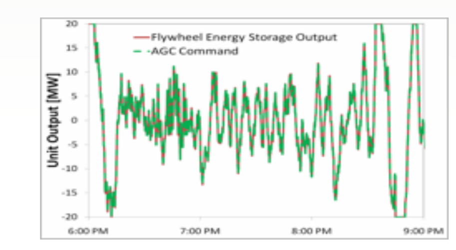
Energy Storage Impact: The economics of flywheel-based energy storage can potentially be improved by a factor of 3 or more. The increased storage/supply is necessary to meet expected future complications expected as alternative energies (i.e., solar, wind, etc.) are introduced.

Goal: Improve the overall strength of composite flywheel materials, so the flywheel can spin faster (store more energy).

Approach: Explore use of nanomaterials in strengthening composite flywheel rims to improve performance. Low load levels (<5%) have led to dramatic property changes.



A coal-fired power plant poorly following a regulation command signal



A 20 MW flywheel energy storage resource accurately following a signal

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

$$E_k = \frac{1}{2} \cdot I \cdot \omega^2$$

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

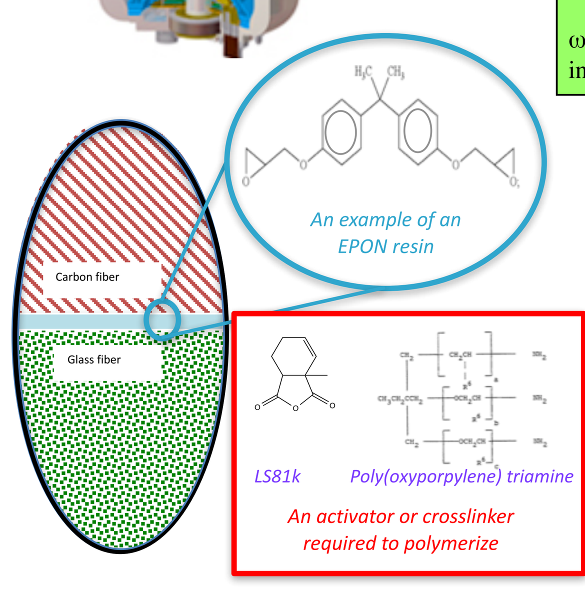
The amount of energy that can be stored is dependent on:

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

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

More electricity will need to be stored to handle the 'green energy' generators. In order to do this, the flywheels merely need to spin faster. In order to do this, the rim material needs to be stronger. Small changes will have big impact on the final energy stored.

2. Approach to Improved Flywheel Materials



- Fillers are a simple cost-effective method to alter resin properties.
- Meso-sized fillers require high loads (> 60%) due to small surface area.
- Nanomaterials are 2D fillers with all surface area, added at low levels.
- Nanofillers' surface functionality can interact with the resin.
- Reactivity can be tailored by surfactant on the nanomaterial
- wires and planes have biggest impact at lowest load level.

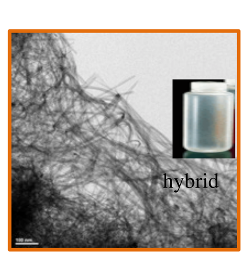
For this study, the interaction of the materials (carbon fiber, glass fiber, and EPON resin 'glue') for a composite flywheel was investigated. The weakest aspect of this is the resin, thus we focused on improving the resin strength. Fillers are often employed to alter a matrix's properties.

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]

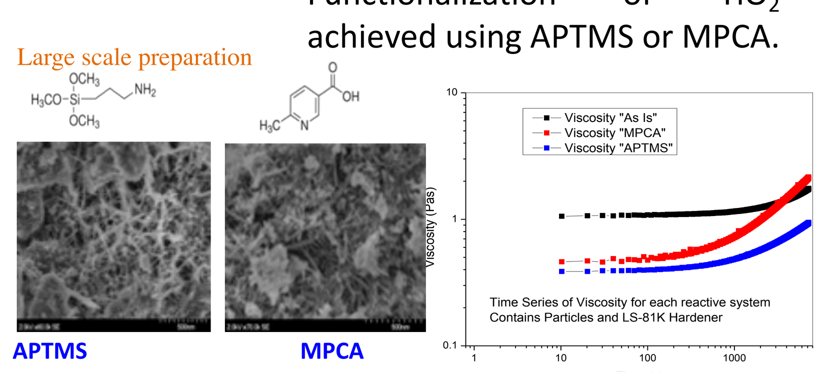
References: 1. M. Lu *et al.* J Polym Res (2008). 2. Guo, J Mat Chem (2006). 3. R. Y. Hong, *et al* J. App Polym Sci (2007). 4. Boo *et al.* J Polym Sci B: Polymer Physics (2006). 5. Sun *et al.* Chem Mater (2010). 6. Lee, X. *et al.* " *Science* **2008**, *321 (5887),* 385-388. 7. Potts *et al. Polymer* 2011, 52, 5-25.

Meso-sized fillers are often added at >60 % to impact properties. In contrast, nanofillers can be added a very low levels (< 5%) with dramatic impact on the properties. This is due to high surface areas of the nanoparticles. Two nanomaterials were investigated: graphene and titania.

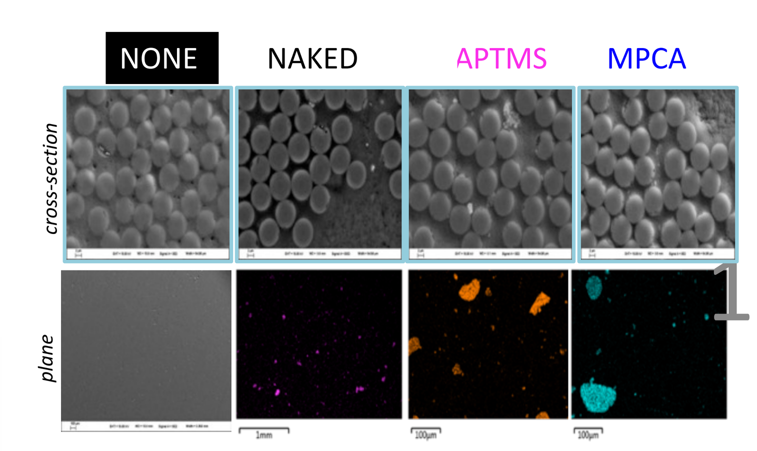
3. Laboratory Testing



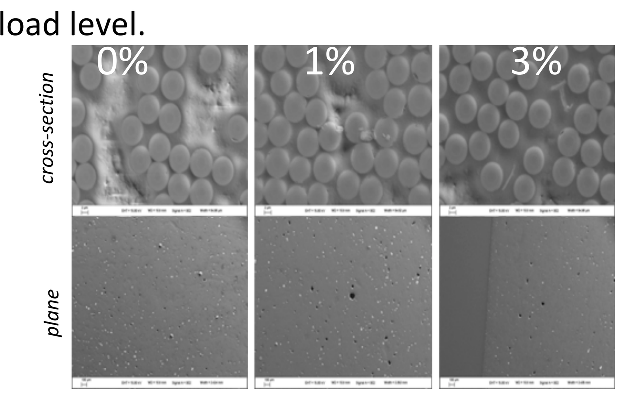
Titania (TiO_2) nanowires were successfully synthesized on a 1 kg scale using an in-house developed hybrid route. Functionalization of TiO_2 achieved using APTMS or MPCA.

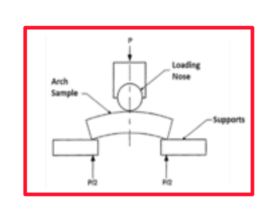


TITANIA: used nanowires with variety of modifiers. APTMS and MPCA proved best dispersants.

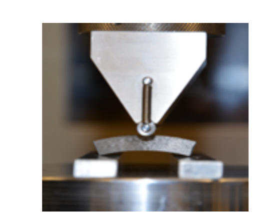


GRAPHENE. Commercially available. Used as received. Varied load level.

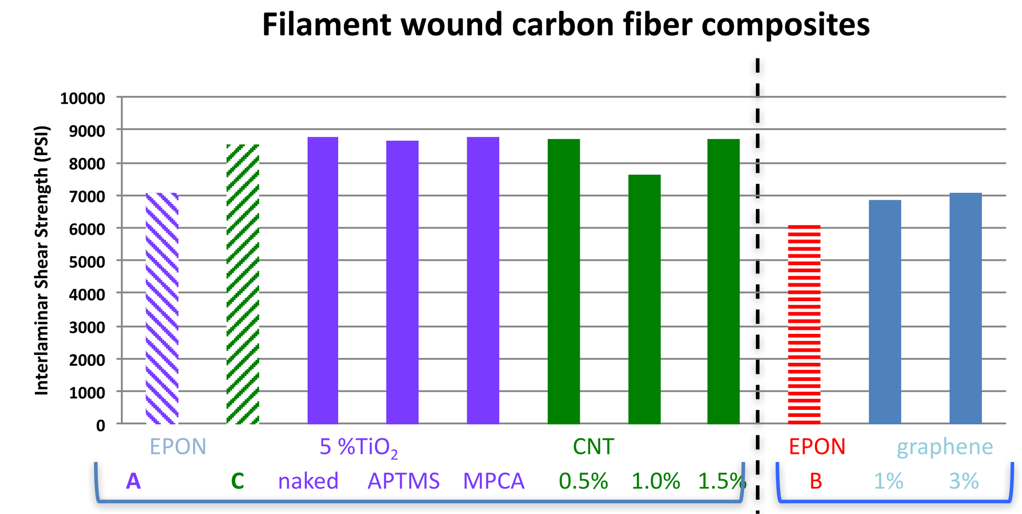




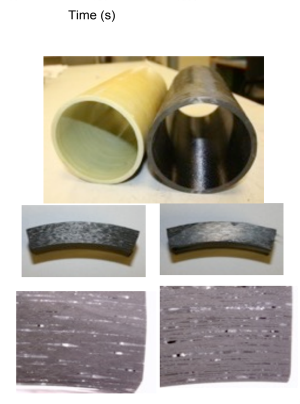
3-bend test on samples proved that both the TiO_2 and graphene nanofillers improved the part's strength by 30 and 18 %, respectively.



Filament wound carbon fiber composites



Test samples were wound at Cobham, using both graphene and titania nanowires. These nanofillers were successfully incorporated into standard processes.



Four Flywheels built:

a. blank for TiO_2 b. blank for graphene
c. filled TiO_2 d. filled graphene

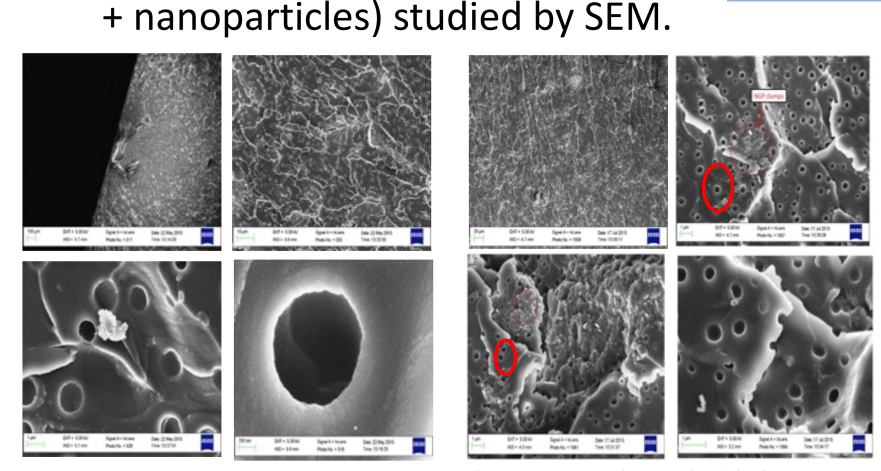
4. Building a Flywheel

The flywheel design by PowerThru was followed due to the smaller size. Limitation on the amount of nano-TiO_2 (8 kg) that could be synthesized required smaller sized test samples.

Uniform distribution required dispersion experts. Samples (resin + nanoparticles) studied by SEM.

Parts built and shipped to Cobham for assembly.

Epon with nanofillers shipped from Zyvex after mixing



The TiO_2 particles appear to wet well with the matrix, act as seeds for the voids, do not appear to slow the cracks. Cavities might lend some improvement of fractures. The TiO_2 are well dispersed

The NGP particles embed below epoxy surface, clump in an agglomerated state (red circles), and forms voids (possibly from trapped air).

Carbon fibers run through EPON solutions and rolled to remove any excess.

'Wet' fibers wound onto mandrel and then dried in oven

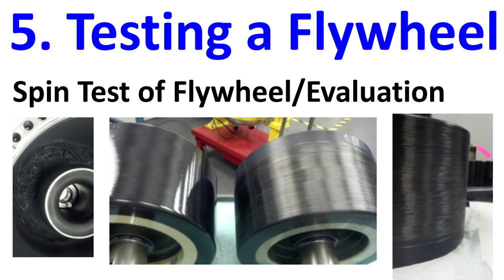
1 ft diameter flywheels produced and tested.

500 g batches of TiO_2 nanowires were synthesized using large carboy, 10 M KOH, and TiO_2 nanoseeds (Aldrich).

These were functionalized as noted above for the smaller samples, using APTMS modifiers.

5. Testing a Flywheel

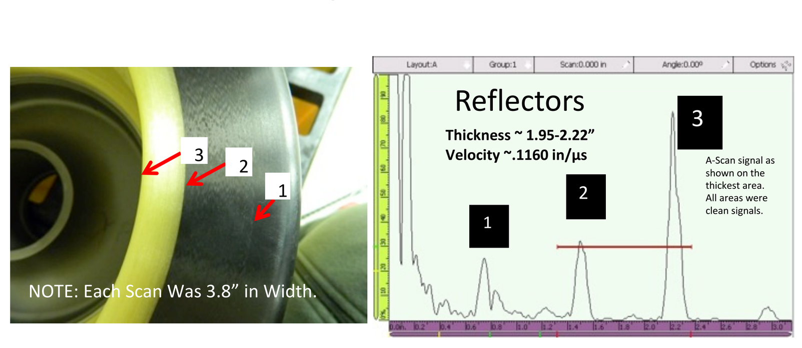
Spin Test of Flywheel/Evaluation



Four flywheels results:

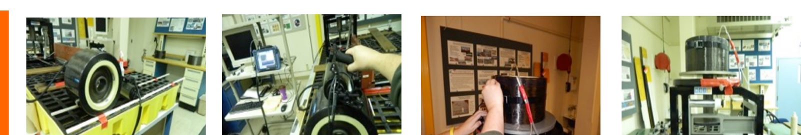
a. blank for TiO_2 spun up to 52,000 rpm: delamination
b. TiO_2 filled spun up to 27,000 rpm: hub imbalance

Ultrasonic Phased Array:MHz GE Wheel

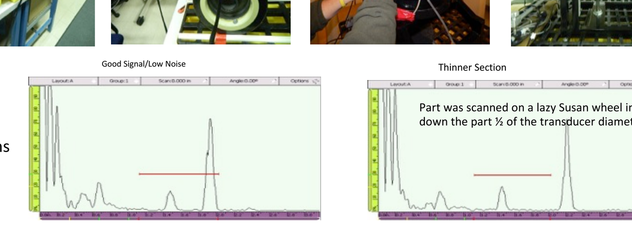


Initial inspections revealed low ultrasonic attenuation levels and that low frequency ultrasonic transducer penetrated the parts.

A-scans: showed clearly noticeable reflections at the different interfaces using the 1 MHz transducer.

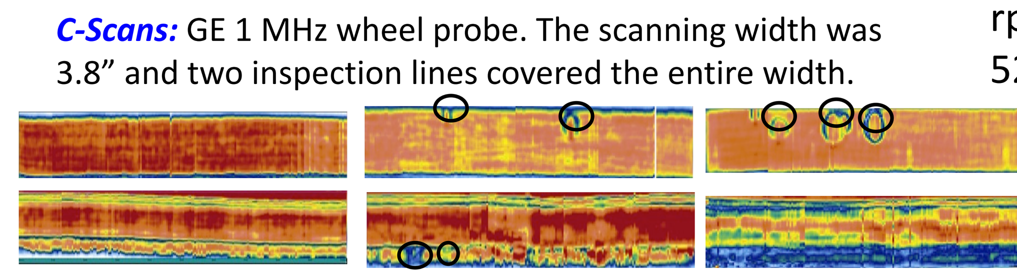


<u>Note</u>: A-Scan signals on all three parts appeared clean with very low noise.
- No signal shifts, indications of porosity clusters, or delamination signal shifts



No concentrated pockets of porosity were noted and the material appeared very clean. No indications of delaminations or disbonding from the hub in any of the flywheels.

C-Scans: GE 1 MHz wheel probe. The scanning width was 3.8" and two inspection lines covered the entire width.



- Parts appeared very clean.
- Similar to PowerThru sample
- Balancing tabs observed, good sensitivity.
- a decrease in amplitude signal, possibly due to resins or bond line.

6. Summary/Conclusions

Nanofillers: funct'd-TiO_2 NW synth (8 kg); graphene (COTS).

Dispersion: uniform distribution using Zyvex. void production observed.

Winding: Graphene cracked, wrong heat schedule: TiO_2 consistent w/ PowerThru.

Testing: Blank Epon A: low speed cycle tested to 27 K rpm (20 times); failed on the 9th high speed cycle test 52K rpm got to hot (close to resin Tg) outer tow shed.

- The TiO_2 NP filled version passed low speed cycle testing but failed (unbalance) during deceleration of the first high speed cycle (52K).

Ultrasconic testing of Flywheel: no voids or delaminations noted; Similar to PowerThru.

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.
SAND No. 2011-XXXXP