



in acetonitrile or an organic carbonate. There is a desire to move away from the  $\text{LiPF}_6$  salt, which can produce hydrogen fluoride (HF) in even traces of moisture. This HF can cause dissolution of the cathode metals, the atoms of which then migrate to and react with the lithium-graphite anode, causing significant loss of capacity. Boron-based salts are of interest because of their higher stability, but in some cases, the SEI layers they form are too resistive. LiBOB and its fluorinated analogs are of particular interest and might lead to completely new systems over the next decade. Another research opportunity lies in ionic liquids. These are salts that are liquid under ambient conditions and do not need any solvent for operation. They also tend to have low vapor pressures and to be nonflammable, but they might be too reactive to be used with lithium and some cathode materials with which they can form complexes. However, the present materials might find application in high-power batteries, such as the dual spinel  $\text{Li}_4\text{Ti}_3\text{O}_{12}/\text{LiM}_2\text{O}_4$  system, or in electrochemical capacitors. This is just the beginning of new opportunities for the electrolyte chemist, and major breakthroughs can be anticipated. For further information, Reference 3 provides excellent reviews on electrolytes and separators.

### Summary

Electrical energy storage is crucial for the effective proliferation of an electric economy and for the implementation of many renewable energy technologies. Transformational changes in both battery and capacitor science and technology will be required to allow higher and faster energy storage at the lower cost and longer lifetime necessary for major market enlargement. Most of these changes require new materials with larger redox capacities that react more rapidly and reversibly with cations such as lithium.

### Acknowledgments

The work at Binghamton was supported by the U.S. Department of Energy, through the BATT program at Lawrence Berkeley National Laboratory. This article also relies on the U.S. DOE workshop presentations held in April 2007, on its subsequent report, and on discussions held with many colleagues. In particular, I thank Bruce Dunn for helpful discussions, Imre Gyuk of U.S. DOE for much useful information on applications, and T. Ohzuku for providing **Figure 5**.

### References

1. K.H. LaCommare, J.H. Eto, *Understanding the Cost of Power Interruptions to U.S. Electricity Consumers* (Energy Analysis Department,

- Lawrence Berkeley National Laboratory, University of California–Berkeley, Berkeley, CA, 2004; <http://certs.lbl.gov/pdf/55718.pdf>) (accessed January 2008).
2. Dinorwig Power Station, <http://www.fhc.co.uk/dinorwig.htm> (accessed January 2008).
3. M.S. Whittingham, R.F. Savinell, T. Zawodzinski, Eds., “Batteries and Fuel Cells”, in *Chem. Rev.* **104**, 4243 (2004).
4. M.S. Whittingham, *Prog. Solid State Chem.* **12**, 41 (1978).
5. D. Linden, T.B. Reddy, *Handbook of Batteries* (McGraw Hill, New York, ed. 3, 2001).
6. J. M. Tarascon, M. Armand, *Nature* **414**, 359 (2001).
7. *Basic Research Needs for Electrical Energy Storage* (Office of Basic Energy Sciences, U.S. Department of Energy, Washington, DC, 2007).
8. R. Kötz, M. Carlen, *Electrochim. Acta* **45**, 2483 (2000).
9. G.G. Libowitz, M.S. Whittingham, *Materials Science in Energy Technology* (Academic Press, New York, 1979).
10. S. Flandois, B. Simon, *Carbon* **37**, 165 (1999).
11. Q. Fan, P.J. Chupas, M.S. Whittingham, *Electrochem. Solid-State Lett.* **10** (12), A274 (2007).
12. M.S. Whittingham, *Science* **192**, 1126 (1976).
13. M.S. Whittingham, *Mater. Res. Bull.* **13**, 959 (1978).
14. Y. Song, P.Y. Zavalij, M.S. Whittingham, *J. Electrochem. Soc.* **152**, A721 (2005).
15. C.S. Johnson, J.S. Kim, A.J. Kropf, A.J. Kahaian, J.T. Vaughney, L.M.L. Fransson, K. Edström, M.M. Thackeray, *Chem. Mater.* **15**, 2313 (2003).
16. A.K. Padhi, K.S. Nanjundaswamy, J.B. Goodenough, *J. Electrochem. Soc.* **144**, 1188 (1997).
17. A123; [www.a123systems.com](http://www.a123systems.com) (accessed January 2008).
18. T. Drezen, N.-H. Kwon, P. Bowenb, I. Teerlinck, M. Isono, I. Exnar, *J. Power Sources* **174**, 949 (2007).
19. Y. Song, P.Y. Zavalij, N.A. Chernova, M.S. Whittingham, *Chem. Mater.* **17**, 1139 (2005).
20. T. Ogasawara, A. Débart, M. Holzapfel, P. Novák, P.G. Bruce, *J. Am. Chem. Soc.* **128**, 1390 (2006).
21. Y. Wang, K. Takahashi, K.H. Lee, G.Z. Cao, *Adv. Funct. Mater.* **16**, 1133 (2006).
22. D.-H. Kim, J. Kim, *Electrochem. Solid-State Lett.* **9**, A439 (2006).
23. A. Windle, private communication.
24. J. Chen, M.S. Whittingham, *Electrochem. Commun.* **8**, 855 (2006).
25. F. Zhou, M. Cococcioni, C. Marianetti, D. Morgan, M. Chen, G. Ceder, *Phys. Rev. B* **70**, 235121 (2004).
26. C.-W. Wang, K.A. Cook, A.M. Sastry, *J. Electrochem. Soc.* **150**, A385 (2003).
27. T. Maxisch, F. Zhou, G. Ceder, *Phys. Rev. B* **73** (2006).
28. G. Chen, X. Song, T.J. Richardson, *Electrochem. Solid-State Lett.* **9**, A295 (2006).
29. J. Breger, N. Dupre, P.J. Chupas, P.T. Lee, T. Proffen, J. Parise, C.P. Grey, *J. Am. Chem. Soc.* **127**, 7529 (2005).
30. C.P. Grey, N. Dupre, *Chem. Rev.* **104**, 4493 (2004).
31. N.A. Chernova, M.M. Ma, J. Xiao, M.S. Whittingham, J. Breger, C.P. Grey, *Chem. Mater.* **19**, 4682 (2007).
32. V. Petkov, P.Y. Zavalij, S. Lutta, M.S. Whittingham, V. Parvanov, S. Shastri, *Phys. Rev.* **B69**, 085410 (2004). □

## Electrical Energy Storage Using Flywheels

M. Stanley Whittingham (Binghamton University, USA)

Flywheel energy storage systems use the kinetic energy stored in a rotor; they are often referred to as mechanical batteries. On charging, the flywheel is accelerated, and on power generation, it is slowed. Because the energy stored is proportional to the square of the speed, very high speeds are used, typically 20,000–100,000 revolutions per minute (rpm). To

minimize energy loss due to friction, the rotors are spun in a vacuum and use magnetic bearings. The rotors today are typically made of high-strength carbon composites. One of the main limits to flywheels is the strength of the material used for the rotor: the stronger the rotor, the faster it can be spun, and the more energy it can store. However, if the strength is exceeded,

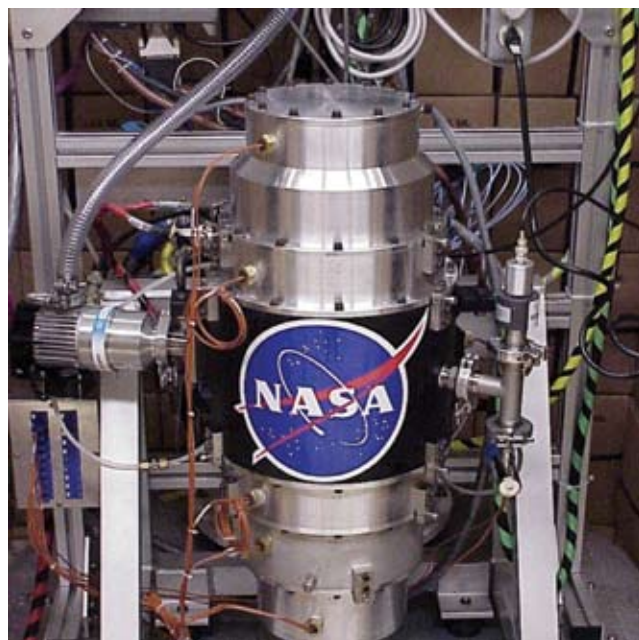


the rotor can shatter explosively, releasing all of its energy much like a hand grenade; thus, these systems are often housed in thick steel containers. Composites have the advantage that they tend to shatter into very fine particles.

The time required for a rotor to come to full charge (speed), within a few minutes, is shorter than that for batteries but longer than that for supercapacitors. Whereas batteries and capacitors can, in theory, store energy for indefinite periods, flywheels consume energy when fully “charged” and are therefore best suited for short-term storage. This energy loss, around 10% per hour, might be reduced by improved magnetic bearings, such as those using superconductors. In this case, high-temperature superconductors are required, along with an outstanding insulating system, so that refrigeration costs and maintenance do not become prohibitive; the ideal system needs to be completely self-contained.

The energy storage capability of flywheels approaches 130 watt-hours per kilogram (Wh/kg), with power capabilities of around 500 watts per kilogram (W/kg). Present capacities range from 2 kWh upward, with capabilities of providing megawatts of power for a few minutes. Flywheels are presently used in conjunction with renewable power systems, such as wind power, to give steady high-quality output and in conjunction with uninterruptible power supplies to improve the power quality (maintenance of frequency and voltage). They are replacing lead-acid batteries for uninterrupted power supply systems, such as those used for telecommunications and information technology systems, having much lower weights and less required maintenance, even though their initial costs of around \$1,000/kWh are about double those of a lead-acid device. Flywheels also find use in other highly cyclic operations, such as dock crane use, where they compete with capacitors rather than batteries. They are not finding much use in general consumer applications, such as electric vehicles or home-level load-leveling because of safety and perceived gyroscopic concerns and because they are optimized for short-term storage.

Most of the advances in flywheel energy storage technology are likely to come from engineering improvements as opposed to materials research breakthroughs. The reader is referred to [www.itpower.co.uk/investire/pdfs/flywheelrep.pdf](http://www.itpower.co.uk/investire/pdfs/flywheelrep.pdf) (accessed January 2008) for further information.



**Figure 1.** G2 Flywheel Module. Source: NASA Glenn Research Center, Power and Propulsion Office; [http://space-power.grc.nasa.gov/ppo/projects/flywheel/img/G2\\_082704\\_front2.jpg](http://space-power.grc.nasa.gov/ppo/projects/flywheel/img/G2_082704_front2.jpg) (accessed January 2008).

## AMERICAN CONFERENCE ON NEUTRON SCATTERING

A meeting of the Neutron Scattering Society of America

May 11-15, 2008 • Eldorado Hotel & Spa • Santa Fe, New Mexico, USA

ACNS2008  
Santa Fe, NM

With the new Spallation Neutron Source coming on line, the recently announced expansion of the neutron facilities at NIST, and reinvigorated programs at other North American facilities, this is truly an exciting time for neutron research in North America. Whether you are already a neutron user, or would simply like to find out how neutrons can help solve your problems in the materials and biological sciences, the American Conference on Neutron Scattering (ACNS) is the essential venue to hear about the high quality and breadth of current neutron-related research across North America.

From fresh insights on macromolecules in motion, through shear-induced phase transformations in soft condensed matter, to materials for hydrogen storage, multiferroics, nanomagnetism and fundamental neutron physics ... hear the latest research results. There will also be opportunities to dream and speculate about what's next on the Q-E map—the great unanswered scientific questions and novel instrument concepts.

More than 40 invited speakers have already signed on, and the three recipients of the 2008 NSSA prizes will be speaking as well.

Register by May 2 at [www.mrs.org/acns08](http://www.mrs.org/acns08)  
for discounted rates:

Pre-Registration..... \$375  
Pre-Registration Student..... \$125

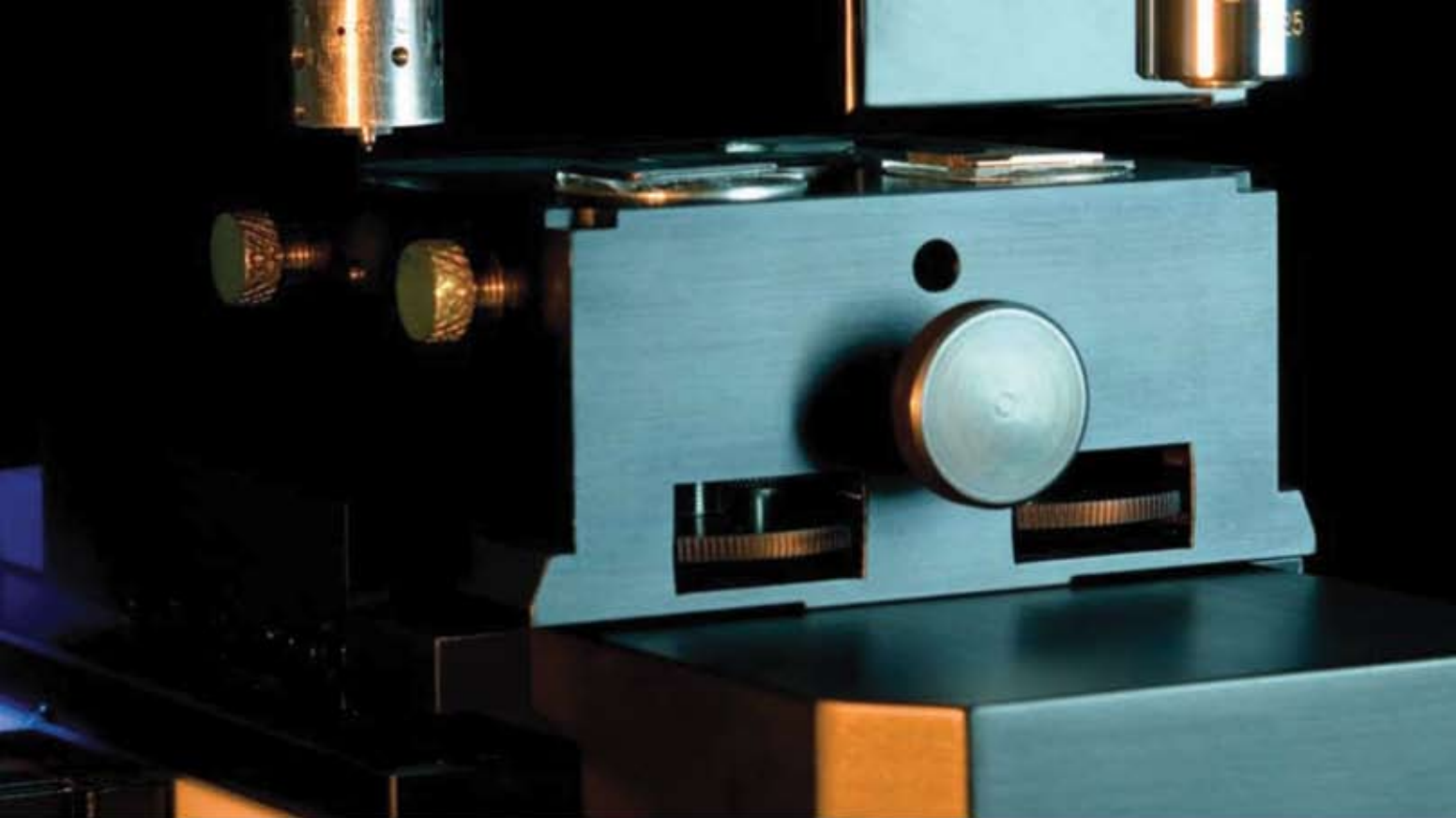
The following rates are applicable  
after May 2:

On-Site Registration..... \$425  
On-Site Registration Student..... \$175

Simon Billinge - Conference Chair, Michigan State University • [billinge@pa.msu.edu](mailto:billinge@pa.msu.edu)

Thomas Proffen - Local Conference Chair, Lujan Neutron Scattering Center, Los Alamos National Laboratory • [tproffen@lanl.gov](mailto:tproffen@lanl.gov)

For the most up-to-date information on ACNS 2008, visit [lansce.lanl.gov/ACNS2008](http://lansce.lanl.gov/ACNS2008).



# Need Tools for Nanomechanics? Introducing the **Nano Indenter® G200**

the market's most powerful, flexible tool for exploring nanomechanics

MTS Nano Instruments is pleased to introduce the new **Nano Indenter G200**, the most advanced platform for characterization of material properties at the nano and micro- scales. Its state of the art motion system speeds sample throughput without sacrificing accuracy. Its electromagnetic actuation-based force transducers ensure the integrity of test results.

Are your experiments challenging? Do you have unique needs? Powered by our industry-leading **TestWorks® 4** software, the **Nano Indenter G200** offers unprecedented levels of experimental control. Imagine controlling experimental progress based on novel calculations. Envision having access to control experimental parameters based on any acquired and calculated data. With a system from MTS, you can!

To learn more about how the **Nano Indenter G200** may support your exploration of material properties, visit us on the web at [www.mtsnano.com](http://www.mtsnano.com) or contact us toll free at 1 800 844-6266.



[www.mtsnano.com](http://www.mtsnano.com)



**NANO INSTRUMENTS**

*innovation to explore your ideas.*