in acetonitrile or an organic carbonate. There is a desire to move away from the $LiPF_6$ 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 $Li_4Ti_5O_{12}/LiM_2O_4$ 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.

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Electrical Energy Storage Using Flywheels

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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,

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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 (accessed January 2008) for further information.

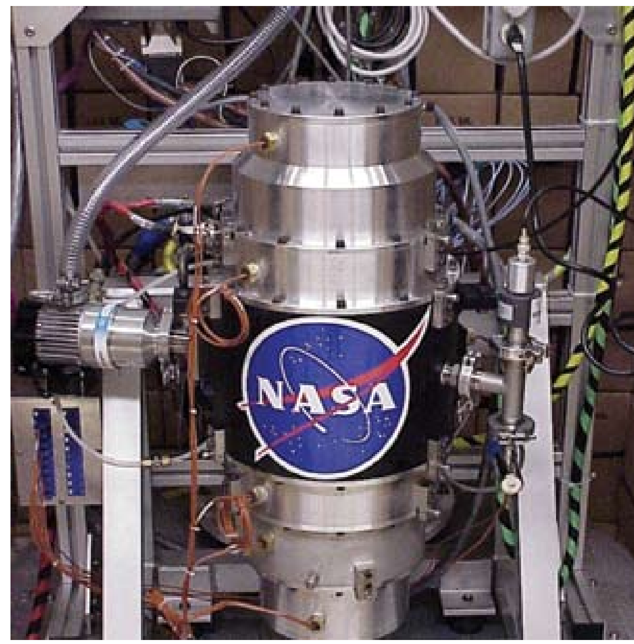

Figure 1. G2 Flywheel Module. *Source:* NASA Glenn Research Center, Power and Propulsion Office; http://space-power.grc.nasa.gov/ppo/projects/flywheel/img/G2_082704_front2.jpg (accessed January 2008).

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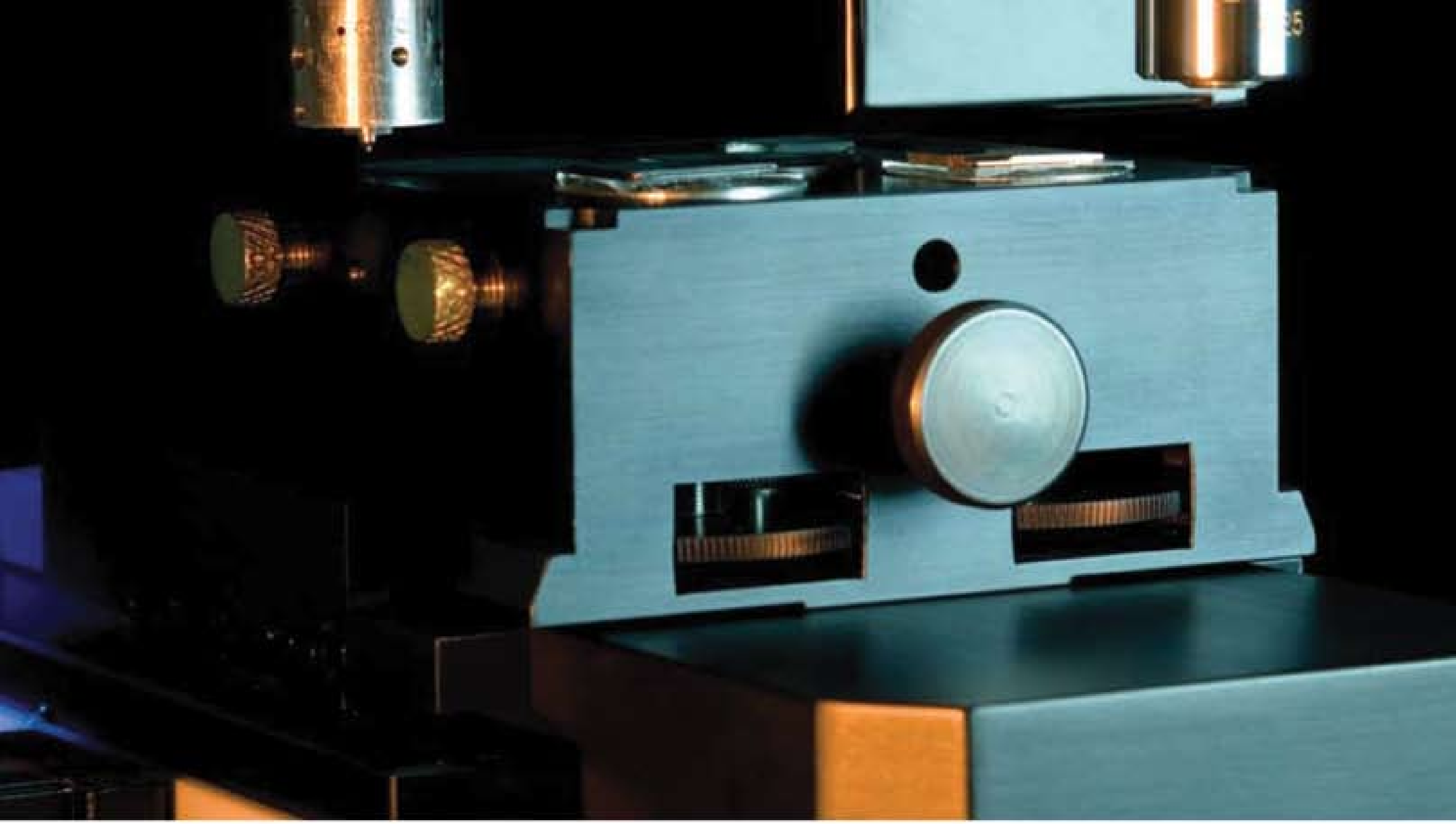

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