Development of Long-life, Low-maintenance Flywheel Electricity Systems†

A.C. Day* and M. Strasik, Boeing Phantom Works, Seattle WA
J. Wood, Jack Wood Associates, Grass Valley CA
P. Taylor and L.C. Johnson, formerly of Energetics Inc., Columbia MD

ABSTRACT

Battery systems have long been relied upon for applications including uninterruptible power supply (UPS) systems and support of renewables. However, the limitations of chemical storage are well known. These include batteries' limited tolerance for non-ideal charge and discharge cycles; reduction in capacity and (usually) replacement of the battery strings within the working life of the host systems; thermal effects; significant weight; and environmental hazards relating to operation and disposal. Relatively new storage options including flywheels, superconducting magnetic energy storage (SMES), and supercapacitors have the potential to outperform batteries in both existing and new applications. Among these, advanced flywheels will eventually have the advantage in storing significant amounts of energy for applications including renewables support, spinning reserve, and backup for telecommunication sites. As such they can have a major impact on the cost, reliability, and environmental consequences of electric power use and generation.

INTRODUCTION

The Boeing Company has been interested in flywheel energy storage for a number of years, partly as an outgrowth of related activities in superconductivity and in advanced composites. An in-house flywheel development project has been ongoing since 1994 with involvement from a wide range of engineering and business disciplines. A system design for a 2 kWh component testbed was developed with a primary focus on passive magnetic suspension using high-T_c superconductors. Figure 1 below shows the composite wheel with the magnet assembly in the hub, which interacts with superconductor disks in the cryostat below. The magnetic suspension and brushless motor design completely eliminate wear surfaces in the main flywheel structure, enabling operation for tens of thousands of cycles with minimal degradation and virtually no maintenance. Unlike active magnetic bearings, the high-temperature superconducting (HTS) version will consume less power [1] and be much simpler to construct and operate. The bearing requires no sensors, servos, or logic to maintain rotor position, and is therefore expected to be more reliable at high speeds and for extended use. Boeing is now ramping up the pace of development through partnerships involving the Department of Energy, Sandia National Laboratory, utilities, and other companies.

A major thrust in this effort is a seven member Boeing-led Superconductivity Partnership Initiative (SPI) Cooperative Agreement funded jointly with the Department of Energy. The objective of this three-year project is to design, build, and test a 10 kWh storage system for terrestrial uses with an emphasis on grid-connected UPS. The SPI will provide ongoing R&D focused on high-T_c material growth [2], and will also give us parametric data from which point designs can be developed.

Figure 1. The Boeing 2 kWh flywheel testbed

(*) The author may be contacted at arthur.day@pss.boeing.com
(†) This work was supported in part by the U.S. Department of Energy through Sandia National Laboratory contract BF-9318A and Cooperative Agreement DE-FC36-99G010025.

PROGRESS TOWARD A SYSTEM DEMONSTRATION

A preliminary system design for a 10 kWh flywheel has recently been completed. Major components are shown in a 3-D rendering in figure 2 below. The suspension consists of a permanent magnet (PM) lift bearing as well as a hybrid PM/HTS bearing for stability. The superconducting materials in this case are thick wafers of YBaCuO single-grain materials fixed in a non-rotating fiberglass/epoxy enclosure. A high-gradient magnet array is built into the flywheel hub and gives the system stability through flux-trapping in the superconductors. These components, partially assembled, are shown in figure 3. The superconductors are cooled by a passive flow of liquid nitrogen. The coolant temperature is maintained with a closed-cycle pulse-tube refrigerator that operates at 65 – 80K. In modest production, the cost of such coolers is expected to be no more than a few thousand dollars.

The hub assembly also includes a touchdown bearing for safe operation and a permanent magnet motor. A bi-directional motor controller commands up to 10 kW of power to or from the motor/generator. The busbar voltage of the unit is 300VDC.

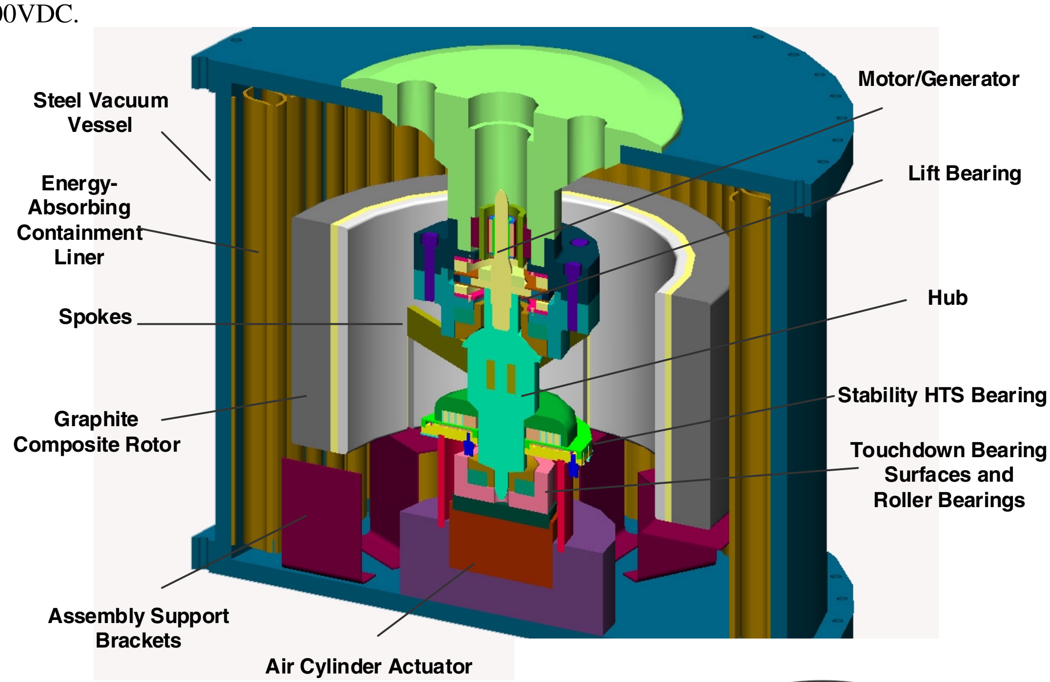

Figure 2. 10 kWh preliminary s

Figure 3. YBaCuO crystal array for the HTS bearing stator and a high-gradient magnet assembly for the bearing rotor

The flywheel rim includes both glass and carbon fiber/epoxy composites. The combination allows more flexibility in how the hoop and radial stresses are distributed in the rim, with the goal of reducing cost while increasing the safety of the system. The flywheel's hub and rim are connected with a proprietary spoke system. Also noteworthy is the S-bracket containment structure (patent pending). This design allows a series of metal brackets to deform relatively uniformly, without excessive stress on welds or the outer vacuum wall. Finite element analysis of the container predicts that it will deform primarily in the plane of the rotor in the event of a hoop burst, constraining material to stay near that plane rather than flow vertically toward the chamber lid or base.

Most of the components needed for the above design have now been fabricated. Our immediate goal is to test all such components to at least 80% of their design speed by the fall of 2000. The motor/generator has already been taken to twice its design speed before failing. It also met requirements for core loss and for low side forces. The bi-directional controller performed flawlessly. The container concept has also been partially tested in a subscale (1 kWh) version. The result of a high-speed rotor drop on the container is shown in figure 4. Close examination showed almost no damage to the S-brackets. A subsequent test will attempt to show how the structure withstands a hoop burst.

Figure 4. Container with 1 kWh wheel after drop at 41,000 rpm

OFF-GRID APPLICATIONS OF FLYWHEELS

Recently we have also been working with Sandia National Laboratory with a focus on applications for off-grid generation technologies. The effort brought in Energetics Inc and Jack Woods Associates to assist in identification and analysis of power markets, applications, and host sites. Energetics analyzed a number of information sources compiled by the World Bank to arrive at a global picture of the potential need for off-grid storage, particularly with renewable energy sources. As shown in Tables 1 and 2 below the outlook appears to be excellent. The need for storage to counteract load and supply variations, and the potential hybridization with some amount of diesel generation, will be common to wind, solar, and hydro systems. It was estimated that there could be approximately 100,000 off-grid generating installations worldwide with storage needs of 45 kWh or more.

TABLE 1. Off-grid Storage Applications and their Requirements

Application	I. Single Home: Developing Community	II. Developing Community: No Industry	III. Developing Community: Light Industry	IV. Developing Community: Moderate Industry	V. Advanced Community or Military Base	VI. Military Base
FES System Attributes	.5 kW 3 kWh	8 kW 45 kWh	40 kW 240 kWh	400 kW 3600 kWh	1 MW 1.5 MWh	5 MW 3 MWh
Power	Base: 0.5kW	Base: 5kW Peak: ≤8kW	Base: 10kW Peak:≤40kW	Base: 100kW Peak:≤400kW	Base: 100kW Peak: ≤1MW	Base: 5MW Peak: ≤8kW
Discharge duration	5 to 72 hours	5 to 72 hours	5 to 24 hours	5 to 24 hours	0 .5 to 1 hour	0.5 to 1 hour
Maximum Power from System (kW)	0.5	10	50	500	5000	?
Daily Energy from System (kWh)	1	15	120	1800	60000	?
Maximum Power from Storage (kW)	0.5	8	40	400	1000	5000
Total Energy from Storage (kWh)	3	45	240	3600	1500	3000
Load Voltage V_{DC}:	12	12, 24, 48	12, 24, 48	12, 24, 48	DC less likely	DC less likely
V_{AC}:	AC less likely	120	120	120, 240, 480	480, 15000	480, 15000

TABLE 2. Total Estimated Market for Off-grid Storage Applications for Rural Homes and Communities					
Application	**I. Single Home: Developing Community**	**II. Developing Community: No Industry**	**III. Developing Community: Light Industry**	**IV. Developing Community: Moderate Industry**	**V. Advanced Community or Military Base**
Projected Number of PV Hybrids	**47 Million**	**129,000**	**24,000**	**65,000**	**121,000**
Projected Number of Wind Hybrids	**1,000**	**7,000**	**14,000**	**7,000**	**5,000**
Projected Number of Hydro Hybrids	**400**	**500**	**2,000**	**12,000**	**5,000**
Total Projected Number of RAPS	**47 Million**	**137,000**	**40,000**	**84,000**	**131,000**

In the U.S and particularly in Alaska, a number of "high-penetration" wind power installations will be coming online in the near term. The success of these installations will rely heavily on storage technologies being available as well as efficient back-up strategies employing diesel [3]. Without storage, a reliable system would require nearly constant operation of a diesel generator at some low fraction of its rated power. This is highly inefficient. A preferred strategy is to use storage to ride out all but prolonged drops in available wind energy. A flywheel system meeting the requirements of a high-penetration wind-generation site thus presents itself as an excellent target application on which to base development efforts.

SYSTEM SIZING AND ANTICIPATED COST TRENDS

We have developed initial designs for Applications I and II above (3 kWh and 45 kWh systems). We selected a rim of filament-wound T700S carbon fiber composite over an E-glass inner ring. Stresses in both the hoop and radial directions were calculated with a spreadsheet design tool based on published equations [4,5]. Predicted stress distributions are shown in figure 5. The wheel speed and the dimensions of the rings were chosen so that there will be a Factor of Safety of at least 2 on material strength in all directions. For the 45 kWh design the operating speed is 12,500 rpm and the dimensions are 0.42m ID, 0.63m OD, and 0.6m tall.

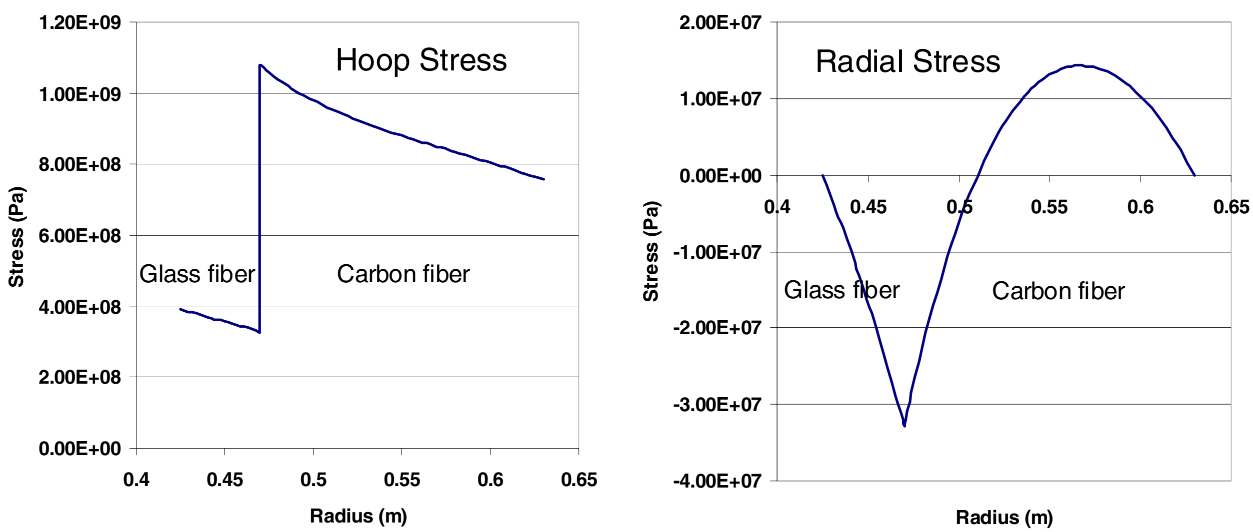

Figure 5. Stress distributions in T700S/E-glass flywheel rims for 45 kWh. Wheel is designed for F.S = 2 at 12,500 rpm.

Next, the costs of manufacturing the 3 kWh and 45 kWh systems were estimated. We assumed that for each there would be a hybrid PM/HTS suspension and closed cycle cooling, and that both would be built out to a DC bus level. The aims of this study were twofold: first, to see what would be reasonable cost targets in production (assumed to be 1000 units or more); and second, to determine the cost drivers for each system. Learning curves were applied to each of the major system components based on manufacturing experience at Boeing and among our development partners.

The trends are shown in figure 6 below. We concluded that the 3 kWh system would cost about \$2 - \$4/Wh in production. The HTS bearing and its cooler would likely be the largest cost component, followed by the composite rotor and then the motor/generator and motor controller. In a 45 kWh system the cost would come down to \$1 - \$2/Wh with the composite rotor as the largest cost driver, followed by the containment system and then the HTS bearing. At this level the initial costs are competitive with those of large battery projects such as have been installed in Puerto Rico and Alaska. The long-term cost picture is at least as significant. A battery bank will typically entail disposal and replacement costs within 4 – 7 years, and for many types, frequent maintenance. The HTS-suspended flywheel system should last 15 – 30 years with only occasional (once in 5 years) attention to the cooler's

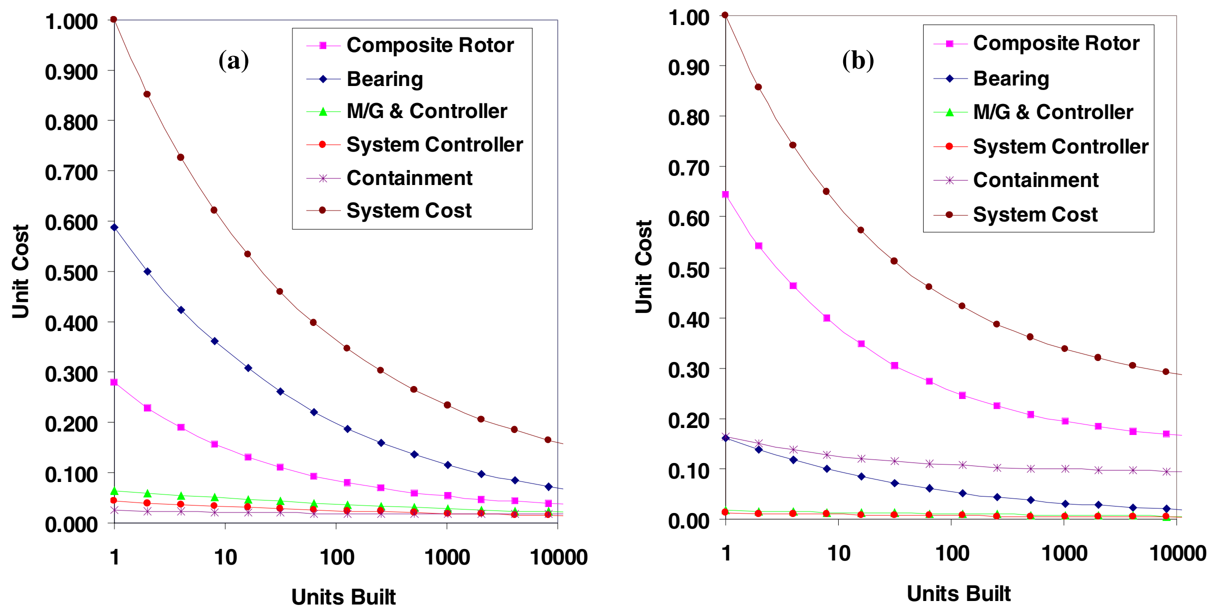

Figure 6. Cost trends among flywheel components for (a) 3 kWh and (b) 45 kWh systems

compressor. The flywheel, bearings, and motor/generator should require virtually no maintenance over the life of the system.
There are at present still many gaps in the technology supporting advanced flywheel systems. We have recently initiated work to better quantify allowable design strengths for both the composite materials and the rotating permanent magnets. Gradual or even rapid improvements can also be expected in the capabilities of the HTS materials. Improved current densities will mean more efficient systems; increases in the transition temperatures of new compounds could rapidly reduce the cost of cooling these bearing systems. Superconducting motors may also improve efficiency and increase output powers substantially. Safety systems for flywheels are now approached with a great deal of conservatism, but as the materials and systems become well developed and characterized, we may find that catastrophic failures cease to be a concern. Aircraft turbines and many steel flywheels are cases in point.

REFERENCES

1. Hull, J., Hilton, E., Mulcahy, T., Yang, Z., Lockwood, A., and Strasik, M., J.Appl. Phys. **79** (1996).
2. Hicks, W.C., Dogan, F., Strasik, M., Day, A.C., and McCrary, K.E., "The Effect of Platinum and Excess 211 Phase on the Loss of the Liquid Phase in Melt Textured $YBa_2Cu_3O_{7-x}$", IEEE Transactions on Applied Superconductivity **9** (2), pp. 2060-2065 (1999).
3. Infield, D.G., "Wind/Diesel System with Flywheel Energy Storage," IEA Workshop on Wind-Diesel Systems, Rutherford Laboratory, England, June 1987.

4. Genta, G., “Kinetic Energy Storage”, Butterworths, Boston (1985).
5. Gabrys, C.W., and Bakis, C.E., "Design and Testing of Composite Flywheel Rotors" in Composite Materials: Testing and Design, 13th vol., ASTM STP 1242, 1997 pp. 1 - 22.