FLYWHEEL ENERGY STORAGE SYSTEMS WITH SUPERCONDUCTING BEARINGS FOR UTILITY APPLICATIONS

Cooperative Agreement No. DE-FC36-99GO10285

FINAL REPORT EXECUTIVE SUMMARY

May 1, 1998 – July 31, 2007

Submitted by:
Boeing Phantom Works

Program Manager:
Dr. Michael Strasik
(206) 544-5389

Principal Investigators:
Mr. Arthur Day
(206) 544-4661
Mr. Philip Johnson
(206) 544-5777
Dr. John Hull
(206) 544-5803

Team Members:
Boeing Phantom Works
Southern California Edison
Praxair Specialty Ceramics Corporation
Ashman Technologies
Mesoscopic Devices
Argonne National Laboratory

Table of Contents

SPI PROGRAM OBJECTIVE

This project's mission was to achieve significant advances in the practical application of bulk high-temperature superconductor (HTS) materials to energy-storage systems. The ultimate product was planned as an operational prototype of a flywheel system on an HTS suspension. While the final prototype flywheel did not complete the final offsite demonstration phase of the program, invaluable lessons learned were captured on the laboratory demonstration units that will lead to the successful deployment of a future HTS-stabilized, composite-flywheel energy-storage system (FESS).

EXECUTIVE SUMMARY TECHNICAL RESULTS

This report consists of an executive summary combined with detailed quarterly reports covering 33 quarters of effort. The executive summary consists of six sections describing work on the six major subassemblies and also includes a seventh section on system-level testing. At the end of each section is a lessons learned summary. The following is a synopsis of the technical results and lessons learned on the subsystems. A brief summary of this flywheel project was published in M. Strasik, et al., "Design, Fabrication, and Test of a 5-kWh/100-kW Flywheel Energy Storage Utilizing a High-Temperature Superconducting Bearing." *IEEE Trans. Appl. Supercond.* **17**, 2133-2137 (2007).

Rotor Assembly

The first large rotor assembly for the SPI program was a spoke design with the stored energy of the rotor set at 10 kWh. Dynamic analysis of this rotor system had shown some instability inherent with the first proposed 120-degree spoke design, and the team chose a 90-degree spoke configuration as the build design. Solid models of the flywheel rotor were utilized to establish the center of gravity of the rotor assembly, and the touchdown surfaces were designed in reference to the center of gravity location. (Quarter 6)

Two 10-kWh composite rotors (one cut down to a height of 4 inches and one at the full height of 15 inches) were fabricated by Toray Composites of America using their proprietary winding process. Materials used in the rotor consisted of an inner ring of e-glass/epoxy and an outer ring of Toray T-700S graphite/epoxy. The full-size rotor was dimensionally inspected at the vendor. The ID of the ring was 24.495 +/- .002 inches and the OD was 31.407 +/- .003 inches. The overall height of the ring was 15.518 – 15.519 inches. The ring was also inspected for resin and void content. The fiber volume was found to be 67.14% for the e-glass/epoxy and 67.86% for the T-700/epoxy. The void content was found to be 1.84% in the e-glass/epoxy and .45% in the T-700/epoxy. The weight of the full-size rotor was 281 lbs. (Quarter 6)

Theses two rotor systems, following NDI and other dimensional testing, were mounted in a spin test pit (4-inch at Toray and 15-inch system at Barbour Stockwell in Boston) for alignment, balancing and spin testing to 80% of full operating speed or to the operational limits of the spin pits. The test sequences were terminated prior to achieving 80% operating speed (16k RPM) due to test fixture problems and/or alignment-driven vibration exceeding pre-determined limits. However, the systems reached sufficiently high speeds to permit validation of most aspects of system design and operation. The 4-inch system achieved a speed of 12k RPM at Toray before the amplitude of vibration shut down the spin tester and the 15-inch system achieved 14k RPM when sub-synchronous vibration and a failure of the test interface caused excessive vibration that destroyed the air turbine damper bushing and O-ring. (Quarter 6)

Additional analysis of the spoked-hub design showed higher then expected stresses in the upper and lower hub details. Bolts were added to the design in an effort to strengthen the hub. Analysis indicated that the hub details would still yield at about 16,000 rpm, and the rotor speed was thus limited and would not make it to the 20,000 rpm upper speed limit. The structures team decided to continue with the assembly of the rotor as designed in order to begin collecting spin test data. The analysis done to date indicates the spokes and ring grow at the same rate up to about 16,000 rpm; however, they begin to separate at about 16,000 rpm. (Quarter 8)

At this time in the program, the team decided to assemble and test the 4–inch-tall rotor before assembly of the full-size rotor was attempted. This would give the team a chance to identify and correct any problems during the assembly process and provide data on the performance of the various rotor components during operation. (Quarter 9)

After assembly of the 4–inch-tall rotor, the rotor was balanced using a horizontal 2-plane method. This method of balancing is usually not recommended for this type of rotor, however, the team believed some useful data could be acquired from the shorter rotor, and, thus, this method was attempted. This balancing method was not attempted on the larger rotor; instead, an alternative method was utilized. (Quarter 9)

Spin testing of the 4–inch-tall rotor was conducted at Toray Composites of America in Tacoma, WA. Several low-speed tests were run to verify the rotor balance, as well as verify operation of the data-collection and spectrum-analyzer hardware and software. After verifying that all systems were operational, several attempts were made to bring the rotor up to a target speed of 16,000 RPM. However, due to instability of the rotor, the target speed was not achieved. The maximum speed reached for all runs was 11,200 RPM. (Quarter 9)

The structures team worked to design the 100-kW, 5-kWh, flywheel system. Several significant changes were made to the design based on lessons learned during the fabrication and assembly of the 10-kWh system. Finite element analysis and dynamic analysis tools were used to refine the new system design. The most significant change to the system design was the elimination of the spoked-hub concept. The flywheel team decided a solid metal hub was the preferred concept for the 100-kW flywheel system. One significant challenge for the design team was the ability to design a hub and ring interface that would remain in contact throughout the operating range of the rotor. With expertise from Toray, the team developed a concept for a 3-ring, press-fit, rim. This design had the ability to limit the growth of the ring, unlike the continuous wound ring used for the 10-kWh system (Quarter 14)

Two Finite Element Modeling (FEM) codes were used by the team to predict dynamic behavior. One was NASTRAN, which can model arbitrary complex systems of masses and forces in great detail. This was used for the 10-kWh spoke system, which was not axisymmetric. The second code, the spreadsheet-based XLRotor, was used for a series of fast-turnaround design changes to find a solution. XLRotor models rotors as cylindrical beam elements, with lumped stiffnesses for bearings and motors, and can predict mode shapes and amplitudes for sinusoidal excitations. The predicted bending mode speed of the new rotor was now above 30,000 rpm in the XLRotor model. XLRotor and NASTRAN have correlated very well with each other and with experiments. (Quarter 15)

Toray Composites of America in Tacoma, Washington fabricated the 5-kWh flywheel rotor rim. The rim had three parts, an inner ring of glass fiber/epoxy composite and two outer rings of carbon fiber/epoxy composite. The inner rings have been fabricated without difficulty. The outer rings have been slightly more problematic, with wrinkling appearing through about 2/3 the thickness of the rings. In an attempt to overcome this problem, an insulating shroud was being adapted to the winding machine. (Quarter 16).

In addition, the team embarked on designing the 10-kWh rotor, based on an assumed spin speed of 20k RPM. The ground rules for the design of the 10-kWh system are listed as the following: (Quarter 18)

1) Modify existing 5-kWh system;
2) Press fit an additional rim, or rims, to the existing hub rotor assembly;
3) Spin Speed = 20k RPM;
4) Address axial & inter-laminar shear stress issues.

Close attention to item 4 listed above has led the team to believe that an alternate hub design should be considered. The existing hub was shrunk fit to the composite rotor assembly. The difference in axial heights of the hub and rotor, coupled with the interference fit could result in problematic axial and shear stresses in the composite rotor. Alternate hub materials and geometry were studied to counteract design shortcomings. (Quarter 18)

In June 2005, Toray Composites (America)'s Composites Development Center (CDC), decided to exit the business of manufacturing thick composite flywheel rims. After this, Boeing had to find a replacement manufacturer, and the team decided to subcontract with Alliant Techsystems (ATK) located in Salt Lake City, Utah. Toray used their unique proprietary in-situ filament-winding process, using heat and specialized resin. In this process, the resin cure advances while the part is being wound. This partially cured material provides a semi-rigid substrate to wind subsequent layers. Using this method has the added benefit of preventing the substrate layers from micro-buckling as additional layers are added.

This process was particularly suitable for rapid and low-cost manufacturing of composite rotors. Other manufacturers have developed a stage-winding process that uses tow-preg material. In this process, layers are wound in stages. After winding each stage (of approximately 0.25” thick), the composite is cured in an autoclave. The process is continued until the required rim thickness is achieved. In between stages, the surface is sanded down lightly to provide suitable surface for the subsequent winding. This process is more time consuming and is commercially not as cost competitive as Toray’s in-situ process in a production environment. (Quarter 30)

At ATK, after the composite was cured and extracted from the mandrel, the composite rim was inspected. There were a few wrinkles running mostly from the ID to the OD surfaces. The wrinkles seem to be associated with ply (fiber) buckle in the axial-circumferential plane. It was not clear if the wrinkle was associated with the scrap region only (which is about 1” long). It was decided to machine 1” off one face to examine the surface. For the most part, the rim surface looked good and acceptable. There was one wrinkle that was still visible on the machined surface. It should be noted, that because of the certain fiber stress direction in a spinning rotor, wrinkles in the axial-circumferential (hoop) plane are not as detrimental as wrinkles in the axial-radial plane. Nevertheless, it was decided to try to improve on the process to eliminate any forms of wrinkles. (Quarter 30)

Using the process described above, the first rim was fabricated at ATK and extracted off the mandrel. In general, the winding went very well and the process executed according to plan. Once the ends were removed and examined, it was noted that the rim was cracked at about mid-thickness. The crack (delamination) ran around the circumference and through the entire length of the rim and was noted on both ends. Based on these observations, it was concluded that the rim most likely cracked during the post-cure operation and possibly even during the stage winding. A distinct difference between the first trial wind and the second winding of the 4th rim is that the second process used heat to stage the resin. This differential temperature most likely caused residual stresses to build in the rim. These residual stresses, in combination with the weak material radial strength, lead to cracking of the rim. The effort with ATK was terminated. (Quarter 32)

Rotor Lessons Learned

- Spoke-hub design, although desired from a weight and cost standpoint, proved to be too risky for an initial flywheel design.
- The rotor rim/hub interface design is one of the most challenging aspects of high speed composite flywheel design.
- Metal hub designs work well up to medium energy density flywheel design. To achieve very high energy density flywheel designs, composite hubs will need to be employed, as the tip speed of the metal hubs would exceed the strength of metal hubs.
- The first rotors required additional dynamic and stress analysis to analyze the instabilities found during spin testing.
- NASTRAN FEM worked well to model arbitrary complex systems of masses and forces.

- XLRotor modeling software worked well to model cylindrical beam elements, with lumped stiffnesses for bearings and motors, and can predict mode shapes and amplitudes for sinusoidal excitations.
- Toray had a unique in-situ filament winding process in which the resin is advanced using heat and specialized resin to thus prevent the substrate layers from micro-buckling as additional layers are added. Other venders did not have this technique mastered and was an expensive lesson to learn.
- Need method for repair of composite structures during low level failures.
- Need leveling method for rotor during chill down phase of testing.

High Temperature Superconducting Bearing and Cryogenics

YBCO Process

Work focused on improving the superconducting properties of Boeing's YBCO fabrication process and to develop scale-up process for manufacturing the bulk crystals in larger quantities in order to reduce production cost, while maintaining uniform properties of the resulting bulk materials. The process as developed through the early part of 1999 required Boeing to carry out the powder mixing to obtain the desired compositions of Y123, Y211, and Pt. Boeing also performed jet milling of the mix to reduce particle size and homogenize the mixture. The results were excellent in terms of current density and physical aspects of crystal growth, including low distortion and weight loss. The physical labor involved in this process was considerable; however, so later batches of powder were premixed by PraxAir Specialty Ceramics (PSC). (Quarter 2)

Several batches of powder were received from PSC and processed at Boeing. Consistency within and between batches was explored through several avenues - both at Boeing and at PSC. Methods used included XRD, BET, particle-size analysis, carbon analysis, DTA, and ICP. The most significant changes seen in the DTA data were apparent shifts in the temperature for resolidification from the melt. A systematic thermocouple probing of the Boeing furnaces showed that the vertical temperature gradients are approximately three times higher than desired. (Quarter 2)

A study of the effect of Rare Earth (RE) oxide addition on the crystal growth behavior and superconducting properties of $YBa_2Cu_3O_{7-x}$ (Y123) was completed. The results showed that even a small amount (<1 mol %) of RE-oxide addition affects the nucleation and growth kinetics of seeded Y123 crystals. In order to improve the flux pinning capacity of Y123 single crystals, the samples were doped with Nd, Sm, Gd, Er, and Yb oxides. Magnetization measurements on RE-doped Y123 single crystals revealed very high current density (J_c) values as compared to undoped Y123 single crystals. This was especially true at high magnetic fields. For example, small additions of Sm and Er increased Jc to 20,000 A/cm^2 at fields near 2 Tesla. (Quarter 2)

One important observation made during this study was that the precursor powder distribution within a storage container was changing during the handling of the container while preparing samples. The precursor powder was prepared in large batches to ensure uniformity and was then stored in 1-kg containers. The melting and solidification temperature of the powder taken from the top of the container was found to be significantly lower than powder from the bottom of the container. It was determined that the 211 phase with slightly larger particle size settled to the bottom of the container as the container was being handled. The higher 211 distribution in the bottom of the container resulted in a higher melting and solidification temperature that consequently reduced the crystal growth yield, due to required higher processing temperature. (Quarter 3)

Substitutional and secondary phase dopants were added to YBCO powders to improve the critical-current density and ultimately the magnetic flux-trapping properties of the bulk single crystals. The addition of dopants, whether substitutional or as a secondary phase, created very fine distributions of sub-micron non/weak superconducting sites. Limiting factors to the dopant quantity were primarily new phase kinetics that can disrupt the growth of the single crystals, and the formation of overlapping non/weak superconducting sites that ultimately result in a non/weak superconducting crystal. (Quarter 12)

Neodymium and praseodymium oxides were explored as substitutional dopants, which could substitute both on the yttrium and barium sites. Substitution into the barium sites may effectively create very small weak/non-superconducting unit cells, which may act as flux pinning sites much closer to the coherence length of these materials. Furthermore, Pr123 forms a non-superconducting cuprate assumed to arise from the magnetic properties of praseodymium disrupting the charge reservoirs on the basal planes. Low-level substitution of praseodymium into either yttrium or barium sites may more effectively disrupt superconductivity in very small local regions. (Quarter 12)

Secondary phase particles of barium cerate and barium zirconate were added to create a very fine distribution of non-superconducting particles throughout the matrix. The secondary phase particle addition gave the added benefit of increasing the capillary forces of the liquid, thus resulting in less liquid loss and setter (substrate) contamination. Furthermore, studies have shown that both ceria and barium zirconate additions can yield very small, ~0.1-1 μm inclusions, however, there has been a great deal of difficulty in achieving homogeneous dispersions of the dopant throughout the crystal due to particle-pushing effects. Early studies on ceria additions focused on the replacement of platinum, which is typically added to the precursor powder to suppress the grain growth of the non-superconducting Y211 green phase during the crystal growing process. It has been shown that CeO_2 can improve magnetic flux-trapping properties, however, there has been no suggested optimum quantity that could be utilized for commercial crystal growth processes. (Quarter 12)

While research indicated that the overall Y211 content can affect the flux-pinning characteristics of YBCO materials, no studies have confirmed this behavior on melt-textured crystals. Prior to dopant additions, YBCO crystals were grown with 10, 20, 30, 40, 50, and 60 mol % excess Y211 to establish the ideal properties of the Boeing reference crystals. (Quarter 12)

The trapped field drops dramatically when increased past 40 mol % Y211. This can be explained by the overall decrease in the superconducting volume fraction of the sample. Given the dramatic drop after 40 mol %, optimal additions for melt texturing should lie to the left of the curve maximum at ~30 mol %. Cerium oxide powders were added to improve J_c by creating a fine dispersion of non-superconducting inclusions within the Y123 matrix. Trapped field measurements indicated an approximate 25% increase in trapped field due to 0.3 wt % ceria additions. (Quarter 12)

Preliminary studies on neodymium-doped Y123 proved unsuccessful in quantities ranging from 2 – 5 mol%. This difficulty was linked to formation of Nd123, which has a melting point approximately 65 degrees higher than Y123. As the Y123 cools, the Nd123 clusters solidify and act as nucleation sites (seeds) for single-crystal growth. The resulting YBCO crystal was then composed of approximately 1 mm^2, randomly oriented single crystals. For the neodymium-doped system, the process is limited by the solubility limit of neodymium in Y123, which appears to be in the range of 1 mol %. Bulk 2.5-cm-diameter single crystals have been grown successfully with 0.1 mol % neodymium oxide. (Quarter 12)

The yield from the processing of the bulk crystals has improved to the point that about 75% of the crystals manufactured are of sufficient quality and uniformity to be used in flywheel stability bearing. This can be attributed generally to raw powder material improvements, and to the development of more stringent growth profiles. The trapped fields are also generally more uniform and consistent. (Quarter 16)

Cryogenics

A pumped liquid nitrogen (LN_2) cryogenic loop system has the advantage of simplicity and was relatively well characterized for the performance of the HTS bearings. However, the cost of a liquid-nitrogen circulating pump is on the order of $20,000 for a single unit. This cost was determined to be prohibitive. A passive thermosyphon loop does not require any active mechanical components, but has greater uncertainty in the heat transfer at the HTS crystals due to heat input to the top of a boiling stream. While there was greater technical risk for the loop thermosyphon, it had the potential to be a much less expensive solution in the long term. Therefore, this option was selected for further development. (Quarter 2)

The thermosyphon was gravity fed, relying on the liquid head to drive the nitrogen through the loop. The cold head was located higher than the HTS bearings and outside of the containment vessel. The cold head condensed nitrogen, which was collected in a small LN_2 reservoir beneath the cold head. Two lines connected the LN_2 reservoir to the cryostat. One line carried LN_2 from the bottom of the reservoir to the cryostat. The other line returned the gas/liquid nitrogen mixture from the cryostat to the reservoir, where it was recondensed by the cryocooler. (Quarter 2)

Sealing problems were encountered with the original G-10 cryostat for the HTS crystals and were resolved. The cryostat had large sealing areas on the inner and outer diameters that had leaked, in spite of numerous incremental strategies taken to “quickly” solve the problem. The difficulties in identifying the leaks were made much worse by their tendency to only appear when the cryostat was fully chilled and in the vacuum chamber. Ultimately, a more systematic effort identified the problem areas, and the original sealing surfaces were machined off (with the crystals still installed). New sealing rings with threaded joints were made and applied with a carefully prepared adhesive. (Quarter 8).

Based on results in the first phase of the FESS project, Mesoscopic Devices redesigned the cold head in Phase 2 to address manufacturing difficulties. The primary difficulty the team had was related to sealing the system. The solution to this set of problems was to make the final joint in the cold head a bolted joint to ease modifications to the cold head for testing, and to switch to a high-temperature braze for all dissimilar metal joints. These techniques were successfully demonstrated on their MD-200 development under an SBIR program sponsored by NASA and were adapted to this cold head. (Quarter 9)

Mesoscopic Devices measured the cooling power for four cases of varying input power with the cold end of the cryocooler near room temperature. The cooling power under these conditions is approximately equal to the "gross cooling power" – i.e. the total refrigeration power of the cryocooler. The useful or net cooling power is the gross cooling minus internal losses. When the cold and warm ends of the cryocooler are at the same temperature, these internal losses are negligible with respect to the gross cooling power. Mesoscopic Devices used the computer software DeltaE to model the cases and estimated the acoustic power at the cold end of the cryocooler. These tests indicated the problem was excessive internal losses rather than insufficient gross cooling capacity. (Quarter 10).

The preliminary conclusion was that the single largest source of poor performance was poor utilization of the regenerator due to non-uniform feeding of the regenerator at the cold end. The cold tip in the configuration at that time was a slotted copper block. A previous test with a foam cold heat exchanger indicated better performance. The previous cold head was not fully tested due to a leak that developed internally during the initial testing. The change to a slotted copper block was based on good performance observed on a similar configuration for a 200-W cryocooler. However, test results indicated that this slotted configuration did not scale well to the 600-W size (Quarter 10).

Next, Mesoscopic Devices completed fabrication of a new cold head. This cold head used copper foam for the cold heat exchanger. The copper foam was used in the first cold head built, but was replaced in the second generation with a copper screen stack/slotted copper block design. Analysis of the results of testing with the second cold head suggested that flow maldistribution from the cold heat exchanger to the regenerator was probably the reason that Mesoscopic Devices was not able to meet their cooling capacity predictions. (Quarter 12)

Due to a change by the supplier of the copper foam, previous techniques for fabricating the cold heat exchanger did not produce the desired results. Mesoscopic Devices developed another technique that allowed them to machine the copper foam into the desired shape, including a tapered region that distributes the flow from the cold end of the pulse tube to the cold end of the regenerator, a significant flow area change. They developed a technique for brazing the copper foam to the solid copper cold tip. This technique provided minimal thermal resistance between the helium at the cold end and the exterior surface of the cold tip, where the condensing fins were to be attached. (Quarter 12).

A final change incorporated in this cold head was a two-piece pulse tube. This was an outer, thin-walled sleeve made of stainless steel, and an inner tapered pulse tube insert made of G-10. The stainless-steel sleeve had the regenerator screens outside of it. The sleeve was to remain in place while the inserts were interchanged, allowing the team to test several different pulse-tube taper angles without changing the regenerator. Preliminary shakedown tests on the cryocooler indicated a problem with pressure instrumentation. The pressure sensors indicated a higher pressure amplitude at the intertance tube to warm heat exchanger interface than at the compressor. This was counter to all expected behaviors. The Mesoscopic Devices Team did not complete the pulse-tube system. (Quarter 12)

The team experienced occasional instabilities in operation of the thermosyphon loop. A heater had been placed on the exhaust line to force flow in the proper direction, but the Seattle test team did not have experience in optimizing loop operation. Christine Martin of Mesoscopic Devices, which built the loop at their facility, came to Boeing on December 18-19, 2001 to help characterize the system. Two sets of tests were run. The first set of tests measured the pressure drop through the cryostat and the bypass line to be used in the thermosyphon testing. The second set of tests observed the behavior of the thermosyphon when operating with a dummy test load. (Quarter 11)

The team measured the pressure drop through the cryostat with a simple configuration. Pressurized, room-temperature nitrogen gas was flowed through the cryostat. The flow rate was measured with a rotameter at the inlet. The nitrogen exhausted to ambient at the cryostat outlet, so a pressure gauge upstream of the cryostat gave a measurement of the pressure drop through the cryostat. There was approximately 15 inches of ¼-inch-diameter tubing between the pressure gauge and the cryostat. (Quarter 11)

Using the same test configuration, the team measured the pressure drop through the bypass line that would subsequently be used for testing the thermosyphon. The bypass line had a 0.110” orifice installed to approximate the pressure drop through the cryostat. These results indicated that the pressure drop of the bypass should be comparable to that of the cryostat during thermosyphon testing. The Mesoscopic Devices team was replaced by Praxair Cryogenics Company. (Quarter 11)

The cryogenics design for the 100-kW, 5-kWh FESS were redesigned and consisted of a stainless-steel cryostat which contained the YBCO crystals, mounted on a G10 composite isolation ring, fed by a liquid-nitrogen reservoir via stainless-steel transfer tubes, driven by a thermosyphon loop, and chilled to cryogenic temperatures in a “closed loop” by a Gifford McMahon 60-Watt cryocooler and air-cooled compressor. (Quarter 15)

The thermosyphon loop for the 100-kW FESS was designed by Praxair and was connected to the vacuum vessel via a 6” conflat flange. The cryocooler that was used was a modified

Cryomech AL60 cold head in combination with a Cryomech CP415 air-cooled compressor. (Quarter 15)

During Quarter 23 of the project, the HTS bearing closed-loop cryogenic sub system for the 5-kWh FESS was successfully completed, and full system integration and functional testing were accomplished. The cryogenic system-level test consisted of the full integration and functional test of the Boeing cryostat; the 60-Watt Cryomech cold head and compressor; the Praxair thermosyphon and controller; and the Lakeshore controller and sensors. The flywheel chamber was under a normal operating vacuum (approx. 5.0 E-5 Torr) during the integration and functional tests. The liquid-nitrogen system was operated successfully in a closed-loop configuration and performed nominally within the range 77 K and 70 K. In addition, the closed-loop cryogenic system operated nominally over an extended period of time. (Quarter 23)

HTS Bearing System

It is well known that the restoring force due to the relative motion of a permanent magnet and a superconductor is approximately proportional to the gradient of the external field. A 2-D magnetic model running on Vector Fields software was used in a design of a permanent magnet to increase the total field gradient at the surface of the HTSs. Peaks in the field correspond with the position of the steel poles in the magnet assembly, which concentrate and direct magnetic flux. The magnetic code can also calculate field derivatives, take the absolute values and finally integrate the rectified curve to come up with the total gradient over the superconductor area. These integrated values were roughly proportional to the total currents which would flow in the superconductor. This approach missed the importance of the field magnitude (the B in $F = J \times B$) but offered a rapid means of examining the influence of changing the magnet geometry. (Quarter 3)

The stability bearing consisted of a rotating permanent magnet assembly and the fixed superconductors in a non-conductive cryostat in the flywheel's vacuum chamber. The bearing rotor included a 3"-dia. steel shaft, a composite transition piece, and a confinement hoop for the magnets. (Quarter 7)

Axial stiffness of the HTS bearing can be estimated even with the rotor at rest and suspended over the chilled superconductors. The test system was constructed to allow the rotor to be held in vacuum above the cryostat while the cryostat is chilled; and after the HTSs are sufficiently chilled, the rotor is released. It drops under its own weight until repulsive forces maintain its position. The amount of drop and knowledge of the rotor mass then give an axial stiffness. (Quarter 7)

The HTS bearing was spun and the rigid-body resonant frequency, corresponding to the radial vibration mode, was measured as the peak of radial vibration amplitude versus frequency. The observed modes corresponded well with rotordynamic predictions made by the Boeing Propulsion group and were closer to the curves generated with high-stiffness assumptions. From the critical speeds, the team calculated a value of radial stiffness, $K_r = 69$

N/mm. This was very close to 0.5 x K_a (where axial stiffness, K_a = 144 N/mm) which was the prediction given by John Hull (then at Argonne National Laboratory) based on his extension of Earnshaw’s Theorem. These measurements of the HTS bearing stiffnesses were thus a substantial accomplishment of the design/build/test program. (Quarter 7)

The HTS bearing, consisting of the HTS crystal array, cryostat, and rotating magnet assembly, was spun to 15,000 rpm at the end of July 2001. These runs proved the stiffness of the bearing to be more than sufficient for the flywheel. The team extrapolated from the 2.0 W of direct bearing loss at 12,000 rpm (before refrigeration or parasitic losses) to predict a full-speed (20,000 rpm) loss of 4.8 W. The loss showed significant speed dependence, usually a sign of eddy-current loss rather than AC loss in the superconductors. The AC loss contribution may have been as low as 0.67 W, an important distinction, since eddy-current losses will not usually require refrigeration overhead. Measurements of the temperature dependence were the clearest way to separate these loss mechanisms, and were also important for determining an optimum HTS temperature. (Quarter 11)

Bearing test runs took the bearing to speeds of 15,000 rpm at temperatures of 66, 71, and 77 K. These measurements were done with a fixed gap (magnet to cryostat) of 4 mm, which is the expected operating gap for the flywheel. (Quarter 11)

The HTS bearing performance improved dramatically since the April - July 2002 runs. The lower temperature, and also improved setup procedures, are believed to be responsible. For possibly the first time anywhere, we showed that a lower temperature does reduce the spin-down rate as would be expected for AC losses. This was seen by comparing the 71 K and 77 K runs on 1/17/02 and 1/18/02. The zero-speed spin-down rate decreased from 1.9 rpm/min (77 K) to 1.25 rpm/min (71 K) and (in a separate run) to 0.9 rpm/min (66 K). AC losses therefore dropped by approximately a factor of two. (Quarter 11)

The Stability Magnet Assembly (SMA) was successfully spin tested up to 105% of the maximum expected operating speed during this reporting period. The SMA was the last of the individual components requiring full-speed spin-qualification testing prior to full-system integration. (Quarter 23)

At 1000 RPM, the synchronous (1/revolution) vibration was nominal on both sensors (<. 001” Peak-Peak and the SMA rotor was accelerated to the maximum safe speed for the open-air operation of 2500 RPM for balance checks. The unbalance checks without correction on this assembly were initially measured at ~ 1oz-in. The bode plot and the spectral profile revealed a sub-synchronous vibration at ~ 10 Hz that stayed constant in amplitude and frequency over the speed range. This phenomenon is not unexpected and analysis indicated it would diminish at higher speeds. This sub-synchronous vibration was also observed and predicted from analysis performed prior to high-speed spin testing. (Quarter 23)

Analysis of rotor vibration at high speed indicated that there could be some significant critical frequencies the SMA would have to run through. The worse amplitudes anticipated by analysis were located at the quill, and a two-step balancing sequence of the SMA was performed to minimize the amplitudes during spin testing. (Quarter 23)

Modeling of the air turbine used for spin-testing individual flywheel components prior to full system assembly was performed using a dynamics software package (XLRotor). This model was based on the manufacturer's turbine data and was combined with the geometry and material properties of the SMA. The upper section of the model geometry includes the weights and moments of the turbine while the horizontal lines represent the turbines bearing and damper system (which can significantly impact the rotor dynamics during spin test). (Quarter 23)

High Temperature Superconducting Bearing and Cryogenics Lessons Learned

- Cerium oxide additions not only provide improvements in the magnetic flux pinning, but also yield lower liquid losses and shape deformation of the melt textured crystals.
- Neodymium oxide has shown to improve the flux pinning in very low quantities, below the solubility limit of Nd_2O_3 in YBCO.
- The HTS bearing operated stably and consistently, and its performance can be predicted from analytical and computer models.
- 2D magnetic modeling codes are not accurate enough to predict correct bearing characteristics in a flywheel system.
- Eddy current losses are the dominating loss for Boeing bearing – not a cryogenic load.
- To reduce hysteretic AC losses requires higher J_c superconductor.
- High J_c is required for increased damping.
- For good HTS materials, stiffness is a weak function of J_c.
- Hysteresis loss is a strong function of amplitude and J_c.
- Large YBCO crystals are desired – less Eddy current loss in magnet rotor, less AC loss in stator results in reduced refrigeration load.
- HTS bearing may not have adequate damping for certain flywheel.
- HTS damping decreases with decreasing operating temperature.
- Need to develop methods to improve the rate of superconductor crystal shaping .
- Thermosyphon is not the best method to use for flywheel cooling due to higher losses and complex set-up.
- Cryostat design was improved by using stainless steel system that was sealed on a first try, and is able to be opened-up, if needed, to inspect or replace HTS crystals.
- HTS bulk crystals proved to be very reliable and resilient, not degrading at all over the many years of the project.

Lift Magnet Assembly

In the Boeing design, the majority of the flywheel's weight was supported by a three-ring lift magnet assembly (LMA). The lift magnets and their supporting structures were located above the center hub in the system layout. The center ring, which was attached to and rotated with the rim, was attracted to a fixed upper ring and repelled from a fixed lower ring. (Quarter 3)

The total lift force of this initial design was approximately 295 lb. in the centered position. The flywheel weighed approximately 330 lb., so that the remaining weight was supported by the superconducting bearing. This combination provided net stability in all axes and largely eliminated the flux creep problems that can limit designs supported by HTS levitation only. Two-ring designs had also been considered, due to the much simpler assembly sequence. However, finite element models showed very large instabilities for such designs. Following consultation with John Hull (then at Argonne National Laboratory - Boeing's CRADA partner) a three-ring approach was pursued. (Quarter 3)

The chosen design for the LMA provided a small amount of radial stability but was weakly unstable in the axial direction. This force variation was analyzed with the help of Larry Turner, also at ANL. The slope of the line near the zero crossing is nearly constant and amounts to less than 10 N/mm of "negative stiffness." This was easily overcome by the positive stiffness (restoring force) due to the HTS bearing. (Quarter 3)

The lift magnet assembly was tested in an Instron tensile test machine to determine the axial force characteristics. During normal operation of the flywheel system, the center magnet ring will rotate as part of the flywheel, while the upper and lower magnet rings are fixed with respect to the chamber. The design of the lift system, done in collaboration with Argonne National Lab, arrived at a system of rings predicted to have about 292 pounds of axial force and a negative axial stiffness of 15 N/mm. Rings were inverted from normal position in the flywheel, so that the center lift magnet would pull down on the load cell. Forces were measured as a function of the position of the center magnet and also with various gap settings of the fixed rings. It was determined that this lift system as fabricated produced a force of 325 pounds with the nominal design gaps, and had a negative axial stiffness of about 27 N/mm. With an increased gap between the center and lower magnets the force could easily be reduced to 300 pounds or less, and the negative stiffness decreased to 15 N/mm. This design thus met the force and stiffness targets established originally. (Quarter 8)

A test was completed to check for the possibility of a creep-induced failure in a thermoplastic used to support the rotor. The rotating lift magnet required a non-conductive transition piece to attach the magnet ring to the shaft. Nylon was used in the first design and a spin test was carried out the preceding summer to verify its performance. The part failed at a speed lower than was expected based on the strength and modulus of the material, so an alternate material had to be evaluated. (Quarter 12)

The replacement transition ring was made of a more stable material - Ertalyte. A test for load-carrying ability under sustained load was carried out with a structure nearly identical to that which will be present in the 10-kWh flywheel. The Ertalyte ring had steps on the inner and outer diameters to accept features on the shaft and magnets. (Quarter 12)

A recalculation of forces in the three-ring magnetic circuit was completed to account for a material change in the housings. The housings were intended to be made of stainless steel, but a shop miscommunication resulted in substitution of mild steel, which affects the interaction of the nearby magnet rings. A calculation using the Vector Fields electromagnetic design code showed the axial lift force would have changed from about 380 lb. to nearly 480 lb., potentially overwhelming the HTS stability magnet. (Quarter 12)

A simple solution was found that substituted the upper lift magnet, originally 0.75" tall, with a spare copy of the lower lift magnet at 0.50" tall. This brought the axial force close to the target value. Fine-tuning of the lift with a mild-steel shim ring brought the lift force back to the original 380 lb. (Quarter 12)

With the previous 10-kWh flywheel system, the team learned that the radial and axial adjustment of the lift magnet stage was crucial, because the lift and lateral forces were greatly affected even over small displacements. Typical magnet tolerances of 4 – 6% must be compensated for by shimming and mechanical adjustments. The axial forces the team predicted well using 2D magnetic analysis codes, but there are also radial stiffnesses that were estimated by more indirect methods. New 3D modeling tools from Vector Fields were acquired and were applied to study many such effects, and to more accurately estimate magnetic stiffnesses for the motor and lift magnet interactions. (Quarter 25)

The 2-D model previously predicted a stable operating point for the lift magnet assembly when the center (rotating) magnet was about 0.040" above the midpoint between the non-rotating magnets. At the midpoint position, the lift force passed through a minimum value; above it, the radial stability improved. The 3D model confirmed that the system would remain stable in this position even when tilt stiffness were included. (Quarter 25)

To compare the lift magnet assembly properties with the predicted model of the lift magnet assembly, a hydraulic jack, two specialized fixtures, and a load cell were used to measure the vertical force within the lift magnet assembly as a function of distance from the HTS cryostat. The data indicated the position was on the correct side of the curve for radial stability near the optimal location. The data also indicated the upper lift magnet would provide additional radial stiffness. One discrepancy from the model was the amount of lift provided. The whole flywheel lift assembly was shimmed properly to account for the latest modeling data, and this change itself resulted in a much better radial and axial stability of the flywheel system. (Quarter 25)

Lift Magnet Assembly Lessons Learned

- The LMA reduces the amount of superconductor required for stable operation. There is sufficient variation in magnet manufacture that it is difficult to calculate precisely the actual force generated with such systems. Thus, the design must allow for adjustment of magnet positions to achieve the desired forces in this component.
- The SMA, LMA and hub design for the 10-kWh system were all speed limited. This was a result of inadequate opportunity to iterate the design due to limited analysis

resources. The situation was improved but not alleviated for the 5-kWh design. It is imperative that the analyses and design cycle are linked closely together.

- Need to have a better position sensor system to directly measure magnet gaps in the SMA and LMA assembly.
- Would be helpful to color-code the lift magnets for easy identification and proper orientation of the magnetic poles.
- Need more non-magnetic tools and fixtures.

Containment and Vacuum Chamber

The containment design concept was essentially the same as used for the prototype 2-kWh system. The FESS containment vessel was redesigned to incorporate enhancements identified through analysis of the containment design using the 10-kWh requirements.

The first change to the original design was to attach the upper and lower lids separately to the container wall, rather then to each other. A further change was to use thicker material in the energy absorbing blades. The overall height of the blades in relation to the rotor was increased as well (approximately 2:1 ratio with the rotor). (Quarter 2)

A subscale test of Boeing's S-bracket containment concept was successfully completed. A 1-kWh rotor was taken to a speed of 36,000 rpm, at which point it exploded and flattened the brackets. The degree of flattening agreed with analytical modeling of the container. (Quarter 13)

Post-test analysis of the burst data revealed good correlation with predicted values. An FEA analysis comparing predicted performance to actual was completed. (Quarter 14).

Containment and Vacuum Chamber Lessons Learned

- The S-bracket containment system is a robust design, whose performance can be calculated. The large surface area of the brackets produces a large virtual-leak for the vacuum pumps, which is acceptable for a laboratory system. However, for a commercial system, encasing the brackets with a covering surface would allow smaller pumping systems and lower overhead energy costs.
- For a commercial flywheel system, need to have a passive getter system to eliminate active pumping.

Motor Controller and Power Electronics

A slotless stator design was selected for detailed design for the FESS. The major components of the flywheel motor-generator (M/G) system include a permanent magnet

(PM) assembly on the rotor, a copper-coil stator surrounded by a laminated backiron, a 10-kW IGBT power module, and a DSP-based digital controller. The control software was developed for this system and down loaded into the controller hardware. The function of the IGBT power module was to convert 350-400 DC voltage to a series of variable-frequency AC voltages, according to the command from the digital controller.

A test-stand was developed for determining the operating characteristics of the M/G. In this test stand, two (2) identical PM machines were mechanically coupled, back-to-back, one functioning as a motor and the other as a generator. Speed of the M/G unit was directly controlled by the frequency of the AC voltage from the power module. Since these machines are of 4-pole design, 500 Hz AC voltage corresponds to the motor speed of 15,000 rpm. (Quarter 6)

The control algorithm that was developed and used in this system is a rotor-position sensorless control, which operates the system without a rotor position encoder or resolver. Consequently, the system was planned to be more mechanically reliable and robust and cost effective, as compared to the system that uses a mechanical sensor to continuously monitor rotor position and speed. (Quarter 6)

The flywheel 3-kW PM M/G controller system was tested. The tests included controller functionality, PM machine back-EMF, resistance and inductance parameters, loss components, and loaded operation at a speed range from 300-24,000 rpm. The load test was conducted up to 3 kW. The performance of the M/G controller system was in good agreement with specification requirements. The armature reaction of the PM machine was found to be stronger than conventionally designed PM machines, which indicated that 15% adjustment of winding turn number would be needed only to meet overload requirements. (Quarter 6)

The 10-kW motor and controller was installed on the 1-kWh flywheel system. This provided the most suitable test conditions for the controller and motor in preparation for installing the motor and controller system into the 10-kWh flywheel system. During the tests on the 100-lb flywheel, it was discovered that the current-mode startup procedure was not reliable enough to consistently bring the flywheel to 2000 rpm to close the high-speed control loop. The other drawback of the current-mode startup was that it caused the motor to overheat during start up. (Quarter 12)

A new method of starting the flywheel using Hall sensors was developed and tested. This low-speed closed-loop method was used to bring the flywheel to a speed where the transition to the high-speed sensorless control loop can be made. Hall sensors were installed in both the back-to-back motor test rig and the motor installed in the flywheel system. The control software was modified to incorporate the Hall-sensor control loop. (Quarter 12)

The Utility Interface Unit that was being supplied by Ballard Power Systems was a modified version of their Ecostar Power Converter (EPC). The power system and control specification was written in close coordination with Boeing, Ballard and Ohio State University (OSU).

The overall operational scheme that the power system and control specification was derived from the FESS operational and test requirements. (Quarter 15)

OSU tested the motor controller on a DC bus before connecting it to the Utility Interface Unit. Ballard requested that a Plexiglas shield be added to the controller's frame for addition safety. Unfortunately, the Ballard technician used an arc welder on the motor controller's frame to attach a series of brackets. There was evidence of welding slag and splatter in the power modules. An attempt to clean the module was made and a test run was made. The controller did not function correctly, and it was found that power modules and power diodes were damaged. (Quarter 15)

Only one problem appeared during the Ballard integration testing. When the Ballard power inverter began switching at 600 VDC, EMI noise caused the CAN bus on the OSU control board to produce error signals and shut down. The noise was isolated and a quick fix was put in place to allow the sequencing test to be completed to the satisfaction of Ballard, OSU and Boeing. The control board was returned to OSU's lab. The noise environment was duplicated at the OSU lab. The source of the noise was identified and the problem was eliminated. This involved more shielding on the CAN bus cable and the replacement of an obsolete TI receiver chip on the control board. TI shipped the updated replacement that is more resistant to noise to the lab. (Quarter 16).

The controller was next tested in three steps. The first two steps required a laboratory DC power supply to simulate the DC bus voltages and current for the DC bus that normally would exist between the motor controller and the inverter. The third step required a variable voltage AC source to simulate the M/G on the flywheel rotor. On the first visit by the OSU design engineer for commissioning the motor controller, it became evident the laboratory DC power supply used to simulate the DC bus on the motor controller was lacking in voltage regulation during demands for high current. A decision was made that a high-power 480-VAC Variac system be used in combination with a rectifier circuit to support steps 1,2, and 3 of the commissioning effort. The Boeing Lab Operations group paid for the design effort, part procurement, and labor for the assembly/checkout of the new Variac power supply. The system consisted of a used three-phase 480-VAC 100-amp Variac, combined with a rectifier circuit and associated controls and protection/disconnects. (Quarter 24)

Due to an anticipated slight difference between the mechanical and electrical center of the stator, the exact alignment of the stator had to be determined. The tolerance to centering had to be within 10% of the free gap in the stator to rotor motor. This gap was 0.100", which made the centering tolerance 0.010". While the position of the rotor was well known in relationship to the weldment during chill and release of the rotor, the electrical center was not. The upper weldment alignment pins had to be removed to allow the entire weldment, including the stator, to be adjusted horizontally by small increments. Each time the weldment was moved, the flywheel system was spun at low RPM in order to determine the effect of the displacement. Once the optimal location was determined, the stator housing was relocated and pinned for repeatability. The alignment pins for the upper weldment were replaced at this point. Once the optimized stator alignment was achieved, the flywheel centering issue was greatly reduced, and the flywheel rotated almost within the magnetic and electric center. (Quarter 25)

Another point of interest in understanding the influence of the 100-kW motor controller is the control algorithm. It was believed that the motor controller software was providing an additional frequency during run up either by error, or due to the lack of proper software filtering. (Quarter 25)

The motor drive system ideally controls the field in the motor windings to maximize torque and minimize the orthogonal component of the field to reduce radial displacement of the rotor. During initial start-up testing at lower speeds, the combination of stator alignment errors and a poorly tuned motor resulted in the rotor being pulled to the wall or being pulled far enough off center to cause the system to become unstable. Data acquired during system testing and motor tuning showed a clear relationship between motor drive and the rotor spin axis. An increase in current spikes was shown to cause low-frequency oscillation in the rotor. It was believed that a high-density of strong current spikes could drive energy into a natural mode of the rotor. While a series of spikes can cause the rotor to oscillate, an increase in average current tends to pull the rotor spin off axis. (Quarter 26)

The 100-kW motor stator experienced excessive heating during operation. This issue limited the team's ability to increase the rotational speed of the flywheel system during integration testing past 15,000 RPM. The 100-kW motor was anticipated to operate at fairly high efficiency, with losses (heat) in the stator anticipated to be approximately 2.5 kW peak during 100-kW operation. The cooling jacket (heat exchanger) was designed to remove a minimum of 2 kW (average) of heat via closed-loop water cooling by an external chiller system. Analysis indicated that the fiberglass tape surrounding the copper wires within the stator was a probable insulating agent, preventing the heat in the copper wires from reaching the back-iron and cooling jacket. (Quarter 27)

During the system testing, the motor/controller failed to operate properly. Mr. Song Chi (OSU), arrived at Boeing to assist in troubleshooting the failure. It was determined that at least two IGBT modules were shorted. The team was informed by the manufacturer that the particular part number was out of stock and would take 12-14 weeks to manufacture and deliver. The Boeing team worked with the manufacturer to resolve the IGBT issue and significantly reduced the delivery time. (Quarter 28)

Motor Controller and Power Electronics Lessons Learned

- Motor/generators (M/Gs) and associated controllers for flywheel energy systems that use HTS bearings are NOT off-the-shelf items, and their design requires careful attention to detail.
- In addition to exhibiting low rotational loss, the M/G needs to be designed to produce low negative stiffness, both during idling and during powered modes.

- Communication protocols between the different controllers of the system need to be standardized and preferably one that is used by other commercially available equipment.
- We need to have a better control of sub-contractors, as we found out after a lengthy investigation of heat build-up in the 100 kW stator, that the sub-contractor for the M/G manufacturer didn't build the stator to specs and included too much coil insulations without documenting the fact. This prevented effective heat removal by incorporated water cooling channels.
- Ballard Power System UPS system failed when delivered.
- Need better shielding for various electrical components in the motor/controller, as the system was very sensitive to stray fields.

Diagnostics

The flywheel systems were instrumented with an optical tachometer and displacement sensors providing a physical reference for an Ono Sokki CF3400 Fast Fourier Transform (FFT) analyzer with an integrated balancing capability. For balancing the rotor, the FFT analyzer monitored the synchronous (1 per revolution) vibration and calculated a correction vector suggesting a correction weight and location following a trial weight process to calibrate the equipment. Conventional multiple-plane balancing techniques were attempted. Several spin tests were dedicated to performing dynamic balancing to minimize vibration. (Quarter 10)

Temperature of the crystals were monitored via Cernox temperature sensors (part number CX-1070-SD-4L), silicon diodes (part number DT-470-SD-12), and a Lakeshore 218 Temperature Monitor. In addition to monitoring the temperature, the magnetic field was measured with a cryogenic bare-element Gauss probe from Lakeshore (part number XMCT-1019-1), in combination with a F.W. Bell Gauss Meter. Pressure in the thermosyphon loop was monitored via a PCB Piezotronics (102A10) cryogenic pressure transducer in combination with a PCB power unit (482B06). (Quarter 15)

During preliminary testing and use during balancing, it was determined that the instrumentation package from STI would be acceptable for use in the complete system as a master diagnostic package. This sensor package was a significant upgrade from what was available at the time of the testing of the 10-kWh flywheel in November of 2002. The sensors and associated hardware had the capability for the precise measurements required during preliminary testing, and also had the specialized outputs for part of the automated control system. These measurements indicated the health of the Flywheel Rotor Assembly during high-speed operation. It had the ability to monitor and automatically control most of the flywheel components using inputs from various sensors monitoring the condition of the flywheel and its associated systems. It had both visual and signal indications for outputs, and the ability for bypass operation during testing and initial startup. It also had emergency manual stop buttons for rapid shut-downs. (Quarter 17)

The FESS system was instrumented with position and vibration sensors to provide necessary information regarding how close the rotor is to stator elements during testing. This data was displayed in real time for operational observation, and was simultaneously sampled at 2.5 Hz to trip the shutdown sequence in the event that the position or vibration places the rotor at risk of contact. The team also monitored the rotor in real time with FFT analysis of the vibration sensors. FFT can often quickly show structural changes that cannot be picked out in a time-based scope display of the data. FFT data was archived for comparison to the spectral profile at various speeds, as well as comparison between test runs. Shifts of the spectra would be good indicators of balance shifts, structural faults, or component slippage. (Quarter 24)

Careful attention to the sensors operation and physical location of the FRA were taken to assure that the actual location of the rotor was well characterized prior to testing, and therefore able to provide data warning of close proximity between rotor and stator elements. The data acquisition consisted of the following:

- 2 Vertical Position (displacement / vibration) of the Rotor Assembly
- 4 Horizontal Position (displacement / vibration) of the Rotor Assembly
- Rotational Speed of the Rotor Assembly
- Temperature Data of the Cryogenic System
- Temperature Data of the Motor / Generator System (Quarter 24)

Diagnostics Lessons Learned

- HTS bearings typically allow larger excursions from the equilibrium position than is generally found with other bearing systems. Position sensors, thus, need to have a larger dynamic range.
- Need common target materials.
- Need longer range sensors.
- Would be helpful to have more robust sensors (damage resistant).
- Improved software needed (visual indications, increased bandwidth, FFT upgrade, enhanced post-processing).
- Laboratory prototypes are typically heavily instrumented. The number of sensors required for a commercial installation would be kept to a minimum required for a safe system operation and self-diagnostics, and autonomous shut-down.
- Add more video cameras and lights inside the chamber.
- Need digital oscilloscope for capture of single frame frequency spectrum data.
- Need scheme for overnight self-monitoring (interlocked) of spin testing.
- Need better method for release of rotor from mechanical connections.

System Level Testing

During a spin test on November 6, 2002, the rotor experienced a catastrophic failure resulting in the destruction of the 10-kWh rotor and most of the related internal hardware. Post-test analysis of the spin data showed that the rotor came into contact with something, possibly the upper touch-down bearing surface, causing the rotor to start orbiting about the inner race of the touch-down surfaces. The orbit caused very high compressive loads to be applied to the rotor spokes, resulting in their eventual failure. Once the spokes failed, the rotor rim spun to rest on the vacuum containment floor. (Quarter 15)

The test on November 6th, 2002 was the third successful run of this rotor, with success being defined as operating the system without contact, fully suspended and stabilized by the Boeing passive magnetic suspension system. Earlier test runs demonstrated operation through the first critical speed, verifying non-contact operation, adequate damping, stiffness and strength of lift to safely proceed to the higher speeds required for balancing. These runs were stable, with unbalance remaining constant, and were terminated due to the safety limit of the facility configuration at the time of test. (Quarter 15)

The November 6th, 2002 test sequence was to run this system to a maximum speed of 12,000 RPM, with trim balancing as required, to verify the HTS bearing and magnetic suspension system at higher speeds. The rotor was initially balanced at low speed (440 RPM) on the lab facility's vertical air-turbine balancing system and additional trim balancing on the HTS bearing was foreseen as a requirement at higher speeds (due to the finite stiffness of the spokes). Data collected during each run was evaluated to characterize the increase in amplitude with speed. The earlier runs to 2000 RPM, coupled with displacement data and the size of the spin envelope, indicated that a doubling of the amplitude would be an acceptable point to gather data for balancing prior to spinning to higher speeds. (Quarter 15)

The composite rotor spun stably to a record (at that time) stored energy of 1 kWh (~6,000 RPM) when the vibration (dominated by unbalance) as measured at the HUB began to gradually increase. At ~ 6,200 RPM, a sudden increase in vibration caused contact with the upper backup bearing, starting an axial and radial oscillation. The air-actuated backup bearings were activated and briefly captured the rotor, reducing the vibration. Rotor inertia and severe vibrations defeated the lower bearing, allowing the oscillations to continue, driven now by collision and a subsequent increase in amplitude. The rotor rim broke free of the spokes, destroying the rotor stability magnet, instrumentation, and cameras. The rim fell to the bottom of the chamber, leaving the steel hub, upper lift assembly and motor rotor captured in the backup bearings and the hub components captured in the rim. The rim spun to rest in about 7 minutes. (Quarter 15)

Data reduction and analysis, review of the dynamic data, video log and post-mortem inspection of the hub showed that no component failure occurred. The HTS and fixed magnetic suspension system did not fail. The condition of the permanent lift magnet following the failure and the sequence of events from visual inspection and data analysis were consistent with a conclusion that the rotor lift assembly was intact at the time of failure. The vertical position data that would be expected to precipitate a suspension system failure was not present. The main vacuum vessel remained intact with several external welded penetrations broken during the event. Every vertical structural bolt on the vessel was loose except the turret bolts fastening the article to the pit floor. (Quarter 15)

Rotor/Stator - Since the flywheel system design was to be substantially modified for the 100-kW UPS system, the financial impact to the program is minimal. This rotor assembly would have been retired following a run to 8,000 - 10,000 RPM and was not a contract deliverable but a test rotor.

Motor Rotor – Survived
Motor Stator – Survived
Rotor RIM – Totally destroyed, no need to replace
Rotor Hub – Damaged, no need to replace
Rotor spokes – Totally destroyed, no need to replace
Rotor stability magnet – Totally destroyed, would have been used for run to fail, no need to replace
Rotor Lift magnet - Damaged, possibly useable for failure testing, no need to replace
Stator lift magnets - Survived
Cryostat HTS bearing - Damaged, possible 2-3 crystals useable
Cryocooler - Survived
Instrumentation - destroyed tach, 9 laser displacement sensors
(Quarter 15).

Work on a new 5-kWh, 100-kW system began, according to the original plan. After assembly of the system was complete, the team initiated low-speed full-system testing. During the initial low-speed testing of the completed flywheel rotor, data indicated a possible problem with one of the sets of the touchdown bearing assemblies. It was discovered that several of the ceramic ball bearings were not spinning freely. Analysis revealed the stepper motors, while operating in the maximum-current mode, placed an excessive load on the inner bearing races. Changes to the configuration of the stepper motors limited the maximum current available during operation. New bearing replacements were ordered and received. These ceramic bearings were lubricated with Aerospace Lubricant Tribolube-47. (Quarter 23)

In addition, the team investigated incorporation of an o-ring damper system within the touchdown bearing system. This addition would assist in damping the shock of the rotor impacting the touchdown bearing system during radial displacement. The system proposed could be implemented with slight modifications to existing components. No new parts were required except for o-ring material. (Quarter 23)

In May of 2005, the DOE/ Boeing 5-kWh, 100-kW rotor assembly was moved off the center line by 0.050”, resulting in contact with the touchdown bearing surfaces (or hard excursion surfaces) during release from the mechanical constraints or during the first application of motor stator current. It was determined that only a limited number of items could be creating this problem. The Boeing Team by process of data collection, analysis and elimination; resolved this hard-contact displacement problem. However, at that time there was then a problem of a larger than anticipated upper-orbit amplitude during low-speed rotation of the flywheel. (Quarter 25)

Data from multiple HTS chill down and free floats indicated that the flywheel rotor assembly came in contact with the excursion surfaces during release. Alignment of the entire system was accomplished by dimensional control of the each of the components per mechanical tolerances and configuration control, as well as alignment pins to create repeatability during assembly, disassembly, and reassembly. There were 8 alignment pins that were intended to accurately locate the major assemblies together. These upper and lower aluminum weldments then become the datum for internal components located within each of these weldments. The primary concern was that the upper weldment unit, which houses the upper touch down system, the lift magnet assembly and the motor stator; could be out of alignment with the lower aluminum weldment that contains the HTS bearing and lower touchdown bearing system. Each weldment had an original tolerance of ± 0.005" radial. Each touchdown system had a tolerance within ± 0.001" of the center of the weldment. Several methods for verification of the alignment were attempted. The Ludeca laser-shaft alignment system gave us the most accurate and repeatable data. (Quarter 25)

In order to accomplish the alignment check, two test fixtures with precision drill bushings (± 0.00025) were fabricated, which could be located in the center of the upper and lower touch-down assemblies. Each fixture had a precision shaft located in the center of the fixture. The two shafts were connected via a flexible coupling. The Ludeca laser source was connected to upper-shaft assembly, while the retro device was located on the lower shaft. (Quarter 25)

After reviewing each of the technical issues described above, two changes were made that together gave dramatic improvements in low-speed operating performance of the rotor. The first was to improve the rotor's state of balance, as described in the previous section. The other was to make an adjustment to the permanent lift magnet assembly to increase the radial stability of the upper part of the rotor. At this point, we initiated new spin-testing experiments to verify that the adjustments to the system resolved the previous inconsistent spin-testing results. The flywheel performance tremendously improved, where the lower runout was practically nil and the top was less than 0.005". These results were perfectly repeatable on different days and at different speeds. (Quarter 25)

A remaining challenge was with the motor-control system, where tuning of different current and voltage parameters was required in order to spin the flywheel smoothly to higher speed. The first mode of operation for the motor controller was to start the flywheel spinning from zero speed to a speed where the controller could transition to its normal sensor-less closed-loop control operation. The plan was to try the simplest method first, which was open-loop control. Several attempts using the open-loop control method were tried. It was discovered, that the motor would lose synchronization when the rotor encountered a low-speed resonance. This was tried with the live centers engaged and disengaged. This process provided an opportunity to perform preliminary current regulation tuning of the controller, although it didn't allow us to spin at a speed high enough to accomplish a transition to the sensor-less closed-loop operation. It should be noted that the low-RPM operation is the most challenging part of the controller operation. Once the controller transitions into sensor-less mode of operation, the back EMF generated by the motor will provide better position information to the controller, which in turn will smooth out the spin-up characteristics of the flywheel system. Once the controller is optimized with the correct parameters, the spin-up orbital excursions should be identical to coasting characteristics of the flywheel system. For example, we observed, that the spin orbits on coasting at 900 RPM are just as small as during spin-up. (Quarter 25)

Sub-synchronous whirl also became an operational concern. Data collected during operation was analyzed to identify any correlation of the whirl with external and system influences. Early in the testing, no clear connection was identified as a cause or contributor to the whirl other than possible synchronous vibration (unbalance). While unbalance can only influence the rotors dynamics at the spin speed, past experience has shown that whirl may be influenced by a rotor's "state of balance". Quill testing has shown that a rotor whirl can actually decrease with a rotor that is poorly balanced. While unbalance can contribute, it should be noted that different spin tests have had reduced whirl and even the absence of whirl at different speeds. This led the team to an effort to identify other sources of whirl. (Quarter 26)

In an effort to identify the driving force putting energy into the low-frequency whirl, accelerometers were installed external to the flywheel chamber. The accelerometer data was recorded for analysis, as well as displayed during operation. Motor-control and accelerometer data were recorded and cross-correlated to identify any causal relationship to the whirl. One source of vibration identified was a vacuum rough pump that was relocated in order to reduce mechanical coupling to the vacuum chamber. In summary of this effort, no external source or driver at the whirl frequency or harmonic was identified external to the vacuum chamber. Additional tap testing and sine-sweep (small shaker) testing was planned on internal chamber hardware to continue the troubleshooting of this energy source. (Quarter 26).

The subsynchronous vibration begins at a rotor rotational rate of about 25 Hz. The frequency of this vibration is approximately 5 Hz and changes very little over the entire range of rotor rotational rate. The frequency is equal to that of the main bearing resonance frequency. The amplitude of the vibration increases monotonically with the rotor rotational rate. At a given frequency, the amplitudes during acceleration, deceleration, and coast modes were nearly identical. In other tests, sometimes switching from acceleration to coast would result in a noticeable jump in the subsynchronous amplitude, and sometimes moving into the deceleration mode would slightly decrease the amplitude (Quarter 31).

We developed a theory for the subsynchronous whirl, and designed experiments to increase damping in the system, to reduce or eliminate the subsynchronous whirl. This theory was initially verified with experiments, where the flywheel bearing support was slightly modified to install a proprietary damping solution and the system was tested up to 8,000 rpm to verify the results. We are not reporting details of the solutions, as this technique is presently regarded as Boeing Proprietary, and Boeing has applied for a US patent for this technique "Improved Damping in High -Temperature Superconducting Levitation Systems". The subsynchronous vibration was almost negligible over the entire frequency range tested. We observed some instability at higher speeds, and we concluded that the initial damping modifications made were not sufficient for higher speeds. We have determined an improved damping method, and are currently implementing the improved fix (Quarter 33).

System Level Testing Lessons Learned

- Accurately positioning the flywheel during cooldown proved to be an important step in successfully levitating and spinning the rotor. Accurate sensors to determine the position need to be incorporated into the design, together with accurate live centers.
- Standardization of data communications and analysis techniques is important to minimize the time spent to post-process and analyze the large amount of data taken during each experiment.
- Need to have a better and more reliable speed monitoring system.
- Would be good to have real time interpretation of experimentally observed vibrational frequencies and correlate them real-time with predicted models.
- Need better mechanical capturing system of a whole flywheel system in case of emergency or to faster mechanically slow down the system while testing.
- Sub-synchronous critical frequency was not well characterized and understood, and it took a lot more effort than anticipated to minimize its effect on the successful operation of the flywheel system.