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Canadian Electromechanical Battery Development Program: Definition Phase

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Prepared by:

Flywheel Energy Systems Inc.
25C Northside Road
Nepean, Ontario, Canada
K2H 8S1

Tel: (613) 596-0856
Fax: (613) 596-6052
E-mail: fesi@magma.ca
http://www.magma.ca/~fesi

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Notices

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Project Team

R. Flanagan, Ph.D.	(Flywheel Energy Systems Inc.)
D. Banicz, P.Eng.	(Flywheel Energy Systems Inc.)
L. Menard, P.Eng.	(Flywheel Energy Systems Inc.)
J. McArthur	(Flywheel Energy Systems Inc.)
M. Lee	(Flywheel Energy Systems Inc.)
D. Flanagan	(Flywheel Energy Systems Inc.)
J. P. Hobson, Ph.D.	(National Vacuum Technology Inc.)
J. Lo, Ph.D.	(CANMET Materials Technology Laboratory)
G. Shen, Ph.D.	(CANMET Materials Technology Laboratory)
R. Santos	(CANMET Materials Technology Laboratory)
M. Tasnon, P.Eng.	(Composite Materials Centre)

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16. Abstract

In recent years, the flywheel battery, or electromechanical battery, has seen significant advancements and prototype development for space, power quality, and hybrid vehicle applications. A hybrid vehicle propulsion system has recognized advantages regarding operating efficiency and emission control. These advantages are most effectively realized in the urban bus application. The energy management device that has shown the greatest promise is the electromechanical battery. In this phase, the goals were to develop the design base and to define the components, suppliers, and phase objectives that would result in commercial, integrated electromechanical battery systems applicable to both stationary and mobile markets.

Rotor dynamic and thermal models were developed and correlated with measured data. Vacuum compatibility studies on new components were completed. A catastrophic failure containment subsystem was modelled, and a failure mode and effects analysis completed. Standards and certification strategies were explored. Alternative hub materials were assessed. Component technology specifications were set and sources of these technologies were evaluated. A phased development plan for hybrid urban bus demonstration was outlined.

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16. Résumé

La batterie électromécanique, ou système d'accumulation d'énergie basé sur le volant d'inertie, a réalisé des percées majeures ces dernières années, avec la mise au point de prototypes destinés aux applications spatiales, aux véhicules hybrides et aux dispositifs nécessitant une qualité d'alimentation supérieure. Un groupe motopropulseur hybride comporte des avantages reconnus aux chapitres des performances et des émissions polluantes, avantages qui sont maximisés dans le cas des autobus urbains. Pour ce qui est de la gestion de l'énergie, c'est la batterie électromécanique qui s'est révélée la technologie la plus prometteuse. Les travaux de la présente phase consistaient à mettre au point la base de calcul d'une batterie électromécanique et à en définir les composants ainsi que les fournisseurs potentiels, et à fixer les objectifs des phases ultérieures du projet. Le but ultime étant de développer une batterie électromécanique commerciale intégrée et convenant à des applications fixes ou mobiles.

Des modèles dynamique et thermique du volant ont été mis au point et comparés avec les données mesurées. Des analyses ont été effectuées afin de déterminer si les caractéristiques des nouveaux composants sont compatibles avec le maintien du vide. Un sous-ensemble de confinement en cas de défaillance catastrophique a été modélisé, et une analyse des modes de défaillances et de leurs effets a été réalisée. Une recherche a été menée en ce qui a trait aux normes et aux exigences de certification applicables. Des matériaux de substitution pour le moyeu ont été évalués. Les spécifications relatives aux technologies des composants ont été définies et les fournisseurs de ces technologies ont été cotés. Enfin, un plan de développement par étapes a été élaboré en vue d'un projet de démonstration d'autobus urbain équipé d'une batterie électromécanique.

17. Mots clés Palier grande vitesse, volant d'inertie, dispositif de stockage de l'énergie, confinement, modèle thermique, batterie électromécanique, analyse des modes de défaillances et de leurs effets (AMDE), propulsion électrique hybride	18. Diffusion Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

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Summary Report

Introduction

Future vehicle propulsion systems will likely be a hybrid combination of an efficient, primary energy supply coupled with an energy management device. A hybrid propulsion system has recognized advantages regarding increased operating efficiency and reduced emissions of all sorts: hydrocarbons, nitrogen oxides, carbon monoxide, carbon dioxide, particulates and acoustics. These advantages are most effectively realized in the stop and go duty cycles endured by buses, taxis and delivery vans. The energy management device that has shown the greatest promise is the electromechanical battery (EMB); however, prior to deploying a viable EMB system in hybrid vehicles, a number of technical challenges (such as vibration, heat, vacuum, safety, cost, weight) need to be resolved. Such challenges are to be tackled according to a phased development plan, but are given consideration in this program definition phase. Canadian representation in this technology is led by Flywheel Energy Systems Inc. The company possesses a technology lead in the composite flywheel area, and is seeking to grow its technology base to become a competitive EMB system integrator.

Contract Rationale

Given the technology potential, Flywheel Energy Systems Inc. (FESI) and the Transportation Development Centre (TDC) of Transport Canada agreed to co-fund the definition and preliminary design phase of a multi-phase EMB development program. The objective of this work is linked to Transport Canada – TDC's Urban Bus Technology Program to develop and apply energy efficient technology to urban bus design, manufacture and operation. The funding source for Transport Canada – TDC's involvement in this project is the Program for Energy Research and Development. The goal of the work was to develop the design base and define the components, suppliers and phase objectives that would result in commercial, integrated EMB systems applicable to both stationary and mobile applications.

Achievements

The set objectives of the program have been met. Rotor dynamic and thermal models have been developed and correlated with measured data. Vacuum compatibility studies on new components have been completed. A catastrophic failure containment subsystem has been modeled, and a failure mode and effects analysis completed. Standards and certification strategies were explored. Alternative hub materials have been assessed. Component

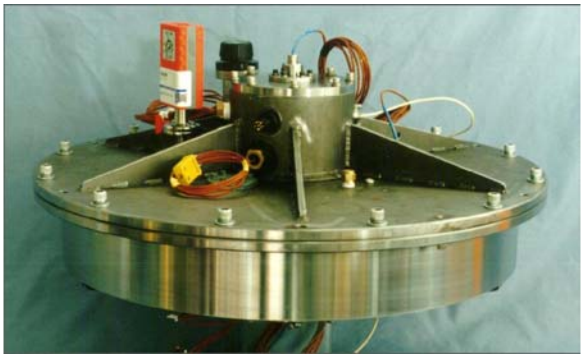


Figure 1 *Attitude Control Energy Storage (ACES) System*

technology specifications have been set, and sources of these technologies have been evaluated. A phased development plan has been structured to govern the follow-on work to a hybrid urban bus demonstration.

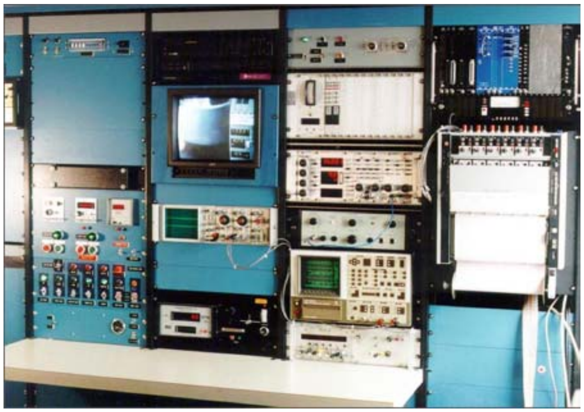


***Figure 2** FESI Data Acquisition Equipment Room*

Test Set-Up

Under contract with the Charles Stark Draper Laboratory, Inc. (CSDL), FESI developed and tested two EMB systems for CSDL's satellite Attitude Control Energy Storage (ACES) program. Additional program partners included SL-Montevideo Technology, Inc. (SL-MTI) and Mechanical Technology Incorporated. The testing of the first ACES unit, shown in Figure 1, coincided with the rotor dynamic and thermal model development undertaken in this program, thereby providing the rare, and highly desirable, opportunity to correlate the models with measured data. Dynamic testing was conducted in house. The data acquisition equipment is shown in Figure 2, and a schematic diagram of the test set-up is shown in Figure 3. The data from 126 test runs, or 129 hours of running time, were captured.

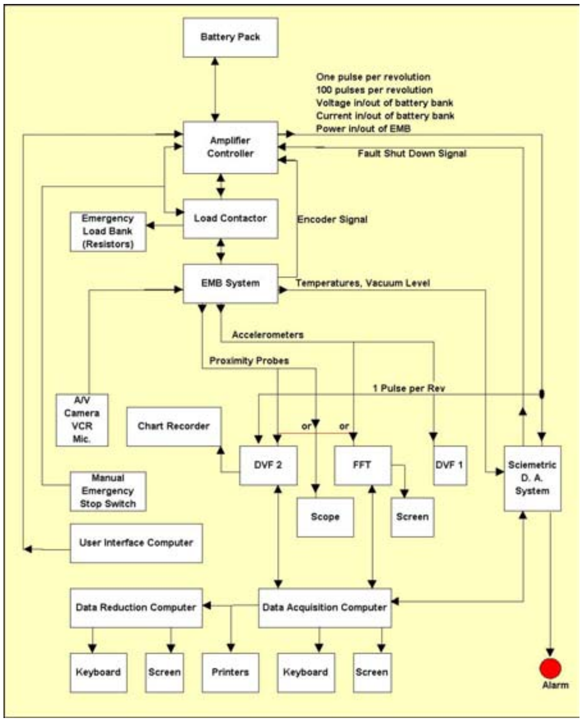


***Figure 3** ACES Test Configuration Schematic*

Rotor Dynamic Model

High performance flywheels operate at super critical speeds. The design must permit the rotating elements to traverse first critical, and must position the operating window of the EMB between first and second criticals. While conventional high speed equipment is often designed in this operational mode, rarely does this equipment have such a broad operating window (e.g. 15,000 rpm to 45,000 rpm).

EMBs are designed to store energy and utilize highly stressed, heavy rotors which push the dynamic needs beyond current state-of-the-art designs. Obtaining a high precision balance at a fixed operating speed or even over a narrow operating window can be readily accomplished. However, composite ring radial growth not only challenges the

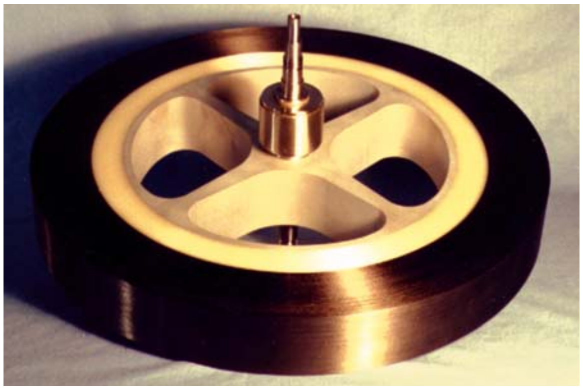


Figure 4 *Rotating Components of the ACES1 System*

hub design, but also challenges the dynamic suspension design. Retaining balance of the rotor throughout its wide operating speed range has been a primary design target for FESI. FESI flywheels are believed to be the truest running composite rotors built. Even so, an EMB suspension design must account for some mass shifting within the operational window. That is, the suspension must be designed to cope with some unbalance under normal operation. Also, FESI flywheels are designed with a hierarchy of "soft" failure modes. These "soft" failure modes result in a substantial unbalance in the rotating assembly. The suspension design must be capable of handling such an occurrence, without precipitating further failure. Thus, dynamic response to unbalance conditions becomes an essential consideration of the suspension design for normal operation and for operation under failure conditions.

To gain some insight into the unbalance response of the ACES1 system, the rotating components of the system (Figure 4) were modelled together with the bearing and housing suspension components. A static unbalance was introduced at the flywheel, and introduced at the motor. The modelled unbalance response was able to reproduce the dynamic response measured on the ACES1 system. This response is typified in Figure 5, where first critical synchronous housing vibration peaks at 0.2 g's at approximately 11,500 rpm.

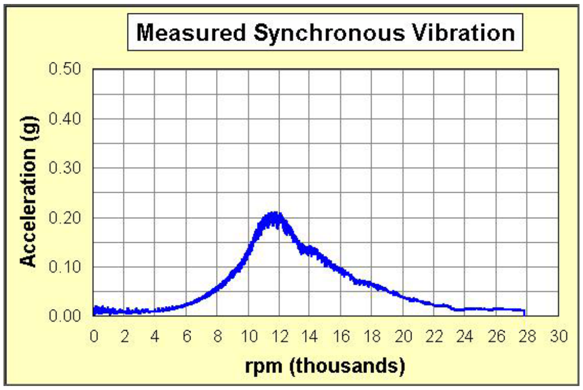


Figure 5 *Measured Synchronous Vibration of the ACES1 Housing*

For the ACES2 system, the suspension was "tuned" according to behaviour predicted by the model. Figure 6 shows the more desirable dynamic response, where first critical synchronous housing vibration peaks below 0.05 g's at approximately 10,000 rpm, and remains very flat (~0.025 g's) throughout the design operating range of 15,000 rpm to 30,000 rpm.

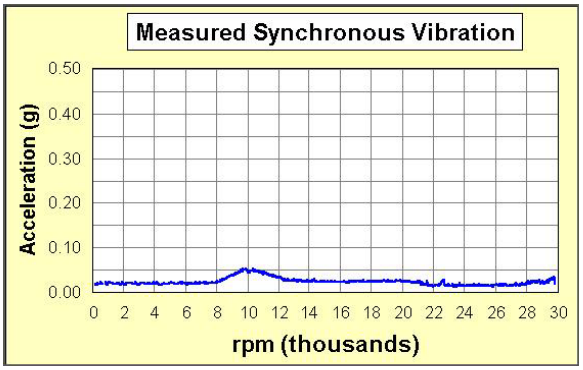


Figure 6 *Measured Synchronous Vibration of the ACES2 Housing*

The diagnostic and predictive capability of this model is evident.

EMB Loss Calculations

Accurate knowledge of the losses in the EMB is mandatory for thermal analysis. The main sources of heat generation in the ACES EMB are copper and iron losses in the motor/generator, mechanical losses in the rolling element bearings, and aerodynamic losses in the rotating assembly. Experimentally determined bearing loss data for a representative bearing were provided by CSDL. Theoretical loss data for the motor/generator were provided by SL-MTI. To establish the drag losses, an aerodynamic model was developed and verified with internally developed data and publically available data. Losses were then curve fit for representation at any operating speed and charge/discharge rate. These data output to the thermal model.

Thermal Model

A finite element heat transfer analysis module was added to the finite element stress module used to design hubs, motor rotors and other components. The new module permits steady state and transient thermal analysis.

Material properties, required for the finite element analysis (FEA) model, such as thermal conductivity, specific heat, emissivity, and density have been collected from a variety of sources. These sources include periodicals, reference manuals, journals, and manufacturers and suppliers such as SKF, Unique Mobility, SL-MTI, CSDL, Dupont, Owens Corning, Grafil, and Toray.

Model accuracy increases with the number of components used or individually modelled. Attention to this detail also allows flexibility to redefine component geometries and to analyze accessory heat paths. Hence, especially for future analyses, the geometry of the ACES systems was matched with considerable detail. Further, special attention was given to the rotating system model including the heat paths and input heat sources.

The ACES systems lend well to axisymmetric modelling. This reduces the model's complexity, thus reducing computer run time, without sacrificing accuracy. The system is mostly constructed of discs, thick rings and cylinders; however, there are a few exceptions. To compensate for complex geometries, such as the flex-rim hub and bearings, a disc of equivalent volume and heat path was used. The containment rings were modelled as a single thick ring.

The geometric representation of the ACES EMB comprises twenty-one individually drawn, meshed and decoded components. An automatic meshing algorithm was used. This algorithm creates small elements where higher accuracy is needed and less dense meshing in areas such as the housing. A schematic drawing of the ACES EMB is shown in Figure 7.

Each component is defined within a group and assigned a colour. Material properties are defined within the group, whereas colours define environmental conditions (e.g. radiation, convection, heat generation). A batch file assembles the components into the FEA model. The assembled model can then be analyzed with either the steady state heat transfer processor or the transient heat transfer processor. The model output was then correlated with data collected from testing the ACES systems.

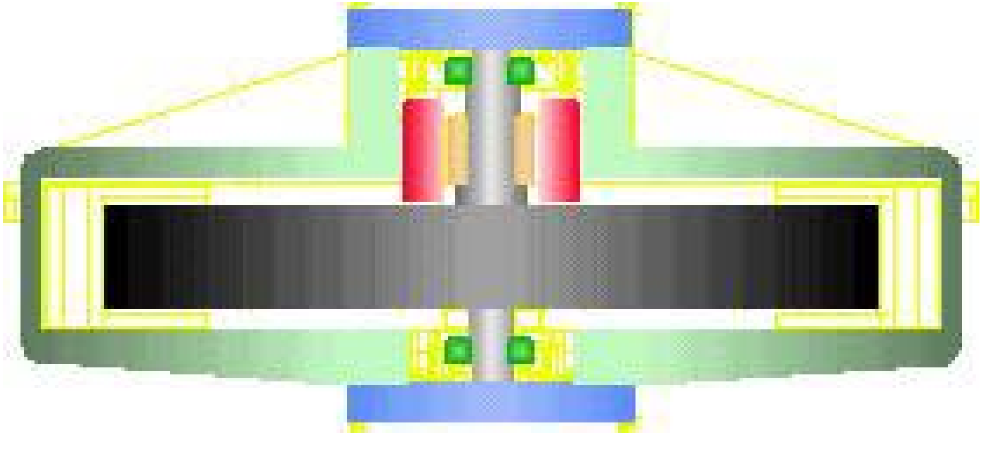


Figure 7 *Schematic Drawing of the ACES EMB*

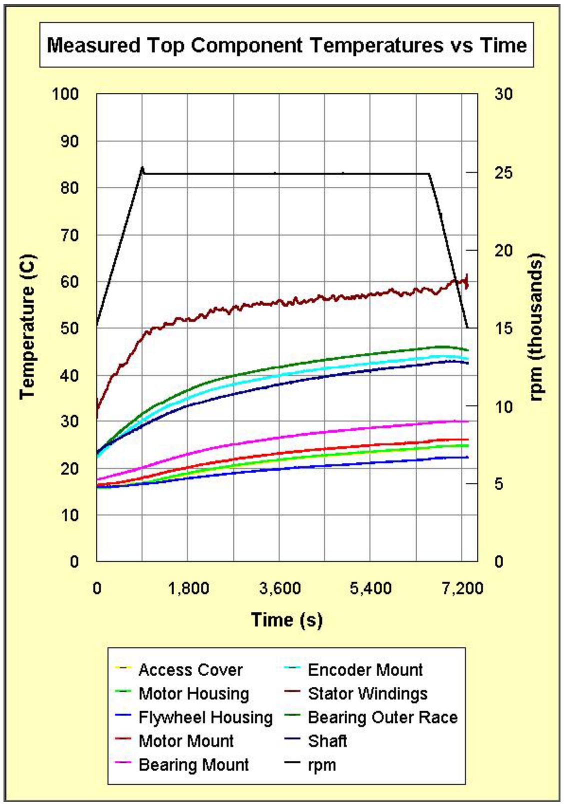


Figure 8 *Measured Top Component Temperatures vs. Time (ACES2 at 25,000 rpm)*

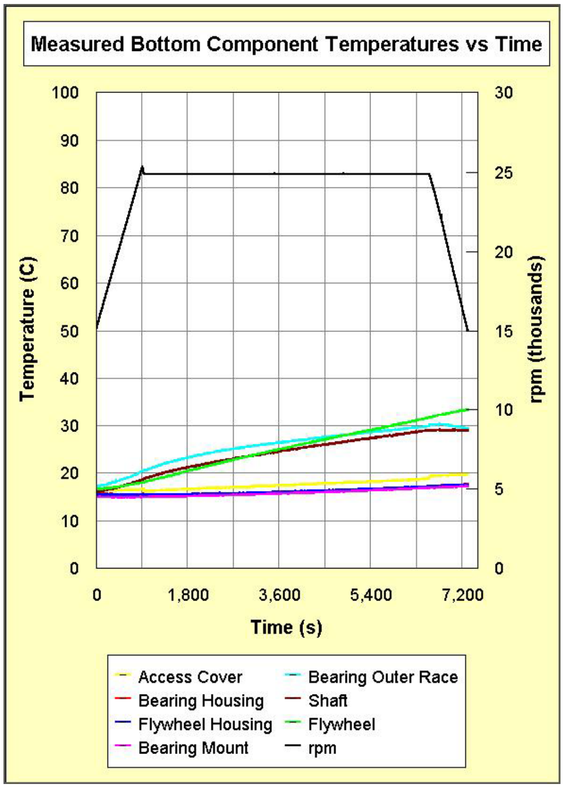


Figure 9 *Measured Bottom Component Temperatures vs. Time (ACES2 at 25,000 rpm)*

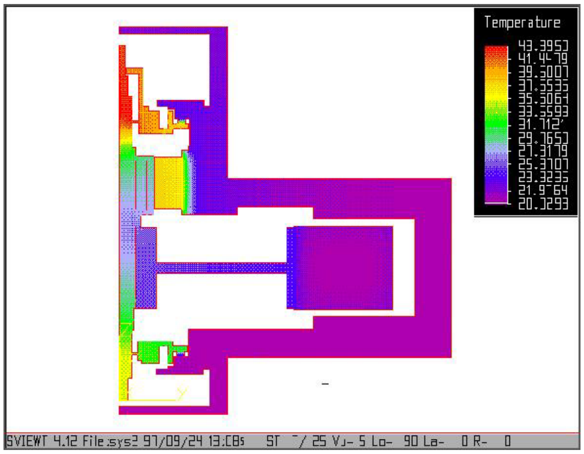
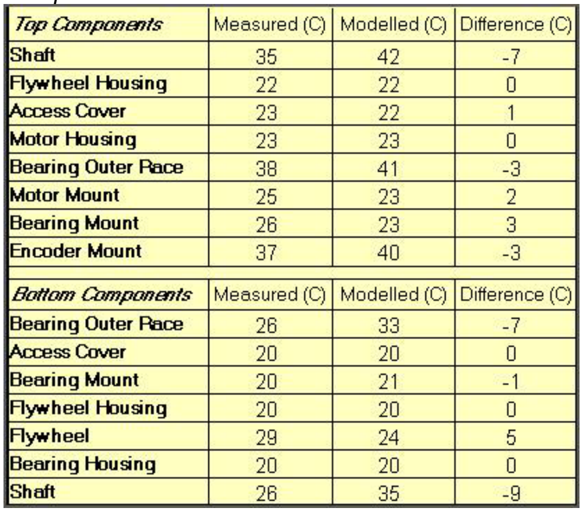


Figure 10 *Modelled Steady State Thermal Map (ACES2 at 25,000 rpm)*

The thermal model was instrumental in identifying and isolating unanticipated motor rotor heating in the ACES1 system, as well as identifying a faulty thermocouple. Modifications to the ACES2 system were made to address the motor rotor heating. The measured temperatures of the ACES2 system for the top and bottom components versus time in a steady state run at 25,000 rpm are shown in Figures 8 and 9, respectively. Figure 10 shows the thermal model output for the same conditions, and Table 1 compares the measured and modelled results.

The diagnostic and predictive capability of this model is evident.

Table 1 *ACES2 Measured vs. Modelled Temperature Comparison*



Top Components	Measured (C)	Modelled (C)	Difference (C)
Shaft	35	42	-7
Flywheel Housing	22	22	0
Access Cover	23	22	1
Motor Housing	23	23	0
Bearing Outer Race	38	41	-3
Motor Mount	25	23	2
Bearing Mount	26	23	3
Encoder Mount	37	40	-3
Bottom Components	Measured (C)	Modelled (C)	Difference (C)
Bearing Outer Race	26	33	-7
Access Cover	20	20	0
Bearing Mount	20	21	-1
Flywheel Housing	20	20	0
Flywheel	29	24	5
Bearing Housing	20	20	0
Shaft	26	35	-9

Vacuum Compatibility

There are two ways to preserve the vacuum environment required for low loss operation of the EMB: removal and non-removal pumping. Together with Dr. J. Peter Hobson, FESI has proven a non-removal method for preserving the EMB vacuum. In June 1991, a full complement of EMB components were sealed in a bell jar. This one-of-a-kind experimental setup held a minimum vacuum level of 3×10^{-5} torr for six years prior to disassembly to relocate the equipment.

Initial running of the ACES units indicated that the gas loads were higher than desired, but likely manageable with non-removal pumps. Although the ACES units were never intended to employ non-removal pumping methods, the hardware and components are representative of follow-on work, and hence, the gas loads are meaningful.

The bearings provided by CSDL represent a departure from the dry-lubricated bearings in the baseline experimental setup noted above. In order to determine if the bearings were responsible for the additional gas, an outgassing study was conducted.

The study showed that the bearings were not contributing the majority of gas to the system.

Containment Model

There exists an industry wide focus to develop and test structures to contain catastrophic failure of a flywheel. FESI has devised and modelled a concept which possesses many of the attributes required of a successful containment structure: self contained, passively activated, ready state, zero torque transfer to the external housing, light weight, low cost, *etc*.

The model permitted failure into any prescribed number of equal sized composite ring segments and predicted the real time failure sequence. Parametric studies were performed as a function of the containment ring physical size, cost, weight, and design clearances, expressed as a function of the controlling parameters. During failure, heat, energy absorption, forces and torques are tracked as is the speed and position of the composite ring segments and containment structure. Numerical integration was performed by a commercially available software package. The ordinary differential equations, generalized forces, pressure and normal force, deformation force and energy calculations were programmed as compound blocks. For the calculations, the adaptive 5th order Runge Kutta algorithm, with a step size of 10^{-6} seconds, was used. Output data streams were stored or directly plotted for visual representation. For this investigation, the flywheel selected was the Series 45 Mk 3 with an axial thickness of five centimeters (two inches) operating below its design speed of 45,000 rpm at its rated speed of 43,200 rpm where it stores 520 Wh.[1]

The failure sequence is very rapid. At failure, the composite ring segments move tangentially, reaching a maximum radial velocity in just under 0.3 milliseconds as

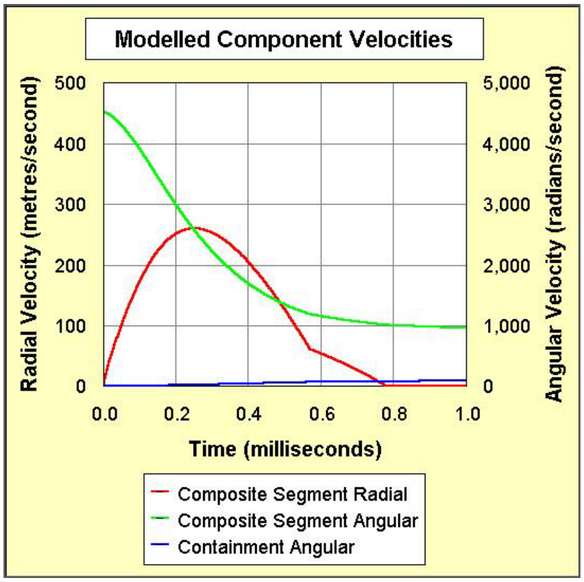


Figure 11 *Modelled Component Velocities at Failure*

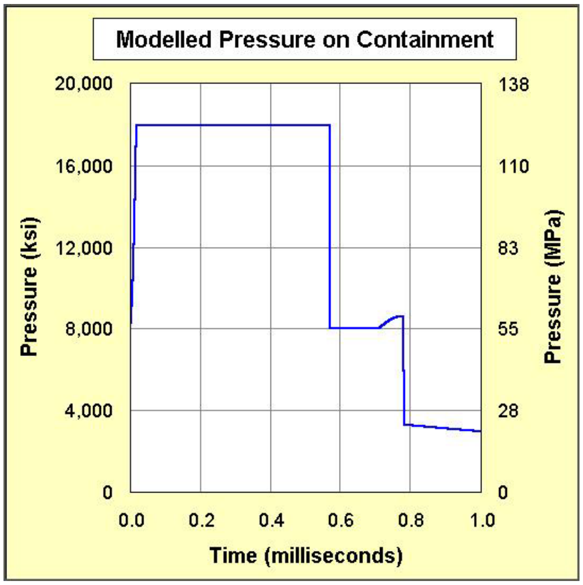


Figure 12 *Modelled Pressure on Containment at Failure*

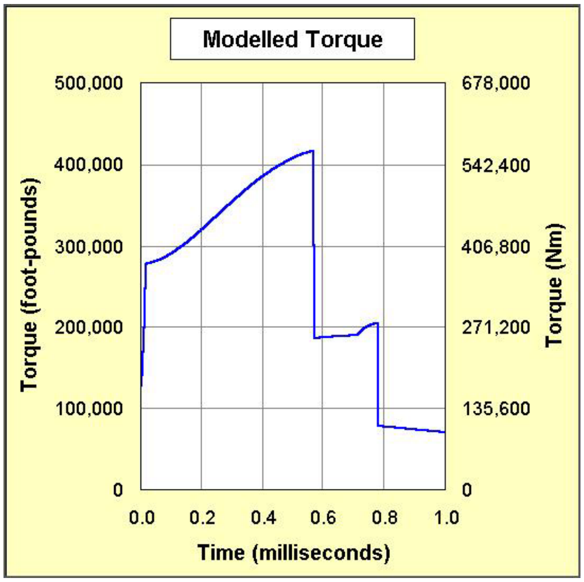


Figure 14 *Modelled Torque at Failure*

shown in Figure 11. Figure 12 tracks pressure on the containment structure which builds rapidly. At just under 0.6 milliseconds, containment radial deformation, shown in Figure 13, exceeds ten centimeters (four inches) and the torque between the composite segments and the containment reaches a maximum of over 400,000 ft-lbs (542,400 Nm), as shown in Figure 14. At this time, composite segment energy, (shown in Figure 15) has already dropped by 83%. The radial motion of the composite segments (Figure 11) has been arrested by approximately 0.8 milliseconds. At this point, the critical period of failure and containment can be considered complete although the composite segments are still rotating relative to the containment.

This system comes to a final stable rotational state of 176 radians per second in just

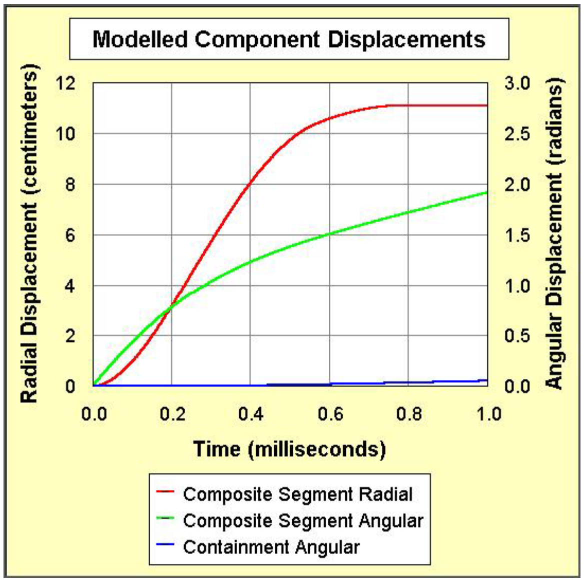


Figure 13 *Modelled Component Displacements at Failure*

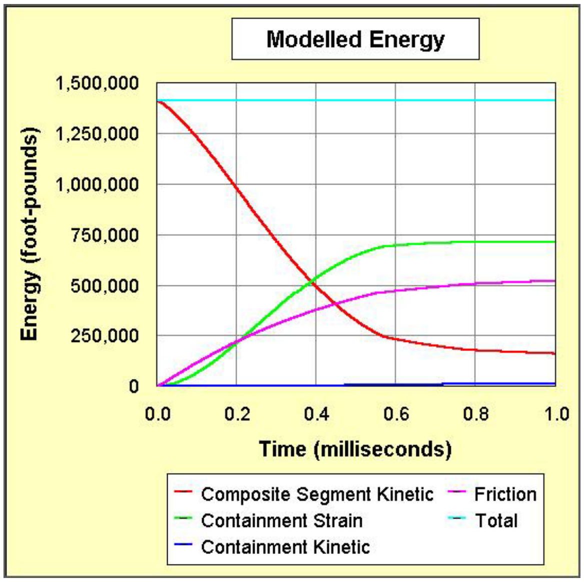


Figure 15 *Modelled Energy at Failure*

over twenty milliseconds, or 1.4 revolutions of the composite and 0.5 revolution of the containment. Energy in the composite segments drops rapidly and, for the set conditions described above, strain energy absorption dominates. The model indicates successful containment of the failed flywheel segments; however, this approach exacts a penalty in volume, weight and cost. The Series 45 Mk 3 flywheel being contained has a composite mass of 6.1 kg and a raw material cost of US$365. By comparison, the containment will have a mass of over 40 kg and an estimated raw material cost of US$800.

It is clear that designing a containment for flywheel catastrophic failure is not a logical approach to safety. Simply derating the flywheel, to obtain an extreme safety factor in the design, is more effective. And even if the flywheel were fully contained, the broader concern of EMB safety has not been addressed. This prompted an investigation into the possible failure modes of the EMB.

Failure Mode and Effects Analysis

A thorough analysis of the failure modes was conducted. Over twenty-five modes were identified, their effect assessed, and detection and prevention mechanisms devised. Based on these findings, further development and testing efforts are recommended to characterize failure onset signatures and to prove safety subsystems. An implementation schedule has been devised based upon product exposure, funding access and successful proof testing.

Standards and Certification

An investigation was conducted to gauge the applicability of conforming to existing standards as a measure to ensure safe EMB operation. As a new product, the EMB possesses operational idiosyncrasies that distinguish it from currently established standards. Thus, while there are existing standards to which the EMB may be considered to conform, demonstrating conformity does not necessarily ensure safety.

The investigation found a well established body of standards for electrical equipment (respecting high voltage requirements, special enclosures, grounding provisions, motors and generators, industrial control equipment, power supplies, etc.) to which the EMB could conform readily.

The investigation found a well established body of standards for machinery (respecting vibration, acceleration, shock, noise, balance quality, flexible couplings, isolation mounts, identifying symbols, etc.) that may be useful to orient the development of a standard for the EMB.

The investigation also found that the industry practices associated with similar equipment (e.g. turbine rotors or turbo molecular vacuum pumps) make use of extensive product development programs, vigilant inspection practices, and well designed quality control programs to engineer for safety. This approach to product safety has the greatest significance for the EMB industry--especially given its current degrees of limited product exposure, competitive secrecy, and early product life cycle stage.

The investigation concluded that an assembly of existing standards, existing practices, and well designed development, testing, and quality control programs can be used to generate internal standards for the EMB. However, prior to embarking upon a formal certification program, the motivations and desires of the industry segment, regulatory authorities, and equipment users must be strongly advanced.

Alternative Hub Material Evaluation

With the high performance flywheels, induced hub stresses increase as a result of the increased operating speed and the larger radial dilations of the composite rings. Although currently manageable, advanced hub configurations are required to realize additional cost reductions and performance gains (i.e. greater than 100 Wh/kg at 10^5 cycles). The FESI flex-rim hub has been proven stable and capable under extensive testing, and to date, has led the industry in this area.

This study called for a broad evaluation of alternative materials for hub construction. To assist the material selection process, three parametric studies were conducted to determine the relationships among the material properties and the desired radial dilation. This resulted in a material properties evaluation “formula” that permits quick assessment of alternative materials.

Subcontracts were let to the Composite Materials Centre (CMC) and to the CANMET Material Technology Laboratory (MTL) to assemble a long list of potential fibre composite and metal matrix composite materials, including a full range of reinforcement materials, matrices and fabrication techniques. Materials were evaluated as above, and successful candidates were then short-listed for further consideration.

Component Specifications

The purpose of this element of the work was to identify companies or entities capable of designing, manufacturing and/or testing certain component subsystems for the EMB. The fields of enquiry included the motor/generator, power conversion and control electronics, and bearings. Also, the candidates were solicited to determine their willingness to contribute in-kind support or complementary funding to the development program goals. Domestic sources for the high speed motor/generator and controller components were not forthcoming, however, this effort resulted in a key list of domestic and international supply alternatives to draw upon.

Follow-on Work

The development program structured is a multi-year phased effort which culminates in the demonstration of a hybrid drive urban bus. Clearly, the work undertaken in the program described herein, as well as the more than fifty conclusions and recommendations that issued, are foundational to the follow-on work. The major program building blocks envisioned are shown in Figure 16.

The high performance 1.5 kW EMB system development is underway. The system represents a significant advancement across the industry featuring the high performance flywheel, reduced parts count, simplified component architecture, and lightweight construction necessary to bring the EMB to a production feasible stage. Sized for uninterruptible power supply (UPS) applications, the system acts as a proving ground for new components, a technology ambassador for FESI's EMB capability, a development platform for hybrid vehicle units, and a demonstration article for UPS end use. The system components feature a flywheel, hub, shaft, bearing suspension, housing, and vacuum preservation strategy by FESI. The flywheel is the 95 Wh/kg Series 45 Mk 3 model designed for 45,000 rpm operation. At speed it stores 1 kWh (net). The 1.5 kW motor/generator and DSP controller are designed and fabricated by SL-MTI. This phase of the work is co-funded by the CANMET Energy Technology Centre of Natural Resources Canada, Flywheel Energy Systems Inc. and SL-Montevideo Technology, Inc.

The high performance 50 kW EMB system builds upon the 1.5 kW EMB platform. It incorporates many of the proven components from the 1.5 kW EMB and targets high power operation. The 50 kW power target is suitable for a hybrid drive, light duty delivery van or taxi, and two such units would provide the 100 kW desired for a hybrid drive urban bus. At present, funding initiatives for this phase of the work are being explored.

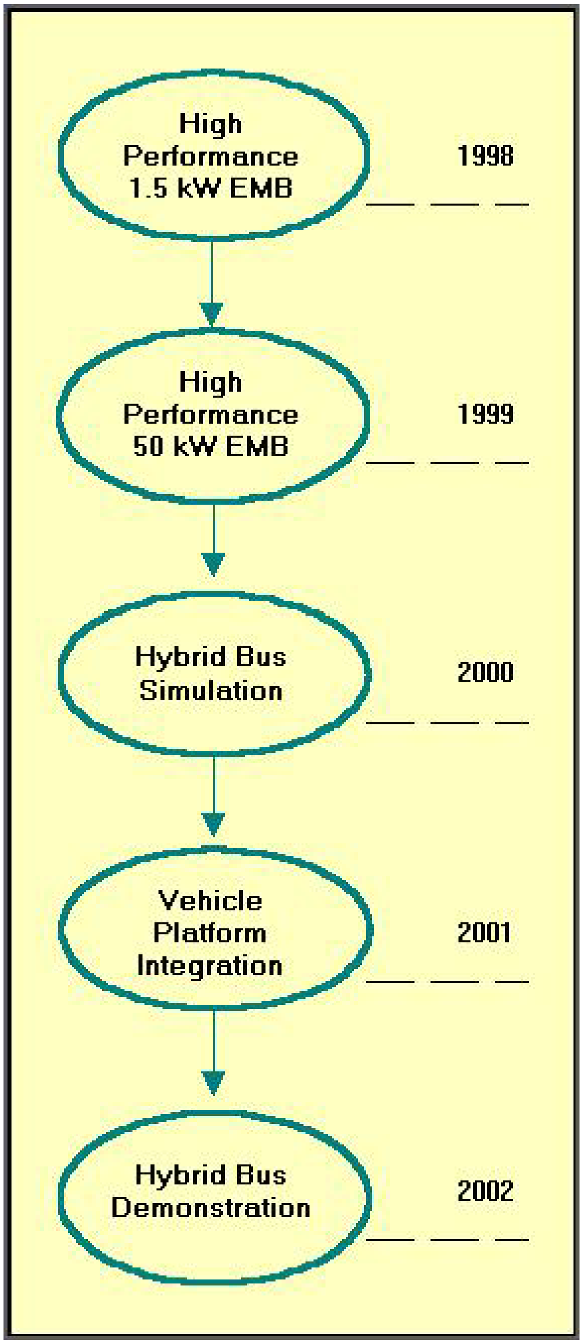


Figure 16 *Program Building Blocks to Hybrid Bus Demonstration*

The hybrid bus simulation is a laboratory setup of all of the drive line components in a simulated application environment. It may be desirable to develop a “rolling laboratory” vehicle, which would then also have significant demonstration value. This phase is a first cut at interfacing the numerous (and not necessarily optimized) components in the drive system: primary energy source(s), storage device, drive motor(s), and power conduits and controllers for the above. In addition to resolving component technology integration issues, such a simulation would permit efficiency and emission reduction mapping for selected drive schedules and/or for actual transit routes.

The vehicle platform integration seeks to combine more optimized drive components into a vehicle platform. This stage will require additional emphasis on component/vehicle interface and mounting techniques, physical integration issues, safety subsystems, and health monitoring functions.

The hybrid bus demonstration is a planned series of demonstrations to raise public, transit authority and investor awareness of the technology. Field trials will gauge the operational acceptance of in-service use. Initial deployment of the flywheel hybrid buses will likely occur on urban transit routes that suffer high daily passenger loads and a frequent stop/start duty cycle. The deployment strategy takes advantage of maximum exposure of the clean, quiet hybrid vehicle to riders, and the frequent stop/start duty cycle favoured by the electromechanical battery storage device.

References

1. Flywheel Energy Systems Inc. *Development of High Performance Flywheels for Electromechanical Batteries*. Contract No. 23440-4-1191/01-SQ Final Report. March 1997.