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CRADA FINAL REPORT
FOR
CRADA NUMBER ORNL96-0435

PHASE I STTR
FLYWHEEL MOTOR/ALTERNATOR
FOR HYBRID ELECTRIC VEHICLES

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Prepared by the
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Oak Ridge, Tennessee 37831
managed by
Lockheed Martin Energy Research Corporation
for the
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TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	1
STATEMENT OF OBJECTIVES	1
BENEFIT TO THE FUNDING DOE OFFICE'S MISSION	1
TECHNICAL DISCUSSION OF WORK PERFORMED BY ALL PARTIES	2
Flywheel Energy Storage System–Level Design and Analysis	2
Motor/Alternator Design	2
Motor/Alternator Test Bed Design	2
Motor/Alternator Proof of Concept Demonstration	2
Project Documentation	10
INVENTIONS MADE OR REPORTED	10
COMMERCIALIZATION POSSIBILITIES	10
PLANS FOR FUTURE COLLABORATION	12
CONCLUSIONS	12
DISTRIBUTION	13

FIGURES

	<u>Page</u>
Fig. 1. Adhesive shear stress profile at 10,000 rpm between the flux return plate and the magnet showing coincidence in the return plate's plane (a), the midplane (b), and the magnet's plane (c)	4
Fig. 2. Effective stress contours at 10,000 rpm in the magnet	5
Fig. 3. Mechanical schematic of ORNL's motor spin test configuration for driving VCS's Beta-3 unit as a generator	6
Fig. 4. Test frame used to support Beta-3 motor on the lid of the motor test tank	7
Fig. 5. Test team completing evaluation of the Beta-3 motor/generator	11

ABSTRACT

Visual Computing Systems (VCS) and the Oak Ridge National Laboratory (ORNL) have teamed, through a Phase I Small Business Technology Transfer (STTR) grant from the U.S. Department of Energy (DOE), to develop an advanced, low-cost motor/alternator drive system suitable for Flywheel Energy Storage (FES) applications. During Phase I, system performance and design requirements were established, design concepts were generated, and preliminary motor/alternator designs were developed and analyzed. ORNL provided mechanical design and finite element collaboration and Lynx Motion Technology, a spin-off from VCS to commercialize their technology, constructed a proof-of-concept axial-gap permanent magnet motor/alternator that employed their Segmented Electromagnetic Array (SEMA) with a survivable design speed potential of 10,000 rpm. The VCS motor/alternator was successfully tested in ORNL's Motor Test Tank using an ORNL inverter and ORNL control electronics. It was first operated as an unloaded motor to 6000 rpm and driven as an unloaded generator to 6000 rpm. Output from the generator was then connected to a resistance bank, which caused the loaded generator to decelerate to 3860 rpm where data was collected. After about 4-1/2 minutes, the test was terminated because of an impact noise. Subsequent inspection and operation at low speeds did not reveal the source of the noise. Electrical performance of the motor was excellent, encouraging continued development of this technology. Phase II efforts will focus on further design development and optimization, manufacturing development and prototype construction, testing, and evaluation.

STATEMENT OF OBJECTIVES

The five original technical objectives of this Phase I STTR were:

1. Produce a FES system design for a six-passenger sedan conforming to the guidelines of the Partnership for a New Generation of Vehicles (PNGV) as a basis for design of motor alternators;
2. Produce a detailed motor/alternator design candidate capable of operation at 35,000 rpm for Phase II construction based on the FES system from objective 1;
3. Produce a mid-level design of a motor/alternator test system capable of simulated vehicle operating conditions. This test system will be constructed during the Phase II effort and will be an expansion of the computer-based monitoring/control system developed for VCS motor testing with input from a vehicle consultant, DOE, and the National Institute of Standards and Technology;
4. Construct and demonstrate a motor/alternator capable of operation at 10,000 rpm using SEMA components already developed at VCS. The actual maximum test speed was reduced to 6000 rpm by agreement with the DOE sponsor; and
5. Produce a final report summarizing the Phase I activities and deliver a Phase II proposal.

BENEFIT TO THE FUNDING DOE OFFICE'S MISSION

The Department of Energy's Office of Transportation Technologies is participating in a cooperative program with U.S. automakers through the PNGV. The goal is to produce an economically competitive hybrid electric vehicle (HEV) with greatly improved fuel efficiency and environmental compatibility. High-speed motor/alternators capable of high-speed operation with adequate thermal

management in a vacuum have been recognized as one of three enabling technologies for the HEV. Another mission of DOE is to expand and stimulate the private sector's participation in research and development that will help reach the PNGV goal. To achieve this, they requested STTR grant applications whose deliverable would be a high-speed motor/alternator with its inverter drive and controls that can introduce and extract power from a flywheel.

The Phase I tasks were planned to support DOE's and PNGV's goals by providing a basis for development of a fully functional high-speed motor/alternator and its inverter drive in the Phase II effort. The Phase I work provided a system-level FES description, some candidate designs from which the Phase II prototype will be selected, a proof-of-concept intermediate-speed prototype built from existing SEMA components, and design of a test system to be used for Phase II testing.

TECHNICAL DISCUSSION OF WORK PERFORMED BY ALL PARTIES

Each of the five objectives proposed for the Phase I STTR has been met, with end results in several areas surpassing the research team's expectations.

Flywheel Energy Storage System (FESS)—Level Design and Analysis

Personnel of VCS produced a generic system design for an HEV based on existing vehicle platforms. The vehicle drive system has been designed to be packaged in a six-passenger sedan currently in production.

Motor/Alternator Design

Personnel of VCS created and optimized a high-speed motor/alternator design, based on a coil-magnet arrangement designated the permanent magnet SEMA for use in electric vehicle FESSs. During this research, they developed an extensive refinement of software tools used to model SEMA designs. Using the refined software, they found that a variation on the SEMA concept applied to a synchronous reluctance motor appears to have the greatest potential to meet the cost target of \$500 per FESS for quantities of 100,000.

From their economic and performance analyses, VCS has selected two axial-gap candidates for future investigation. They are the synchronous reluctance motor/generator with permanent magnet flux barriers and the ceramic ferrite permanent magnet motor/generator.

Motor/Alternator Test Bed Design

Personnel of VCS created a design for hardware and software needed to test the proposed Phase II motor/alternator and its associated inverter. The plan is to use ORNL's power converter and control electronics. ORNL also plans to design and build a steel flywheel to provide a load for the Phase II prototype motor/alternator at design levels. ORNL and VCS will collaborate on test equipment.

Motor/Alternator Proof of Concept Demonstration

The Phase I design effort produced a motor/alternator, based on earlier SEMA architecture, that was capable of operation at 10,000 rpm. Minor modifications were made to the original VCS beta design, including a variation in the flux returns and the use of Litz wire in the coil to reduce eddy currents. During the design phase, ORNL performed rotating component design analyses and finite-

element analyses to confirm mechanical aspects of the design. The analyses indicated that reduced loading and reduced thermal excursions were necessary. VCS personnel determined that the magnet thicknesses could be reduced to half their initial value and that temperatures would never exceed 120°F. The team decided that an external composite support ring could not practically be used for three reasons. First, it would severely impact the Phase I motor performance if forced into that footprint; second, its fabrication would introduce unacceptable costs in the Phase I program; and third, the adhesive strength was sufficient to support the shear load at 10,000 rpm provided the temperature didn't rise above 120°F and the magnets were half the original thickness. Results from a finite-element analysis of the Beta-3 configuration show that the maximum shear stress in the adhesive bond is 2370 psi and the maximum effective stress in the magnet is 9082 psi. The adhesive vendor's shear strength is quoted as 3000 psi, and the magnet vendor's tensile strength is quoted as 16,200 psi. The adhesive shear stress profile and the magnet effective stress contours are shown in the following figures.

Because of the safety factors warranted in testing a prototype at high speed, VCS and ORNL agreed that the Beta-3 device would be spun in a thick-walled steel tank rated to contain fragments that could be generated during catastrophic failure of the spinning unit. The team collaborated by phone, fax, and e-mail to assure that ORNL's Motor Test Tank was compatible with the geometry of VCS's Beta-3 motor/generator, and that ORNL instruments were compatible with VCS's data acquisition system. A schematic of the Beta-3 Motor Spin Test Configuration is shown in Fig. 3.

Another preparatory activity was to formulate a preliminary test plan. The plan's two objectives were to spin the Beta-3 device as a motor up to 6000 rpm and to spin it as a generator while measuring its power output.

On March 18, 1997, Keith Seymour and Karl Dockstadter, electrical engineer and mechanical engineer members, respectively, of the VCS team, transported the Beta-3 device, which was designed specifically for the joint VCS/ORNL effort, to the ORNL facility located at the Y-12 site in Oak Ridge, Tennessee. They also brought a data acquisition system and a large power relay switch for switching to the resistance load bank as part of VCS's contribution to instrumentation. They joined the members of the ORNL team, John McKeever, project manager; Matthew Scudiere, designer of the control system for the ORNL inverter; and George Ott and Cliff White, electronics engineers, to finalize the test plan and begin testing.

After the Beta-3 unit was unpacked, connected, and driven in both directions to be sure it had not been damaged during the trip, VCS's relative incremental encoder was replaced by ORNL's absolute encoder.

On Wednesday, March 19, a sensorless inverter was used to spin the Beta-3 motor to 600 rpm for each phase in both directions to obtain the necessary back electromotive force (emf) map vs the absolute encoder output. This information was used by ORNL's computer based software controller to control the 70 kW hard-switched inverter in the Pseudo Pulse Width Modulation (PPWM) inverter configuration.

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Fig. 1. Adhesive shear stress profile at 10,000 rpm between the flux return plate and the magnet showing coincidence in the return plate's plane (a), the midplane (b), and the magnet's plane (c).

DISPLAY 111 - GEOMETRY MODELING SYSTEM (93.0) PRE/POST MODULE

EFFECTIVE STR

VIEW : 93.28377

RANGE: 9881.594

(Band x 1.0E1)

Max	988.2
13	843.9
12	779.6
11	715.3
10	651.1
9	586.8
8	522.5
7	458.2
6	394.0
5	329.7
4	265.4
3	201.1
2	136.9
1	72.59
Min	8.328

ETRC-HISA/DISPLAY

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TIME: 0.20000E+01

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Fig. 2. Effective stress contours at 10,000 rpm in the magnet.

On Thursday, March 20, the Beta-3 motor was removed from the horizontal test stand and positioned on a rolling dolly in the build frame for vertical mounting. The lid was placed on the top of the build frame. As a safety backup, the lift forks remained in the lift channels when the build frame was being used.

The frame consisted of eight vertical 1/2-13 threaded rods screwed into holes drilled in the lid. Threads were protected by the spacing pipes that also held the Beta-3 housing parallel to the lid. Four brace bars were bolted to threaded 3/8-in. thick aluminum angles connected between the vertical supports that were 30 degrees apart. Figure 4 shows the test frame. From bottom to top, the test train components are the absolute encoder, the Beta-3 motor, the Trantorque coupling, and the lower flange of the torquemeter that was installed when the Beta-3 unit was driven as a generator.

The 2-in. diameter brass shaft adapter was placed on the shaft of the radial gap permanent magnet (RGPM) motor that would later be used to drive the Beta-3 motor, and two set screws were securely tightened against the RGPM motor's shaft. This motor was fastened to an aluminum plate with four tapered headed machine screws using threadlock to resist vibrational loosening. Four 3/8-16 x 1 grade 5 bolts with flat washers and lock washers were then used to fasten the aluminum plate to the lid of the test tank.

Fig. 4. Test frame used to support Beta-3 motor on the lid of the motor test tank.

Electrical and instrument leads were threaded through two 2-in. diameter holes in the lid and anchored against the vertical pipes. Thermocouple wire from the Beta-3 motor was connected to a meter so that its coil temperature could be monitored. A 3-phase relay was connected so that the leads to the Beta 3 motor could be switched from the PPWM inverter driving it to a power sink consisting of Y connected resistors. The Beta-3 motor was driven to 600 rpm by the PPWM inverter to check all the circuitry, the connections, and the relay. The lid with its test frame was placed in the test tank, and the eight lid bolts were tightened. Limited access warning signs were posted. Because of the close tolerances, a piece of clay was affixed to the bottom of the encoder. When the test frame was removed later, the thickness appeared to be less than 1/16 in.

The formula for estimating the power sink resistance that would limit the current through a phase to I amps is

$$R_{eq} = V_{l-l} / (1.732 \times I) = 0.0258 \times \text{rpm} / (1.732 \times I) = 0.0149 \times \text{rpm} / I,$$

where V_{l-l} is the line-to-line voltage, and rpm is the rotational speed in revolutions per minute. To limit the current through the Beta-3 motor to 20 amps at 3000 rpm, the resistance in each phase should be at least 2.23 ohms. The actual resistance was obtained by connecting 14 ohm resistors in parallel until their resistance exceeded R_{eq} . Five resistors were connected in parallel in each phase of the power sink for a resistance of 2.8 ohms. The measured series resistance across two phases was verified at 5.6 ohms. This will allow the current at 3000 rpm to be 16 amps, which is below the limiting value.

The Beta-3 motor was driven to 3000 rpm and switched from the drive to the power sink. A mild resonance appeared at about 2400 rpm. The Beta-3 motor was run to 1000 rpm to check the sample time and to verify data acquisition. The Beta-3 motor was driven to 3100 rpm where it was switched from the drive to the power sink and data acquisition was successfully completed and recorded.

The resistance bank was rewired so the current at 6000 rpm would not exceed 19 amps, the limiting value for the motor. An attempt was made to drive the Beta-3 motor to 6000 rpm, but the maximum power available was limited by the dc power supply so that it could only achieve 4300 rpm. The motor was switched from the drive to the power sink, and data acquisition was successfully completed. The current and voltage read from the meters were 9 amps and 135 volts indicating a drag power of about 1215 watts at 4300 rpm. To obtain more power, the entire drive system was connected to a 3-phase Variac that received power from a 460-volt, 3-phase circuit.

Since the system had behaved well during the drive to 4300 rpm, the power sink was rewired so the current in the regenerative mode at 6000 rpm would not exceed 40 amps. This would have expedited testing on Friday barring other problems. At 6000 rpm, this would have corresponded to a generated power of 10,094 watts.

On Friday, March 21, the Beta-3 motor was successfully driven to 6000 rpm with the PPWM inverter and the 440 V power source. The starting temperature of the motor was 76°F and the final

temperature was 107°F. At 6000 rpm, the motor was switched from the drive to the power sink and data acquisition was successfully completed. The driveup and deceleration time was about 1/2 hour.

The torque sensor calibration produced a linear voltage representation of torque. The formula is

$$T = -1.538 - 101.9 \times V,$$

where T is the torque in ft-pounds and V is the analog voltage from the torque sensing bridge. These constants were entered into the DAS to scale the analog voltage to torque in ft-pounds.

The torquemeter was attached between the Beta-3 motor and the 32 kW RGPM motor that would drive it. The PPWM inverter was connected to the Beta-3 motor to drive the RGPM motor for determining its emf as a function of encoder position. After some phase problems were remedied, the low-speed mapping proceeded successfully.

The PPWM inverter was connected to the RGPM motor and the train was driven to 500 rpm to check out mechanical alignment and electrical circuitry. The lid with its test frame was placed in the test tank, and the eight lid bolts were tightened. The 3-phase relay was connected so that the leads to the Beta-3 motor could be switched to the power sink while the Beta-3 motor is being driven as a generator. Thermocouple meters were connected to both the Beta-3 motor and the RGPM motor. The thermal limit of the RGPM motor, above which testing would be terminated, was 250°F.

The objective on Monday, March 24, was to drive the Beta-3 test train to 6000 rpm with the RGPM motor, switch the Beta-3 leads to the power sink, and drive it as a generator for two minutes. The RGPM motor drove the train to 5000 rpm at which point a very loud vibration indicated an alignment problem and prevented further acceleration of the unit. The generator was switched to the power sink, and at 4100 rpm data acquisition was initiated. A 30-amp peak current was measured. The Beta-3 motor temperature, which started at 87°F, reached 93°F. The RGPM motor temperature reached 199°F. There was significant vibration. After the train decelerated, an attempt to drive the RGPM motor failed because some part of the shaft had slipped destroying the relative positioning between the RGPM motor and the absolute encoder. The problem was remedied by tightening the Trantorque coupling. Alignment of the torque meter was improved.

The PPWM inverter was again connected to the Beta-3 motor for a remap of the emf to encoder position. The PPWM inverter was reconnected to the RGPM motor and the test train was driven to 600 rpm as a system check. A different trapezoidal wave form was used to drive the PPWM inverter during the final test. The lid with its test frame was placed in the test tank, and the eight lid bolts were tightened. The 3-phase relay was connected so that the leads to the Beta-3 motor could be switched to the power sink. Thermocouple meters were reconnected.

The Beta-3 generator was driven without a load quickly and easily to 6000 rpm where it was switched to the power sink. There was still vibration, but much less than on the first run. Data acquisition was initiated, and the train decelerated to 3860 rpm before the PPWM inverter could drive the RGPM motor now loaded by the generator's deposition of power into the resistance bank. An immediate decision was agreed upon by both test engineers to continue the drive time for 5

minutes or as long as possible; however, after 4 minutes and 20 seconds there was a harsh noise followed by a loud metallic report. Current was removed from the RGPM after which the train coasted smoothly and quietly. A short trial drive showed that the RGPM motor could still be driven by the PPWM inverter.

When the train was removed from the tank there was no evidence of broken components. Everything was in place. When a screwdriver was placed against the housing of the Beta-3 motor, and the shaft was turned, a distinct but faint grinding could be heard. The test engineers concluded that the test had successfully demonstrated the motoring capability of the Beta-3 unit at 0000 rpm and had shown its generating capability for a 5-minute period at 4300 rpm before experiencing an internal mechanical failure.

Project Documentation

The research team has drafted, reviewed, revised, and published a final report detailing the research accomplished and the findings and results, with an estimate of their technical feasibility. That report, submitted on April 10, 1997, as a proposal for a research grant, DOE Grant No. DE-FG02-96ER86052, contains identified proprietary information. This final STTR Phase I report is intended to provide a summary, with no protected CRADA information or proprietary information, for unlimited distribution.

Figure 5 shows the Phase I Test Team driving the Beta-3 motor. Individuals from left to right are Cliff White, John McKeever, Keith Seymour (at the data acquisition system), Matthew Scudiere (operating the computer control system for ORNL's inverter), George Ott (operating the Variac), and Karl Dockstadter (checking the motor temperature). The Lexan box, on the right, houses the pulse width modulated inverter used to drive the Beta-3 unit.

INVENTIONS MADE OR REPORTED

No inventions were made during the Phase I effort. The Beta-3 motor was built using proprietary SEMA technology and tested at ORNL.

COMMERCIALIZATION POSSIBILITIES

Commercial benefit from this work will be a high-speed motor/alternator and inverter drive technology that will advance development of commercially competitive FESS for hybrid electric passenger cars. The system components may be scaled up for commercial trucks, military vehicles, and large utility grid power conditioning applications. The Navy has great interest in this technology for use with electrical systems on board ships. A major power utility company is interested in this technology for energy storage and power conditioning. Or it may be scaled down for use in small power conditioning modules. Furthermore, the designs for efficient motor/alternators may be developed for use in high-speed electric applications, such as turbine alternators and air conditioners. Major aerospace companies have reviewed the technology and have expressed an interest in using it in advanced aircraft.

Fig. 5. Test team completing evaluation of the Beta-3 motor/generator.

PLANS FOR FUTURE COLLABORATION

Evaluation of the Phase I research and testing indicates that further research and development has high potential for success. Application for a Phase II proposal has been submitted to obtain a grant for additional work. The grant has been awarded to VCS, who will again team with ORNL, to focus on further motor/alternator design development and optimization, manufacturing development, and prototype construction, testing, and evaluation.

CONCLUSIONS

From the Phase I analysis and testing, VCS and ORNL personnel reached the following conclusions.

1. Both engineering machine design calculations and finite-element analysis showed that the Beta-3 rotor could probably survive operation at 10,000 rpm if the magnet thickness was half its original value and if the temperature didn't exceed 120°F. In the adhesive holding the magnets to the flux return plate, the maximum shear stress did not exceed 2370 psi and maximum von Mises stress did not exceed 4144 psi. The vendor's adhesive shear strength (steel-to-steel) is 3000 psi, and his tensile strength is 3000 psi. In the magnet material the maximum transverse shear stress did not exceed 4195 psi and the maximum von Mises stress did not exceed 9082 psi. The vendor's magnet shear strength is not given, and his tensile strength is 19,200 psi. The team concurred that operation at the scaled 6000 rpm was desirable.
2. The proof-of-concept prototype motor/alternator, Beta-3, was successfully driven as a motor to 6000 rpm using the ORNL inverter. The speed was scaled from the original Phase I value of 10,000 rpm because it was necessary to resize the Beta-3 motor/alternator from the size originally specified.
3. The Beta-3 unit was successfully driven as an unloaded alternator to 6000 RPM using a commercial radial-gap permanent motor provided by ORNL and driven by the ORNL inverter. When the Beta-3 alternator was loaded by switching its output to the resistance bank power sink, the train decelerated to 3860 rpm before the ORNL inverter could stabilize. The ORNL inverter then successfully drove the Beta-3 unit for sufficient time to demonstrate an excellent 14.3 kW power delivery capability.
4. Although internal mechanical noises indicated that further testing would not be prudent, sufficient data was obtained to demonstrate excellent electrical performance of the Beta-3 unit as both a motor and generator. Performance of the Beta-3 unit encourages further development of this technology.
5. The Pseudo-PWM inverter used to test the Beta-3 motor had reached the limits of its ability to drive the motor. The electrical speeds of this motor/alternator test were near the limit of the transistor switches in the inverter. At these speeds it would be more efficient to drive with a six-step approach. This would probably enable the inverter to drive the motor at higher power. Integration of the drive inverter with the motor/generator will be crucial as development of motor/alternators that employ SEMA technology continues.

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