IV.E Air Management Subsystems

IV.E.1 Turbocompressor for PEM Fuel Cells

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Objectives

- Develop an optimum turbocompressor configuration by working with fuel cell system manufacturers and by improving upon previous project results.
- Reduce turbocompressor/motor controller costs while increasing design flexibility.
- Develop and integrate the turbocompressor/motor controller into a fuel cell system.

Approach

- Use automotive and aerospace turbomachinery technology to reduce cost and weight/volume.
- Use VNT® variable nozzle turbine inlet geometry to improve performance across the desired flow range.
- Use a mixed flow type compressor to improve low flow performance.
- Use contamination/oil free and zero maintenance compliant foil air bearings.
- Use a modular approach to improve design flexibility.
- Use a high efficiency, low cost two pole toothless motor.
- Use a low cost, no sensor required, variable speed motor-controller topology design.

Accomplishments

- Accomplished numerous start/stop cycles with no appreciable wear.
- Continued demonstration of a modified turbocompressor with increased turbine inlet temperature (315^{o}C) capability and aerospace quality variable speed brassboard motor controller in the 50-kW DOE/Honeywell fuel cell brassboard system.
- Completed the analysis, design, and fabrication of the turbocompressor with a mixed flow compressor and VNT® variable nozzle turbine.
- Completed the analysis, design, and fabrication of a vehicle ready motor controller.
- Completed testing of the mixed flow compressor.
- Completed integration testing of the turbocompressor and vehicle-ready motor controller.

Future Directions

- Complete testing of the turbocompressor VNT® variable nozzle turbine.
- Complete analysis, design, fabrication, and testing of a reduced cost and enhanced performance turbocompressor.
- Complete analysis, design, fabrication, and testing of a reduced cost and enhanced performance motor.
- Complete analysis, design, fabrication, and testing of a reduced cost and enhanced performance motor controller with no sensor requirements.

Introduction

The objective of this work is to develop an air management system to pressurize a light-duty vehicle fuel cell system. The turbocompressor is a motor-driven compressor/expander that pressurizes the fuel cell system and recovers subsequent energy from the high-pressure exhaust streams. Honeywell designed and developed the motor driven compressor/expander and evaluated performance, weight and cost projection data. As compared to a positive displacement technology, the turbocompressor approach offers high efficiency and low-cost potential, in a compact and lightweight package.

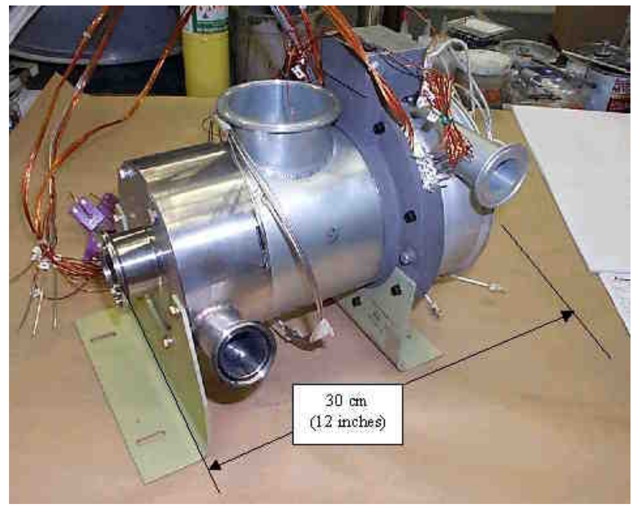

Figure 1. Honeywell Fuel Cell Turbocompressor with Mixed Flow Compressor and VNT® Variable Nozzle Turbine

Approach

The turbocompressor design depicted in Figures 1 and 2 consists of a compressor impeller, an expander/turbine wheel, and a motor magnet rotor incorporated onto a common shaft operating up to a speed of 110 krpm on compliant foil air bearings. A motor controller drives and controls the motor, which is capable of driving the turbocompressor to the maximum design speed. The air bearings are lubrication free in addition to being lightweight, compact, and self-sustaining. Thus, no pressurized air is required for operation. The current turbocompressor operates by drawing in ambient air through the motor/bearing cavities, where it is pressurized by the compressor, delivered to the fuel cell stack, used to oxidize any excess fuel in a tailgas combustor, then expanded through the turbine to aid in the overall turbocompressor/fuel cell system efficiency.

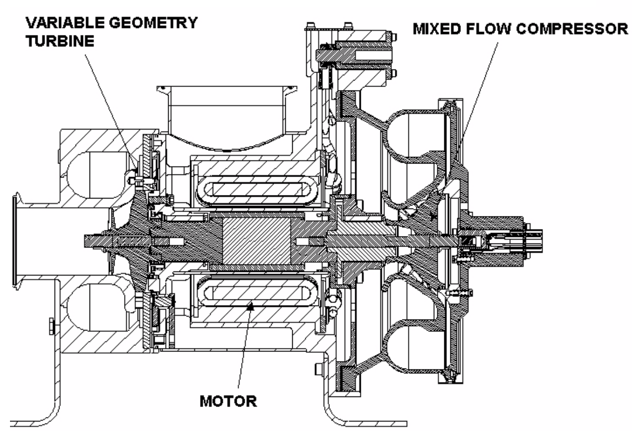

Figure 2. Cross Section of Fuel Cell Turbocompressor with Mixed Flow Compressor and VNT®

Results

The current turbocompressor has operated for more than 450 hours at varying conditions. To date, a maximum speed of 110 krpm has been attained.

To support the DOE/Honeywell fuel cell brassboard system testing, the turbocompressor was modified to handle increased turbine inlet temperatures. In addition, a modified aerospace quality motor/controller was assembled and used in the DOE/Honeywell fuel cell brassboard system, replacing a previously used motor/controller commercial unit. Testing of the DOE/Honeywell fuel cell brassboard system was initiated in late 2000 and is expected to be completed in mid 2002.

The turbocompressor and vehicle-ready motor controller was analyzed, designed, fabricated, and tested (see Figures 1, 2, and 3, and Table 1). The turbocompressor incorporates a mixed flow compressor and a VNT® variable nozzle turbine. These features were incorporated to improve the low-flow performance while maintaining efficiency across the flow range. These changes included the following: the redesigned mixed flow compressor improved low flow performance with an improved surge line; however, the VNT® variable nozzle turbine, which would have further improved performance and, consequently, lowered overall power consumption, was not tested due to program constraints. The vehicle-ready motor controller is of reduced size. Although its new technology requiring no sensors was not incorporated due to project constraints, the controller topology is configured to reduce production costs. Predicted performance of the turbocompressor and motor controller with the mixed flow compressor test results is presented in Figure 4.

Conclusions/Future Work

The turbocompressor concept using self-sustaining compliant foil air bearings has demonstrated low power consumption and moderate pressure ratio at low flow rates in a compact lightweight package. Predicted power consumption, which includes the predicted effects of the VNT® variable turbine nozzle can be further reduced if increased expander/turbine temperatures can be provided by the fuel cell system. The turbocompressor, capable of increased expander/ turbine temperatures, continues to be demonstrated in the DOE/Honeywell 50-kW fuel cell brassboard system. The latest turbocompressor with mixed flow compressor and variable inlet nozzle turbine technology, which, however, has not been utilized to date, demonstrated improved low-flow performance,

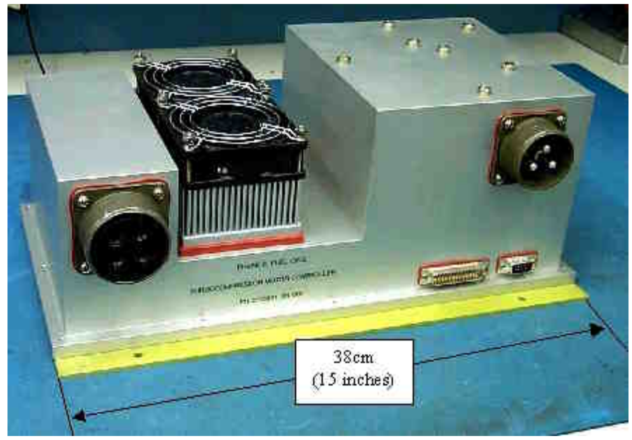

Figure 3. Fuel Cell Turbocompressor Motor Controller

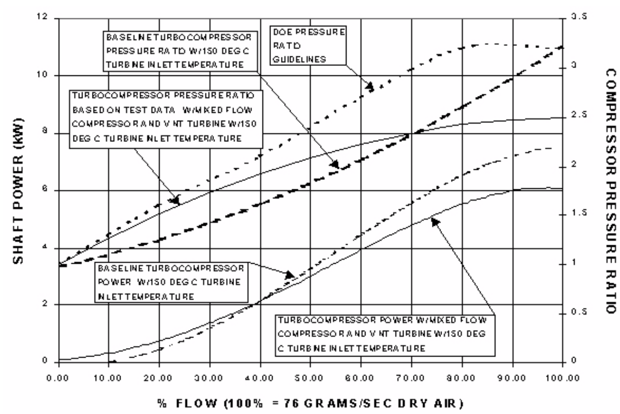

Figure 4. Turbocompressor Shaft Power/Compressor Outlet Pressure Ratio vs. % Flow

DOE Parameters	DOE Guidelines	Honeywell Turbocompressor
Volume	4 liters total (w/o heat exchangers)	Turbocompr.: 6 liters Controller: 13 liters
Weight	3 kg total (w/o heat exchangers)	Turbocompr.: 9 kg max Controller: 6.5 kg max

Table 1. Fuel Cell Turbocompressor Physical Parameters

while the latest variable speed motor/controller demonstrated reduced size, weight, reliability, and cost. Future work will investigate turbocompressor designs that incorporate flexibility to better meet the various vehicle fuel cell system developers' needs in the rapidly changing vehicle fuel cell system market, while continuing to improve performance and reduce cost.

IV.E.2 Development and Testing of a High Efficiency Integrated Compressor/ Expander Based on Toroidal Intersecting Vane Machine Geometry

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Objectives

- Develop a Toroidal Intersecting Vane Machine (TIVM)-based air management system that satisfies DOE's 50-kWe automotive fuel cell system requirements and is readily adaptable to alternate user requirements.
- Select and demonstrate design features to assure adequate sealing, minimum porting pressure loss, and low friction operation.
- Measure the performance of the TIVM compressor/expander across the operating range.
- Fabricate and deliver a compressor/expander/motor prototype for independent testing.

Approach

- Test candidate materials for friction and wear using standard laboratory tribilogical methods.
- Test candidate seal and port designs as well as low friction materials in simplified test configurations to select the best performing options for the TIVM compressor/expander.
- Optimize the vane surface solution methodology to provide a more efficient design process.
- Fabricate a TIVM compressor/expander prototype using seals, porting, and materials selected from the simplified feature tests and evaluations.
- Conduct performance tests of the prototype covering the full operating range.
- Refine the prototype features as necessary to obtain optimal performance.
- Integrate a high efficiency motor with the TIVM prototype and test the combined unit across the operating range.
- Deliver a TIVM compressor/expander/motor prototype to ANL for testing.

Accomplishments

- Initial friction and wear tests have identified one suitable material pair for the TIVM operating conditions and lifetime requirement. Additional tests are underway.
- A simplified single vane test rig has been designed for screening of seal and port designs and low friction materials. Hardware has been procured and assembly is in progress.
- CFD calculations have been initiated to guide seal and port designs.
- Analyses have been performed to determine port flow area and timing requirements.

- Design optimization has reduced maximum speed from 4800 rpm to 3500 rpm with no increase in volume.
- A Linear Intersecting Vane Machine test device has been designed to allow simplified testing of vane interaction features.
- Experimental expander vanes are being fabricated to potentially qualify a unique powder metallurgy process that provides net shape, finish, and hardness without secondary operations.
- A theoretical mathematical analysis of the surface solution methodology has been initiated.
- Initial thermal analyses have been performed to evaluate geometric changes caused by differential thermal expansion.

Future Directions

- Screening tests will be performed in the single vane test device using candidate seals and ports as well as low friction materials. Results will be evaluated to select the best options and to identify additional options to be tested.
- The Linear Intersecting Vane Machine test device will be fabricated and used with selected seals, ports, and low friction materials to provide basic performance data applicable to the TIVM and to further down-select options.
- The best performing design and material options will be implemented in a fully functional TIVM compressor/expander prototype, which will be tested across the operating range using Mechanology's automated test stand.
- The TIVM prototype will be refined based on empirical and analytical data to optimize performance.
- A high efficiency motor will be integrated with the TIVM compressor/expander and a prototype compressor/expander/motor unit will be fabricated and delivered to ANL for independent testing.

Introduction

The Toroidal Intersecting Vane Machine (TIVM) is an innovative mechanical concept, invented and patented by Mechanology, that can be configured as an integrated, positive displacement compressor/expander or compressor/compressor. In FY99 DOE investigated the TIVM concept for potential application to automotive fuel cell systems and determined that the inherent efficiency, compactness and thermodynamic attributes of this concept might be of significant benefit. Mechanology developed a prototype design specifically for the 50-kWe automotive system and evaluated its potential performance. Based on the encouraging results obtained, a first generation compressor/expander prototype was built and tested. Figure 1 illustrates this prototype partially assembled to show the compressor and expander. The compressor/expander prototype tests indicated that the TIVM runs smoothly with no mechanical problems; however,

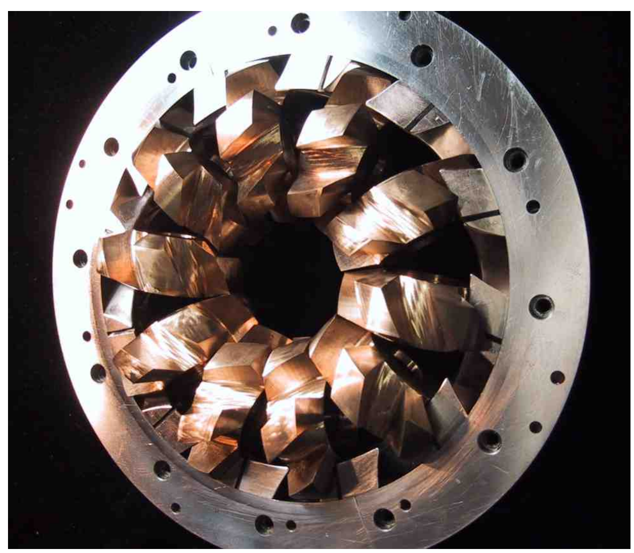

Figure 1. Partially Assembled First Generation TIVM Compressor/Expander Prototype

improvements are required to limit air leakage. Additional tests using the generic prototype with temporary seals demonstrated the capability of the TIVM to produce the necessary flow and pressure. The TIVM compressor/expander development plan was subsequently refocused on development and demonstration of seals, ports, and low friction materials. These are necessary to satisfy the functional performance requirements with low parasitic power. Although not the main focus of the current development program, the requirements for air management system packaging, noise, and cost are also considered critical for a successful TIVM based system and are carefully considered as development progresses.

Approach

The basic functions of the TIVM compressor/expander (kinematics, pressure, flow) have been demonstrated; however, development and qualification of specific seals, flow ports, and low friction materials are required to meet the performance requirements.

During 2002 Mechanology has focused on the use of simplified feature tests to allow rapid, efficient characterization of a broad range of design options for later inclusion in a full TIVM device. The initial simplified tests use a single vane test device to measure the leakage and friction characteristics of candidate vane seal designs and the effectiveness of alternate flow port designs. Computational Fluid Dynamics (CFD) analysis of the vane/housing/air interactions will be used to guide the design and testing of these features. Additional tests will be performed using a Linear Intersecting Vane Machine (LIVM) which introduces the vane interactions in simplified geometry. These tests will be used to further screen seal, port, and material candidates.

Definition of the vane surface configurations required for a specific TIVM can be accomplished through an iterative process developed by Mechanology. With sufficient iterations, a very good meshing surface solution can be obtained, as evidenced by the generic TIVM prototype vanes. However, this process is quite time consuming. Mechanology is exploring alternate mathematical approaches to develop a more efficient surface design methodology.

Low friction materials are necessary for the intersecting vanes to realize the predicted energy efficiency of the TIVM compressor/expander. Additionally, these materials must have sufficiently low wear under the TIVM operating conditions to perform acceptably during a 6,000-hour lifetime. Several candidate material pairs and potential coatings have been identified based on published data. To qualify materials for the TIVM, standard laboratory friction and wear tests are being performed. Successful materials will be tested in the single vane and LIVM devices, and the best materials will be used in a TIVM prototype.

One or more full TIVM compressor/expander prototypes will be fabricated by Mechanology and tested across the full operating range. Modifications will be made as necessary to optimize performance. Subsequently, a high efficiency electric motor will be integrated with the TIVM to form a complete compressor/expander/motor (CEM) component. This unit will be tested by Mechanology and then delivered to ANL for independent testing.

Results

ANL has constructed a tribology test rig that operates at the speed and interface pressure of the TIVM compressor/expander vanes at full power. This test rig is depicted in Figure 2. Initial dry friction and wear tests with stainless steel and low friction engineered polymer samples provided by Mechanology have indicated an acceptable friction coefficient at the TIVM operating conditions and wear rate consistent with the lifetime requirement. Additional tests are being conducted with high humidity and different material combinations.

A simplified single vane test rig has been designed for screening of seal and port designs and testing of low friction materials with vanes traveling at speeds in the planned operating range. The single vane test device design with the pressure cover removed is illustrated in Figure 3. This device is designed to permit parametric variation of clearances and seal preloads as well as rapid change out of materials and seal designs. Test hardware and

Figure 2. ANL Tribology Test Equipment

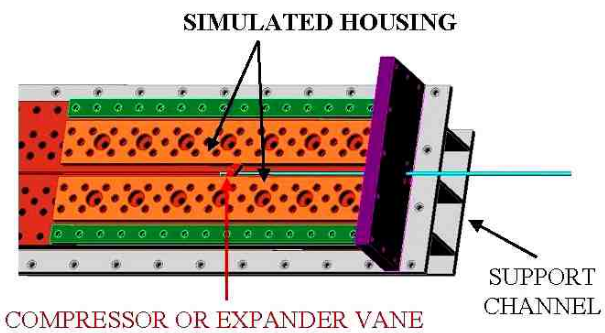

Figure 3. Single Vane Test Apparatus Design

instrumentation have been procured, and assembly is in progress. A computer control and data acquisition program has been written to allow testing at specified speeds and pressure differentials with automated data logging.

CFD calculations have been initiated at ANL using Mechanology's single vane test configuration. These analyses will be used to understand the interaction of the vane/seal/air system as a function of operating conditions and to guide seal and port designs.

Optimization of the geometry detail has reduced the speed required for 100% flow from 4800 rpm for the first generation TIVM to 3500 rpm for later generations with no increase in the component

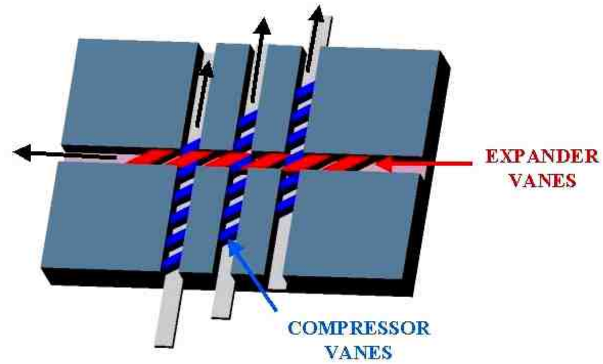

Figure 4. Linear Intersecting Vane Machine Design

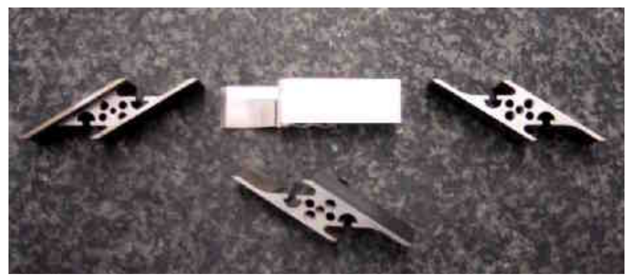

Figure 5. Vanes for Linear Intersecting Vane Machine Testing

overall dimensions. This has reduced the peak vane interaction speed by 25%.

A Linear Intersecting Vane Machine (LIVM) test device has been designed to allow simplified, rapid testing of vane interaction features. The LIVM design is shown schematically in Figure 4. The expander vanes in the LIVM, just as in the actual TIVM, drive the compressor vanes. The LIVM is instrumented to measure flows and pressures in the compression and expansion chambers as well as the force required as a function of time. Figure 5 shows an initial set of compressor vanes, with cutouts to accommodate various seal design inserts, to be tested in the LIVM.

Conclusions/Future Work

Design and analysis of the first generation TIVM compressor/expander has shown that this concept has the potential to meet the DOE requirements for automotive fuel cell applications with better performance than many other options. Testing of the compressor/expander and generic TIVM prototypes has demonstrated correct kinematic functioning and the capability to produce the required pressure and flow. These tests have also highlighted the need for efficient seals and flow ports in the TIVM. Laboratory tribology measurements have indicated acceptably low friction and wear for one of the material pair candidates for the intersecting vanes. The ongoing development program is focusing on selection of seals, porting, and material options through simplified feature tests and then, sequentially, more prototypic TIVM tests. A full prototype TIVM compressor/expander/motor will be fabricated and tested to measure actual performance with the selected options. Subsequent work will include development and qualification of cost efficient manufacturing methods for high volume production and development of features to assure compliance with noise requirements. Additional testing will focus on the operating environment and reliability/endurance issues.

FY 2002 Publications/Presentations

1. Toroidal Air Management System Development and Testing Status, presented to the FreedomCAR Technical Team, April 17, 2002.

IV.E.3 Turbocompressor for Vehicular Fuel Cell Service

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Subcontractors: MarNor Enterprises, Newport Beach, CA (instrumentation); FD Contours, Costa Mesa, CA; Prestige Mold, Santa Ana, CA (fabrication)

Objectives

- Test the design and performance of air bearings for turbocompressors.
- Test the performance of the expander and compressor for fuel cell system service.
- Test the endurance of Argonne National Laboratory's (ANL's) near-frictionless carbon (NFC) coatings in air bearings.

Approach

- Design, build, and test a specialized, instrumented test rig for measuring the performance of a new, high performance air bearing.
- Measure the performance of the DOE/Argonne near-frictionless carbon coating.
- Design, build, and test the prototype of a turbocompressor system supplying 76 g/sec of air for a fuel cell rated for 50-kWe output.

Accomplishments

- Demonstrated a mechanically simple (leafless) journal bearing for small (~1 kg weight, ~2 cm shaft diameter) rotors with lift-off and landing speeds of about 900 RPM, corresponding to a rubbing speed of about 1 m/s and a total rub of about 2 m per start-stop cycle.
- Completed over 10,000 start-stop cycles with minimal NFC wear during NFC endurance testing; also demonstrated 3,700 start-stop cycles with DuPont Vespel journals and 1,300 start-stop cycles with DuPont Delrin journals.
- Demonstrated radial bearing take-off and landing without any low friction coatings (i.e. steel-on-steel surfaces) using a low-acceleration startup.
- Demonstrated radial and thrust bearing rotordynamic stability to 27,000 RPM.
- Demonstrated a mechanically simple self-centering thrust bearing with a stiffness of 1.92 kilo-Newton/mm (11.0 klb/in) at 20,000 RPM and 6 psig bearing feed pressure, increasing to 4.50 kn/mm (25.7 klb/in) at 20,000 RPM and 12 psig bearing feed pressure.
- Integrated prototype air bearing turbocompressor with commercial automotive positive-displacement compressor, instrumentation, and test bench.

- Demonstrated turbocompressor expander, radial bearing, thrust bearing, and compressor performance to 33,000 RPM.

Future Directions

- Complete performance testing of bearings and turbocompressor prototype to design speed.

Introduction

Meruit Inc. has developed a novel air bearing for use in a small high-performance automotive fuel cell turbocompressor. A suitable air bearing must be inexpensive, durable, stable, and stiff enough to survive the automotive environment. Meruit has one main task: to validate its air bearing for automotive compressor/expander use. Development of an air bearing turbocompressor meeting DOE's specifications was also pursued under the project.

Approach

A specialized test rig was designed, built and instrumented to investigate the radial (journal) lift-off and landing performance, radial bearing longevity with low-friction coatings, radial bearing rotordynamic stability, and thrust bearing stiffness. Meruit's mechanically simple (i.e. cost effective) bearing demonstrated floating, non-contact operation, low lift-off and landing speeds, over 10,000 start-stop cycles, high stiffness, and rotordynamic stability to the test rig limit of 27,000 RPM.

A prototype turbocompressor using this air bearing system, designed to deliver the DOE-specified mass flows and pressure ratios, was built, integrated into an instrumented turbocompressor test bench simulating an automotive air system with an in-line positive-displacement compressor, and demonstrated to 33,000 RPM (35% of design speed).

Results

Radial (Journal) Bearing Lift-off

It was experimentally determined that while a large diameter (>75 mm) radial (journal) gas bearing would easily float a steel bearing in steel journals, the scaled-down (~20 mm) gas bearings intended for the DOE application would not lift off ("float") satisfactorily. This condition, present only when the shaft begins to turn from rest, could be remedied by lowering the coefficient of friction between the journal and gas bearing, and several low friction remedies were found to work: DuPont *Vespel,* DuPont *Delrin,* and ANL's *Near Frictionless Carbon* (NFC). Since the Meruit bearing only suffers wear on take-off or landing, the longevity of the bearing is measured in number of start-stop cycles (rather than operating hours). A bearing test rig was configured as an endurance tester to cycle the tested materials. For one start-stop cycle, the drive air is turned on, accelerating the rotor past the lift-off point; the air is turned off; and the coasting rotor floats until it lands and slows to a stop. Steel bearings with Vespel bushings in the journal were tested to 3,700 cycles; steel bearings with Delrin bushings were tested to 1,300 cycles; and both bearings could have continued for more cycles.

ANL applied a NFC to the bearing shaft, which was tested with uncoated steel bushings. It was found that the bearing floated the ~1 kg rotor at just over 900 RPM with about 1 m of sliding contact and a rubbing speed of about 1 m/s. One NFC trial coating reached 5,800 cycles, and another reached 10,200 start-stop cycles.

Modeling of the take-off process revealed that another way to achieve a clean take-off was to reduce angular acceleration ("slow start"). This was experimentally confirmed with bare steel bearings on bare steel journals.

Radial Bearing Rotordynamic Stability

It was determined that while the large diameter (>75 mm) three-lobe gas bearing could be accelerated to 30,000 RPM with no evidence of rotordynamic instability, the scaled-down ~20 mm bearing became unstable at about 14,000 RPM. This instability was not a resonance that could be accelerated through; higher speed operation led to repeated bearing contact with the journal and eventual bearing destruction. CFD modeling suggested that at the smaller diameter, a four-lobe design would be stable over the entire design speed range. Several shafts with four lobes were designed, built, and tested with and without NFC coating. A ~20 mm four-lobe shaft, otherwise identical to the three-lobe shaft, floated at a slightly higher (~950) RPM than the three-lobe shaft, but was shown to be stable to the test rig limit of 27,000 RPM (almost twice the critical speed of the three-lobe bearing). A 23-mm shaft demonstrated stability to 33,000 RPM in the turbocompressor test rig.

Axial (Thrust) Bearing Stiffness

Another aspect of the bearing test program was the experimental measurement of the thrust bearing's stiffness, force, and damping properties. The thrust bearing's stiffness is computed to increase with bearing feed air pressure, air temperature, and RPM; any increase in these values leads to a stiffer bearing with a more strongly damped response to shocks. Even a slight air flow through the bearing at zero RPM will center the bearing in its clearance and provide some stiffness. The test rig was configured with a thrust piston to apply controlled axial loads and instrumented to measure the resultant axial displacement as a function of bearing feed air pressure at speeds ranging from zero to 27,000 RPM.

The measured stiffness at about 20,000 RPM was found to range from 1.92 kn/mm (11,000 lbs/in) at a feed pressure of 41.3 kPa (6 psig) to 4.50 kn/mm (25,700 lb/in) at 82.7 kPa (12 psig). The measured stiffness at a constant feed pressure of 6 psig at speeds of 21,000 and 27,000 RPM was found to be 1.92 kn/mm (11,000 lb/in) and 2.24 kn/mm (12,800 lb/in) respectively. These speeds are low compared to the design turbocompressor speed of 95,000 RPM, and yet the bearing still generates substantial and useful centering forces that resist thrust loads. Bearing air consumption was measured at about 0.08 g/sec, which is negligible in comparison to the 76 g/sec design air flow of the DOE turbocompressor.

Air System and Turbocompressor Design/ Performance Testing

To make up the difference between the expected expander returned power and the required compressor input power, Meruit designed an air system using a commercially available positive-displacement compressor driven by an electric motor in tandem with Meruit's turbocompressor. Meruit designed a family of compressor and expander wheels with varying characteristics (specific speed, dimensional ratios, etc.) representing different compromises in providing performance compatible with the DOE specifications. After extensive evaluation, a compressor wheel was chosen to provide a desired pressure curve over a wide range of mass flows, and a turbine wheel was matched to it. The chosen compressor wheel is intended to trade peak efficiency for extended turndown performance.

The basic expander configuration comprises variable inlet vanes (nozzle segments) for the control of back pressure and mass flow for matching the performance of the compressor. Figure 1 presents the geometry of the inlet vanes and their relationship to the blades of the turbine wheel. The turbocompressor uses Meruit's radial and thrust gas bearings with ANL's NFC coating; the rotor is illustrated in Figure 2, and the turbocompressor body without the expander and compressor housings is presented in Figure 3.

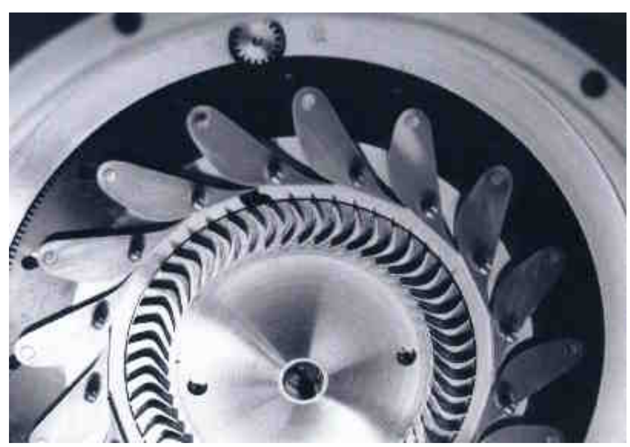

Figure 1. Meruit Variable Nozzle Expander

Figure 2. Meruit Turbocompressor Rotor

Figure 3. Meruit Turbocompressor Body

Using the valving of the test rig and the variable nozzles of the turbocompressor, the expander can be tested through a full range of nozzle openings from zero to 115% at various turbine feed pressures and mass flows. The compressor can be independently evaluated over a range of mass flows at each value of RPM. After the four-lobe bearing was demonstrated in the bearing test rig, the turbocompressor was fitted with a 23-mm four-lobe bearing. At the speeds tested to date (i.e. one-third of design speed), the compressor generates very little pressure (i.e. about one-ninth of design pressure), but all of the compressor performance data available so far indicate the designed pressure-to-mass flow performance with increases in mass flow at each speed.

Conclusions/Future Directions

Meruit's leafless radial air bearing for small shafts has demonstrated low-speed lift-off and landing, trouble-free take-off, longevity, stiffness, and stability to moderate speeds. The leafless thrust bearing has demonstrated self-centering at zero speed and adequate stiffness at moderate speeds for automotive applications. Meruit's turbocompressor using these air bearings has demonstrated the desired flat pressure performance to the speeds tested so far. Work continues to demonstrate rotordynamic stability and turbocompressor performance at higher speeds.

References

1. Ajayi, O.O. et al. 2002. *"Low Friction Coatings for Fuel Cell Turbocompressors"*, in *DOE 2002 Review OTT Fuel Cells Program*, U.S. Department of Energy Office of Transportation Technology, May 2002.

IV.E.4 Motor Blower Technologies for Fuel Cell Automotive Power Systems

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Subcontractors: Phoenix Analysis and Design Technologies (PADT), Phoenix, AZ; R&D Dynamics, Bloomfield, CT

Objectives

- Develop small, lightweight, motor driven blowers to provide cathode air and fuel processor air for a near ambient pressure fuel cell operating on gasoline.
- Demonstrate the performance of various types of air blowers via integration into a power plant.
- Evaluate both fuel processor air blower approaches, regenerative and centrifugal, and identify which technology is superior.
- Identify and develop manufacturing methods that will allow the blowers to be produced at low cost in large production volumes.

Approach

- Define performance requirements, flows, pressures, and temperatures, as well as cost and life targets, for both the cathode and fuel processor air blowers.
- PADT will develop and build a mixed flow type blower to meet requirements for cathode air and a regenerative type blower to meet fuel processor air requirements. Prototypes will be used to evaluate aerodynamic performance as well as life and durability.
- R&D Dynamics will develop and build a high-speed centrifugal machine supported by air bearings to meet the fuel processor air requirements.
- UTC Fuel Cells will demonstrate operability and performance of both approaches by integrating the units into a power plant.

Accomplishments

- Requirements for both the cathode air blower and fuel processor air blowers have been defined and documented.
- PADT has completed design of the mixed flow axial cathode and regenerative fuel processor air blowers.
- PADT has developed and calibrated a regenerative wheel performance model.
- R&D Dynamics has completed design of a high-speed centrifugal machine for the fuel processor air blower utilizing air bearings.

Future Directions

- Complete the prototype production of all three machines.
- Complete performance and endurance testing of all three blower types.
- Integrate blowers into a fuel cell power plant and test for operability.

Introduction

Near ambient pressure fuel cells running on gasoline require two sources of air, one for the fuel cell cathode and one for the gasoline fuel processor, which generates hydrogen. Due to the relative pressure differences required by the two applications, it is not energy efficient to fulfill the two air requirements with a single blower/compressor as is commonly utilized in pressurized type fuel cell systems. This project will define different types of machines to meet each air supply requirement; specifically, one type of machine will be evaluated for the low-pressure cathode air blower, and two other different types of machines will be evaluated for the higher-pressure fuel processor air blower. Air blower development targets are presented in Table 1.

Capabilities	Cathode Air Blower	Fuel Processor Air Blower
Max Flow Rate (cfm)	170	70
Pressure Rise	1 psi	12 psi
Ambient Temperature (F)	-40 – 140	-40 – 140
Overall Efficiency[a]		
100% flow	60%	50%
25% flow	35%	30%
Production Unit Cost[b] @100,000 units/yr	\$75	\$75
Service Life (hrs)	5000	5000
Power Supply	200 Vdc	200 Vdc

a Includes motor, controller, mechanical and isentropic efficiency
b Includes motor controller and blower

Table 1. Blower Development Targets

Approach

For the near ambient pressure cathode air blower application, the best machine is clearly a mixed flow type of axial blower. This type of machine, illustrated in Figure 1, yields excellent overall efficiency in a very compact package and can be produced, in quantity, at a relatively low cost. Specific speed analysis indicates that a mixed flow machine will yield a high efficiency machine at reasonable rotational speeds. In this project, PADT will design, build, and test an optimized mixed flow blower which meets the performance requirements established and is readily producible using standard manufacturing processes.

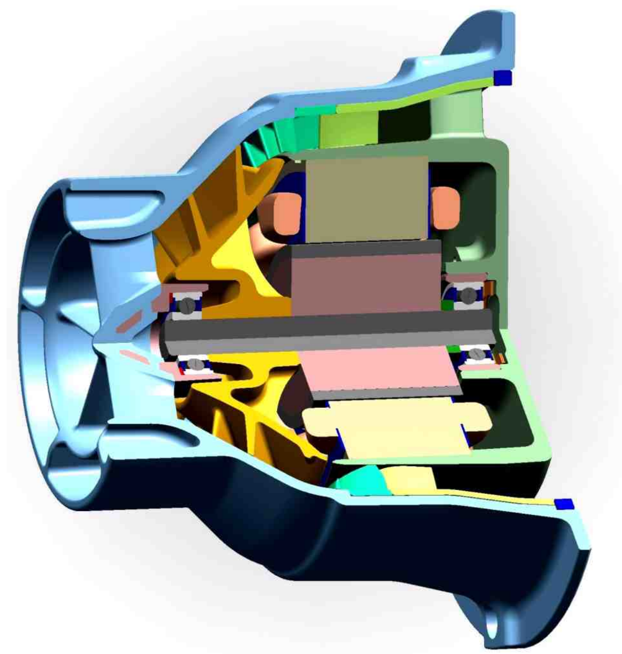

Figure 1. Solid Model of PADT Designed Cathode Air Blower

For the higher pressure fuel processor air blower application, the optimal type of machine is not as clear. As part of the preliminary sizing, a variety of machines were evaluated, including rotary lobe, sliding vane, radial, centrifugal, and regenerative. Although the rotary lobe and sliding vane type machines could be developed to yield high overall efficiencies, they were eliminated as a result of other, non-aerodynamic requirements, primarily concerns regarding excessive size and weight, limited life capability due to wear, and higher production cost due to the need for more precise control of part dimensions and clearances.

A radial type centrifugal machine was viewed to be an excellent overall choice because parts can be mass-produced at a low cost and life should be acceptable. However, in order to achieve peak efficiency and small size, the rotational speed needs to be high, far exceeding the capability of conventional low cost bearings. R&D Dynamics is presently working to develop a machine utilizing air bearings, thereby eliminating the life and speed limitation of conventional grease packed bearings. We believe that R&D Dynamics's proprietary air bearing design can be mass produced at costs consistent with our overall goals and thus have begun development of a high speed (150,000 rpm) radial type, centrifugal machine as shown in Figure 2.

Another equally viable approach to the fuel processing system (FPS) air blower is the regenerative type machine being developed by PADT. The regenerative machine as shown in Figure 3 allows for higher-pressure generation at lower rotational speed. This machine is presently being designed to run at 26,000 rpm and will utilize traditional, low cost, grease packed roller bearings. The theoretical maximum efficiency is not as high as the high-speed radial machine, but the low speed approach minimizes concerns with bearing life, thereby mitigating risk. Two critical tasks in the design of this machine will be to optimize the impeller geometry to obtain peak isentropic efficiencies while minimizing the number of critical clearances and tolerances, and to evaluate cooling schemes and their effect on the overall efficiency and cost of the machine.

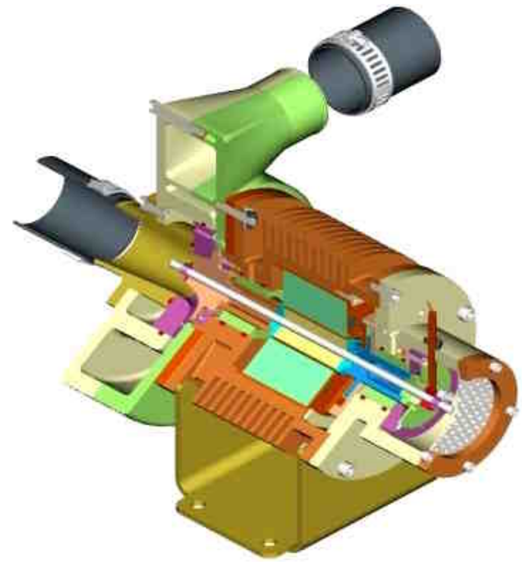

Figure 2. Solid Model of R&D Dynamics Designed Fuel Processor Air Blower

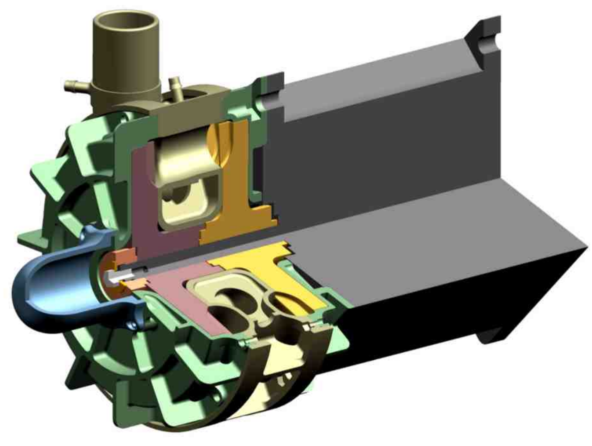

Figure 3. Solid Model of PADT Designed Fuel Processor Air Blower

Results

Work to date has resulted in evolving designs for all three blowers, as shown in Figures 1, 2 and 3. All three designs utilized a typical turbo-machine design process that included tasks such as specific speed analysis, blade optimization, rotor-dynamic analysis, bearing analysis, thermal analysis, and motor optimization studies. Each machine has been designed to be small, yield high efficiency, and be manufacturable utilizing standard production methods commonly found in industry today.

Due to the low weight and small volume requirements dictated by a transportation application, power density is much higher in these machines than in equivalent performing, commercially available machines. Thus, removal of heat from the motor becomes a challenge. This issue of motor cooling has been a particularly troublesome task for all of the blower designs. Heat rejection in the PADT designed regenerative impeller FPS air blower has been particularly challenging, primarily due to the

	Motor Winding Temp	*Motor Housing Temp*	*Pump Head Temp*
Air Cooling	295°C	155°C	155°C
With thermal isolation	267°C	127°C	161°C
Thermal isolation & potted windings	197°C	127°C	160°C
Water Cooling	282°C	142°C	142°C
With thermal isolation	226°C	86°C	160°C
Thermal isolation & potted windings	156°C	86°C	160°C
Note: The above numbers presume a 90%-92% efficient motor and a pump head isentropic efficiency of 40%. These efficiencies are critical to selecting the proper cooling approach and will be validated by testing by the motor and pump head design.			

Table 2. Results of PADT Fuel Processor Blower Thermal Analysis

relatively low efficiency of the pump head. This low efficiency requires the motor to produce more shaft power and thus results in a larger amount of motor waste heat that needs to be rejected. A thermal model has been developed and is being used as a tool to evaluate water cooling and a variety of air cooling techniques. Some of the output from this model, using conservative estimates for motor efficiency, is presented in Table 2. This data was evaluated and the following conclusions were made:

- Sustained operation at the maximum power condition may require water cooling. The water temperature will need to be less than 40°C.
- Thermal isolation between the pump and motor housings will reduce motor winding temperature but increase the forward bearing temperature in excess of 140°C, which is detrimental to the bearing lube.
- Motor windings, which are thermally potted to the motor casing, will decrease the winding temperature and may allow air cooling if motor efficiency is 90%-92%.
- Motor efficiencies greater than 92% may allow air cooling without thermally potting the motor windings.

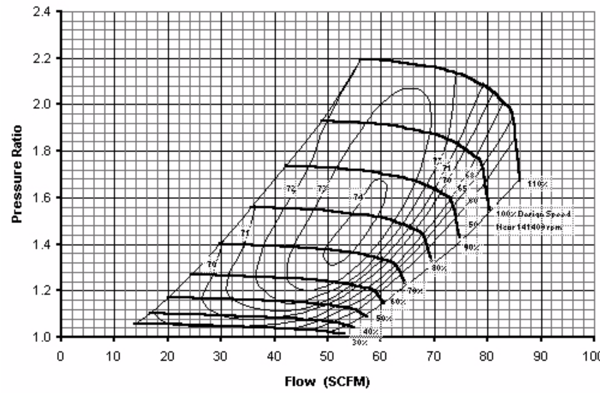

Figure 4. Predicted Performance of R&D Dynamics Fuel Processor Blower

In the case of the R&D Dynamics machine, the isentropic efficiency of the machine is high; therefore, the shaft power required is lower than that required for the regenerative unit, and the amount of waste heat generated by the motor is lower. The predicted performance of this machine is presented in Figure 4. Because of this, placing fins on the motor casing and ducting air over the fins can cool the motor. The amount of cooling air is expected to be minimal and will be verified through thermal testing of the first prototype unit.

For the near ambient pressure PADT cathode air blower machine, depicted in Figure 1, heat rejection is accomplished by rejecting energy from the motor housing directly to the process air, utilizing the mixed flow cathode air blower design itself. This technique is possible for several reasons. The axial geometry of the blower lends itself to this type of approach; the amount of work done on the process fluid is fairly small and the volumetric flow rate relatively high; thus, the temperature rise of the process air is very small, and a large temperature differential exists between the motor housing and the process air.

Conclusions/Future Directions

PADT is presently building an aerodynamic development rig that will be used to validate a model that was developed to predict aerodynamic performance of their fuel processor blower. Prototype motors have been designed and will be tested to establish "real-world" efficiencies. R&D Dynamics has manufactured blowers with both radial and thrust air bearings and is preparing to run these units in a test rig to determine the load capability of each bearing.

All three designs are nearly completed and production of parts for the prototype units has begun. Two prototype units for all three designs will be complete by November 2002. Performance testing of the units will commence immediately thereafter to verify aerodynamic performance and efficiency of each design.

IV.E.5 Hybrid Compressor/Expander Module

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Subcontractors: Concepts NREC, White River Junction, VT; Scroll Corporation, Carlisle, MA

Objective

- Based on the experience of two previous generations of scroll-based compressor/expander modules developed with DOE, design and build a hybrid compressor/expander module using both turbomachinery and scroll compression.
- Develop the algorithms and hardware to ensure stable and effective control of the hybrid system.
- Deliver a system with equivalent thermodynamic performance, at significantly lower weight and volume, when compared to previous generations of scroll compressor/expander modules.

Approach

- In the first year, develop system architecture and subsystem designs consistent with the overall goals of maintaining thermodynamic performance while reducing weight and volume relative to previous generations.
- In the second year, complete detailed engineering and initiate fabrication of subsystem components, and develop the control system hardware and algorithms.
- In the third and final year, complete fabrication of components and conduct subsystem assembly and test, followed by system integration and performance verification.

Accomplishments

- Defined basic system architecture, including preliminary allocation of performance requirements to subsystems.
- Initiated detailed design tradeoff studies for scroll machinery.

Future Directions

- Refine subsystem-level performance allocations.
- Initiate detailed design tradeoff studies for turbomachinery.
- Initiate breadboard scroll drive mechanism development and testing.

Introduction

Most current automotive fuel cell systems are designed for pressurized operation in order to reduce system size, boost stack efficiency, and improve water management. Applications for automobiles also require significant partial load capability, since the anticipated level of electrical energy storage is minimal. Due to the aggressive efficiency goals driving fuel cell development, the compressor must operate efficiently over a wide flow range, and efficient waste energy recovery in an expander or turbine is required to offset the compression load.

Traditionally, high-speed centrifugal technology, such as that used in automotive turbochargers, has resulted in a compact high-speed package that delivers high efficiency at the design point, but with performance that falls off dramatically under off-design conditions. Scroll technology, a type of positive displacement machinery, provides high efficiency across a broad range of operating conditions, but results in a package that is significantly larger and heavier than that of high-speed centrifugal technology.

The objective of this project is to develop a hybrid compressor/expander module, based on both scroll and high-speed centrifugal technologies, which will combine the strengths of each technology to create a concept with superior performance at minimal size and cost. The resulting combined system will have efficiency and pressure delivery capability comparable to that of a scroll-only machine, at significantly reduced system size and weight when compared to scroll-only designs.

Approach

The design approach for the Hybrid TurboScroll Compressor/Expander Module (CEM) exploits the experience of developing the first two generations of scroll CEMs, in combination with the substantial experience of our turbomachine subcontractor, Concepts NREC. (Figure 1 shows the Second Generation Scroll CEM on its test stand.) By combining the performance attributes of a positive displacement scroll compressor (electrically driven) with those of a turbocharger (driven by fuel cell exhaust gases), we expect to be able to very closely

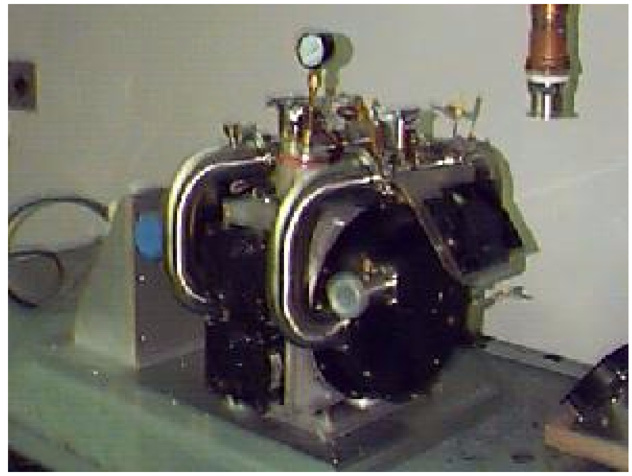

Figure 1. Second Generation Scroll Compressor/ Expander Module

match the pressure and flow requirements of the DOE guidelines in a package that is smaller and lighter than previous generations. Table 1 shows the weight and volume design goals for the program; with acknowledgement that these goals are still somewhat short of the DOE guidelines, they are clearly an improvement over the Second Generation Scroll.

Param.	Hybrid				2nd Gen. CEM
	Turbo	Scroll	Motor	Total	
Dia. (in)	6	7	7	7	12
Len. (in)	5	8	5	18	20
Vol. (l)	2.3	5	3	10.3	30
Wgt. (lb)	10	17	10	37	90

Table 1. Key Envelope Performance Goals for the Hybrid TurboScroll CEM

Our first step was the construction and testing of a breadboard model of the system, as shown in Figure 2. In this configuration, a conventional automotive turbocharger (in the foreground) was coupled to the scroll compressor portion of the First Generation Compressor/Expander Module (in the

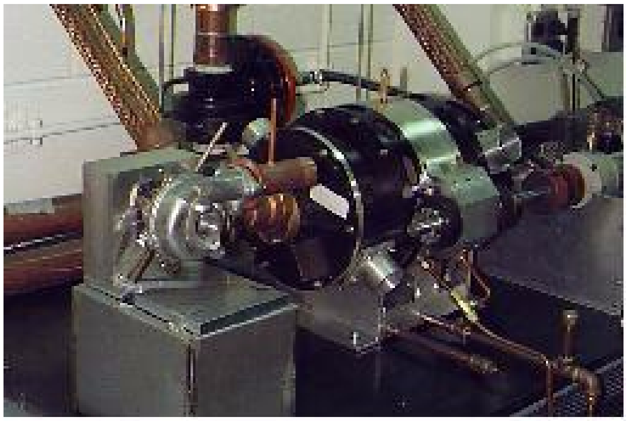

Figure 2. Breadboard Version of Hybrid TurboScroll CEM Configuration

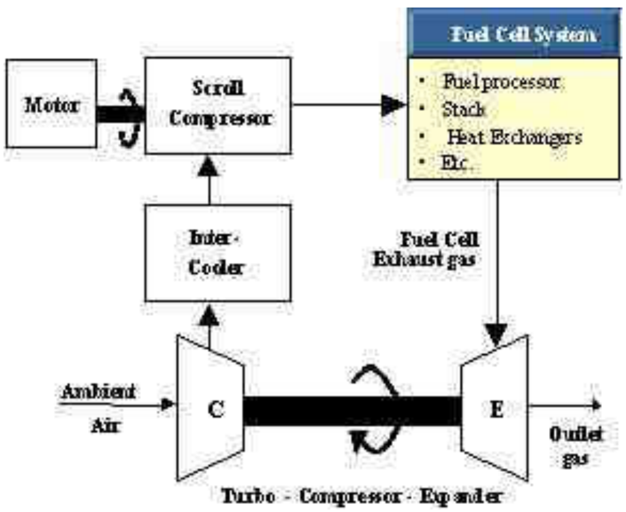

Figure 3. System Architecture of Hybrid TurboScroll CEM

background). The results of that preliminary exploratory testing, while not delivering the desired efficiency, were sufficiently promising to justify the system concept.

Next, the development of an appropriate system architecture resulted in the block diagram shown in Figure 3. In this configuration, the turbocompressor draws in atmospheric air and compresses it to an intermediate pressure. (Note that the specification of this intermediate pressure is a key element in assigning performance requirements to the subsystems.) In order to reduce both the size and operating temperature of the scroll compressor, an intercooler is provided to reject at least part of the heat of compression to the atmosphere. The partially compressed gas, now cooler and denser, is then fed into the scroll compressor, which uses electrical power to achieve the final compression of the gas. Finally, the compressed air is fed into the fuel cell, which increases its temperature and reduces its pressure slightly. The exhaust gas from the fuel cell drives the turbine (through controllable inlet guide vanes) and, with the bulk of its energy extracted, is expelled to the atmosphere. The turbine provides the shaft power to drive the compressor by direct coupling.

This architecture offers some important advantages:

- The turbocompressor is powered only by the turbine, eliminating the issues associated with coupling power into a high-speed rotating shaft.
- Turbine inlet guide vanes provide both inlet control and control of fuel cell stack pressure.
- The scroll compressor provides pressure and flow characteristics that enable efficient operation across a broad range of flow rates.

Capturing these advantages entails overcoming certain challenges:

- Control of coupled turbomachinery and positive displacement machinery,
- Power and waste heat management,
- Isolation of lubricants from the process gas stream, and
- Reduction of size, weight and cost.

Starting with the turbocharger, pictured in Figure 4, the approach to design involves balancing competing elements. Although clearly representing an increase in complexity and parts count, controllable inlet guide vanes for the turbine are considered a necessary minimum. Similar controls on compressor flow will be considered as part of the overall component design tradeoff study. In the interest of simplicity and conventionality, the initial design studies have focused on conventionally lubricated roller bearings. Management of the lubricant, though challenging, is considered more tractable at the present time that the integration of gas

Figure 4. Concepts NREC Baseline Turbocharger Design

bearings or other technologies. The intercooler between the turbocompressor and the scroll compressor has conventional performance requirements, and indeed the preliminary approach is to select an available automotive intercooler of the appropriate size and integrate it into the system.

For the scroll, the design approach has involved the detailed evaluation of three competing configuration options, shown in Figure 5. The first alternative was a conventional crank-driven orbiting scroll, supported on a roller-Oldham bearing system, with grease lubrication. This configuration has the substantial advantage of conventionality, enabling the direct utilization of knowledge gained in dozens of scroll compressor design programs. In the second configuration, the two opposing elements of the scroll both rotate, on offset axes, coordinated in such a way that their relative motion is orbital. The primary advantage of this configuration lies in the relatively conventional bearing configuration, offset in part by a relatively unconventional drive mechanism requirement. The third design gangs multiple scrolls on a common drive mechanism, offering the possibility of reduced noise with the accompanying penalty of a relatively complex drive mechanism.

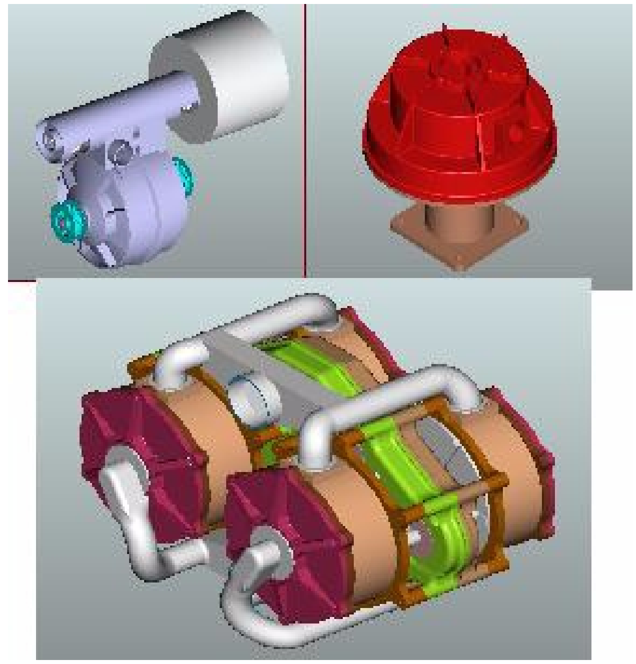

Figure 5. Three Alternate Scroll Compressor Preliminary Design Configurations

Each of the above alternatives was carried to the point of preliminary drive system sizing and overall subsystem layout. Based on that information, our evaluation of the alternatives has led to the selection of the conventional crank-driven orbital scroll as the primary design direction. This represents a conservative choice in the design of this system element, consistent with the overall need embodied in the program objectives to demonstrate the performance of the overall system concept.

The control and data management system configuration depends on both the data acquisition requirements and the control measurement and actuation means configured into the individual subsystems. Design of the hardware and algorithms are to commence following the completion of the preliminary subsystem designs. The test regimen for the subsystems, and ultimately the system as a whole, are anticipated to represent not merely a data acquisition phase, but an integration, test, and debugging phase.

Results

Having conducted a body of preliminary concept feasibility work, the design activities conducted in the first active quarter of this project have focused on the system configuration and the definition of key subsystem requirements. Preliminary designs have been completed for three alternative scroll compressor configurations, and a down-select to the primary configuration has been accomplished. Upcoming work will involve the refinement of key system interface definitions and initiation of detailed design activity for the turbocharger.

Conclusions

Continued, and progressively more detailed, investigation of the Hybrid TurboScroll CEM concept indicates no issues that seem to threaten the viability of the selected system architecture. A substantial degree of additional detailed system and component design work is required to fully explore the issues of practicality and performance, but the design team still believes that the promise of thermodynamic performance substantially equal to that of the Second Generation Scroll CEM, at a substantially reduced weight and volume, is not only achievable, but within reach.

IV.F Crosscutting Fuel Cell Analysis and Demonstration

IV.F.1 Precious Metal Availability and Cost Analysis for PEMFC Commercialization

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Objectives

- Assess current and projected demand for platinum group metals (PGMs) exclusive of fuel cell applications
- Estimate the relationships between supply capacity/reserves and long-term growth in demand for PGMs
- Develop an econometric model to simulate the impact of fuel cell market growth scenarios on PGM supply and pricing
- Perform a sensitivity analysis on supply and pricing to critical parameters in the model related to fuel cell markets and technology advances
- Obtain critical feedback from the important participants in the PGM value chain on the model assumptions and projections
- Develop a cost projection for the recycling of PGMs from fuel cells, and assess the impact on PGM supply and price

Approach

The project has been broken into five tasks as follows:

- Task 1: Collect historical PGM supply, demand, pricing and resource data
- Task 2: Develop fuel cell market commercialization scenarios
- Task 3: Develop PGM recycling scenarios including a high level PGM proten exchange membrane fuel cell (PEMFC) recycling cost model
- Task 4: Develop econometric model for the simulation of the impact of fuel cell introduction on PGM supply and price
- Task 5: Solicit feedback from PGM industry and automotive OEMs

Tasks 1 and 4 were scheduled for the fiscal years 2001 and 2002. The balance of the tasks will be completed in 2003.

Accomplishments

- Completed PGM data collection with inputs from literature sources, PGM industry reports, precious metal trading companies, and geology experts
- Developed econometric modeling approach and presented to PGM industry for feedback

Future Directions

- During the balance of 2002, complete development of the econometric model
- During 2003, develop fuel cell market and recycling scenarios for input to PGM supply and pricing simulation
- Run simulation to project impact of fuel cell commercialization on platinum pricing and supply
- During 2003, obtain feedback from PGM industry and automotive OEMs

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Introduction

Platinum group metals are critical to the commercialization of fuel cells, but they also represent a significant contribution to overall system cost. Depending on operating design parameters, platinum would represent 10 - 20% of the cost of a gasoline fuel cell system produced in high volume. PGMs (primarily platinum and some ruthenium) are critical to catalyzing reforming/shift reactions in the fuel processor and electrochemical oxidation and reduction in the fuel cell, with the fuel cell requirements presently dominating the demand.

Successful adoption of fuel cells in transportation applications over the long-term could create markets on the order of ten million vehicles, leading to significant pressure on PGM suppliers to increase production capacity and supply. Consideration of stationary and portable applications for fuel cells further increases the demands on PGM supplies. Clearly, the combination of stationary, portable and transportation markets for fuel cells will create pressure on the PGM industry to increase supplies and might cause rapidly escalating prices (thereby threatening fuel cell market viability) unless action is taken to guide the process.

The commercialization of fuel cells will also depend on the amount of economically mineable PGM resources and the ability of the PGM value chain to supply the PGM materials in the needed forms at reasonable markups above the London Metals Exchange (LME) price.

The relationship between supply, demand, and price of the PGMs is complicated by several factors, including: the geographical concentration of ore bodies in South Africa and Russia, the control of production by a limited number of companies in these regions, the impact of politics, and the impact of the world economy on demand and price. Significant new demands for PGMs can lead to price increases in the short-term and potentially in the long-term if supply capacity does not increase.

The large layered intrusions that host all the world's major PGM deposits can be easily identified even if covered to depths of a few kilometers by using regional gravity surveys. These rocks have high density and are easily recognizable in such studies. Hence, the likelihood of finding significant new deposits is not high. The discovery of new resources of PGM is likely to be limited to smaller intrusions that may provide small mining activities, but will not influence global production in a significant way.

Approach

The overall goal is not only to develop projections of PGM availability and cost, but also to identify and quantify the industry and market drivers influencing these parameters. On the demand side, we will break down the demand between existing markets and the potential applications of fuel cells. We will identify underlying trends in the industrial/ chemical and lifestyle markets with attention to growth of demand and potential for substitution of alternative materials. In the fuel cell markets, the impact of technology on PGM demands will also be considered.

The modeling approach starts with construction of an econometric model based on historic supply, demand, and price data. A simulation will then be run to study the impact of introduction of fuel cell vehicles on the supply and price of platinum. Figure 1 illustrates the steps in the modeling approach, and Figure 2 shows the structure and outputs of the econometric model.

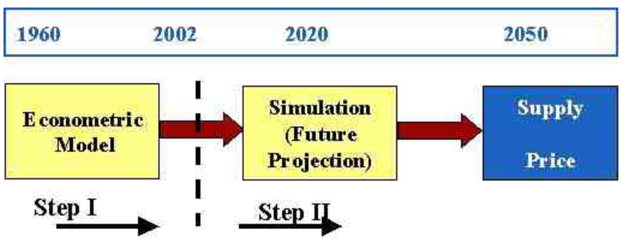

Figure 1. Overview of Modeling Steps in Development of Future Projections of Supply and Price of Platinum

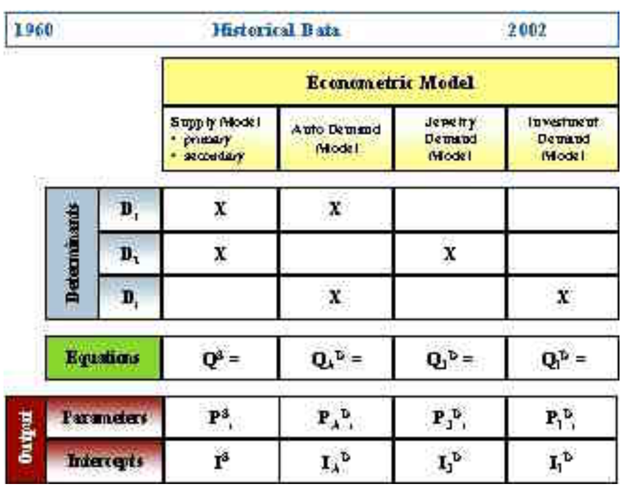

Figure 2. Structure of the Econometric Model and Outputs

Automotive catalysts and jewelry are the two dominant markets for platinum (approximately 80%) and are important elements in the econometric model. The investment industry consumes a minor amount of material but can exert significant influence on short-term price. However, over long periods of time, investment should have zero impact on supply and demand.

The model will be developed to provide at least the following information:

1. *Price Elasticity of Demand:* A measure of the sensitivity of quantity demanded to a change in the price of platinum. It provides a quantitative measure of the price responsiveness of quantity demanded along a demand curve. The greater the elasticity, the greater the effect that a price change will have on the quantity demanded.
2. *Income elasticity:* A measure of how responsive consumption of platinum is to a change in personal income when the price of platinum itself is not changed.
3. *Price Elasticity of Supply:* A measure of the responsiveness of quantity supplied to a change in price. It provides a quantitative measure of the price responsiveness of quantity supplied along a supply curve. The greater the elasticity, the greater the effect that a price change will have on the quantity supplied.

The validity of the model will be assessed first by examining it for theoretical consistency - that is, we will confirm that estimated coefficients have the correct signs as economic theory predicts. Second, we will examine the model's "goodness of fit". "Goodness of fit" refers to a quantitative measure of the extent to which the explanatory variables in the model "explain" the change in the dependent variables (i.e., the quantity of demand and supply of platinum).

After completion and validation of the econometric model, future demand scenarios will be input into the econometric model to project the impact of fuel cell commercialization on supply and pricing. The scenarios for stationary, portable, and transportation applications of fuel cells will range from optimistic to pessimistic and contain volume and time estimates. Economic growth, catalyst technology development, and shifts in automotive powertrain technology will be some of the factors considered in development of the demand scenarios (see Figure 3). The model and the scenarios can be used to conduct sensitivity analyses to the various factors. Recycling will play a significant role as platinum consumption increases further. Recycling of automotive catalysts is now between 10 and 20% depending on the prices of platinum and palladium.

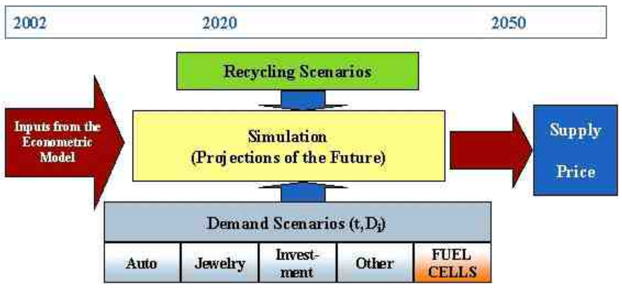

Figure 3. Demand and Recycling Scenarios Will Input to the Econometric Model to Develop Projections of Supply and Price of Platinum

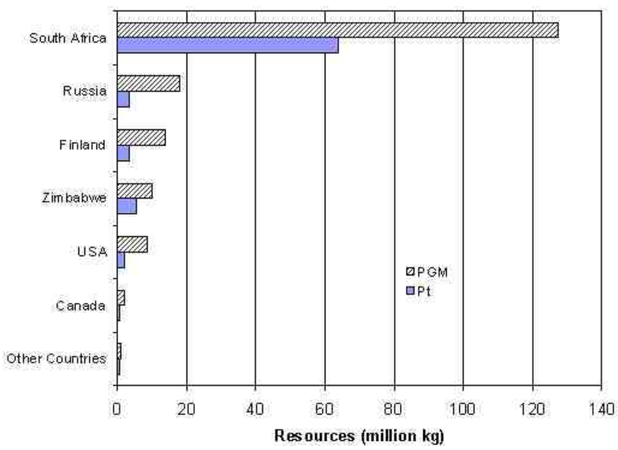

Figure 4. Platinum Resources Summary (Total PGM: 181 million kg, Total Pt: 80 million kg)

Results

Figure 4 summarizes the available resource data for PGMs and platinum. The assumptions and definitions underlying the reported data are critical to selection of values for the resource prediction. The increase in South African resources is based on the revised estimate by G. Cawthorn (2001). Technology advances now allow mining to greater depths, and Cawthorn's increased resource amount assumes a depth of 2 kilometers in all areas of South Africa. The geology of the South African deposits is well characterized and can be extrapolated with confidence.

In contrast, the information about precious metals in Russia is considered a state secret, and much greater variation exists in reported values. Data from a variety of sources were compiled to arrive at the values for the other countries.

Model development started with analysis of the behavior of the real price of platinum over time. The nominal price was deflated by the consumer price index. Preliminary analysis indicates that the mean real price may be constant over a 100 year span; however, statistical tests are being performed to validate this result (see Figure 5). Excursions from the mean real price can be accounted for by specific events, for example, World War I and the U.S. regulations on automotive emissions. However, over time, the supply and demand come back into balance through increases in production or substitution of non-PGM materials.

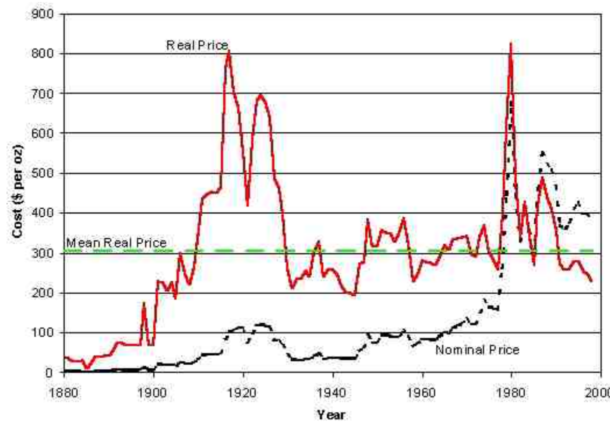

Figure 5. U.S. Geological Survey Platinum Prices with Consumer Price Index (CPI) Deflator

Conclusions

- South Africa will continue to dominate supply of platinum and, in the estimate shown, has 80% of the projected resources.

- If statistical tests support the hypothesis of a constant real platinum price and historical behavior is repeated, then one could expect the introduction of fuel cells to increase the short term price of platinum; however, the platinum prices will then return to traditional values as supply increases.

Reference

1. Cawthorn RG (2001), "Global Platinum and Palladium Deposits," August 2001 Presentation, copy from the author

IV.F.2 Assessment of Fuel Cell Auxiliary Power Systems for Onroad Transportation Applications

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Main Subcontractors: University of California-Davis, Institute of Transportation Studies

Objectives

- The objective of this cooperative study is to determine the viability of the use of proton exchange membrane fuel cells (PEMFCs) and electrode supported solid oxide fuel cells (SOFCs) as auxiliary power units (APUs) for on-road vehicles. The overall objectives of the program are:
- Assess viability considering:
  - Fuel flexibility
  - Start-up time
  - Power level
  - Duty cycle
  - Overall vehicle efficiency
  - Weight and volume
  - Capital and operating & maintenance (O&M) cost
  - Reliability, maintainability, "ease of repair"
- Determine research and development (R&D) needs and possible DOE roles
- Project potential benefits to the Nation
  - Barrels of oil displaced
  - Criteria pollutants avoided
  - Safety improvement & noise reduction benefits

Approach

- Task 1. Project kick-off Summarize the impact of system operating parameters on the design and performance of PEM and solid oxide fuel cells.
- Task 2. Identify APU Requirements Finalize the segmentation of the vehicle APU market by vehicle class and application. For key segments, develop "straw-man" duty cycles, capital cost, O&M cost, and weight & volume targets. Confirm and adjust "straw-man" APU specifications via telephone interviews with industrial contacts. Choose 2 to 3 (total) PEM and SOFC APU applications to advance to Task 3.
- Task 3. Develop Design Concepts Develop system layouts and conceptual designs for the 2 or 3 options selected in Task 2. Conduct a trade-off analysis for the critical design and performance factors.

Address vehicle integration issues. Compare the most promising fuel cell systems with other APU approaches (e.g. internal combustion engines, battery APUs, Stirling engines).

- Task 4. R&D Gap Analysis Determine the current gaps among fuel cell cost, performance and application requirements (look at 2005-2006 technology). Develop a timeline for technology development and commercialization, and extract R&D needs and opportunities for DOE involvement. Project benefits to the nation from technology introduction (e.g. oil displaced, emission reductions, noise reduction, and safety benefits)
- Task 5. Updatea Analysis Update the performance specifications and the implications on system design, after 6 months to a year from the delivery of the draft final report.

Accomplishments

- Held kick-off meeting at Acorn Park headquarters of Arthur D. Little on January 23, 2002.
- Refined scope of project.
- Finalized selection of fuel cell types for analysis. Determined that PEM and planar anode-supported SOFC are the most attractive fuel cell technologies to assess for onroad transportation APU applications.
- Initiated characterization and preliminary selection of fuel cell/APU applications.
- Completed inventory of data gaps in promising APU applications (e.g. capacity, fuel capability, duty cycle).
- Selected long-haul heavy-duty truck cab load application using diesel fuel with a solid oxide fuel cell for conceptual design, layout and vehicle integration analysis.

Future Directions

- Incorporate 21st Century Truck Industry Working Group feedback on heavy-duty truck APU requirements and cost and performance targets.
- Conduct telephone interviews with interested industrial stakeholders on APU applications and their respective specifications for refrigeration applications, utility truck, police car applications, and future passenger car/light-duty vehicle applications.
- Commence design work on heavy-duty truck cab application using planar electrode supported solid oxide fuel cell and diesel fuel. Finalize specifications (e.g. capacity, duty cycle, volume and weight, vehicle integration issues).
- Finalize selection of remaining 1 to 2 systems for detailed study (leading candidates a refrigeration truck and a police car or contractor/utility truck application)

Introduction

Thus far, most of the interest in fuel cell transportation applications has focused on the use for propulsion, a very challenging task. Over the last two years, interest in the use of fuel cells for vehicle APUs has risen. The requirements of APU applications are thought to better match the initial performance and cost characteristics of fuel cells. APUs are also a possible initial fuel cell market application in the transportation sector and a step towards introduction of hybrid and fuel cell propulsion systems. The objective of this cooperative study is to determine the viability of the use of PEM and planar anode-supported SOFCs as APUs for on-road vehicles. In this context, the viability is defined in terms of achieving cost and performance targets.

Approach

Our team combines TIAX LLC and the Institute of Transportation Studies, University of California at Davis. We are concentrating on the application of PEM and anode-supported planar SOFC

Expected Fuel Cell Characteristics						
	Fuel Cell Type	Electrolyte	Operating Temperature (°C)	Power Density (mW/cm^2)	Electrical Efficiency[1] (%, LHV)	Startup Time (hours)
Low Temperature	Proton Exchange Membrane[2] (PEMFC)	Fluorinated-sulfonic acid polymer membrane	70–90[3] 100-160	400-700	30–40% (Low temp.) 35–45% (High temp.)	<0.2
Low Temperature	Phosphoric Acid (PAFC)	Phosphoric acid	160 - 220	200	35–45%	1-4
High Temperature	Molten Carbonate (MCFC)	Lithium, potassium carbonate salt	600–650	120-160	45–55% (FC system only)	5-10
High Temperature	Solid Oxide (SOFC)[4]	Yttria-stabilized zirconium oxide	900–1,100 (tubular) 650–850 (planar)	150-200 (tubular) 200-600 (planar)	45–55% (FC system only) 65–70% (Gas turbine hybrid)	5-10 (tubular) 1-5 (planar)

1. Net electrical efficiency based on natural gas fuel. LHV = Lower heating value. Includes gas compression and other ancillaries
2. Also sometimes called a solid polymer electrolyte fuel cell (SPFC).
3. Recent developments in PEMFC are pushing temperature up to 160°C
4. Solid oxide technology describes both tubular and planar and both electrolyte-supported and electrode-supported technology.

Figure 1. Fuel Cell Performance Characteristics

technologies. With agreement of DOE, the scope has been refined to focus on technologies available in the 2005-2006 timeframe. Applications will be those available from the present time to 2010. We will address applications that use existing fuel infrastructure (namely gasoline and petroleum diesel), alternative fuels (e.g. propane), and future fuel (hydrogen).

We will look at passenger cars, class 1 and 2 light-duty trucks and SUVs, class 3-8 trucks, recreational vehicles, transit buses, and specialized vehicle applications. Military applications are not part of the current scope of work.

Our project is being carried out in five tasks. This first task (completed) confirmed the scope and approach with DOE. Task 2, currently underway, is developing a list and ranking of promising current and future applications for APUs. Sources are publicly available data and input from industry and government contacts. Task 3 will produce conceptual designs and vehicle integration layouts of 2-3 fuel cell APU systems. Task 4 will identify the R&D gaps and possible roles for DOE. Benefits to the Nation will be projected including oil displacement and emission reductions. Task 5 will provide an update 6 to 12 months from the submittal of the draft final report.

Results

Based upon current publicly available data, PEM and anode-supported SOFC technologies are the most promising technologies for transportation APUs, and thus will be the focus of this project. The performance specifications of fuel cell technologies are summarized in Figure 1. The key factors that

Potential Fuel Cell APU Loads	
Hotel loads & Telematics	• Power truck cab/sleeper appliances • Provide AC when parked • Telecommunications, navigational equipment
Refrigeration loads	Replacement of diesel generators to increase efficiency and cut noise
Light-duty idling	Powers accessories during driving cycle, allowing engine-off while stopping
Start-up	Avoid cold-start problems
Engine redesign (Vehicle electrification)	• Redesign of engine • Electric breaking, steering, pumps, etc

Increasing integration with propulsion engine

Figure 2. Potential Fuel Cell APU Loads

influence fuel cell applicability as transportation APUs are power density, efficiency and system volume. Other important factors are fuel capability (and associated complexity of a fuel reformer), startup time and fuel cell stack life. A high-level ranking system yielded that PEM (both current and future high-temperature technology) and planar electrode-supported SOFC technologies appear to be the most applicable technologies for transportation APUs. These fuel cell technologies will be the focus of our study.

The team completed a high-level characterization of potential fuel cell APU applications. The overall process for this selection entailed four steps:

- Identify long list of potential fuel cell APU applications;
- Screen out options unlikely to be of interest based on DOE objective of achieving national benefits directly with APUs themselves or indirectly by facilitating introduction of fuel cells in vehicles for propulsion;
- Characterize applications at a high level; and
- Develop straw-man selection.

The types of loads considered were identified and classified in categories that represent increasing integration with the vehicle's propulsion system. These loads are summarized in Figure 2. The loads can be classified as those associated with hotel loads and telematics; refrigeration; loads during engine idling; aid to cold start; and integration with propulsion (e.g. complete vehicle electrification).

	Vehicles Meeting Market & Price Criteria	
	Annual Sales (thousands)	Starting Cost (thousands)
Luxury passenger cars	900 [1]	$34
Luxury light trucks	300 [1]	$40
Law enforcement large cars	70 [2]	$25
Contractor Special pick-ups	300 [3]	$30
W PTO/utility trucks (Class 3-8)	74 [4]	Highly variant
Recreational Vehicles	193 [5]	$50
Refrigeration units (Class 3-8)	60 [6]	$35
Heavy-duty trucks long-haul	105 [4]	$67

[1]J.D. Power & Associates, 2001 and Davis, Stacey, 2001; [2]Kelly, 2001and NAFA, 2000; [3]Kurylko, 2000; [4]VIUS, 2000; [5]RVIA, 2002 (http://www.rvia.org/consumers/recreationvehicles/types.htm); [6]U.S. Department of Commerce, 2001

Figure 3. Potential Fuel Cell APU Applications - Vehicles Meeting Market and Cost Criteria

The complete list of APU applications considered included:

- Passenger Cars
  - Minicompact
  - Subcompact
  - Compact
  - Midsize (Luxury and Standard)
  - Large (Luxury, Standard and Law Enforcement)
  - 2-Seater
- Light-Duty Trucks
  - Small pickup (<3,500 lbs.)
  - Small van (<4,500 lbs.)
  - Small utility (<3,500 lbs.)
  - Large pickup (3,500-8,500 lbs.; Contractor vehicle and Standard)
  - Large van (4,500-8,500 lbs.)
  - Medium utility (3,500-4,799 lbs.; Luxury and Standard)
  - Large utility (4,800-8,500 lbs.; Luxury and Standard)
- Medium-Duty Trucks (Class 3-6)
  - PTO/Utility (e.g. lift, dump, wrecker, service)
  - Delivery (Refrigerated and Standard)
  - Recreational vehicle
- Heavy-Duty Trucks (Class 7-8)
  - Local (Standard, Refrigerated and PTO/Utility)
  - Line-haul (Standard, Refrigerated, PTO/Utility)
  - Recreational vehicle
  - Motor coach & transit buses

The characterization and selection of systems addressed the following aspects of fuel cell APU applications:

- Potential national benefits, which are the product of the achievable market and the benefit per vehicle:
  - Economic (cost savings)
  - Energy savings
  - Environmental benefits (e.g. carbon dioxide, nitrogen oxides reduction)
  - Noise reduction and safety improvement
- The possibility to either be introduced into the market in the near-term, i.e. an existing APU application (e.g. replacement of existing less-efficient APU technology), or have significant national and user benefits but require longer-term market introduction, e.g. future APU application that may require redesign of vehicle.
- Compatibility with either current or possible future fuel infrastructure.

Screening criteria were used to narrow the initial market analysis of possible APU applications for fuel cells:

- Duty cycle - the duty cycle of the vehicle should be suited to APU use, e.g. long idle times
- Market size - the market potential must be adequate to support investment in APU technology
- Vehicle cost - the initial cost of the vehicle must be high enough that an APU would likely represent a reasonably small portion of total vehicle cost (<15%, assuming a fuel cell APU cost of $5000)

The vehicles meeting the initial criteria are shown in Figure 3.

Subsequent screening criteria used have both a short and long-term outlook:

- Energy savings
- Emissions savings
- Cost savings
- Acceleration of fuel cell introduction

Conclusions

Based on our first-pass APU application characterization and screening, hotel loads for long-haul heavy-duty truck / recreational vehicles, refrigerated trucks, police car and contractor utility trucks appear to be good candidates for further analysis. We will start detailed analysis of the long-haul truck cabin loads using petroleum diesel as a fuel. We will work with DOE to agree on the next 1 to 2 applications for detailed study as part of Task 3.

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FY 2002 Publications/Presentations

1. Presentation to 21st Century Truck Industrial Working Group in conjunction with SAE Government & Industry meeting, Washington, DC, May 15, 2002.

IV.F.3 Guidance for Transportation Technologies: Fuel Choice for Fuel Cell Vehicles

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Objectives

- Support refined R&D targets for direct-hydrogen fuel cell vehicles (FCV) based on an analysis of well-to-wheel energy use, greenhouse gas (GHG) emissions, cost, and safety of direct-hydrogen FCVs and competing vehicle technologies.
- Assess opportunities and risks of various FCV and fuel choices, specifically hydrogen, comparing the technical, efficiency, economic, safety and financial risks of each option with onboard reforming of gasoline.

Approach

- In Phases 1 and 2, TIAX developed detailed well-to-wheel performance and cost calculations, taking into account technology options, system integration and efficiencies, hybridization, vehicle weight, and drive cycle. Last year's annual report included some of the results from these Phases; in this report, we present those results which were not previously reported.
- In Phase 3, we are evaluating the financial risks of various FCV options and potential triggers that may reduce the risks compared to conventional vehicles.
  - Perform detailed analysis of market introduction issues.
  - Evaluate the effect that potential triggers may have on the various stakeholders using a net present value (NPV) analysis.

Accomplishments

- Completed Phases 1 and 2.
- Developed a NPV analysis framework and a preliminary analysis of hydrogen and gasoline FCV options.

Future Directions

- Verify and refine NPV assumptions and analysis and use it to identify low-cost options for introduction of hydrogen or other fuel infrastructures.
- Evaluate the technology risk, financial exposure, and safety and regulatory risks associated with the various fueling options for each respective stakeholder.

Introduction

The focus of this project is to assess the potential impact of on-board storage of hydrogen, rather than on-board reforming of gasoline as a means of supplying fuel to FCVs. The overall risk involved in each of the fuel options for FCVs varies, and the risk may shift from one player in the value chain to another. This risk trade-off is the focus of Phase 3.

Approach

Phase 2

The approach to Phase 2 was described in detail in the full report (Arthur D. Little 2002), as well as in last year's annual report (Lasher, et al 2001). Key points are:

- Fuel cell system and vehicle analysis based on detailed performance and drive-cycle models, but based on a future fuel cell technology scenario, assuming success in current R&D efforts.
- Hydrogen costs based on detailed on-site hydrogen fueling station cost analysis.
- Vehicle cost estimates based on a detailed bottom-up analysis consistent with TIAX's automotive fuel cell costing study.

Phase 3

In Phase 3, we are performing NPV calculations to determine overall and individual stakeholder investment risks for various fuel and FCV options. Minimizing risks will require managing utilization factors, FCV introduction strategies, and infrastructure options. The NPV analysis is being used to evaluate the effect that potential triggers and drivers may have on the various stakeholders for each fuel chain and FCV option. Potential factors include:

- Crude oil and gasoline price increases
- FCV cost reduction
- Value of emissions reduction
- Subsidies and R&D funding and timing
- FCV fuel economy improvements
- Energy and capital cost improvements for hydrogen generation

Results

Phase 2

An overview of the well-to-wheels energy, GHG emissions, and fuel cost results were presented in last year's annual report (Lasher, et al 2001). Complete results can be found in the full report at: http://www.cartech.doe.gov/pdfs/FC/192.pdf. Last year's presentation of vehicle and ownership cost results was preliminary, and the final results are presented herein.

Vehicle Factory Cost Results

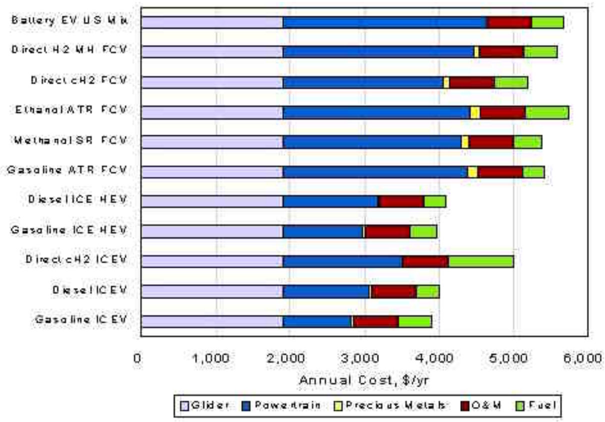
- Based on our scenario analysis, hydrogen-fueled FCV factory costs are around 30% ($4,000 per vehicle) higher than hybrid electric vehicles (HEVs).
- Fuel processor-based FCVs are projected to cost about 10% ($1,000-$2,000 per vehicle) more than compressed-hydrogen vehicles - roughly the same as metal hydride-based FCVs.
- However, FCV costs, even reformer-based FCVs, would be lower than battery EV costs while offering longer range.

Vehicle Ownership Cost Results (Figure 1)

- Vehicle ownership costs are dominated by vehicle depreciation, representing over 70% of annual cost for all vehicles.
- Fuel costs typically amount to less than $500 per year.
  - High efficiency of direct hydrogen and methanol-based FCVs compensates for higher hydrogen and methanol costs, bringing annual fuel costs on par with ICEVs.
- Sensitivity analysis shows that cost differences between FCVs and petroleum ICEVs are statistically significant.
  - Differences among FCV options are not statistically significant.

Safety Analysis Results

- Hydrogen transportation, fueling station, and on-board safety issues can likely be resolved without onerous cost increases.
- However, fuel cell vehicles will require modifications to garages, maintenance facilities,



Notes: Assumes 14,000 mi/yr driving and 350 mile range (except the Battery EV that has 120 mile range); vehicle costs are adjusted for resale value with monthly payments over 5 years at 4% finance rate; insurance, tax, and license costs are excluded.
Assumes identical O&M costs for all vehicles.
Hydrogen is assumed to cost $20/GJ.

Figure 1. Estimated Vehicle Ownership Costs for Various Types of Vehicles

and on-road infrastructure that could be costly and difficult to implement.

Phase 3

We are currently refining our preliminary analysis based on existing information and using the on-site generated hydrogen FCV and gasoline FCV cases as the first examples. We started from the results of the previous phase and made the necessary updates and assumptions needed to perform NPV calculations. Progress towards the preliminary analysis includes:

- An initial set of NPV variables and outputs has been established.
- We have incorporated two FCV introduction scenarios and the associated R&D funding levels, consistent with scenarios used in DOE's Vision Model.
- We have estimated the fueling station capacity requirements based on FCV introduction, utilization factors, and infrastructure limitations.
- High and low production volume FCV and hydrogen fueling station equipment costs have been estimated using progress ratios.
- Large and small fueling station costs have been estimated using scaling factors for individual equipment based on vendor quotes or internal analysis.
- Preliminary costs and revenues of the major stakeholders have been estimated.

Conclusions

FCVs are expected to be able to achieve the lowest well-to-wheel energy consumption, provided efficient fuel chains are used. Direct-hydrogen FCVs carrying compressed hydrogen produced from natural gas can offer well-to-wheel energy consumption of approximately half that of conventional gasoline-fueled vehicles. However, substantial additional technology breakthroughs will be required to achieve FCV cost competitiveness with ICEVs.

Alternative fuels, especially hydrogen, will require significant up-front investment, representing a risk to both vehicle manufacturers and fuel providers. Dealing with this risk represents a formidable barrier to the use of hydrogen for FCVs.

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IV.F.4 Fuel Cell R&D and Demonstration

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Objectives

- Develop a fuel cell test bed to enhance understanding of fuel cell operation under real-world conditions.
- Develop a hybrid fuel cell-powered demonstration vehicle.
- Develop specialized circuitry that can be used to monitor fuel cell stack performance on the benchtop while mimicking real-world loading conditions.
- Develop a fuel cell stack system that operates under both active and passive modes for optimal overall efficiency.

Approach

- Determine power requirements of a standard battery-powered three-wheeled personal mobility vehicle (scooter).
- Design, build, and test a 4-cell, 35 cm^2 active/passive short fuel cell stack to verify performance, heating, and water balance issues.
- Design, build, and test a 40-cell, 35 cm^2 active area active/passive fuel cell stack to power the three-wheeled scooter.
- Design, build, write software/firmware for, and test a custom electronics package to monitor, control, and protect the fuel cell stack and associated electronics.
- Refine the design based on results to enhance performance, accomplish automatic fuel cell stack startup, and incorporate automatic phase-in of power delivery from the fuel cell stack.

Accomplishments

- Determined the power requirements of a standard three-wheel scooter.
- Verified performance, heating, and water issues with a 4-cell short fuel cell stack.
- Demonstrated active/passive dual-mode fuel cell operation on a stack level.
- Built, tested, and installed a 40-cell fuel cell stack in a three-wheeled scooter.
- Designed, built, and wrote software for a custom electronics package to monitor, control, and protect the fuel cell stack.
- Demonstrated fuel cell-powered scooter at public demonstrations and to visiting scientists and DOE officials.
- Incorporated electronics package into other DOE fuel cell project testing equipment.

Future Directions

- Refine software/firmware to accomplish transparent fuel cell stack startup and drive-off and enhance reliability.
- Incorporate additional circuitry to more efficiently control fuel cell stack and power conditioning circuitry and efficiently switch between active and passive modes of fuel cell stack operation.
- Build lifetime and power use profile data for the scooter under real-world operating conditions.
- Incorporate lifetime and power use profile data into benchtop stack testing procedures.
- Develop and build higher power output fuel cell stack to provide enhanced power reserves for severe loading and faster startup transition to all-fuel cell power.

Introduction

Hydrogen fuel cells have yet to have any meaningful commercial success. Obstacles include cost, reliability, fuel supply/storage and entrenched competition. The first market entry points will probably be those areas where the extra cost and fuel inconvenience are offset by the advantages of the fuel cell over the previous technology. A power range where this may apply is on the several-hundred watt level, where batteries are unwieldy and internal combustion engines are inefficient and noisy. A potentially interesting commercial application for several-hundred watt fuel cells is in powering personal mobility vehicles (PMVs). These include powered wheelchairs and three-wheeled electric powered "scooters" often used by the elderly or infirm. The users of PMVs are often located in environments where hydrogen supply could be established (e.g., nursing homes or hospitals) or routine customers of medical supply houses. The usefulness and benefits of PMVs to many users are often limited by battery considerations. The additional range (and possibly life and reliability) offered by fuel cells may more than compensate for higher cost and fuel supply issues.

Figure 1. A Pride Mobility Products Corporation Victory® Personal Mobility Vehicle (scooter)

To this end, we have modified a Victory® personal mobility vehicle (Pride Mobility Products Corporation, Exeter, PA), as shown in Figure 1, to accept a mid-range fuel cell system with a custom monitoring, control, and data logging electronics package. The control system consists of two components - a main monitor and control board which handles low-level monitoring and near real-time protection features, and a Handspring (Mountain View, CA) Visor Pro personal digital assistant that acts as an operator display and data logger and provides manual systems control. The electronics protect the fuel cell stack and store operational information that can be used to further optimize stack installation and operation.

Approach

To adapt a personal mobility scooter to fuel cell-powered operation, it was first necessary to determine peak and average power requirements of a standard battery-equipped scooter. A battery-powered scooter was equipped with current and voltage monitoring circuitry and was driven under common operating conditions. A minimum power output requirement for the fuel cell stack was found. The scooter electrical system and physical

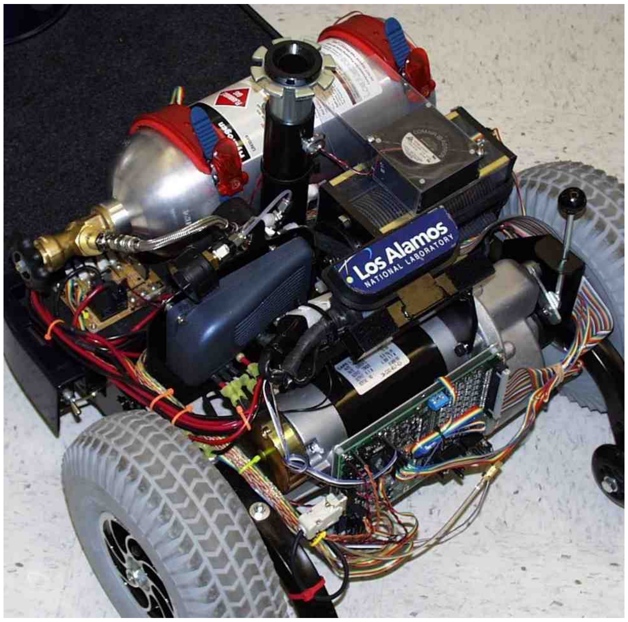

Figure 2. Overview of hydrogen fuel cell installation. The scooter body shroud has been removed for photographs.

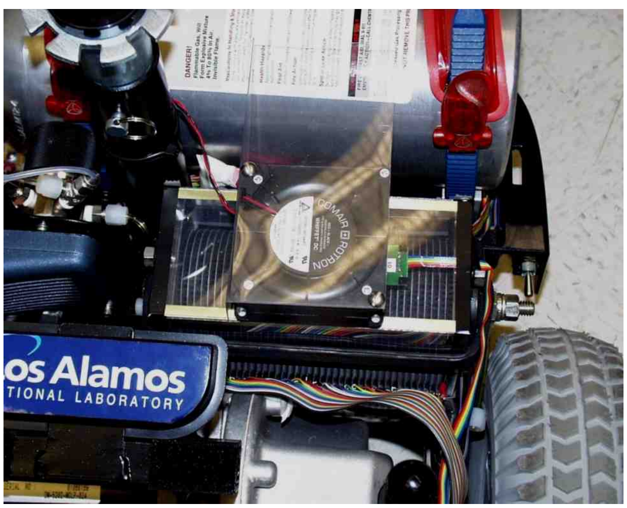

Figure 3. The 40-cell hydrogen stack installed on the scooter chassis. Ribbon cable allows monitoring all cell voltages.

configuration were inspected to find the best way to equip it with a hydrogen fuel cell, hydrogen storage system, and control and monitoring electronics with minimum modification to the scooter and while maintaining the original mechanical outline. Hydrogen storage methods were investigated, and it was determined that a metal hydride would provide the optimum solution without adding significantly to the overall scooter weight.

An initial monitoring and control strategy was determined and suitable electronic circuitry was designed, constructed, tested, and installed. Preliminary testing of the fuel cell system revealed an issue with power distribution between the fuel cell stack and the lead-acid batteries used to supply power during peak loading during acceleration or hill climbing. This issue was addressed and solved to a first approximation with rudimentary additional circuitry. Stack protection methods were further optimized over the initial strategy. A more optimum power distribution and stack protection method that will also significantly increase overall system efficiency was determined.

The original design for passive "air-breather" fuel cell stacks developed under a Hydrogen Program Cooperative Research and Development Agreement was scaled-up and modified to accommodate active (fan-supplied air) operation. Single-cell and short stack testing of various component permutations were used to design the eventual 40-cell stack. While it was necessary to restrict air access in the 40-cell design to prevent dryout, the stack exhibited stable performance and operated well in both active and passive modes.

Results

A hybrid fuel cell powered personal mobility research, development, and demonstration vehicle was constructed based on a commercially available standard three-wheeled scooter and fuel cell designs developed at Los Alamos National Laboratory. The fuel cell-powered scooter required minimal modification to the standard scooter aside from the actual fuel cell, metal hydride cylinder, and electronics installation (Figures 2-5). The electronics package developed for the project has proven valuable in providing insight into operational, gas flow, and temperature issues with the fuel cell developed for the scooter and in testing other fuel cell stacks developed for other DOE projects. The scooter has been used in several successful private and public demonstrations highlighting the utility and advantages of fuel cell power.

Figure 4. Metal Hydride Hydrogen Storage Tank Mounted in Stock Scooter Battery Location

Conclusions

The fuel cell-powered scooter project has provided valuable insights into fuel cell operation under real-world conditions as well as monitoring and control strategies to maximize power and efficiency. The electronics developed for the project have found dual use with other fuel cell testing systems. Additionally, the fuel cell-powered scooter has proven valuable as a way to illustrate and demystify fuel cell systems, and as a public relations tool to promote alternative energy research at Los Alamos National Laboratory.

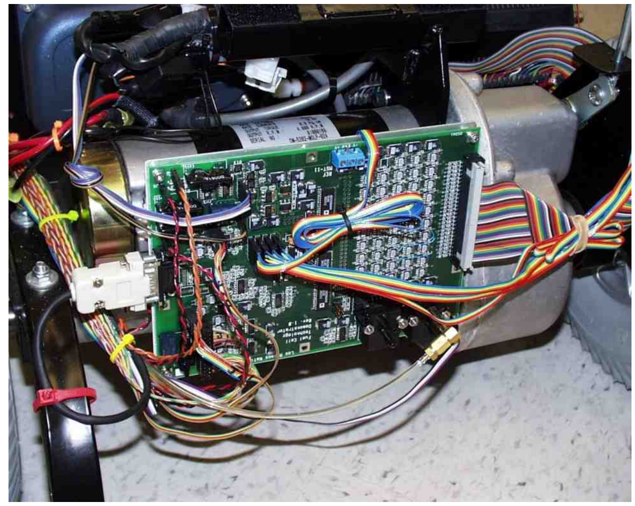

Figure 5. Fuel Cell Monitoring and Control Electronics Circuit Board Mounted on Scooter Drive Unit

FY 2002 Publications/Presentations

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IV.F.5 Advanced Underground Vehicle Power and Control Fuel Cell Mine Locomotive

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Objectives

- Develop a zero-emissions, fuel cell-powered metal-mining locomotive
- Evaluate its safety and performance, primarily in surface tests
- Evaluate its productivity in an underground mine in Canada

Approach

- Design 14 kilowatts (kW) fuel cell powerplant
- Design metal-hydride storage
- Integrate powerplant and hydride storage onto locomotive base vehicle
- Conduct preliminary tests and evaluate
- Refine final design
- Perform safety and risk analysis and complete documentation to meet regulatory approval
- Evaluate productivity performance in an underground metal mine

Accomplishments

- Designed 14 kW fuel cell powerplant and metal-hydride storage
- Integrated powerplant and metal-hydride storage onto locomotive base vehicle
- Performed preliminary testing and evaluation in Nevada
- Conducted safety and risk assessment

Future Directions

- Integrate recommended safety improvements into final design
- Complete documentation for final regulatory approval
- Evaluate performance on surface and underground in a metal mine

Introduction

Underground mining is one of the most promising applications in which fuel cell vehicles can compete strictly on economic merit (1). The mining industry, one of the most regulated, faces economic losses resulting from the health and safety deficiencies of conventional underground traction power. Conventional power technologies - tethered (including trolley), diesel, and battery - are not simultaneously clean, safe, and productive. Fuel cell power would solve the challenges by providing large cost savings relative to the high capital cost of current underground traction power. Lower recurring costs, reduced ventilation costs, and higher vehicle productivity could make the fuel cell vehicle cost-competitive years before surface applications. The fuel cell locomotive is shown in Figure 1.

Figure 1. Fuel Cell Mine Locomotive

Approach

A joint venture between the Fuel Cell Propulsion Institute (a nonprofit consortium of industry participants) and Vehicle Projects LLC (project management) provided the basis for the 2 phase project. In phase 1, Sandia National Laboratories was tasked with the design of the fuel cell powerplant and the metal-hydride storage, as well as system integration. Phase 2 includes system evaluation, safety and risk assessment, and underground testing in a production environment.

To ensure the locomotive was designed with industry in mind, various industry participants were involved in assessing the design for risk and functionality. When the locomotive is tested underground, all regulatory requirements will have been met.

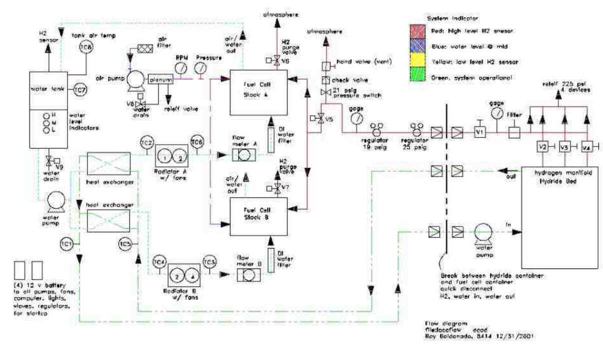

Figure 2. Schematic Layout of Fuel Cell Powerplant and Metal-Hydride Storage

Comparison of Battery and Fuelcell Locomotives		
Parameter	**Battery**	**Fuelcell**
Power, rated continuous	7.1 kW (gross)	14 kW (gross)
Current, rated continuous	76 A	135 A
Voltage at continuous rating	94 V (estimated)	104 V
Energy capacity, electrical	43 kWh	48 kWh
Operating time	6 h (available)	8 h
Recharge time	8 h (min)	1 h (max)
Vehicle weight	3,600 kg	2,500 (without ballast)

Figure 3. Battery and Fuel Cell Specifications

Results

The locomotive's fuel cell power system uses proton exchange membrane fuel cells. No traction battery is employed: thus, the vehicle is a pure fuel cell vehicle. Two stacks in electrical series provide 104 volts and 135 amps at the continuous rated power of 14 kW gross. Waste heat from the stacks provides the heat to desorb hydrogen from the metal-hydride bed. A heat exchanger links the two isolated thermal systems: (a) the hydride-bed heating/cooling loop and (b) the stack cooling loop. Figure 2 depicts the schematic layout of the powerplant and metal-hydride storage. Specifications of the fuel cell and battery versions of the locomotive are compared in Figure 3.

The hydride storage system stores 3 kg of hydrogen, sufficient for eight hours of locomotive operation at the predicted 6 kW average power of its

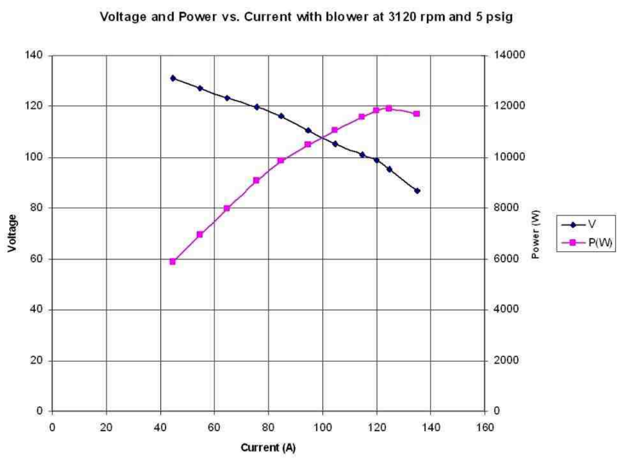

Figure 4. Fuel Cell Power Curve Showing 12 kW Gross Power

duty cycle. Hydride subsystem design allows forrapid change-out (swapping) of a discharged bed with a freshly charged unit. Recharging will utilize gaseous hydrogen and has been measured at approximately one hour.

Bench performance data for the powerplant are shown in Figure 4. Both voltage versus current and gross power versus current are shown. Maximum observed power in the test was 12 kW gross due to air pressure of 5 psig, rather than 7 psig as specified for 14 kW gross power. Parasitic losses are less than 10%, a very good performance result.

Mine Safety and Health Administration (MSHA) focused on possible hazards of hydrogen underground, including detailed review of process piping and electrical routing. The assessment indicated few changes required to meet existing standards and will help establish new standards for hydrogen-fueled underground mine vehicles.

MSHA measured noise levels (Table 1) of the locomotive under a number of operating conditions, including acceleration (2). Unlike some fuel cell vehicles, our locomotive is very quiet under all conditions. It emanates a pleasant, low frequency purring, and normal conversation can easily be carried out while standing beside the operating powerplant. Consequently, the steel-wheel-to-steel-track generated noise will be the most prevalent.

Table 1. Average Recorded Sound Levels

Average Sound Levels for the Locomotive		
Location/Condition	**dBA***	**Linear****
Operator Position/Traveling Forward, Run 1 (Full Throttle)	75.3	80.1
Operator Position/Traveling Forward, Run 2	76.6	85.1
Operator Position/Traveling in Reverse, Run 1 (Full Throttle)	76.6	85.1
Operator Position/Traveling in Reverse, Run 2	76.2	82.2
Operator Position/Idle	74.4	81.2
6 Inches from Blower on Right Side/Idle	78.9	85.3
6 Inches from Top Vent on Right SIde/Idle	80.0	84.3
6 Inches from Control Panel on Left Side/Idle	79.5	84.0
1 Foot in Front of Locomotive/Idle	75.3	81.9
Background Near Area of Tests	73.4	78.3

* Sound Level Using an "A-weighted"network
** Sound Level using and unweighted network (flat response)

Conclusions

The problems of vehicle emissions and noise have negative economic consequences for underground vehicle applications. Fuel cells coupled with reversible metal-hydride storage, by solving these problems, offer cost offsets - higher productivity and lower operating costs - that can make underground fuel cell vehicles cost-competitive sooner than surface applications. Our hydride-fuel cell locomotive, like the battery version, is a zero-emissions vehicle. However, the fuel cell locomotive has greater net power, greater energy storage, higher gravimetric energy and power density, higher volumetric power density, and substantially faster recharging. Because weight is not an issue, safe and compact metal-hydride storage is an ideal storage technology for underground locomotive applications.

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