VAIREX corporation

Key Components for the Fuel Cell Industry

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Final Report to the Department of Energy
PRDA – 2A

Component Development

Advanced Fuel Cells for Transportation Applications

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Summary

This report summarizes the results of the second phase of development based on the Generation I *VAIREX* Variable Displacement Compressor Expander (VDCE™) developed during Phase One (Department of Energy PRDA contract, #DE-AC08-96CE50384, awarded April 6, 1996).

The project included optimization of key system performance parameters as well as a reduction in number of components and of the projected cost, size and weight of the system. *VAIREX* successfully completed the improvements, developing a system that meets or exceeds DOE performance guidelines. This second-generation system is functioning in a test environment as a deliverable unit that meets specifications.

We now have a prototype system with a clear path to a family of manufactured products that meets commercial requirements in automotive fuel cell power system applications for performance, cost, and durability. The customer evaluation unit currently under development is known as the integrated compressor/ expander/motor or iCEM™.

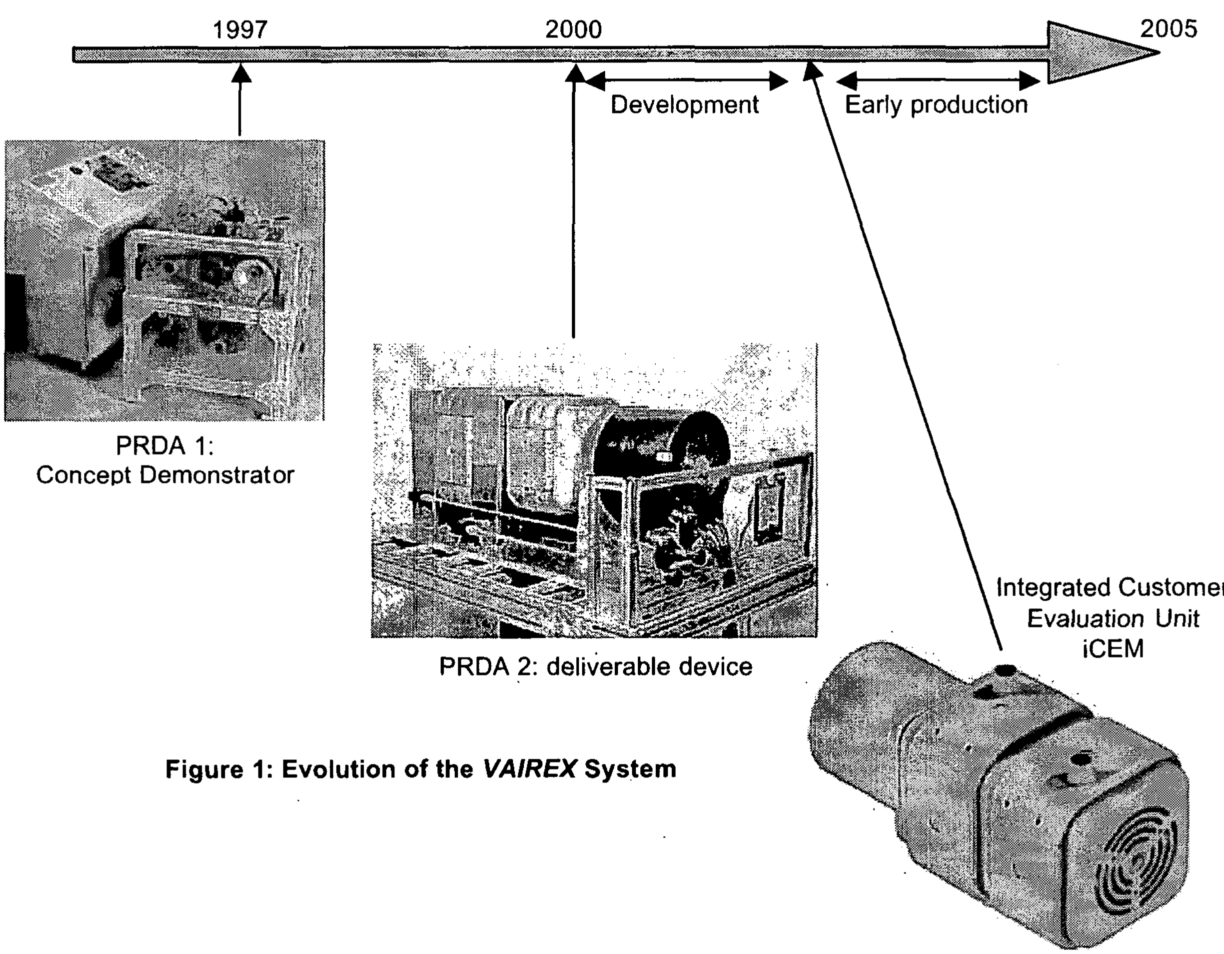

Figure 1: Evolution of the *VAIREX* System

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Objectives/Goals

The items listed below were the objectives set by the PRDA-2A proposal and the resulting contract between *VAIREX* and DOE:

1.0 Assess the relative merits and deficiencies of non-clearance (piston) and clearance (twin-screw) technologies, as to their commercial viability as air-system compressors and expanders in automotive fuel cell systems, where minimizing parasitic power is crucial.

   DONE – Non-clearance (piston) systems show clear advantage in minimizing parasitic power consumption.

2.0 Evaluate component design and technology refinements on improving the performance characteristics of the first generation VDCE, as well as studying operational issues like water and thermal management, using the first generation VDCE.

   DONE – Performance of the current second-generation integrated compressor/expander meets or exceeds all DOE guideline criteria. Water and thermal studies on the first generation VDCE, and subsequent theoretical studies and computer modeling analysis are the basis for further planned improvements.

3.0 Design, fabricate, and fully characterize the performance of a second-generation integrated air compressor/expander/motor, suitable for use in automotive fuel cell systems.

   DONE – The integrated compressor/expander rig, pictured above, is available to be integrated into automotive fuel cell power systems. Customer evaluation units are available in calendar year 2000.

4.0 Develop a manufacturing study focused conceptually on the required changes in technology to take the prototype to a manufacturing level addressing the technical and cost targets.

   DONE – A design matrix of a family of products has been developed. The development program to meet the technical and cost targets is underway, with predictable results within the industry time windows.

5.0 Deliver the second generation PRDA-2A device to DOE in month 24 (December 1999). A six-month extension was granted.

   DONE – The system, while not yet qualified for extended operations, is available for further testing and system integration.

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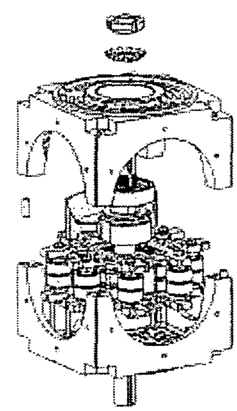
In the previous development phase, a variable displacement piston approach was used with good results, as previously reported. However, early in the current phase, it was recognized that substantial reductions in hardware complexity could be achieved, together with major performance improvements, by moving to a variable delivery/variable valve timing approach for independent control of pressure ratio and mass flow.

The resulting major mechanical changes, while dramatically reducing parts count and enhancing performance, represented a significant increase in the work required. Despite this major change in scope of work, it was possible to maintain the above objectives by incorporating several improvements in methodology.

Achievements

The test results of the deliverable hardware demonstrate that it is fully capable of meeting the performance guidelines. A clear development path has been defined, which will result in a family of integrated compressor/expanders meeting the cost targets and within the time requirements of industry. Units for customer evaluation and system integration will be available in calendar 2000.



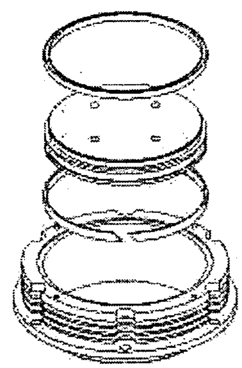
While the manufactured system will be much smaller than the existing hardware, low speed piston-based systems are inherently larger than high-speed clearance technology devices. However, projected volumetric savings in system modules, such as the fuel cell stack and heat exchangers, can more than offset the size disadvantage of the piston system. Size is the only respect in which the *VAIREX* technology does not directly meet or exceed the absolute letter of the DOE guidelines.

Patent Applications

During the course of this contract, we have filed two patent applications. Notification to DOE was made of these filings on November 11, 1999. The applications cover various implementations of variable timing valves as used on the expander and control of multiple air supplies as it applies to fuel cell power systems.

Comparison to Twin Screw

VAIREX was tasked to assess the relative merits of piston, or zero-clearance technology, versus twin screw technology, as representative of clearance technology devices. The *VAIREX* compressor/expander system was compared to an equivalent twin-screw system against the DOE pressure profile and the Automotive FUDS duty cycle.



The piston (zero-clearance) technology demonstrated superior performance in terms of independent control of pressure and flow, higher turndown ratios and lower parasitic power consumption. Although the twin screw technology may have a packaging advantage, it is expected to be more expensive in production.

Remaining Challenges

Although proof of concept has been demonstrated, substantial development work remains to be done in optimizing the air management system. Of key importance is the integration of the air system into a fuel cell power system. Specifically, optimizing expander configuration to actual exhaust stream parameters, and addressing the related control issues is a potentially fruitful area of development, as is investigation of up-stream water management.

In addition, substantial and definable engineering work remains in implementing the technology into a product that is manufacturable, durable, and cost-effective.

These challenges can all be successfully addressed within industry time windows.

Recommendations

VAIREX recommends continued DOE support of the development of the iCEM technology, particularly in areas of system integration and expander optimization.

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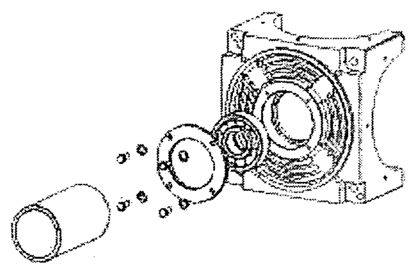
Methodology

The first generation compressor/expander system was based on a variable displacement operating principle. Although this device met the performance specifications of the initial phase of development, it became obvious that a variable delivery/variable valve timing approach would be more suitable to the needs of fuel cell power systems. It was recognized that substantial reductions in hardware complexity could be achieved, together with major performance improvements. By taking a variable delivery/variable valve timing approach substantial advantages could be achieved while maintaining independent control of pressure ratio and mass flow. Therefore, the first-generation device underwent a complete redevelopment to incorporate a new piston/drive design incorporating variable timing.



This major mechanical redirection forced a reprioritization of the project's objectives to meet the goals within the time and budget constraints. As a result of several improvements in methodology, it was possible to maintain objectives.

Improvements in development tools

Design and analysis were streamlined through major upgrades to the development software tools, which now include SolidWorks 2000 from SolidWorks Corp., CosmosWorks from Structural Research & Analysis Corp., and Pro/MECHANICA from Parametric Technology Corp. CFD software tools for gas dynamics are presently being added. Examples of these applications are shown throughout this report. See Appendix B for additional examples of modeling tools in use.

These tools have substantially increased the productivity of the engineering group and were significant contributors to maintaining time and cost targets during the development program. The design software permits, amongst other benefits, direct input to analysis programs and also direct communications with vendors' NC equipment. This has proven a great time saver as well as eliminating opportunities for human error.

Single cylinder test bed

To provide a precise test environment, we built a single-cylinder test bed.

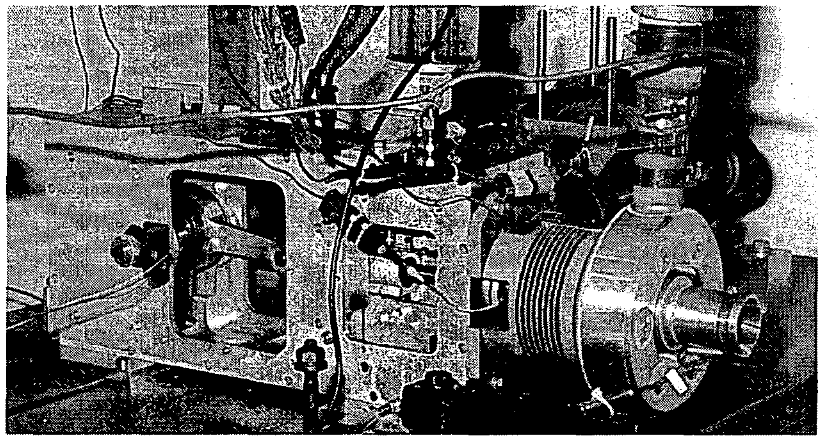


Figure 2: Single-cylinder Test Bed

By evaluating design modifications on the single-cylinder test bed, fabrication and test set up times were substantially reduced. As a result, design modifications were less costly and usually successfully incorporated in only one iteration.

It was hypothesized that the results obtained from the single-cylinder tests would translate with a high degree of correlation to the four-cylinder final model. Correlation between results on the single-cylinder test bed and four-cylinder hardware proved to be very high. Therefore, we are continuing to use the single-cylinder test approach in our current development strategy.

Instrumentation Upgrade

A number of in-house test cell improvements were made that accelerated testing processes and improved data accuracy and repeatability.

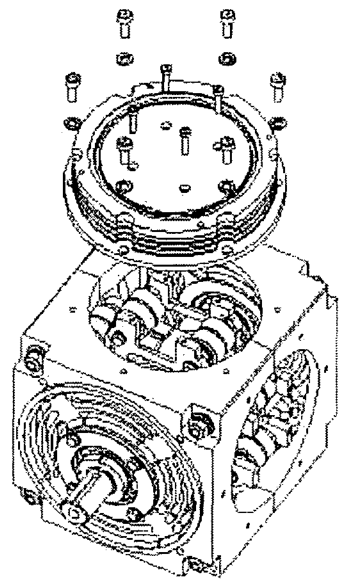
In a cooperative effort with MicroMotion, world leader in industrial mass measurement systems, test bed instrumentation was upgraded with a flow measurement system that increased accuracy from +/- 0.5% to +/- 0.05%.

Other instrumentation improvements, including a new computer system interface for automatic data collection, gave us lower operator intervention (direct read to computer), higher productivity in the test cells, and a reduction in measurement errors.

It should also be noted that the test data system now permits third party calibration.

Sub-system development

The 4-cylinder piston device was developed to function as both a compressor and an expander. Physical differences are essentially only in the valving mechanisms. As a compressor the device supplies pressurized air to the fuel cell while as an expander it recovers energy from the exhaust stream. This commonality allows for efficiency in development and in production, as well as economies of both scale and complexity.



The compressor utilizes a reed valving system that was first assembled and performance-tested on the single-cylinder test bed. Following successful evaluation, the reed valve assembly was incorporated into the compressor and testing of the full compressor began.

The variable valve system for the expander was then tested on the single-cylinder rig. Some modifications were indicated and implemented in a full 4-cylinder expander. The expander was tested using two of the new compressors as the energy source. Test facility limitations precluded testing the expander at the guideline inlet temperature of 150C; maximum attainable gas temperature was 80C.

The single-cylinder test bed proved invaluable in the development of both valving systems. It greatly accelerated verification of projected design results.

Given the time and budget constraints, it was not feasible to have a motor customized to our specific requirements of torque, power, rpm and form factor. Therefore an "off the shelf" model had to be selected. Of the various motor alternatives investigated, the Unique Mobility brushless DC motor and controller best met the torque/speed requirements. However, it has at least twice the required power output and is much longer than a customized motor would be. The controller itself is also oversized.

Finally, the compressor, expander, motor, and controller were assembled into the final rig, which is our DOE PRDA-2A deliverable.

Integration into PRDA-2A deliverable

The PRDA-2A deliverable is designed to function in the integration and testing of fuel cell power systems.

The sub-systems in the PRDA-2A deliverable can be de-coupled to permit modification, upgrading, servicing and testing at the individual sub-system level. While this is an invaluable attribute, the couplings allowing this flexibility add substantially to the axial length. In the customer evaluation units currently under development, with the motor properly sized and optimum direct coupling, the current axial length will be reduced by at least 250 – 300 mm.

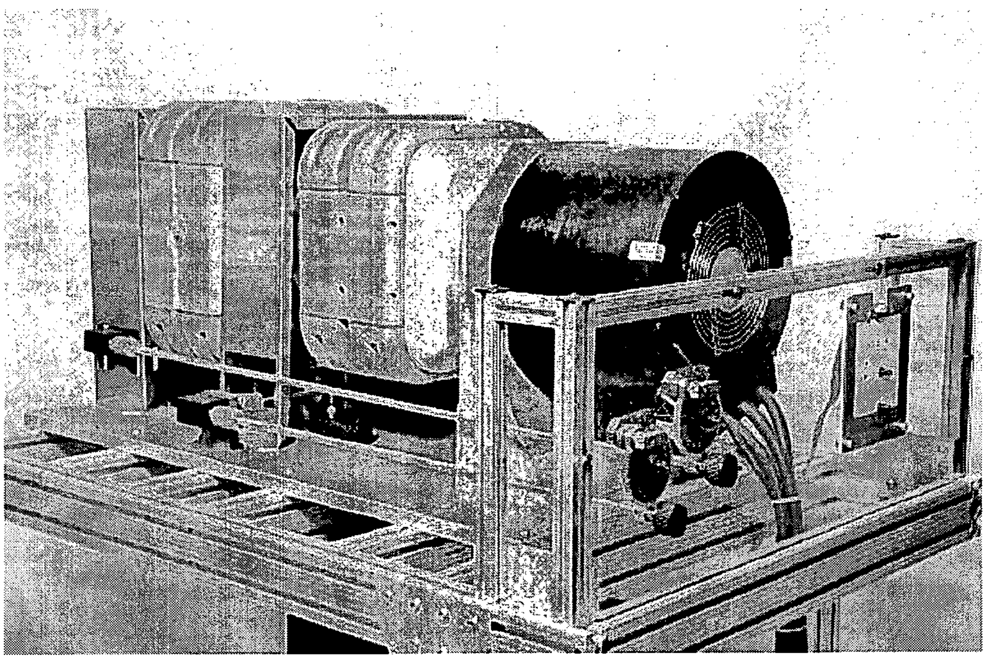


Figure 3: PRDA-2A deliverable

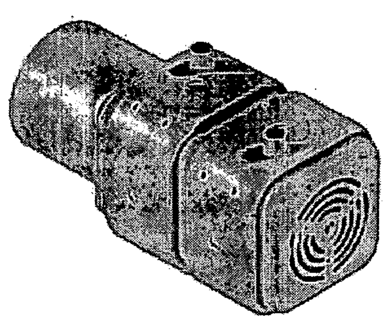


Figure 4: iCEM Customer Evaluation Unit

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Ongoing testing

We are continuing testing and incorporating enhancements based on test results of the system components. These tests and refinements continue with an eye towards the future, including addressing integration issues, performance enhancements, and durability and cost improvements.

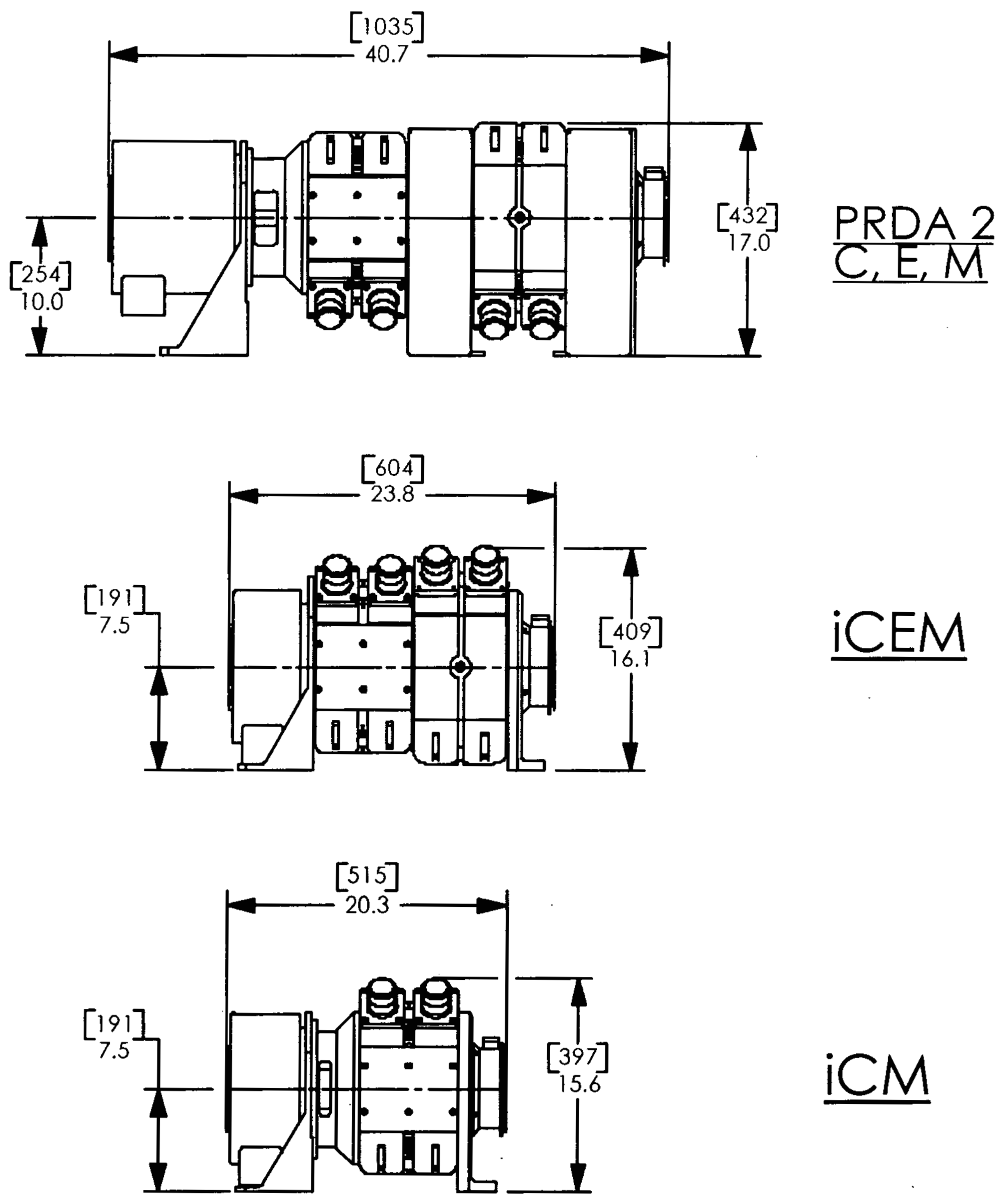

Figure 5: Comparison Drawing

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Operating Description

There is a significant difference in the operation of this device as compared to the generation 1 deliverable. The first generation used variable displacement technology in which the cylinders were dynamically re-sized during operation to achieve variation in flow. In the PRDA-2A deliverable, both the compressor and the expander are an identical fixed cylinder, constant bore and stroke configuration.

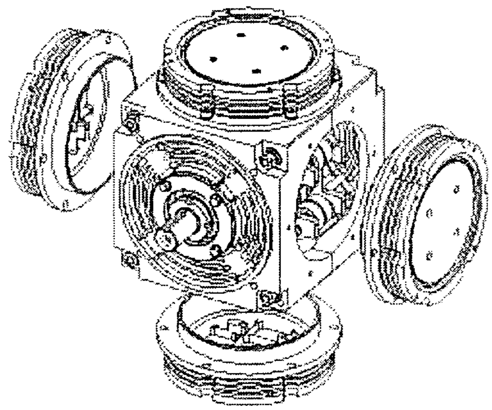

Figure 6: Exploded View of Compressor

The rotating motor shaft causes a scotch yoke core drive mechanism to rotate and drive the four pistons. This type of mechanism minimizes the longitudinal dimension of the assembly and greatly reduces the lateral pressure on cylinder walls from piston thrust.

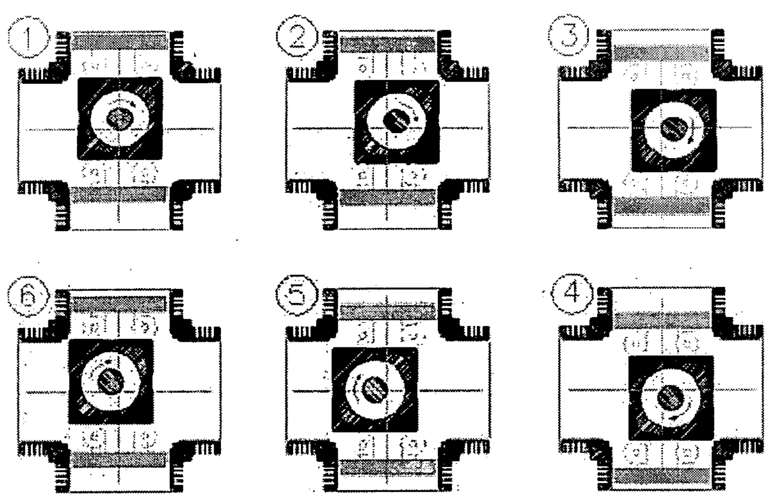

Figure 7: Scotch Yoke Operation

In the PRDA-2A configuration, passive valving is used for the compressor intake and exhaust. The action of the receding piston causes the reed valve to open, sucking ambient air into the chamber. As the yoke brings the piston back up, the air is compressed and pushed out through the discharge reed valve in a compressed state.

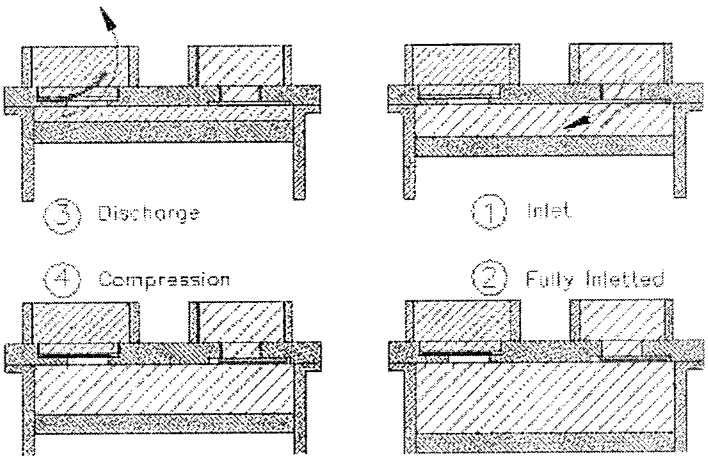

Figure 8: Reed Valve Operation

The expander recovers pressurized air as it is exhausted by the fuel cell and reformer. The expander recovers energy from the inlet air and translates it into power to assist the rotation of the common compressor/expander shaft.

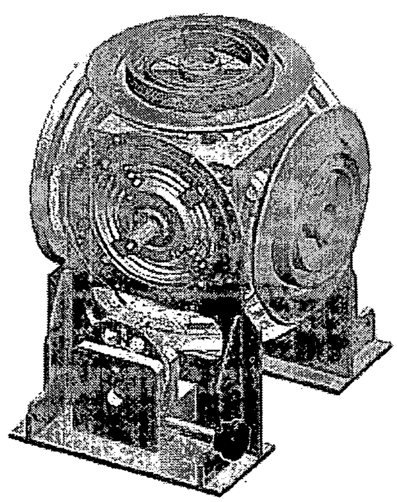

Figure 9: Expander

The proprietary expander active valving can be dynamically adjusted to control timing and duration of the inlet cycle, thus tuning the air system to the fuel cell power system operation, a requirement in a laboratory setting.

Compressor/Expander Results

Compressor, expander and integrated compressor/expander data were presented in October 1999. The data presented at that time is summarized in the next three figures.

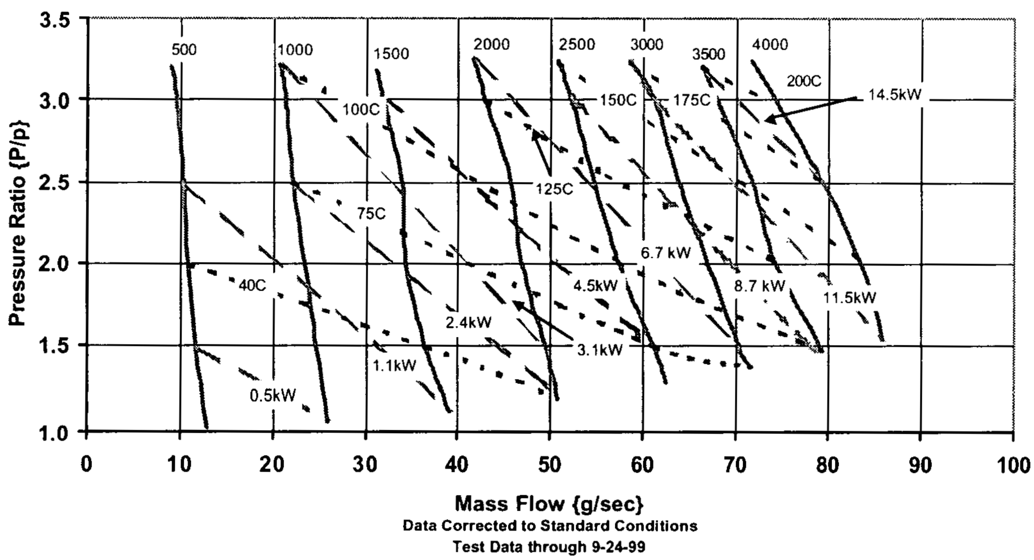

Figure 10: Piston Compressor Performance

The above figure shows a mass flow of 72 g/sec at the 3.2 bar at 4000 rpm. At this level, the compressor consumes 16.8 kW of power.

The earlier expander testing was much less comprehensive than testing of the compressor, and was heavily dependent on single-cylinder test results.

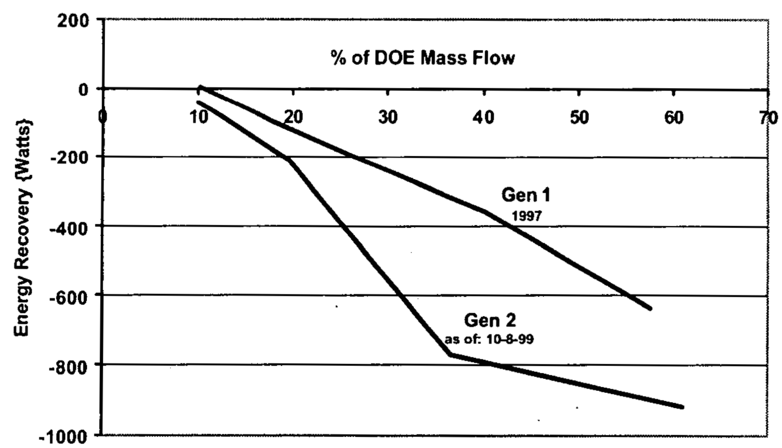

Figure 11: Expander Energy Recovery

However, even the preliminary data showed substantial improvement over the first generation expander, as seen in Figure 11: Expander Energy Recovery.

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Based on this data, power consumption projections were made assuming exhaust gas temperatures of 150 C and 250 C as shown in Figure 12: Expander Adiabatic Performance. This shows power consumption of less than 10 kW, even at 150 C, for the current integrated compressor/expander system.

Testing of the current 4-cylinder expander, subsequent to October 1999, demonstrated results exceeding the single-cylinder projections. Figure 12: Expander Adiabatic Performance shows the improved efficiencies as measured on the 4-cylcinder unit and extends data to 100% mass flow. In this figure, the projected ultimate expander performance is based on the assumption of 150 C expander inlet temperature. Because of test facility limitations, the measured performance was based on actual inlet temperatures in the range of 65 – 80 C.

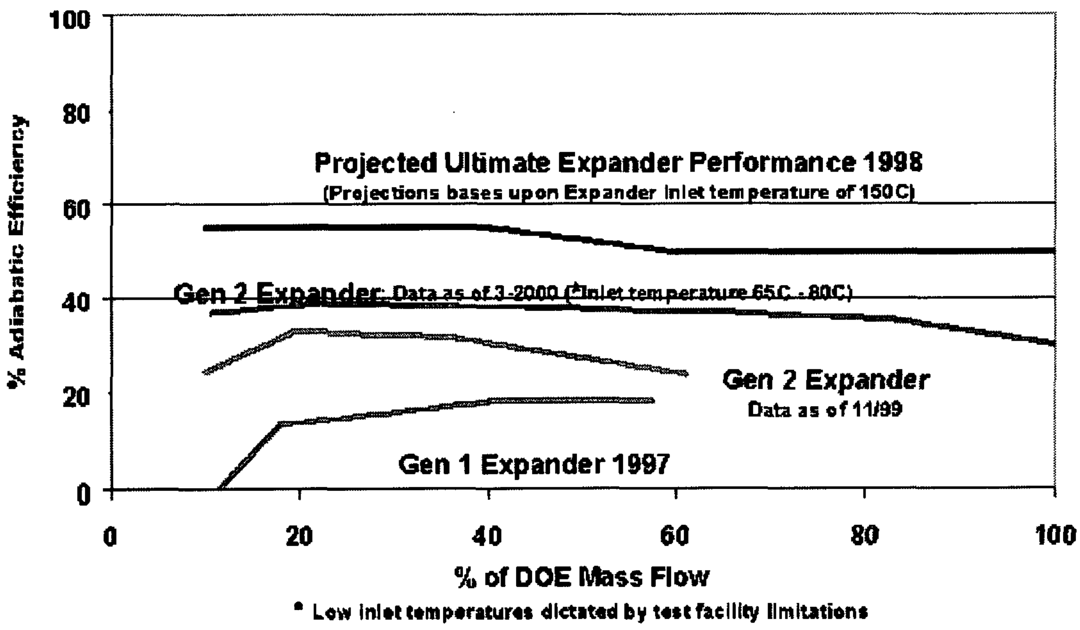

Figure 12: Expander Adiabatic Performance

The newer measured expander data, projected to 150 C inlet temperatures, significantly reduces the 10kW power consumption previously estimated for 100% mass flow at 3.2 bar. As discussed below under Continuing Development, energy recovery by the expander is far more a function of the inlet gas properties than it is of expander performance. The whole question of expander configuration and its integration into the power system is a critical subject for further development.

Data Evaluation

It should be noted that all test data has been corrected to standard conditions and normalized to previous generation data for consistency in comparative evaluation. Midway through the contract period, mass flow measuring devices were up-graded (see discussion under *Instrument Upgrade*, above). The new instrumentation was carefully compared to the original, resulting in a data correction factor. All subsequent data collected with the new instrumentation was modified by the correction factor so as to maintain a basis for comparison of to previous results and the on-going improvements.

The fact that the flow measuring systems yielded somewhat different data raises the need for standardization in testing methods and measurement standards among competing technologies. As competitive air management technologies approach maturity, it will become increasingly important to set critical performance objectives and measurement standards. This will be particularly important as fuel cell power system integration moves forward and comparative evaluations become critical.

To date, all test data comes from the deliverable compressor/expander hardware configuration. The specific design configuration was chosen to provide a test bed that could meet DOE guideline requirements. Where possible, design approaches were chosen to provide flexibility for evaluating and implementing future design evolutions. This has proven to be of substantial value, with most recent testing and design investigations indicating opportunities for significant advancements in both compressor and expander performance.

Intellectual Property

- Application no. 60/158,853: "Variable Timing Valves for Gas Compressors and Expanders" discloses several possible variable valve embodiments.
- Application no. 60/158,765: "Process Control of Multiple Air Supplies" discloses several different strategies of controlling fuel cell powering systems as it relates to the air system.

Continuing Development

After the above results were released, work began on improving volumetric efficiency of the compressor. The compressor reed valves have been identified as a major contributor to less than optimum flow into and out of the compressor chambers. This is where we are currently concentrating our compressor performance improvements.

To date, the redesign and tests on the single-cylinder test bed indicates improvements as noted in Appendix A.

It is projected that the compressor can be reconfigured to deliver 100 g/sec or more at 3.2 bar with about the same power consumption as the current configuration. This projected performance level is independent of the relatively minor measurement issue raised above.

The expander is another critical area needing further investigation and development. Expander energy recovery and contribution to system efficiencies is more a function of expander inlet gas properties than of expander performance. Therefore, development in this area must include design and construction or identification of a test facility that provides conditions such as temperature and moisture range that would be present in any fuel cell system.

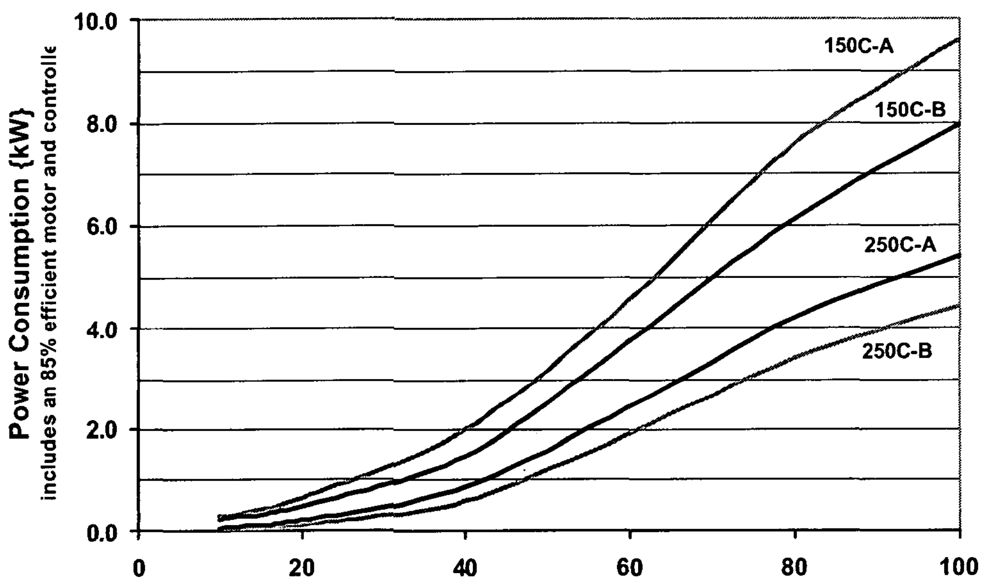

Figure 12: Projected iCEM Performance

The above figure illustrates the wide range of exander contribution to the system under varying conditions of inlet air temperature and moisture. The "A" condition is dry, the "B" condition is moist.

Development is also proceeding towards product for manufacture in several areas. These include, among others, core drive modifications for improved durability and reduced cost, and valve and manifold improvements for improved volumetric efficiency. Design improvements are underway in other areas as well. Based on this work we are projecting meeting manufacturing cost and durability targets within the industry time schedule.

Customer Evaluation Units

VAIREX has received requests for quotations for iCEM evaluation units from:

- Ford
- Fiat
- Chrysler/Daimler

We are also in discussions with

- Ballard
- Nissan / Renault
- General Motors

The customers listed above have specified requirements varying from the DOE guidelines. We envision a product family that meets this variety of requirements. Initially it appears that three products are needed that meet three distinct mass flow rates:

75 g/sec
100 g/sec
120 g/sec

Specified pressure ratios range up to 4 bar.

We have also received requests for quotation from a number of stationary fuel cell power system integrators for air systems to supply air for systems in the range of 3 – 20 kW, net output. The air system requirements for these applications are nominally in the range of 2 bar, with mass flow in the range of 5 – 30 g/sec. These systems typically do not warrant an expander, but require very long operating life. We are quoting a 2-cylinder of the *VAIREX* air system, less expander, and with appropriate motor and controller, for these applications. These are designated iCMs.

We anticipate delivering iCEM and iCM customer evaluation units during calendar year 2000.

Manufacturability Results

The iCEM/iCM product is being designed for both automotive and stationary markets. Instead of one limiting the other, the two market areas are uniquely compatible due to similarities in both energy requirements and overall system design. Economies of scale and cost can be realized by this joining of markets.

A straightforward engineering path has been defined to bring the technology into production. The resulting products are projected to meet industry goals for cost and durability. The basic design is scalable over the performance range envisioned for automotive applications and for smaller (2 – 20 kWe net) stationary fuel cell power systems.

A computerized modular scaling model for compressors has been developed and is in use. The entire range of product demonstrates comparable pressure ratio operating profiles independent of mass flow rates, with turndown ratios well in excess of 10:1.

The very wide range of selectable operating parameters provides the fuel cell power system architect with considerable flexibility.

Cost targets

Cost projections, based on designs for production; indicate manufactured costs (fully tooled volume production) in the range of $ 400 – 500 per iCEM for fuel cell systems in the 50 – 100 kW (net) category. Smaller, compressor-only configurations in less volume, suitable for stationary or mobile systems in the 2 – 20 kWe, are projected to cost $250 – 300.

Cost targets in 1996 dollars:

Compressor	100 - 125
Expander	125 - 150
Motor	75 - 100
Controller	50 - 75
Overall Production Target	350 - 450

Packaging Results

Partially as a result of the decision to move from a variable displacement architecture, the reduction in hardware complexity and the resultant reduction in parts count in the Phase Two deliverable, as compared with Phase One, has been dramatic. Phase Two hardware represents an almost 50% reduction in number of parts, while still incorporating many redundancies and development/test-related features which would not be present in the manufacturable design. The on-going development program will reduce parts count even further.

The PRDA-2A deliverable does not directly meet the size guidelines set by the DOE. While the manufactured system will be much smaller than the existing hardware, low speed piston-based systems are inherently larger than high-speed clearance technology devices.

To offset the size drawback, certain operational characteristics have major impacts on the size, weight and cost of other significant system modules. These operational characteristics include:

- Sustainable high pressure ratios
- Low parasitic power consumption
- Fast response time
- Multiple independent air streams
- Lower output air temperature
- Upstream water capability

One European OEM automotive manufacturer has indicated that savings in fuel cell stack, battery pack, and heat exchanger sizes alone make the Phase Two air system essentially a net zero volume system component.

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Comparison with Twin Screw (clearance technology)

Part of the Contract Scope of Work required *VAIREX* to compare clearance compressor/expander technology and non-clearance system performance. *VAIREX* had extensive experience in applying clearance technology systems to fuel cell power systems as interim air system solutions. Tests were run under identical conditions on a twin screw system, as typical of clearance technology, and the *VAIREX* piston, non-clearance system. Tests were run in compressor-only configuration and as integrated compressor/expander systems.

Below is a brief summary of the assessment comparing the *VAIREX* compressor technology to the twin screw technology. The entire report is available upon request. It should be noted that the following zero-clearance data was taken using first-generation piston hardware. Recent piston test results indicate an even greater advantage for the second-generation piston system across the operating range.

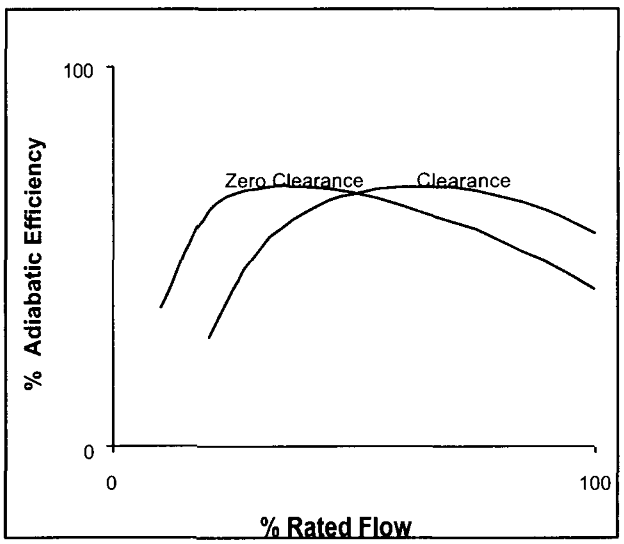

Figure 13: Peak Compressor Efficiency Comparison

Compressor efficiency in a zero-clearance system typically peaks at 20 – 40% of full rated flow, while non-clearance devices peak closer to full load. This is true regardless of the absolute efficiencies of each type. In an automotive application, where the typical operating profile is heavily weighted around 30%, the zero-clearance, piston device has a clear advantage. In more recent tests, the newer generation *VAIREX* compressor has shown efficiencies exceeding the referenced twin screw system across the full range of rated flow.

The full impact of the relative efficiencies across flow ranges throughout the guideline pressure ratios is shown below in Figure 14: Compressor Adiabatic Efficiency Comparison.

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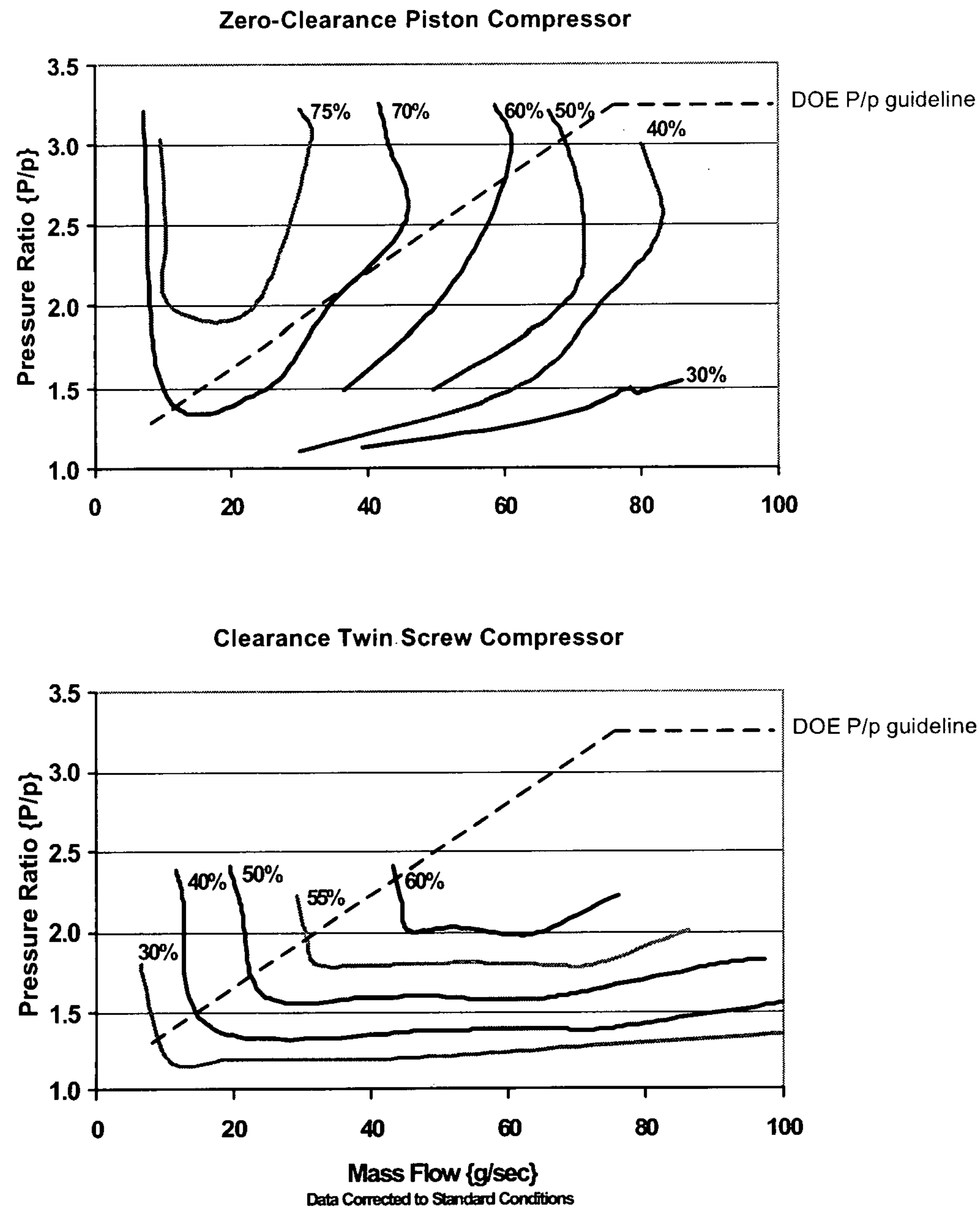

Figure 14: Compressor Adiabatic Efficiency Comparison

The above figure is a topographical representation of efficiency over the full range of operating parameters, more clearly showing the operating advantage of the piston technology in an automotive application. Again, more recent data further enhances the relative value of the piston compressor over a clearance device.

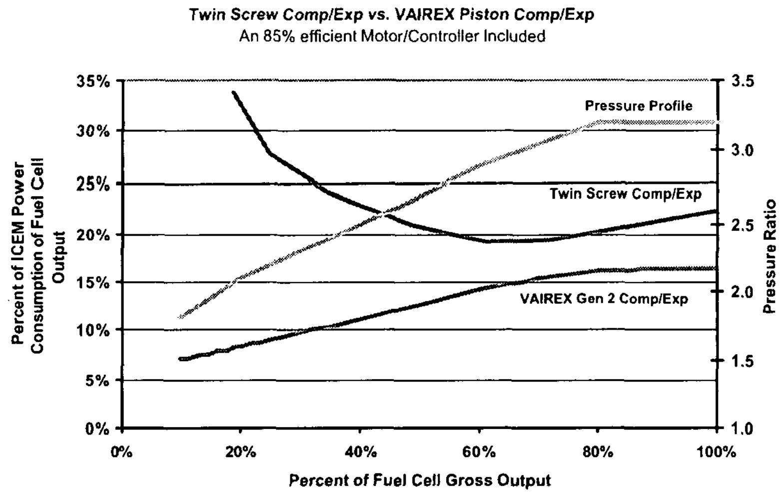

Figure 15: Percent of Fuel Cell Gross Output

The integrated compressor/expander systems were then compared, across the DOE pressure ratio profile, with the results shown in Figure 15: Percent of Fuel Cell Gross Output, in terms of parasitic power consumed as a percent of fuel cell stack output. This figure shows the piston system consuming less of the available power across the full spectrum of mass flow. Newer data shows the *VAIREX* piston compressor/expander percentage power consumption staying well below 15% across the spectrum of mass flow.

As these performance maps show, the piston compressor/expander system has superior performance across the pressure profile throughout the mass flow range. Zero-clearance (piston) systems can maintain higher, more constant pressure ratios over a far greater turndown range. They also consume less parasitic power over the full operating range, but particularly in the most significant area of the system operating profile, the 30 – 40% of full load point. Other advantages of non-clearance over clearance machines, not reflected in these figures, include faster transient response and lower exit air temperatures.

Clearance machines are inherently very high-speed devices, and thus tend to be smaller for a given flow range. However, their high operating speeds necessitate advanced bearing devices to achieve targeted operating life. The design and required precision in manufacturing are not conducive to low cost products.

Non-clearance (piston) machines operate at low speeds and thus tend to be bigger. As noted above, the over-all system effect of the larger size can be more than offset by other system savings. The lower operating speeds permit much simpler, less inherently expensive bearing devices for targeted operating life. The technology is conducive to simple tooling and very low manufacturing costs.

The conclusion drawn from the comparison of technologies is that the clearance machines are a possible interim solution for developmental phases in fuel cell power systems, while piston systems present the greatest flexibility and economic potential in more mature systems.

Recommendations for Future Research & Development

The *VAIREX* iCEM technology is a proven, functional system. However, issues remain to be resolved in the following areas:

1.0 Development of the PRDA-2A deliverable into the iCEM customer evaluation units, including 2.0 and 3.0 below.

2.0 Motor development: specifications for a custom motor family; form factor; sizing for electrical and physical requirement; development of a custom controller and establishing objectives and status.

3.0 System controls development.

4.0 Test facility to generate appropriate expander inlet flows to solve expander issues such as: simplification of size and valving, configuration and degree of integration into compressor; adaptation to actual system exhaust gas parameters; production requirements and adjustment range. Optimization of FCPS operational parameters.

5.0 Continuing compressor design refinements for performance enhancements, for example in volumetric efficiency, increasing flow/revolution and consequent impact on size and durability, and refinement of the valving system.

6.0 Durability testing and improvements for wear surfaces through tribology[1] improvements and advanced mechanical architecture.

7.0 Development of the design for efficient manufacture: Size/weight/cost factors in designing the system and tooling for manufacturing.

8.0 Integration with the Fuel Cell Power System (FCPS) with regards to system controls and energy recovery in response to customer evaluations of iCEM.

9.0 iCEM internal integration: close coupling of iCEM components, potential architectural changes, potential flow improvements creating smaller size, simplification, and improved durability.

VAIREX is continuing its development, aiming at manufactured product meeting industry requirements. Areas of continuing work include all of the above items. However, we suggest strongly that DOE consideration be given to participation in items 1, 7 and 8, where system issues are critical.

[1] Tribology: the study of friction.

Appendix A: Current Performance vs. DOE Guidelines

(as of June 12, 2000)

Compressor

Parameter	Units	DOE Guideline	Current Status	Comments
Max. Flow Rate	g/sec	64 – 76	72	@ 3.2 bar, at rated speed (4,000rpm) Projected: > 76 at full rated speed in current configuration
Water Vapor	G/sec	0 – 4	> 4	Demonstrated with Generation 1 hardware. Compressor design considers water vapor injection.
Stoichiometry Inlet Pressure Outlet Pressure	 Atm. Atm.	2.0 1.0 3.2	NA 1.0 3.2	 3.2 bar demonstrated from 72 g/sec down to 4 g/sec
Temperature: Design Point Extreme	 ° C	 20 – 25 -40 - 60	 13 – 37	 Limited by test facilities. Extremes determined by motor specified.
Max. Shaft Power	kW	12.6	16.8 = 12.6	Current measurement @72 g/sec, 3.2 bar Projected: @ 76 g/sec, 3.2 bar
Turndown Ratio Stages Contamination	 ppm oil	10:1 1 – 2 < 100	> 12:1 1 –	Demonstrated: 72 g/sec to 4 g/sec @ 3.2 bar. In VAIREX piston technology, surfaces exposed to air flow are lubrication free.
Efficiency vs Flow 100% @ 3.2 bar 80% @ 3.2 bar 60% @ 2.7 bar 40% @ 2.1 bar 20% @ 1.6 bar 10% @ 1.3 bar	%	 75 80 75 70 65 50	 45 58 70 73 73 68	

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Expander

Parameter	Units	DOE Guideline	Current Status	Comments
Max. Flow Rate	g/sec	8.2 – 82	8.2 – 82	Test results exceeded requirements.
Water Vapor	G/sec	9 - 16	> 18	Demonstrated in Gen 1. Design considers water vapor injection.
Stoichiometry Inlet Pressure Outlet Pressure	 Atm Atm	2.0 2.8 1.0	NA 2.8 1.0	
Temperature: Design Point Extreme	 ° C	 118 – 150 65 – 150	 65 – 80	 Testing range limited to by facility limitations.
Max. Shaft Power	kW	- 8.3	- 5.9	Measured @ 2.8 bar, 60% of guideline inlet energy
Turndown Ratio Stages		10:1 1	10:1 1	
Efficiency vs Flow 100% @ 3.2 bar 80% @ 3.2 bar 60% @ 2.7 bar 40% @ 2.1 bar 20% @ 1.6 bar 10% @ 1.3 bar	%	 90 90 86 82 80 75	 32 38 39 40 40 38	Projected: 50 50 50 57 57 57

Integrated Compressor/Expander

Parameter	Units	DOE Guideline	Current Status	Comments
Start Up Response	sec	< 5	< 2	
Transient Response	sec	< 4	< 1	
PRDA 2A Deliverable				
Volume	L	4	140	
Weight	Kg	3	95	
Production Cost	$	200	NA	
Noise	db	< 80	95	
iCEM				
Volume	L	4	80	
Weight	Kg	3	75	
Production Cost	$	200	350 - 450	Projected cost in manufacture, incl. motor.
Noise	db	< 80	< 80	Need detailed SPL guidelines.

Appendix B: SolidWorks & Pro/MECHANICA examples