Document: TR-09-002	Date: July 6, 2009	Rev: 0
Title: DMFC Prototype for Consumer Electronics – Final Report		Editor: C Carlstrom

***DMFC Prototype Demonstration for
Consumer Electronics Applications***

DOE Program: DE-FC36-04GO14301

Recipient: MTI Micro Fuel Cells Inc.

***Chuck Carlstrom
Program Director***

Final Report

July 6, 2009

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Executive Summary

The work completed under this program has significantly increased the understanding of how Direct Methanol Fuel Cells (DMFC) can be deployed successfully to power consumer electronic devices. The prototype testing has demonstrated the benefits a direct methanol fuel cell system has over batteries typically used for powering consumer electronic devices.

Three generations of prototypes have been developed and tested for performance, robustness and life. The technologies researched and utilized in the fuel cell stack and related subsystems for these prototypes are leveraged from advances in other industries such as the hydrogen fueled PEM fuel cell industry. The work under this program advanced the state of the art of direct methanol fuel cells. The system developed by MTI micro fuel cells aided by this program differs significantly from conventional DMFC designs and offers compelling advantages in the areas of performance, life, size, and simplicity.

The program has progressed as planned resulting in the completion of the scope of work and available funding in December 2008. All 18 of the final P3 prototypes builds have been tested and the results showed significant improvements over P2 prototypes in build yield, initial performance, and durability. The systems have demonstrated robust operation when tested at various orientations, temperatures, and humidity levels.

Durability testing has progressed significantly over the course of the program. MEA, engine, and system level steady state testing has demonstrated degradation rates acceptable for initial product introduction. Test duration of over 5000 hrs has been achieved at both the MEA and breadboard system level.

P3 level prototype life testing on engines (stacks with reactant conditioning) showed degradation rates comparable to carefully constructed lab fixtures. This was a major improvement over the P2 and P1 engine designs, which exhibited substantial reductions in life and performance between the lab cell and the actual engine.

Over the course of the work on the P3 technology set, a platform approach was taken to the system design. By working in this direction, a number of product iterations with substantial market potential were identified. Although the main effort has been the development of a prototype charger for consumer electronic devices, multiple other product concepts were developed during the program showing the wide variety of potential applications.

Significant progress has been made in the area of codes and standards. Methanol fuel cells and their associated cartridges are now allowed in airline passenger cabins. This allowance is available on a voluntary basis since 1 Jan 2009, final full allowance is required by 1 Jan 2010. Removable cartridges containing 100% methanol have been produced and have demonstrated hot swap capability.

The cartridge size is the major factor driving energy density of the platform. By changing the size of the fuel cartridge, the same fundamental platform design can be used with minimal changes to meet the requirements of the various markets. A small cartridge is best for the applications where the consumer carries the device on his/her body, such as an external charger for portable electronics. A large cartridge is best for applications where reducing service (fuel refills) is important. This large cartridge design is capable of long run applications,

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like unattended ground sensors which are currently powered by lead acid batteries. These two applications bound the extremes of the cartridge size with many other applications falling in between these bounds. Based on the 18 DOE unit's average baseline performance the energy density is projected to exceed 600wh/L when using the large cartridge capable of 2000 hours of run time. The same platform equipped with a single small cartridge, can easily fit in your pocket, which makes it easy to carry, but also results in lower energy density.

Comparison of Actual Accomplishments with Objectives of Project:

List of Program objectives:

1. Demonstrate overall energy density equal to or better than 600 Wh/liter.
2. Accelerate codes and standards activities that allow shipping and use of methanol and hydrogen in airline passenger cabins.
3. Develop straight-forward refueling with 100% methanol, possible while source is on.
4. Demonstrate 1000 hours of continual operation.
5. Prepare three successive generations of benchmark prototypes to evaluate system integration issues and validate performance.

Accomplishments discussion relative to OBJECTIVE 1 “*Demonstrate overall energy density equal to or better than 600 Wh/liter*”:

Three generations of prototypes have been built and tested during the program. Each one of the prototypes improved significantly over the previous generation of the technology especially in the areas of performance, robustness and durability.

The system energy density, used in Figure 1, is one of the objectives listed above for this program. The DOE roadmap target (for the sub-watt to 50 W category) provided a goal line for this program, although it was more applicable to a 50 W system, rather than a 1 W system. The system's ability to beat the battery it would replace in handheld devices was also a good measure of platform development success. The battery capability, shown in Figure 1, was based on MTI's evaluation of current and reasonable improvements in Lithium Ion batteries. Any platform that can be turned into a viable product will likely need to be better than the battery capability.

In addition, battery power packs available in the consumer market have been examined. These rechargeable Li-Ion battery based power packs are used to charge handheld electronic devices on the road. The emergence of these products signals a market need and an entry point for handheld fuel cells. MTI's benchmarking of these power packs showed that they under - performed with respect to the Li-Ion battery capabilities. Current energy density with a fully charged battery was about 100 – 150 Wh/liter. This performance was even lower if one takes into consideration the wall charger as part of the total system volume. Fuel cell products under development for this market need to be significantly better than these battery based chargers in order to attract consumers.

The progression of the prototypes developed in this program is also shown in Figure 1. This progression started with the breadboard demonstration in May 2005. There was an intermediate proof of concept (POC) prototypes built and tested during the suspension period.

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This has been plotted in Figure 1 as reference information. Note that this prototype was about equal to the battery capability.

The test results from the P2 prototypes tested are shown in Figure 1 as the P2 solid triangle. The P2 system did not have a cartridge, so the initially projected cartridge size for the target platform was used to determine the system energy density with refills. The P2 system energy density was based on several refills of a small tank. The test results were very near the target.

System energy density is a function of cartridge size and the number of cartridges carried. The P3 prototype cartridges have been designed in two sizes to meet the needs of two identified markets for this platform. The small cartridge is best for the applications where the consumer carries the device on his/her body and the large cartridge is best for applications where reducing service (fuel refills) is important such as remote sensors. These two applications bound the extremes of the platform with many other applications falling in between these bounds. Based on the 18 DOE unit's average baseline performance the energy density is projected to exceed 600Wh/L and (850 Wh/kg) when using the large cartridge. An example application for the large cartridge is a fuel cell powered remote sensor which currently uses a lead acid battery. A typical lead acid battery has 60 to 75 Wh/L or 30 to 40 Wh/kg. This implies that the fuel cell is capable of providing 10 to 20 times the energy of a lead acid battery for long duration runs. Smaller cartridges have lower energy due to the fuel packing efficiency of the individual cartridge.

The P3 system projected energy density shown in Figure 1 is based on the large cartridge performance described above. Overall, figure 1 shows the methanol fuel cell technology is clearly superior to the basic rechargeable battery as well as the available power packs.

Figure 1, Prototype System Energy Density Targets

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Accomplishments discussion relative to OBJECTIVE 2 “Accelerate codes and standards activities that allow shipping and use of methanol and hydrogen in airline passenger cabins”:

There is a substantial body of regulations that govern the use and transport of hazardous materials. This program has concentrated on the international regulations for fuel transport and fuel cell use in airline passenger cabins. Teams from MTI and the Methanol Foundation have been deeply involved in wide ranging tasks with multiple international bodies, as shown in Figure 2, driving the standards forward. Many milestones have been achieved toward acceptance of fuel cells in airline passenger cabins. In the process, a number of white papers and presentations have been prepared for U.S. DOT and FAA to allow them to become familiar with the fuels and fuel cell technologies and to address their safety concerns.

The International Civil Aviation Organization (ICAO) standard establishing cargo shipping instructions and passenger exception for fuel cells and fuel cartridges became effective on January 1, 2007. The U.S. Department of Transportation (DOT) enacted cargo regulations covering methanol fuel cell cartridges by the end of 2006 and issued a Notice of Proposed Rulemaking (NPRM) on September 20th, 2007, to adopt the ICAO passenger allowance and “harmonize” the U.S. requirements with the international standard. This action by the DOT was encouraged by the MTI and Methanol Foundation teams, which organized a coalition of methanol fuel cell technology companies to urge publication of the DOT notice. On April 5th 2008, representatives of MTI and MF met with key staff at the U.S. DOT in Washington, D.C. to discuss MTI’s design plans to comply with U.S. and international transport regulations. On April 30th 2008, the DOT issued a final rule adopting the ICAO passenger exception, and the MTI/MF team issued a press release to call attention to this critical milestone. In addition, team representatives participated in a USFCC meeting with the DOT on June 10th 2008, to discuss further ICAO revisions relating to fuel cell transport regulations. On July 31st 2008, the DOT proposed a rule-making to further update U.S. transport regulations with additional updates from international regulatory bodies, including ICAO technical instructions taking effect on January 1, 2009. MTI and MF reviewed this proposal, and provided comment through the USFCC.

In addition to encouraging the development of new codes and standards governing the transport and use of micro fuel cells, the MTI/MF team tracked activities of various international code setting agencies as they continuously seek to revise and refine those requirements that have already come into force. Progress has been made on the IEC standard, with revisions to provisions covering close proximity emissions testing. IEC activities have also included review of convener’s response to comments, review of the latest IEC draft standard and Annex A draft, as well as providing comments to the convener status report.

Further, fuel cell transport issues also are directly impacted by homeland security concerns, and agencies like the Federal Aviation Administration and the Transportation Security Administration were taking a close look at the implications of these new technologies. The MTI/MF team worked closely with these security-related agencies to help them better understand safety issues relating to methanol fuel cells.

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- The Methanol Foundation worked with MTI on the development and implementation of fuel cell codes and standards to not only move the commercialization of the technology forward, but to assist MTI in designing compliant products and distribution protocols. This work was aided by a Methanol Foundation subcontract with Jack Paterson, of J.A. Paterson LLC, a prominent attorney who has worked with the U.S. Fuel Cell Council and several fuel cell companies on fuel cell standards activities.

During the first half of 2008 the MTI/MF team focused on life-cycle issues for methanol fuel cartridges. Following up on a 2007 meeting with officials from the New York State Department of Environmental Conservation, information on proper “end of life” options for fuel cell cartridges and fuel cell systems was provided during the quarter. A summary of the RCRA-empty rule was prepared to assist in discussions with NYS DEC. The MI/MTI team is also working with other micro fuel cell companies to raise life-cycle issues with state environmental officials in Ohio.

In late 2008 MTI representatives met with the NY Department of Environmental Conservation (NY DEC) to demonstrate the product intent system and cartridge. The purpose of the visit with the DEC was twofold; first to show production intent cartridges and solicit feedback on how the RCRA-empty rule applies to it, and second to solicit feedback on disposal of the system and how existing electronics recycling rules would apply. All parties seemed satisfied that the RCRA-empty rules would apply and that a sufficiently empty cartridge would be exempt from a state and federal classification of hazardous waste. It was noted that local municipalities and individual landfills may have different regulations. The consensus on the system was that typical electronics recycling rules would apply and that the presence of precious metals (Pt, Ru Au etc) would help drive the economic benefits of recycling. There were several takeaways from the DEC , most of which involved watching pending legislation.

Figure 2, Codes and Standards Activities and Timeline

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Accomplishments discussion relative to OBJECTIVE 3 “*Develop straight-forward refueling with 100% methanol, possible while source is on*”:

The P3 system was the first prototype in this program which included a separate fuel cartridge instead of an internal tank. An internal, user-refillable tank is unacceptable for a commercial product for the following reasons: ICAO rules explicitly prohibit this kind of device from being carried on a commercial flight, and a user directed fluid transfer between the fuel source and an internal reservoir is prone to user-error which could cause unnecessary exposure to methanol. Another advantage provided by the use of a cartridge subsystem is control over the quality and source of the methanol. This is very important to ensure an acceptable life span of the fuel cell system.

Figure 3 shows the P3 cartridge and system. All 18 of the DOE P3 prototypes were tested with a removable cartridge. This cartridge can be replaced without interrupting the steady output of the system.

Figure 3, Removable cartridge and the P3 system

Accomplishments discussion relative to OBJECTIVE 4 “*Demonstrate 1000 hours of continual operation*”:

Multiple P2 and P3 prototypes have demonstrated over 1000hrs of run time. Many of the critical fuel cell components have demonstrated run times much longer while also achieving very low degradation rates.

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Figure 4, P2 System Run Decay

Figure 5, P3 Breadboard Run Decay

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Although multiple P2 systems exceeded 1000 hours of run time (see Fig 4) there was high degradation. A significant source for the high degradation was identified and corrected in the P3 design. Four P3 BB1 units in the brass board configuration were tested for life starting early in 2008. The performance of the system with the longest life is shown in Figure 5. After an early failure and repair, the system was tested for an extensive time in order to determine the appropriate fuel cell parameters. From that point forward, the parameters were locked, and testing resumed. The Figure showed a decay rate of approximately 45% after 5000 hours of operation. The power decayed at a faster pace beyond that point caused by frequent startup and shutdown cycles as a result of several power interruptions in the building.

Accomplishments discussion relative to OBJECTIVE 5 “*Prepare three successive generations of benchmark prototypes to evaluate system integration issues and validate performance.*”

P1 Prototype Builds and Testing:

The P1 prototype was a brassboard prototype used to test various sub components at the system level. This flexibility was key in the early stages of the program when the technology was evolving rapidly. Major hurdles were sometimes encountered on a sub system that would necessitate changing interfacing components quickly. The P1 system served its purpose as being an excellent platform to demonstrate system level performance and resolve early system level issues.

A total of 10 P1 brassboards, as shown in Figure 6, were built and tested. Details of the thermal control system and cartridge are not shown for proprietary reasons. Ten units were evaluated to provide a reasonable statistical performance benchmark. These tests included a prototype fuel cartridge developed by a Fortune 500 company. The best performance achieved was 220 mW and 600 Wh/L of fuel. The total component volume of a 20 Wh system was 120 cc, including fuel. Given the component volume in early-2005 this performance level results in 170 Wh/L at the system level (including the fuel cartridge).

A number of thermal control, insulation and fuel control options were evaluated leading up to the P1 breadboard design. Passive and active thermal control prototypes were assembled and tested, some having a potential cost of pennies per system. Various fuel feed technologies and components were miniaturized and tested for performance and durability.

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Figure 6, P1 Brassboard prototype

P2 Prototype Builds & Testing:

A total of 11 P2 prototypes were built and tested as part of this program. The P2 units were the first units to be built at MTI by assembly technicians rather than engineers. Although there were some design changes that had to be managed the design was stable enough to allow build procedures and assembly metrics to be tracked. There were also in-process checks to qualify sub assemblies and obtain important yield information for each step in the assembly process. This yield and assembly time information helped determine the major areas to focus the effort for the P3 system design. The P2 build utilized a new clean-room environment for all assembly operations. The systems built in this area showed no signs of failure due to contamination (either chemical or particulate). The area consisted of a general work area controlled to class 10k standards with specific build stations controlled to class 100 standards. There was also a “dirty” area to confine operations that generate contaminants.

Figure 7, P2 Prototype

P2 systems, of the type shown in Figure 7 were tested in the second half of 2007. These systems were run through a baseline test to verify their performance. The average power and

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efficiency for the last batch of systems (6 of the 11 total) was evaluated and reported in quarterly reports. After initial baseline runs, these units have been placed on life testing and customer profile testing.

Baseline profile testing was conducted by applying a constant voltage of 3.8 volts to the unit. This allows the unit to run continuously through a full tank of fuel allowing average power and efficiency to be calculated. During the customer profile testing, the unit was allowed to cycle the battery. Starting with a fully charged battery a 0.4 amp load (approximately 2W) was applied to the unit in order to simulate being connected to a device which required charging. Once the unit has been discharged, the load was removed and the unit was allowed to charge back up. Some of the units were tested on the baseline profile testing; whereas the remaining units were tested on the customer profile testing. The average power, efficiency and run time hours were calculated and monitored. These metrics were reported to the DOE in confidential reports.

Several systems which were initially tested in Q4 of 2007, remained on life test during the first half of 2008. Two of the units ran for a total of 350-400 hours, before fueling and electronics issues arose. Multiple systems reached over 1000 hours of run time, achieving a program milestone, and one of these P2 systems went on to accumulate over 1800 hours of run time.

P3 Final Prototype Builds

Forty-eight P3 EVT2 systems as shown in Figure 3 were built in four batches during the second half of 2008. The first three batches and the fourth batch consisted of ten systems and eighteen systems respectively. All systems were initially tested in the brass board configuration. Other testing configurations included partially boxed systems, and boxed systems with a non removable fuel tank. Several issues were identified including blocked air passage, failed pressure sensors, failed electronic boards, and torn o-rings at the ports. Forty-four of those systems were completely assembled in the system enclosure with a removable and refillable cartridge and tested. Additional issues identified included the alignment of the fuel and air subsystems in the enclosure, alignment of the cartridge, and wire routing issues. Six units from the first, second and fourth batch were designated as DOE P3 units. These sets of units were referred to as the Group 1, Group 2 and Group 3 of the P3 DOE units, respectively.

P3 Final Prototype Tests

Initial qualification testing was carried out in the brassboard configuration on all eighteen DOE P3 units. A statistical analysis was carried out on the test results. Customer profile baseline testing was carried out on ten of the DOE P3 units. Other tests included a system orientation test, an ambient temperature and humidity latitude test, and sound measurements in startup and steady state mode of operation.

P3 Final Prototype Initial Qualification Testing

This test was run in the brassboard configuration with a lab manifold and a methanol bottle and lab heat sink. The load profile was set at a constant voltage of 3.6V at the battery terminals. The gross and net power and fuel efficiency of the system was measured. All eighteen DOE P3 units were subjected to this test.

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The normalized gross power during the qualification run of all DOE units was presented in Figure 8. A t-test concluded no statistical difference in the power between the three groups.

Figure 8, Initial Power of Group 1, Group 2, and Group 3 of P3 DOE units

P3 Final Prototype Baseline Testing – Customer Profile

This test was run with a customer profile testing, allowing the system to cycle the battery. The load profile test was run starting with a fully charged battery and by applying a voltage of 5V at the system USB, and 0.5 amp load, resulting in a 2.5W load. The gross and net power, energy and fuel efficiency of the system were measured. The mass of the cartridge was measured before and after the test.

The system baseline testing was carried out on ten out of eighteen DOE systems. Four of the systems were from Group 2 and five systems were from Group 3. The gross power, total energy stored in the system with a full cartridge, and net system efficiency was presented in confidential reports to the DOE. Normalized versions are shown in Figures 9-11.

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Descriptive Statistics

Variable: Normalized P

Anderson-Darling Normality Test

A-Squared:	0.452
P-Value:	0.206
Mean	0.881655
StDev	0.090639
Variance	8.22E-03
Skewness	0.316662
Kurtosis	-1.52128
N	9
Minimum	0.76040
1st Quartile	0.80436
Median	0.86779
3rd Quartile	0.98960
Maximum	1.00000
95% Confidence Interval for Mu	
	0.81198 0.95133
95% Confidence Interval for Sigma	
	0.06122 0.17364
95% Confidence Interval for Median	
	0.80418 0.99453

Figure 9, System Baseline Testing – Normalized Gross Power Histogram
(Actual numbers have been reported in confidential reports to DOE)

Descriptive Statistics

Variable: Normalized E

Anderson-Darling Normality Test

A-Squared:	0.181
P-Value:	0.883
Mean	0.850551
StDev	0.104728
Variance	1.10E-02
Skewness	-6.3E-01
Kurtosis	0.519738
N	9
Minimum	0.64954
1st Quartile	0.78752
Median	0.86518
3rd Quartile	0.93001
Maximum	1.00000
95% Confidence Interval for Mu	
	0.77005 0.93105
95% Confidence Interval for Sigma	
	0.07074 0.20063
95% Confidence Interval for Median	
	0.77323 0.93494

Figure 10, System Baseline Testing – Normalized Total Energy histogram
Note: Actual numbers have been reported in confidential reports to DOE

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Figure 11, System Baseline Testing – Normalize Net Efficiency histogram

Note: Actual numbers have been reported in confidential reports to DOE

P3 Final Prototype Orientation Test

Two DOE systems (DOE2.2 & DOE2.5) were tested under all six orientations. The system normalized gross power was presented in tabular form in Figure 12. It was clearly shown that both systems produced consistent power in all six orientations.

System	DOE2.2	DOE2.5
Orientation		
Standard	1.000	1.000
Vertical- cartridge down	0.949	1.019
Vertical- interface down	0.840	0.962
Facedown	0.928	0.954
Horizontal 1	0.912	1.027
Horizontal 2	0.912	0.987
Average	0.923	0.992
StDev	0.052	0.030

Figure 12, Normalized gross power

Note: Actual numbers have been reported in confidential reports to DOE

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P3 Final Prototype Temperature and Humidity Test

Two DOE systems (DOE3.3 & DOE3.6) were tested in the environmental chamber under various temperature and humidity conditions. The chamber conditions tabulated in Figure 13, included high and low humidity levels at low, normal and high ambient conditions.

Temperature & RH Latitude Test

Temp C	Rel Hum %	Time (hrs)
20	10	3
20	50	2.25
20	90	2.25
10	90	3
10	50	2.25
10	10	2.25
20	10	3
30	10	3
30	50	2.25
30	90	2.25
20	50	2

Figure 13, Temperature & RH latitude test

Typical results were shown in Figure 14. It was clearly shown that the relative humidity had no effect on the gross power of the system. The only reduction in power was caused at the high ambient temperature. This was caused by the 20% reduction of the fuel feed rate from its nominal value. This change was dictated by the firmware which reduced the flow rate when the

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battery temperature exceeded a pre-assigned limit.

Temperature & Humidity Test (DOE3.3 Unit)

Figure 14: Normalized Power During Temperature & Humidity Test

SUMMARY OF PROJECT ACTIVITIES

All of the activities associated with the building and testing of prototypes was covered in the last section. This section covers the overall technical approach as well as highlights some of the key subsystem developments such as MEA, cell design and analysis (Structural & Thermal). Due to the public nature of this report some activities contributing to the high level system accomplishments will not be described in the detail they were during confidential DOE reports and meetings.

Overall Technical Approach:

The overall technical approach MTI has used from the beginning of this program has been to reduce the number of components needed in a typical DMFC system. MTI focused on reducing the complexity of the anode loop and water recovery from the cathode stream. These two systems are interrelated because of water management.

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Figure 15, Typical DMFC Fuel Cell System

Figure 16, MTI Simplified DMFC system

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MTI Water Management:

Water is needed for proton conductance and anode reaction. At anode, one methanol molecule requires one water molecule to complete the reaction

At cathode, three water molecules are produced when one methanol molecule reacts at anode

Overall, 2 net water molecules are produced when one methanol molecule is oxidized

So, fuel cell reaction itself should be able to supply enough water for both hydration and reaction purposes. MTI's fuel cell is designed in such a way that there is a net water transport from cathode to anode through the membrane. This is a passive process that requires no energy. This significantly reduces the system complexity as shown when comparing Figures 15 and 16.

The MTI simplified system achieved the following:

- Neat methanol (i.e., 100%) is used at anode
 - No water added
 - No water tank needed
 - No mixing tank needed
 - No methanol concentration sensor needed
- Fuel utilization is higher than 80%
 - Methanol crossover from anode to cathode is less than 10%
 - Methanol loss from anode is less than 10%
- Ambient air is used in cathode
- No cathode flooding issues
- No water balance issues
- No methanol re-circulation loop
- No cathode exhaust water condensation loop

MEA Performance & Life Testing:

Significant improvements in MEA performance and durability have been demonstrated during this program. Initial MEA performance was very low initially but more than tripled during the course of the program. Degradation rates have also significantly improved going from cell life of just a few hundred hours to over 6000 hours with very low degradation rates.

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Although there have been MEA improvements much of the performance and life improvements demonstrated at the MEA were originated from the cell engine hardware and system design improvements. This is exemplified by the fact that reasonable performance is achieved with a variety of MEAs. Figure 17 shows the performance across a wide range of MEA architectures. Included are a range of thicknesses of PFSA membrane, supported and unsupported catalyst, and different membrane types. This robustness to MEA types increases MTI's options for MEA component suppliers enabling cost to be the prime factor in selection.

Figure 17, Various MEA Performance

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Figure 18, V-I and P-I curves at different methanol flow rates

Figure 18 shows how stack power can easily be controlled by controlling fuel feed rate.

LIFE TESTING:

Figure 19 shows the endurance test on an MEA . The test lasted for over 6000 hours before the cell was finally damaged by a power outage. Before this damage occurred, the cell had experienced more than 10 unplanned shutdowns or power outages, but it had not been seriously damaged. The power density decayed for a total of 30% in 6000 hours, translating to a 5% decay rate per 1000 hours.

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Figure 19, Over 6000-hour endurance test of an MEA

Decay rate: less than 10% per 2000 hours & less than 30% over 6000 hours

Figure 20, Polarization curves of MEA life test over time

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Figure 20 shows how the polarization curves change over time during the life test. Based on the nearly parallel downward shift of the V-I curves, it can be concluded that the performance decay was mainly due to kinetics degradation.

P3 Stack/Engine Performance

During the P1 and P2 prototype development there was a significant fall-off in performance and life as you moved from a pristine lab cell test to a compact engine stack. By the time of the P3 prototype this issue was fully resolved. Figure 21 shows the average power of an engine running an endurance test. The decay rate is as low as the decay observed on the ideal laboratory cell used for testing MEAs.

Stack Engine durability test

Figure 21, Normalized Power vs. Time - Complete Stack/Engine

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Figure 22, Internal cell resistance over time

The cells internal resistance was measured periodically using current interrupt method (see figure 22). The internal resistance changed little during 1,800 hours of testing, indicating that the membrane resistance and the contact resistance did not increase and that the MEA kept its integrity.

Structural and Thermal Analysis

Structural and thermal analysis was used extensively in all three generations of prototypes. Although most of these studies contained proprietary system and fuel cell engine designs there were two examples where detailed analysis have been publically disclosed. These examples are presented here. One is the structural analysis of the Fuel Cell Chip's spring and the other is the thermal analysis.

Structural Design of Fuel Cell Engine

A cell unit is made of a membrane electrode assembly (MEA) sandwiched between two current collectors or bipolar plates. The MEA consists of the catalyst coated membrane (CCM) and an anode and cathode gas diffusion layers (GDL) . The CCM is made of nafion and coated with platinum ruthenium (anode) and platinum (cathode). The GDLs are made of carbon-fiber-based products such as non-woven papers and woven fabrics (cloths) which have high porosity and good electrical conductivity. The MEA can be constructed in a variety of ways, including positioning of the layers adjacent to each other or hot pressing and bonding which create a 5-

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layer integrated assembly. The MEA characteristics are typically orthotropic with significant differences between through-plane and in-plane values. Typical data in the literature for the MEA include through-plane and in-plane resistance and gas permeability. Mechanical properties of the MEA like modulus of elasticity, tensile strength and through-plane and in-plane thermal conductivity are rare or non-existent. The membrane electrode assembly (MEA) must remain at under uniform compression and uniform temperature over the entire surface in order to maintain hydration uniformity, maximize current, power density and fuel utilization. The MEA compression must remain uniform and within a specified range over the life of the fuel cell system as the fuel cell system components experience creep.

Figure 22, Fuel Cell stack/ chip

Structural Design Methodology

The structural design required the fuel cell stack to be spring loaded in order to counteract the creep characteristics of the fuel cell subcomponents. Typical properties of the GDL, CCM 2 and experimentally obtained properties of MEA were presented in Figure 23. Since the MEA is orthotropic, the data presented at the Table represented the through thickness properties.

Mechanical Material Properties

	k	p	E	v	α	Cp
	W/mK	Kg/m3	MPa		10-6/K	J/KgK
Literature						
Nafion		1980	249			
GDL	0.3	400	10000	0.25	-0.8	500
CCM	0.259	2000	249	0.25	123	1050
Test						
MEA	0.198	2000	5.9	0.00		500

Figure 23, Mechanical properties

In order to address this problem, a compact spring loaded fuel cell was designed. The design consisted of a series of near flat springs in order to maintain the desired compression in the fuel cell assembly. The springs are typically located in the stack under the top plate shown in Figure

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22. The springs can be approximated by a series of simply supported beams with a distributed load.

Figure 24: Typical Spring Design- Top view

Figure 25: Typical Spring Design- Front view

The governing equations for a simply supported beam with a distributed load are given by:

$$u(x) = \frac{wx(2lx^2 - x^3 - l^3)}{24EI} \quad (1a)$$

$$M(x) = 0.5wx(l - x) \quad (1b)$$

$$u_{\max} = -\frac{5wl^4}{384EI} \quad (1c)$$

$$M_{\max} = 0.5wl^2 \quad (1d)$$

$$\sigma_{\max} = \frac{0.5Mh}{I} \quad (1e)$$

$$I = \frac{bh^3}{12} \quad (1f)$$

where, l, b, h and I are the beam characteristics, that is the length, width, depth and 2nd moment of inertia and u, M, σ and x represent the displacement, moment, bending stress and distance from the end of the beam, respectively. The aforementioned equations are typically valid for the linear behavior of the beams. Finite element analysis (FEA) was thus used to determine the spring behavior in the nonlinear domain. This was demonstrated in Figure 26 where the ratio of the displacement over the spring height was plotted as a function of spring thickness under constant load. It was clearly shown that the displacement diverges from the

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beam theory prediction as the spring flattens and asymptotically approaches its maximum value of 1.

Figure 26, Spring Thickness Variability Study

Spring Material Selection Process

Material	Grade	Condition	Modulus E Gpa	Yield Strength Mpa	Tangent Modulus Gpa	Yield Strength/Modulus ratio $\times 10^{-3}$	Elongation %	Electrical Resistivity mohmcm
Stainless Steel	316L	Annealed	193.1	206.9	0.789	1.07	50	74
Stainless Steel	17 7 PH	TH1050	200.0	1103.2	2.189	5.52	10	82
Aluminum	7075	T6	71.7	503.3	0.667	7.02	11	5.7
Titanium alloy	Ti6Al4V	Aged	113.8	1068.7	2.147	9.39	10	177
Berrillium Copper	C17200	1/4 hard	127.6	1034.3	1.501	8.11	10	118.6

Figure 27, Spring material Selection

The springs were analyzed and optimized in ANSYS Workbench environment taking into consideration the variable contact area between the springs the other components and the materials nonlinear characteristics described by bilinear isotropic hardening. The springs were designed to operate in the plastic domain in order to accommodate the thickness tolerance stack-up of the various parts. The nonlinear analysis and design optimization was performed in

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the ANSYS Workbench environment. Several materials were considered as shown in Figure 27. Typical stress and displacement results were presented in Figure 28 and Figure 29. The spring holes were shaped in order to obtain near constant stress along the beam length. The spring loading was designed to occur in two cycles as shown in Figures 30 and 31. During the first cycle the springs were yielded as clearly shown in Figure 30. After unloading and reloading the springs created a more consistent loading on the fuel cell stack assembly. It is important to realize that the spring behavior was nonlinear during both loading cycles. The nonlinearity during the first cycle was caused by the material bilinear isotropic properties and the spring/compression plate variable contact area. Only the latter part was true during the second cycle. The presented methodology resulted in a compact spring loaded stack assembly.

Figure 28, Von Mises Stress

Figure 29, Spring Deformation

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Figure 30, Applied Pressure vs. Time Step

Figure 31, Applied Pressure vs. Time Step

Thermal Design

The selection of the operating temperature of the fuel cell is key to attaining good performance and long life. The fuel cell operating temperature of a portable micro fuel cell system can be optimized with respect to several parameters, like maximum power, maximum efficiency, or minimum volume. A methodology was developed, where the fuel cell operating point defined by the fuel cell voltage and temperature was determined by a multidisciplinary optimization algorithm which met power and total energy requirements by minimizing the system volume which included the fuel cell, insulation package and amount of fuel. The algorithm used as input parameters, the thermal conductivity of the insulation, the rate of heat removal from the outer

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surface by natural convection and radiation, and the electrochemical characteristics of the fuel cell described by the experimentally obtained polarization curves at various fuel cell temperatures. This methodology was applied on a simplified geometry in order to obtain the optimal operating point which met the fuel cell system requirements.

The constant temperature (i.e. the optimal operating temperature) and temperature uniformity of the MEA over a range of environmental conditions is also a challenge. Military requirements require the portable fuel system to operate in the extreme range of -40°C to 40°C. In order to achieve the low end of the temperature range, the fuel cell system has to be insulated.

Extremely low conductivity materials, like aerogel, are one of the few viable materials required in order to meet the size criterion of a portable fuel cell system. In order to achieve this thermal latitude, the thermal design had to accomplish variable thermal resistance to the environment, passively or actively. Typical active methods include external fans for instance, which consume power and significantly affect the parasitic power of a portable fuel cell system. Passive methods like heat pipes can be more appropriate in some cases because they consume no power. Heat sink size and weight considerations are also important in order to meet the size criterion of a portable fuel cell system.

Simplified thermal models based on one dimensional (1-D) heat conduction were used to predict the overall temperature profile of fuel cell systems. It was found out that the interaction of multiple components of a fuel cell system with multiple interfaces and heat generation at multiple locations made the 1-D model inaccurate when compared to actual experimental data. Thus, a three dimensional (3-D) thermal model of the entire fuel cell system was developed and utilized in the thermal design.

Thermal Design

Operating Temperature

Critical input parameters to the thermal design of the micro fuel cell system are the desired operating temperature, and the environmental temperature latitude. The selection of the fuel cell operating temperature was optimized with respect to minimum volume for a given requirement of power and total energy. The optimization scheme was presented in Figure 6. The governing equations for heat generation and energy density were:

$$q_{heat} = (E_{meoh} - E_D) \frac{P}{E_D} + P(1 - \eta_{DC}) \quad (2)$$

$$E_D = u_f E_{meoh} \frac{V}{V_0} \quad (3)$$

where, q_{heat} is the heat created by the fuel cell, E_{meoh} is the methanol energy content (~5Whr/cc), E_D is the energy density, P is the gross power of the fuel cell and η_{DC} is the efficiency of the DC to DC converter, V_0 is the ideal open circuit voltage for methanol equal to 1.2V, V is the applied voltage, and u_f is the fuel utilization efficiency. Other parameters shown in Figure 32 are defined as follows: I_d is the operating current density, P_d is power density, A_{act} is the active

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area of the MEA, t_{insul} is the thickness of the insulation package, and Vol_{total} is the sum of the fuel volume Vol_{fuel} and the insulated fuel cell volume Vol_{cell} .

The multidisciplinary optimization algorithm which was applied to a simplified geometry, met power and total energy requirements by minimizing the system volume which included the fuel cell, insulation package and amount of fuel. The algorithm used as input parameters, the thermal conductivity of the insulation, the rate of heat removal from the outer surface by natural convection and radiation, and the electrochemical characteristics of the fuel cell described by the experimentally obtained polarization curves at various fuel cell temperatures (figure 33). A Matlab constrained optimization routine was used to determine the optimal design.

Optimization Scheme

Figure 32, Optimization Scheme

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Figure 33, Typical VI Curves at Various Temperatures

Ambient Temperature Latitude

The amount of insulation determined by the optimization scheme was used as guidance in the micro fuel cell system thermal design. The volume of insulation was minimized by using extremely low conductivity materials like aerogel. Clearly, for constant fuel cell temperature operation, the amount of required insulation is driven by the low end of the temperature latitude, that is the lower the ambient temperature the higher the insulation required.

In order to achieve constant fuel cell operating temperature over a range of ambient temperature a variable thermal resistance to the environment is required. This can be accomplished actively with external fans, or liquid cooling, or passively by the implementation of heat pipes. Both methods have their advantages and disadvantages. The implementation of external fans is quite simple but their size and power consumption can limit their implementation in portable micro fuel cell applications. Liquid cooling is more complicated but it can be much more effective. Although the heat pipe operation can be simple, its effectiveness can be compromised by spread resistance issues.

Typical heat sink materials considered. The performance penalty of replacing machined aluminum (6061) with castings was evaluated. A 3-D thermal model of the entire fuel cell system was developed and utilized in the thermal design (Figure 34).

The thermal design was analyzed and optimized in the ANSYS Workbench environment and verified experimentally. Typical results like the temperature profile of the MEA at the extreme temperatures and the temperature of the enclosure were presented in Figure 35, 36 and 37. The MEA temperature in both Figures 35 & 36 was normalized with respect to the optimal

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operating temperature determined by the optimization algorithm. Figure 35 clearly indicated that at low ambient temperatures, a very uniform temperature profile of the MEA with maximum variation of 1.3% from its mean. This was caused by the fact that in this case, additional active or passive cooling was not required. The heat traveled through the insulation package which was generally symmetric. Figure 36 indicated that at high ambient temperatures, the average temperature remained near the optimal value, whereas temperature profile of the MEA had a maximum variation of 2.0% from its mean. In this case, additional cooling was required, which created a planar thermal path, allowing heat to travel from one side to the other side of the MEA (top to bottom as shown in Figure 37). The average MEA temperature remained constant over the entire ambient temperature latitude. Both of the aforementioned temperature variations were considered acceptable within the specification limits of the design. Another critical parameter of the thermal design was the maximum temperature of the case. A typical temperature distribution of the case at the 40oC ambient temperature was shown in Figure 37.

Figure 34: FEM of the portable fuel cell system

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Figure 35: Normalized MEA Temperature Profile at low ambient temperature

Figure 36: Normalized MEA Temperature Profile at high ambient temperature

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Figure 37: Temperature of Enclosure at 40C ambient temperature

PRODUCTS DEVELOPED UNDER THIS AWARD:

MTI Micro is currently focusing all of its effort on taking the Mobion technology to a product ready level. The portable consumer electronics market was identified as an initial target for a Mobion based product. As mobile device manufacturers added features and performance to handheld devices, a gap began to open between the power needs and the battery industries ability to meet them. Lithium Ion batteries are the most common type of battery in today's mobile devices. However technology advances have not kept up with the industry demands. Technologically, these batteries have matured and there is very little room for significant performance improvement. Therefore an entirely new technology is required. Unfortunately there is no alternative battery chemistry in the near future that can replace Lithium Ion batteries and fill the gap. Fuel cells are currently the most promising technology to address this need. Recently a new market has arisen for small auxiliary battery packs that the consumer can purchase and use to recharge their mobile devices while on the go. This market has grown substantially in the last few years and MTI has identified this as a good initial entry point for its fuel cell products.

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Figure 38, Auxiliary Charger

As a result MTI has engineered a product based on the Mobion technology to compete in this auxiliary charger market (figure 38). This device can provide power via a standard USB port to any portable device with an appropriate cord. The system uses replaceable cartridges filled with 100% Methanol. Methanol is a common, inexpensive, biodegradable alcohol. Each cartridge contains about 25 Whrs of energy. An average recharge of a cell phone requires roughly 2-4 Whrs depending on the type of phone and level of depletion. This means each cartridge could charge the users phone up to 12 times (up to one month for typical user) before running out of fuel. These cartridges are small and spares are easily carried. The cost to the consumer would be less than \$5 per cartridge.

Fuel cells have a distinct advantage over batteries for this kind of application. Foremost, fuel cells have the potential to carry significantly more energy in a package of equal size and weight. For the user this translates to more charges of your cell phone or other portable device. Secondly, fuel cells can offer a different usage model that batteries cannot duplicate. With a battery pack, ultimately the user must return to a wall outlet to recharge the pack. With a fuel cell the user can remain off the grid and on the go as long as fuel is available. Initially, the target for these devices would be the high end business traveler. This customer can justify the higher initial cost of fuel cells because of the enhanced mobility it would provide.

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Portable Device Market: Unit Shipment Forecast (World), 2004-2014

Figure 39, Shipment Forecast

Ultimately the goal is to embed micro fuel cells into a variety of handheld products. The early stand alone markets are seen as necessary to jump start the industry and begin to drive down the cost of the components. As the cost comes down and the technology advances MTI will be able to embed them into the devices themselves. This opens the market to a wider array of users and evolves the usage model from an accessory used only when traveling to an everyday power source. Figure 39 shows the projected growth of the portable device market over the next several years. Capturing even a small part of this market would represent a huge return for MTI. The environment benefits of devices with embedded fuel cells are also evident. A recent study showed that over the course of a year the wall chargers for portable devices can consume as much energy as the device being charged. This is due to the fact that they remain plugged in 24 hours a day but are only in use for about 8 (in the case of a cell phone charger). During idle time they consume a small amount of power that adds up to significant energy use over time. Devices with embedded fuel cells would alleviate this problem and over time reduce the load on the grid.

MTI's strategy is to leverage the credibility of an established device manufacturer to help gain consumer acceptance. By supplying to a Brand name OEM device manufacturer, MTI avoids the additional cost of sales and marketing for the end product. It also makes it possible to leverage distribution networks and retail connections that are already in place. Currently MTI Micro has established formal relationships with several major players in the consumer electronics industry.

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Acronyms

CSA – Canadian Standards Association
DGAC – Dangerous Goods Advisory Council
DMFC – Direct Methanol Fuel Cell
DOE – Department of Energy
DOT – Department of Transportation
FAA – Federal Aviation Administration

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GDL – Gas Diffusion Layer
ICAO – International Civil Aviation Organization
IEC – International Electrotechnical Commission
MEA – Membrane Electrode Assembly
MTI – Mechanical Technology, Inc.
OEM – Original Equipment Manufacturer
PDA – Personal Digital Assistant
POC – Proof of Concept
UL – Underwriters Laboratory