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Title: Commercialization of 1W Consumer Electronics Power Pack	Editor: C Carlstrom	

***Commercialization Effort for 1W Consumer Electronics
Power Pack***

DOE Award: EE0000477

Recipient: MTI Micro Fuel Cells Inc.

***Chuck Carlstrom
Project Director***

Final Report

June 29, 2011

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Executive Summary

A commercial ready fuel cell charger has been further developed, demonstrated, and field tested during the three phases of this project. The work performed and demonstrated has shown the commercialization readiness of this future product and underlying technology.

The tasks in phase 1 of the project focused on component cost reduction, redesign for manufacturability, performance & reliability testing, and system integration. The end of phase 1 was completed on time and was signified by passing the Go/No-Go checkpoint. As shown in the report all technical metrics have been met or exceeded and the Go/No-Go checkpoint was passed in November of 2009.

The tasks in phase 2 focused on tool fabrication and tooled component prove-out in working systems. The end of Phase 2 was the accomplishment of building working systems made almost completely of tooled components.

The tasks in phase 3 of the project were preparing for and executing a 75 unit field test of the DMFC charger product developed in Phase 1 and phase 2. This field test demonstrated the functionality of the DMFC in the hands of real users while also providing feedback for potential design improvements. This was the first time a significant number of MTI units were put into the field to test usability and functionality. Feedback from the field test was positive and the units functioned well in the field.

Comparison of Actual Accomplishments with Goals and Objectives of the Project:

Overall Goal: To demonstrate and field test a commercially viable one watt Direct Methanol Fuel Cell (DMFC) charger for consumer electronic devices

- Design for low cost, high volume manufacturing processes and ease of assembly.
- Demonstrate performance across temperature and humidity range of consumer electronic devices.
- Deploy 75 units into the field to obtain real world usage feedback.

A major focus of this project was to reduce the cost of MTI's Direct Methanol Fuel Cell (DMFC) powered charger to attain a competitively priced product when in production. To achieve a low cost system many of the components had to be redesigned so that they could be produced using low cost, high volume, manufacturing processes. The system also had to be redesigned for ease of assembly to increase build yield and reduce the amount of labor content needed. In addition, the assembly process had to be simplified so that technicians and assemblers could perform the assembly rather than engineers and scientists.

During phase 1 of this program many parts and process steps were completely eliminated or were significantly simplified. In one instance a complete subassembly, with all associated cost and reliability issues, was eliminated. Phase 1 of the program was completed during the fall of 2009 and there was a successful Go/No-go review meeting that occurred on November 5, 2009 at MTI's facility in Albany, NY. At the completion of phase 1 almost all components were redesigned for reduced cost and high volume manufacturing. The following are examples of

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component redesigns implemented to reduce cost and make the components capable of being manufactured using common, low cost, high volume manufacturing processes:

- Plastic components previously machined were designed to be injection moldable.
- Sheet metal components previously machined were redesigned to be stamped and coined.
- Laser cut free-standing gaskets were redesigned to be profiled gaskets, either over-molded onto components they seal or otherwise easily placed.
- Many adhesives and small bridge plates were completely eliminated by integrating their function in other interfacing components.

The below lists the target metric and results achieved during the program:

System had to achieve predetermined levels of:

- ✓ Continuous run power (Achieved 1.04W net, Target was 1W net)
- ✓ Energy from 1st cartridge (Achieved 28.9Whr, Target was 26Whr)
- ✓ Life time (Target of 2000 hrs)
  - Achieved over 6000hrs at 5% loss per 1000 hrs on Stack/Engine
  - Achieved over 2000 hrs on multiple systems
- ✓ High volume unit production cost projection (\$ MSRP target achieved but confidential)
- ✓ Total labor content reduction (Achieved 74% reduction, Target was 50%)

Demonstrate robust operation for consumer electronics application:

- ✓ 0-40C temperature operation with 10%-90% relative humidity
- ✓ 0-8K Feet altitude operation
- ✓ Other: Orientation Independence, drop testing, touch temperatures
- ✓ Complete 75 unit field test

SUMMARY OF PROJECT ACTIVITIES

The project has been organized into three phases. The tasks in phase 1 include component cost reduction, redesign for manufacturability, performance and reliability testing, and system integration. Phase 2 tasks include tool fabrication, debugging, and tooled component prove-out in working systems. Phase 3 tasks include demonstrating the DMFC charger's functionality in the hands of real users while also providing feedback for potential design improvements. This field test is the first time a significant number of MTI units are put into the field to test usability and functionality. The objective of the field test is to generate user feedback on product viability as well as identify potential product improvements.

Phase I: Redesign for low cost manufacturing

- Redesigned all components to be produced using processes capable of low cost and high volume.
  - Plastic components went from machined to injection molded

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- Sheet metal components went from being machined to formings and stampings
- Laser cut free-standing gaskets were replaced with profiled gaskets over-molded onto components they seal
- Test stacks/engines for improved performance & degradation
- Test complete systems to predetermined performance metrics

Go/No-Go PHASE GATE: Must achieve predetermined performance, cost, and manufacturing goals.

Phase II: Complete tooling for all components

- Build and test Beta systems with components from hard tooling

Phase III: Deploy 75 units in the field for real world feedback

- Build and test all units to quantify performance prior to shipping.
- Create Web support for online sign-up, user support, and feedback.
- Execute field test and analyze feedback for potential product improvements

Figure 1 is a picture of the fuel cell charger that was developed and field tested during the three phases of this program.

Figure 1, Fuel Cell Charger developed and field tested during program

Technical approach:

As shown when comparing figures 2 and 3, MTI's system is much simpler than traditional DMFC systems due to its reduction in complexity and number of components. The elimination of the liquid anode circulation loop and hardware required to capture liquid water from the cathode eliminates many of the failure modes associated with DMFC systems.

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Figure 2, Conventional DMFC system

Figure 3, MTI's simplified DMFC system

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MTI has previously shown that the elimination of this was loop reduces the amount of methanol crossover even when very thin membranes are used in the MEA. Figure 4 shows the destination for fuel that is sent to the cell/ engine. Over 90% is converted to electricity, about 6% exits the anode port and only about 2% ends up crossing over the membrane.

Figure 4, Contributions of fuel that is fed to the anode of stack/engine

One effect of this very low crossover is very low MEA degradation compared to traditional DMFC systems. Figure 5 shows an engine/stack completing over 6000 hours of operation with a decay rate of only 5% per 1000 hours. This decay rate was achieved on multiple engine/stack subsystems.

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Figure 5, Stack/engine life test demonstrating 6,000 hours at 5% decay per 1000 hours

Another benefit of not having a liquid anode loop is that power can be changed by changing the fuel feed rate. Fig 6 shows how varying the fuel feed rate from 1X to 2X can vary the power level of the system. Since there is no large volume of fluid this change can happen very quickly.

Figure 6, Power density curves for various fuel feed rates

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As part of this program the engine stack subsystem also demonstrated increased performance for MEA power density. Figure 7 shows the power density of 85mw/cm² and 100 mw/cm² corresponding to two different fuel feed rates. Part of this achievement was due to engine/stack design changes that enable the engine to efficiently consume methanol at higher fuel feed rates. In past engine/stack designs there was a substantial efficiency fall off at higher fuel feed rates. Figure 8 shows the stack/ high obtaining both high power density and relatively high fuel efficiency at increased fuel feed rates.

Figure 7, MEA Power Density

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Figure 8, Stack/engine Power density and efficiency vs. pump rate

Although high engine performance at high fuel feeds was demonstrated the system used for the duration of this program used the baseline fuel feed rate. The higher power demonstrated will help future system designs meet higher power densities.

System Level Testing:

A detailed test plan was developed which addressed all critical system specifications. Systems built as engineering prototypes were designated EVT. EVT2 systems were built with components prior to the redesigns required for low cost, high volume manufacturing. EVT3 systems were built with components that represented the changes required for low cost, high volume manufacturing. The objective of the testing was to show that there was no loss in performance when redesigning the components for low cost, high volume manufacturing. Baseline testing was carried out on all EVT2 and EVT3 systems. The power, energy and efficiency showed consistent performance and overall improvement from EVT2 and EVT3 systems (Figures 9 & 10). Although the improvement was mainly achieved in the variability, the average values also showed an increase of approximately 5%.

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Figure 9: Normalized Gross Power Comparison

Figure 10: Normalized total energy comparison

Temperature and humidity latitude testing was carried out in the range of 0 to 40C and 10% to 90% RH (Table 1). The normalized power history was presented in Figure 11. The results indicated that the system was capable of producing stable power over the entire latitude. It is important to note that the reduction in power at the higher ambient temperature (40C) was caused by the 20% reduction of the fuel feed rate from its nominal

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value. This change was dictated by the firmware which reduced the flow rate when the battery temperature exceeded a pre-assigned limit.

**Table 1: Temperature & RH
Latitude Test**

Temp C	Rel Hum %	Time (hrs)
20	10	2.25
20	50	2.25
20	90	2.25
0	90	2.25
0	50	2.25
0	10	2.25
20	10	2.25
40	10	2.25
40	50	2.25
40	90	2.25
20	50	2

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Figure 11: Temperature and Humidity test- Normalized power vs. time

Two Evt3 systems were tested in all six orientations. The normalized gross power and normalized efficiency was presented in tabular form in Table 2. It was clearly shown that both systems performed consistently in all six orientations.

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Table 2: Orientation Test

Orientation	Norm Efficiency	Norm Power
Evt3-71		
standard	1.04	1.04
upside down	1.05	1.05
Cartridge down	1.04	1.04
Cartridge up	1.00	1.00
Horizontal 1	0.99	0.99
Horizontal 2	0.98	0.98
standard	0.96	0.96
Evt3-72		
standard	1.01	1.03
upside down	1.08	1.01
Cartridge down	1.00	1.04
Cartridge up	1.02	0.98
Horizontal 1	1.01	0.97
Horizontal 2	0.97	0.93
standard	0.99	0.97
Avg	1.01	1.00
StDev	0.033	0.036

Altitude Testing

A system was tested in an altitude chamber simulating the elevation of 4, 8, and 10 thousand feet. At 4 thousand feet the unit had no decrease in performance from sea level. At 8 and 10 thousand the unit ran but with decreased power. The unit also has reliably detected and shutdown safely at altitudes it could not run properly.

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Figure 12: Normalized Gross Power of System at Altitude

ESD Testing

During an initial screening test, applying an electro static discharge to the metal heat sink of the unit was shown to affect the electronics. A design solution was identified. The change was implemented and testing has show the unit is not affected by ESD.

Thermal Shock

A storage thermal shock test was performed that cycled a unit between -20°C and 60°C. Initial results show no negative effect on the performance of the units.

During phase 2 of the program, tools were fabricated and parts were produced for evaluation of the design intent systems. This required several iterations of part, tool and process changes until the parts produced off of the tooling met the design requirements. Comprehensive subsystem level testing was carried out to quantify the impact the tooled subsystems had on durability and performance. There was also a significant amount of system integration work

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done to bring the tooled subsystems together. Testing at the system level was used to verify that the system is capable of operating well during transients such as start-up and shut-down and at all specified temperatures, humidity, and orientations.

At the system level there were several configuration changes that required system integration activities followed by complete system characterization testing. Testing at the system level included:

- Algorithm development
- Performance & qualification testing
  - Sound testing
  - Cold and hot ambient start-up
  - Surface temperature measurement
  - Drop testing
  - Temperature & humidity latitude (0C-40C, 0-90% RH)
  - Altitude testing
  - Orientation independence
- Life testing
  - Steady state decay rate
  - Start - stop decay rate

Phase 2 activities were also focused on reduction of labor content and build consistency .The quality of tooled components continued to improve reducing the amount of rework required to deflash, or trim parts. Metal parts that were over-molded with seals were used for the build with minimal deflashing.

Figure 13 shows the improvement in the man hours required to build an engine from Q1 of 2008 to the previous quarter. Q1 2008 build was executed with machined parts to prove the design concept. The EVT build was also executed with machined components, but the design was refined to satisfy the requirements of size. Over 150 engines were built in the EVT phase for system builds and developmental testing like performance mapping against variables and life testing. DVT build was executed with partially tooled components, the purpose was to check manufacturing feasibility and validate the tooled design. The PVT build utilizes fully tooled components off improved tooling and manufacturing processes. The ideal PVT includes improved fixtures.

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Figure 13: Man hours to Assemble & Test Engine

All fuel cell engines were completely tested as a subsystem prior to being installed into a system. This was done to assure both, the quality of the engine as well as to establish a baseline to use as a comparison to end-of-life test results. Figure 14 shows the power relative to the specification for the 25 engines built that will be participating in the field test. The average power is over 20% greater than the specification as shown in the accompanying statistics. This performance is both higher and more consistent than previous builds.

Figure 13, Normalized power for first 25 engines delivered for field test

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During phase 3 of the program 75 user evaluation kits were sent out which contained the contents shown in Figure 14. The kit included a mobion handheld charger, two cartridges filled with methanol, quick start guides, and a cable that had interchangeable tips enabling use with all of the common connections for handheld electronic devices. Although only two cartridges were sent with the units there were more available upon request.

Figure 14: Contents of box field trial participant received

The fuel cell systems were deployed to the groups specified in the statement of work including individual users, Original Equipment Manufacturers (OEM's), various military groups and government agencies. The allocation of the units is shown in Figure 15.

Figure 15, Allocation of the 75 units deployed for field trial

The MTI web site was given a link for potential users to sign-up for the field trial. A screen shot of the web site is shown in figure 16. Selected participants were also given access to a post test survey page along with phone interviews after the completion of the field test. These were

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the prime source of feedback from the field trial. A draft of the online post test survey was given to a contact at a national lab for feedback following a recommendation from the DOE. There was an updated version of the survey completed based on the improvements suggested. Figure 17 is a screen shot of one of the pages from the web based post test survey form.

Figure 16, Field trial Web based sign-up page

Figure 17, Example pages from online survey form

"Just finished off my first cartridge today. I charged my (iPhone) phone approx 10x from ~25% to 100% battery before it needed replacement" - OEM

"We were impressed with the form factor and with the chemical conversion technology. It repeatedly charged our iPhones in a timeframe similar to that from a standard electrical outlet." - OEM

“The device works excellently and has not provided many inconsistencies. Mostly, not being able to have the fuel cell in an enclosed space (i.e., laptop bag) while it is generating power was an inconvenience though not a major problem.” – Individual user

"Alternative energy on the battlefield is evolving into one of the most salient issues of the day. We believe that despite initial concerns, Mobion should continue advancement of this unique technology to potentially meet some of the existing and future tactical energy requirements." - Military

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The online post-test survey was used to capture user feedback at the completion of the field trial or when users requested additional cartridges. Figure 18 shows results from one of the questions on the survey that captured the attributes users liked and figures 19 shows areas for improvement. Theses are just two of the questions on the survey given at the completion of the field trial.

Figure 18 – Results from feedback form - What users liked

Figure 19, Results from feedback form - Areas for improvement identified by users

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This field trial accomplished the objective of obtaining real world usage feedback and identifying areas of product improvement. Valuable feedback was coming in just days after the initial units were being shipped. For example, there was a compatibility issue the fuel cell had when connected to one of the newer smart phones. The issue was quickly resolved and did not reappear throughout the duration of the trail. This issue exemplifies the enormous value the field trial added to the product development process. There are some issues, such as the one described, that will not show up in the lab and that will only be uncovered when units are deployed into the field in significant numbers.

The user interface was another area that benefited greatly from this user field test. Figure 20 shows the user interface used for the field trial units. This user interface functioned well but was confusing to some users because it had two buttons. The feedback on the user interface from this field trial led to the development of a new single switch user interface and other features to make the device more intuitive. Considering the feedback focused around user wants, such as user interface improvements and product options, testifies to the fact that the underlying technology did not fail and the devices functioned well in the field.

Figure 20, User interface used for field trail

A secondary benefit of the field trial was that it enabled the participant and the organizations they represent to become aware of the commercial readiness of this product. In general, the participants that have evaluated fuel cell offerings from other companies in the past were most impressed with the Mobion charger during the field trial. Sending units for evaluation gave credibility to the product claims, specifications, and commercial readiness. Several business relationships initiated or strengthened by the field trial will further impact the commercialization of this product and technology in the coming months.

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Project Summary:

- All program technical targets/metrics have been met or exceeded
- High power density and high fuel efficiency has been achieved simultaneously
- Low stack degradation rate exceeding product requirements has been demonstrated
- Reduced cost and improved manufacturing and assembly.
  - Machined components to plastic injection molding or metal stamping
  - Over 50% reduction in labor content to build a system
- Performance of system at the temperature & humidity range for consumer electronics (0C-40C, 0-90%RH) has been demonstrated
- Product qualification testing completed:
  - Sound testing
  - Cold and hot ambient start-up
  - Surface temperature measurement
  - Drop testing
  - Altitude testing
  - Orientation independent
- 75 unit field test has been completed:
  - 75 units built, tested, and shipped.
  - Valuable user feedback obtained
  - Product improvements identified and acted upon

Although this project is complete several product improvements have been identified that will continue to guide our product development in the coming months.

Publications/Presentations

Carlstrom, C, 2011, "Commercialization of 1 Watt Consumer Electronics Power Pack", DOE Annual Merit Review, Arlington, Virginia USA.

Prueitt, J., 2010, "Portable Fuel Cell Panel," Clean Energy Conference, Boston, MA

Carlstrom, C, 2010, "Commercialization of 1 Watt Consumer Electronics Power Pack", DOE Annual Merit Review, Arlington, Virginia USA.

Lim, P, 2010, "MTI Micro's latest development of fuel cells system for mobile use," FC Expo, Tokyo, Japan.

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Prueitt, J., 2010, "MTI Micro's latest development of fuel cells system for mobile use," Small Fuel Cells 2010, Cambridge, MA

Prueitt, J., Qi, Z., Lu, G., Liu, W., and Carlstrom, C., 2009, "Performance and Durability of Direct Oxidation Fuel Cells Fed with Neat Methanol," Small Fuel Cells Conference, May 7-8, Orlando, FL.

Acronyms

DMFC – Direct Methanol Fuel Cell
DOE – Department of Energy
GDL – Gas Diffusion Layer
MEA – Membrane Electrode Assembly
MTI – Mechanical Technology, Inc.
OEM – Original Equipment Manufacturer
RH – Relative Humidity
ARRA – American Recovery and Reinvestment Act

Flyer of product developed under this award:

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