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Five Kilowatt Fuel Cell Demonstration for Remote Power Applications Task 2.02.1

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Abstract

While most areas of the US are serviced by inexpensive, dependable grid connected electrical power, many areas of Alaska are not. In these areas, electrical power is provided with Diesel Electric Generators (DEGs), at much higher cost than in grid connected areas. The reasons for the high cost of power are many, including the high relative cost of diesel fuel delivered to the villages, the high operational effort required to maintain DEGs, and the reverse benefits of scale for small utilities.

Recent progress in fuel cell technologies have lead to the hope that the DEGs could be replaced with a more efficient, reliable, environmentally friendly source of power in the form of fuel cells. To this end, the University of Alaska Fairbanks has been engaged in testing early fuel cell systems since 1998. Early tests were conducted on PEM fuel cells, but since 2001, the focus has been on Solid Oxide Fuel Cells.

In this work, a 5 kW fuel cell was delivered to UAF from Fuel Cell Technologies of Kingston, Ontario. The cell stack is of a tubular design, and was built by Siemens Westinghouse Fuel Cell division. This stack achieved a run of more than 1 year while delivering grid quality electricity from natural gas with virtually no degradation and at an electrical efficiency of nearly 40%. The project was ended after two control system failures resulted in system damage.

While this demonstration was successful, considerable additional product development is required before this technology is able to provide electrical energy in remote Alaska. The major issue is cost, and the largest component of system cost currently is the fuel cell stack cost, although the cost of the balance of plant is not insignificant. While several manufactures are working on schemes for significant cost reduction, these systems do not as yet provide the same level of performance and reliability as the larger scale Siemens systems, or levels that would justify commercial deployment.

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Executive summary

While most areas of the US are serviced by inexpensive, dependable grid connected power, many areas of Alaska are not. In these areas, electrical power is provided with Diesel Electric Generators (DEGs), at much higher cost than in grid connected areas. The reasons for the high cost of power are many, including the high relative cost of diesel fuel delivered to the villages, the high operational effort required to maintain DEGs, and the reverse benefits of scale for small utilities. This problem has been exacerbated by the recent price spike in diesel fuel, resulting in cost of electrical power to levels several times that of urban areas.

Recent progress in fuel cell technologies have lead to the hope that the DEGs could be replaced with a more efficient, reliable, environmentally friendly source of power in the form of fuel cells. To this end, the University of Alaska Fairbanks has been engaged in testing early fuel cell systems since 1998. Early tests were conducted on PEM fuel cells, but these proved expensive, unreliable, and thermodynamically less efficient than existing technology [1]. In particular, the energy required to reform hydrocarbon fuels needed to come from the incoming fuel [2], given the low temperature heat generated by the fuel cell, resulting in a system efficiency of about 25%, which is less than the 35% efficiency typical of a new diesel generator. These results have been verified by the DoD residential fuel cell program [3].

Since 2001, the focus at UAF has been on Solid Oxide Fuel Cells (SOFC), which are capable of higher system efficiencies due to the high operating temperatures, which provide heat of sufficient quality to drive the reformation reaction. This results in a much higher system efficiency, which can approach 50% for large systems operating on natural gas. [4].

Small scale SOFCs are being developed as part of the US DOE SECA program [5], which are of the proper size (a few kilowatts) for distributed residential applications [6]. The major effort of the SECA program focuses on the development of small planar SOFC stacks, while most SOFC demonstrations to date have used tubular cells. Most of the SECA participant teams are currently still in the laboratory stack development stage, and that program is not currently advocating the deployment of these systems in the field.

However, SOFCs are still very much in the pre-commercial development stage, typified by initial unique prototypes requiring significant assembly effort. This also means that the cost of these units is very high, significantly more than any commercial market could bear. First units to leave the factory are typically sent to “safe” locations, where technical support is available, and failure is not public. UAF has played this role for several fuel cell companies, receiving first units shipped, testing them in private, providing technical support, and reporting successes when they occur.

In this program, a cooperative agreement was created between the UAF AETDL (funded by NETL) and Fuel Cell Technologies, of Kingston, Ontario, to demonstrate an “alpha” pre-commercial prototype 5 kW SOFC intended for residential use with combined heat and power. This project was proposed in February, 2002 with an intended delivery of the fuel cell in late 2002. However, delays in the delivery of the stack resulted in a delivery date to Fairbanks of August 1, 2003.

In summary, this demonstration achieved significant technical milestones in demonstrating a small scale SOFC operating on natural gas, with an efficiency of nearly 40%, and stable operation for more than a year in a field location. However, significant additional development needs to occur before small scale SOFCs are ready for large scale commercial deployment.

Background

Electrical grids are capable of providing large amounts of electrical power to consumers and industry at reasonable rates, using large scale coal, natural gas, nuclear, and hydro plants, typically at about 6-10 cents per kW-hr. However, in areas not served by electrical grids, other means need to be found to provide electricity. The most common form generating small amounts of power (1 kW to 2.5 MW) is the diesel electric generator. However, a reasonably efficient DEG can provide about 13 kW hours of electricity per gallon of fuel consumed, a diesel cost of \$1.00 per gallon gives a fuel cost alone of 7 cents per kW-hr. Recent fuel costs have gone much higher, with proportional increases in the cost of power. Typical diesel generators require frequent oil changes, and the high number of moving parts result in significant maintenance costs. While capital costs for DEGs are relatively low compared to other forms of power of generation, the system lifetime is only about 5 years, as opposed to 20-50 years for larger power plants. All of these factors contribute to the high cost of electricity produced from DEGs. Typically, in Alaska, these rates are 20 cents per kW-hr, or higher. These rates are also directly related to the cost of diesel fuel, which has recently increased due to the rising price of crude oil.

Fuel cells have been proposed as a more efficient, environmentally friendly, reliable, and cost effective source of electricity in these remote areas of Alaska. However, justification for many of these claims are based on projected performance and system costs based on estimates provided by the US Department of Energy and fuel cell suppliers. Typically these projections assume efficiencies of near 50% AC out based on the lower heating value of natural gas, system lifetimes of 40,000 hours (5 years) or longer, and stack costs of \$400 per kW, and total system costs of under \$1500 per kW. If systems could be developed that meet these specifications, fuel cells would likely find a large market and displace diesel generators in Alaska. However, the industry still needs to demonstrate that these performance objectives can be met in mass produced commercial devices.

Fuel cells have been in existence for a long time, having been first invented by Grove in 1839. Attempts to generate electricity directly from coal were made in the early 1900's, but the first notable success of fuel cells came during the space program in the 1960s. Fuel cells operating on pure hydrogen and oxygen were introduced during the Gemini program, and continue to be used on current shuttle missions. Fuel cells are ideal for space applications, as the produced water, the waste heat, and the electricity are all useful products, the power to weight ratio is higher than for batteries, and the spacecraft have an ample supply of liquid hydrogen and oxygen already on board for propulsion. However, these fuel cells operate for only short mission lifetimes (less than 1000 hours) in an environment where high performance is valued much higher than the cost of electricity. One additional issue is that the fuel cells used in the space program are alkaline fuel cells, and operate well on pure oxygen, but are contaminated by the carbon dioxide found in the earth's atmosphere.

Fuel cells for terrestrial applications need to be competitive with conventional methods of generating electrical power, which are typically based on combustion to provide the energy for operation of a heat engine. Combustion is a three dimensional gas phase reaction that scales with volume, and is relatively insensitive to impurities. Fuel cells are open system electrochemical devices, and electricity is produced at the solid gas interface. This interface scales with surface area, and is very sensitive to impurities in the system. This requires the use of filters on the reactant flow streams, especially the fuel stream, where the naturally occurring sulfur compounds must be removed. Some fuel cells are sensitive to impurities in the air, such as PEM sensitivity to hydrocarbons. Low temperature fuel cells are also contaminated by CO in the fuel stream.

High temperature Solid Oxide Fuel Cells (SOFCs) use a solid ceramic material as the electrolyte, and use oxygen ions as the ionic transport medium. However, at the operating temperatures required to provide the oxygen mobility, other ions can also move in the structure. This means that impurities in the oxide are mobile, and can form new phases, which can block ionic transport. SOFCs are therefore also sensitive to impurities and interface effects in the materials of construction.

Previous demonstrations of solid oxide fuel cell systems have shown that high efficiency, low degradation, and long lifetimes are achievable. In particular, the Siemens Westinghouse web site indicates that one stack operated for 69,000 hours with little noticeable stack degradation. [4] Conversation with those close to that experiment, however, reveal that that particular system was a stack of only 4 cells constructed with high purity oxide materials, operated inside a tube furnace on pure hydrogen. Achieving this same level of operation on a large stack (a 200 kW stack has about 2300 tubes) using a real fuel (natural gas) has not yet been demonstrated.[7] Field demonstrations have been for 35,000 hours or less, and the hybrid system at Irvine operated for only 3400 hours.

One issue for Siemens Westinghouse has been the need to reduce manufacturing costs for their fuel cell systems. During the 1990's fuel cell tubes were manufactured using an Electro Vapor Deposition (EVD) process which provides a very uniform and consistent

electrolyte layer, but the equipment necessary to do this process is both expensive and slow. A new technique called plasma spray was developed, but switching between these two processes resulted in inconsistent product, and a significant delay in shipping completed stacks to customers. However, as of this writing (February, 2008) it appears that the cost reduction strategies have not been as successful as hoped.

The University of Alaska Fairbanks has been involved in independent third party testing of fuel cells for nearly a decade. The role of an independent test site is to answer several basic questions

1. What does the fuel cell supplier promise: delivery date, specifications, performance? How closely does the fuel cell company meet its own specifications?
2. How long does the fuel cell run, and how much attention does it require to keep it running?
3. What is the cause of shutdowns? Are they scheduled or unscheduled?
4. What is the efficiency of the unit, and how does this compare to other ways of generating power?
5. What is the cost of power from the fuel cell?
6. Is the unit ready for further field demonstrations?

The History of FCT

The fuel cell tested in this project was provided by Fuel Cell Technologies (FCT) of Kingston, Ontario. FCT began in the early 1990s as a company to provide power supplies for unmanned underwater vehicles. These power supplies used aluminum as the energy storage media, and were much like fuel cells in terms of operation and control. In this business activity, FCT developed expertise in Balance of Plant (BOP) and control systems for small power systems in conditions that demanded extremely high reliability, a skill set which they determined to be transferable to the new, growing field of fuel cells. By 2000, FCT's business plans called for development of integrated fuel cells for commercial sale based on the purchase of SOFC stacks from other sources. This strategy took advantage of FCT's expertise in Balance of Plant (BOP) designs from previous products.

In June of 2000, FCT signed an agreement with Siemens Westinghouse Power Corporation to study SOFC systems for residential and remote applications [8]. The agreement was followed by a more formal Joint Development Agreement in November 2000, which indicated that Siemens was responsible for the design and testing of the fuel cell stack, while FCT would design, build, and test the Balance of Plant (BOP), carry out system integration and performance testing, and have demonstration units operating and available in mid-2002. The agreement allowed FCT to market fuel cells under 50kW, while Siemens focused on larger units.

FCT began attempting to market their 5 kW units in the summer of 2001. At that point in time, they were offering units to be shipped between July and December of 2002 at a cost

of \$5,000 per kW, or \$25,000 per unit. This unit was described in a brochure printed for potential customers and investors. FCT contacted UAF for the first time in July, 2001 [9]. By fall, the price had risen to \$50,000 for a 5 kW unit.

At that time, UAF recommended that FCT prepare a proposal for consideration by the newly formed Arctic Energy Technology Development Laboratory (AETDL) at UAF. A proposal package was prepared for the 2002 RFP, which closed at the end of February, 2002. However, part of the discussion leading up to the proposal was the fact that the funding was intended for cooperative R&D efforts, and the total support requested by FCT was for \$169,000, to include engineering support for the design and building of the unit. Additional funds were requested by UAF for support of the demonstration phase. The project was selected by the review panel as one to be recommended for funding.

FCT was also taking orders for other demonstration units at \$50,000 each, and at one time had at least 18 standing orders. However, by late 2002, it was apparent that there was a problem with the supply of fuel cell stacks from Siemens. Instead of a delivery of 25 stacks that FCT anticipated in 2002, only 4 stacks were actually delivered, and those much later than anticipated, in the spring of 2003. FCT was placed in the unfortunate position of needing to cancel contracts, and elected to do so in a way that prioritized delivery of systems to their highest value customers. Because the contract we negotiated with FCT provided additional funding for support of engineering efforts, FCT decided that the UAF contract would be honored.

The initial delivery date given in the February 2002 proposal was for the end of year in 2002. However, due to the delay in stack delivery noted above, the unit was not delivered to Fairbanks until July, 2003, and start-up of the unit was not done until August 1, 2003.

Experiment

Description of this project

In this work, a 5 kW fuel cell was delivered to UAF from Fuel Cell Technologies (FCT) of Kingston, Ontario. The cell stack is of a tubular design, and was built by Siemens Westinghouse Fuel Cell division. The cells were of a 70 cm length, unlike the 150 cm cells typically used in Siemens' larger stacks. A total of 88 tubes were assembled in two bundles to form the total stack.

A brochure from FCT printed in February, 2002 lists the performance characteristics of the SOFC system anticipated. These parameters are listed in Table 1, and compared to the properties of the unit actually delivered to the program. It should be noted in fairness to FCT that the brochure described the anticipated performance of a high volume commercial unit, which, at the time of this writing, has yet to be achieved.

The unit shipped to this program was described as an “apha” unit, meaning that there were several features of the unit that were considered to be unacceptable for commercial field units. These features were: 1) the need for a purge gas of 4% hydrogen in nitrogen for start-up and shut-down (to be replaced with a methanol and water system), 2) electrical heaters of 15 kW for unit pre-heating (to be replaced by a combustor), 3) the need for 40 psig natural gas (to be reduced to 1 psig for commercial units), 4) an inverter capable of only discrete power outputs (commercial units need to load follow), 5) and weight and volume of the unit were above intended specifications. The expectation was that each of these problems could be solved through engineering solutions, though some of the problems were more difficult than others.

The need for 40 psig gas was particularly troublesome, as in most locations this requires both a gas compressor and a special dispensation from the local fire marshal, but the requirement was driven by the need to re-circulate anode tail gas as a source of steam for the reformation of natural gas. In commercial units, this could be accomplished by use of a high temperature fan, but these devices are not common commercial hardware.

The role of the UAF Arctic Energy Technology Development Laboratory in this project was to act as a first customer for this technology.

The first decision that needed to be made was the location for the demonstration. The natural gas infrastructure in Fairbanks is still limited, as there are no local natural gas fields or major pipelines currently passing through the town (though many residents are hoping this changes soon.) However, Fairbanks Natural Gas was founded in 1998 and delivers natural gas to commercial and residential customers. The gas supply currently comes from Cook Inlet, and is liquefied in Wasilla, and trucked to Fairbanks, where it is vaporized and sent through the local pipeline system. The University had no natural gas service at the time of the beginning of the project, and installation of the fuel cell in the laboratories there would have required the extension of the local pipeline by about two miles, at a cost of approximately \$350,000. This was beyond the installation budget of this project.

During the assessment of the cost of bringing gas to the university, it became apparent that Fairbanks Natural Gas was very interested in fuel cell technology, so discussions were held to see if FNG would have a suitable site for the demonstration. One advantage in using the FNG site was that while all residential and commercial customers provided with gas at 2psig for safety reasons, as the natural gas utility, FNG had both access to and permission to deliver gas at higher pressure into their facilities, at 35 psig, eliminating the need for a gas compressor. A second benefit was that the FNG site was capable of absorbing the entire electrical output of the fuel cell at all times, with the produced power simply offsetting the power that needed to be purchased from the local utility. FNG was willing to provide the natural gas at no charge in exchange for the generated power (about a break-even proposition for them, given the retail value of the gas in Fairbanks). Additional considerations were that the unit was physically larger than a typical residential doorway, and heavy (2700 pounds).

A suitable spot was identified in the FNG warehouse to place the fuel cell, and installation was undertaken, with the assistance of Mr. Jim Buckley, from Energy Alternatives, who was acting as the field representative for FCT. This site was close to a large overhead door, had a robust poured concrete floor, a nearby unit heater capable of using the produced heat, and was available for use. In addition, the site was not open to the public, and access to the warehouse was controlled, and visitors monitored through a sign-in sheet at the reception area.

The site preparation required mechanical hookups for 1) Natural Gas at 35 psig, 2) Nitrogen 4% Hydrogen mix at 50 psig, 3) Three phase electrical service for 15 kW (to operate the start-up heaters), 4) plumbing for the heat recovery glycol loop, 5) plumbing for the summer heat dump load, outside the building, 5) an exhaust line for removal of the combustion products, and 6) a high speed data port for data acquisition and control. Supply air for the unit was from the existing heated space. In addition, utility grade gas meters and electrical meters were installed for measurement of the overall efficiency measurements.

The site preparation was somewhat more complicated than a typical home boiler installation, and the costs were significant—about \$15,000 for materials and labor for all the electrical, mechanical, and communications lines. While this number probably overstates the costs that would be associated with the installation of a SOFC system in a residential application in the future, it must be noted that most residential mechanical rooms are separate from the electrical service to the home, and that some modification to homes or home design would be required to minimize the additional cost that installation of these units might cost.

There were many delays in the initial schedule, which called for delivery and start-up of the unit by the end of 2002. FCT's plan called for deployment of 4 field units in 2002, and an additional 50 units in 2003. However, the stack supplier was unable to fabricate fuel cell bundles as quickly as anticipated. This unit was completed at the factory in Kingston, Ontario in May of 2003, and shipped to Fairbanks in July, 2003. Start-up occurred on August 1, 2003.

Results

Table 1 Run log for FCT Unit at UAF

	Date	Meter Hours	Cum Hours
Factory Start-up	6/3/2003	384	
Fairbanks Start-up	8/1/2003	0	384
E-Stop (1)	9/8/2003	921	1305
Restart	9/17/2003	921	1305
Stop (2)	3/19/2004	5342	5726
Start	4/1/2004	5342	5726
E-stop	7/20/2004	7971	8355
Start (70% power)	7/31/2004	7971	8355
E-stop (4)	9/23/2004	9267	9651

(1) Unit faulted due to backpressure on exhaust line. Blower installed in exhaust line, and several other repairs made, including data transfer protocols to store data

(2) Unit shut down deliberately to change de-sulphurizer bed material.

(3) Control system failure occurred, uncontrolled shutdown, some damage to stack occurred. Problem traced to "housekeeping" records in software that were not deleted from buffer, eventually filled available memory, and system failed.

(4) Second control system failure, traced to error in fix for problem (3) above. Second uncontrolled shutdown caused crack of one tube, and a field repair was not attempted.

The unit performed quite well during the testing period, with a steady run of 921 hours before the first shutdown occurred, to allow the correction of several minor installation issues. This was followed by a continuous run of approximately 4421 hours, when a shutdown was scheduled to replace the desulfurizer bed. The unit was then restarted and ran for 2629 hours until an emergency stop occurred. This was determined to be due to a control system issue, as the computer controlling the system was creating daily buffer files, which were exported off the machine and deleted, but each record also resulted in a software "housekeeping" record which was inadvertently not deleted, and eventually filled all available memory. When the memory filled, the operating system crashed, resulting in an uncontrolled shutdown, with some damage to the stack occurring. The unit was restarted, but operated at about 70% of the original power level. The unit failed again on September 23, 2004, once again due to a software failure in the control system, this time due to a small error in the repair done to correct the initial problem. This second uncontrolled shutdown resulted in additional damage to the stack, and restart attempts were not successful. And inspection of the stack revealed that at least one tube had been cracked. There was some discussion about plugging the cell and jumping

around it, but it was decided that this was not practical. The unit had achieved approximately 9267 hours in the field, and the stack had reached 9651 hours when the time at the factory was included. During the field demonstration, this represents an availability (time producing power divided by total time) of 92.2%, which is very good considering that much of the down time was due to the time needed to schedule a restart rather than any difficulty in repair.

The efficiency of the unit can be measured in several ways, and the internal instruments on the fuel cell indicated a first law efficiency of about 40%, as claimed by FCT. However, UAF also installed utility meters to measure the natural gas consumed by the unit and the net AC power produced by it, and these measurements indicated a slightly lower efficiency of 37%, with the discrepancy between the two numbers due to differences in the fuel consumption value.

Stack degradation was anticipated, but measurements taken did not indicate a statistically significant (more than .5%) change in stack performance over the life of the test. This is due in part to the fact that the system was operated at a single set point for several months, then changed to a different static set point, making changes somewhat difficult to observe, but also indicates that the stack was not experiencing rapid degradation.

Based on the long system run, the excellent efficiencies achieved, and the absence of degradation, this demonstration was quite successful. These results were shared with the fuel cell community in a press release, and in a paper presented at the 2004 Fuel Cell Seminar in San Antonio in November 2004.

However, there were several issues that remain to be addressed before SOFC's can be considered for most field applications. Some of these issues are specific to this unit, and can be solved through better product development, while others are perhaps a bit more difficult to address.

The specific issues identified with this unit include:

1. The need to provide significant amounts of electrical power to the system during start-up (15 kW for about 24 hours).
2. The need to provide purge gas during start-up and shutdown.
3. The system size and weight (2700 pounds).
4. Operation on natural gas (usually available only in urban/suburban areas, where grid connected electricity is also available).
5. Requirement that natural gas be provided at 40 psig rather than at the 1-2 psig typical of utility natural gas.
6. The lack of load following ability due to the inverter selection.

The more general issues for all small scale SOFCs include:

1. The cost of producing SOFC stacks
2. The intolerance of SOFC systems to thermal shock and thermal cycling
3. System degradation

In fairness, it must be noted that the issues identified on this list are being addressed by the SOFC industry. In particular, FCT was aware of the issues identified, and was attempting to create a fleet of “beta” units for testing that addressed most of the issues on the first list. The US DOE SECA program is intended to address the broader issues of the SOFC industry, and significant progress is being made on issues on the second list.

Parameter	FCT 2002 Brochure	FCT Hardware Achieved
Dimensions	24x31x67	32X36X76
Weight	350 lbs	2700 lbs
Output (Electrical)	0-5kW load following	2.8 and 3.2 kW fixed
Efficiency (Electrical)	47%	38%
Efficiency (overall)	90%	69%
Fuels	Utility natural gas, propane, hydrogen	Natural Gas @ 40psig
Operating life	16 years	1 year
Operating conditions	-40C to 50 C	0 C to 30 C
Service Interval	6 months	6 months
Cost	\$1000 per kW in high volume	\$52,000 per kW in Alpha unit

Table 2 Comparison of specifications to delivered unit.

Discussion and Conclusions

By many measures, this project was a significant success:

- A 5 kW SOFC was delivered to a field site.
- The unit started as expected.
- After correcting minor installation problems, the unit ran flawlessly for a year.
- The unit delivered three phase grid quality power to a commercial building.
- Stack degradation was negligible during the run.

- The system balance of plant was very robust.
- The system efficiency (AC electricity out/ Natural Gas energy in) was 37%.
- The project was ended by two control system failures (not stack issues).

The project also revealed that there is considerable need for improvement in these SOFC systems before they will be commercially viable. These issues include:

- Requirement of high pressure natural gas (40PSIG) for operation
- Requirement of significant electrical power for start up (15 kW needed for heaters)
- Requirement for bottled purge gas for start-up and shut down
- Improvements needed in electrical deliver system to allow load following

Several issues were also noted with the economics of this unit. These include:

- The rising price of natural gas means that producing electricity from this fuel is not competitive with other forms of power generation.
- Fuel cell system prices in general, and SOFC prices in particular need to fall dramatically before these systems can compete with conventional power generation. In this study, the price of the fuel cell system rose over the project (from \$25,000 to \$50,000 to \$169,000 to \$300,000 for a 5 kW system).
- The expectation was that as time passes, mass manufacturing techniques would increase the availability of fuel cell stacks, and lower the cost. During the period of 2001 to 2007, this did not occur.

The economic issues identified above led to the end of FCT as a company in October, 2006. While the authors of this report were not privy to the details of this business failure, perhaps some general observations could be made. First, FCT decided that its strength was in the production of the balance of plant for fuel cells, and created a business plan based on their strength. As a small company, FCT wisely decided that it could not compete effectively in the development of the fuel cell stacks, and left this task to others. The quality of the systems they developed, the engineering, component selection, control software, and field support, were excellent. However, they depended on other fuel cell developers to supply stacks to them, and negotiated contracts for these to be supplied to them. These contracts were not fulfilled, leaving FCT with no product to ship, unhappy customers, rising costs, and, ultimately, failure of the company.

However, FCT is not alone in its failure, as currently there are no companies delivering a commercial small scale fuel cell product to the market. While the DOE SECA program is still investing in this technology, commercial products still are at least several years away.

What this project did show, however, is that producing a small scale, efficient, robust, reliable solid oxide fuel cell is possible—there are no barriers in terms of science. However, the engineering questions—producing these systems in sufficient volume to meet market demands, improving the product to operate in field conditions, increasing

the robustness of the control system, and, especially, reducing the cost to provide real value to the customers—remain open. It is not clear if the potential markets will justify the investments needed to make these systems real.

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