Report Title

# Small Scale Fuel Cell and Reformer Systems for Remote Power

## Final Topical Report

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## *Abstract*

New developments in fuel cell technologies offer the promise of clean, reliable affordable power, resulting in reduced environmental impacts and reduced dependence on foreign oil. These developments are of particular interest to the people of Alaska, where many residents live in remote villages, with no roads or electrical grids and a very high cost of energy, where small residential power systems could replace diesel generators.

Fuel cells require hydrogen for efficient electrical production, however. Hydrogen purchased through conventional compressed gas suppliers is very expensive and not a viable option for use in remote villages, so hydrogen production is a critical piece of making fuel cells work in these areas. While some have proposed generating hydrogen from renewable resources such as wind, this does not appear to be an economically viable alternative at this time. Hydrogen can also be produced from hydrocarbon feed stocks, in a process known as reforming. This program is interested in testing and evaluating currently available reformers using transportable fuels: methanol, propane, gasoline, and diesel fuels. Of these, diesel fuels are of most interest, since the existing energy infrastructure of rural Alaska is based primarily on diesel fuels, but this is also the most difficult fuel to reform, due to the propensity for coke formation, due to both the high vaporization temperature and to the high sulfur content in these fuels.

There are several competing fuel cell technologies being developed in industry today. Prior work at UAF focused on the use of PEM fuel cells and diesel reformers, with significant barriers identified to their use for power in remote areas, including stack lifetime, system efficiency, and cost. Solid Oxide Fuel Cells have demonstrated better stack lifetime and efficiency in demonstrations elsewhere (though cost still remains an issue), and procuring a system for testing was pursued.

The primary function of UAF in the fuel cell industry is in the role of third party independent testing. In order for tests to be conducted, hardware must be purchased and delivered. The fuel cell industry is still in a pre-commercial state, however. Commercial products are defined as having a fixed set of specifications, fixed price, fixed delivery date, and a warrantee. Negotiations with fuel cell companies over these issues are often complex, and the results of these discussions often reveal much about the state of development of the technology. This work includes some of the results of these procurement experiments.

Fuel cells may one day replace heat engines as the source of electrical power in remote areas. However, the results of this program to date indicate that currently available hardware is not developed sufficiently for these environments, and that significant time and resources will need to be committed for this to occur.

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## *Introduction*

The University of Alaska Fairbanks (UAF) Arctic Energy Technology Development Laboratory (AETDL) was formed with the mandate of evaluating new technologies for electrical production in remote areas. In the enabling legislation that created the office, fuel cells were specifically named as one technology of interest.

Fuel Cell work was begun at UAF several years prior to the formation of AETDL, in the Rural Alaska Power Program (RAPP), funded through the US DOE EE Hydrogen office. This work involved independent third party evaluation of PEM fuel cell technologies for residential stationary power. This report will discuss the results of that program, including the desire of AETDL to broaden the technology evaluation to include other fuel cell technologies, especially SOFC systems.

## *Executive Summary*

Alaska's rural communities experience very high energy costs, especially for electrical power, due to the lack of electrical grids and roads, resulting in electricity production mostly using Diesel Electric Generators (DEGs). Electrical power costs in these communities ranges from $.20 to $.80 per kilo-Watt hour, which is a burden to both the residents and businesses of these communities. The high costs are from several factors, including the cost of transporting and storing diesel fuel, the cost of maintaining the generators in small communities where maintanence crews need to be flow in from outside to make necessary repairs, and the poor economies of scale from running a small utility.

Fuel cells designed for residential power offer several attractive benefits over the existing system. First, higher efficiency electrical power generation means less fuel would need to be transported to the village, reducing costs. Secondly, small, quiet units could be placed within individual residences, allowing efficient heat recovery, further reducing the fuel consumed by the village. High reliability would also result in significant cost savings, reducing the dependence on outside expertise for necessary repairs. Reliability of the system could also be improved, as a distributed network of units could provide back-up power for each other, much as larger grids improve reliability to all users by compensating for outages at individual plants.

While the benefits of these proposed fuel cell systems are quite apparent, the fuel cell hardware currently under development is still not readily available for use in remote villages in Alaska. Most fuel cell technology is still very much in the early product development stages, with manufacturers building prototypes for internal evaluation, or releasing hardware to carefully selected sites for evaluation. In 1998, UAF became involved in the Rural Alaska Power Program, intended to evaluate diesel fueled PEM fuel cell systems for residential power. This project was fueled by suppliers who claimed that they had beta test units capable of achieving 40% net electrical power out from diesel fuel, with system lifetimes of 40,000 hours, and that these units would be commercially available in 2001, with a project cost of $3,500 for a 5 kW unit. The UAF role in the project was to provide independent third party verification of this performance so that these units could be deployed in rural Alaska.

Unfortunately, the results of the project were not encouraging. First, the overall system efficiency of PEM fuel cell reformer systems was measured to be about 25%, which is lower than the current diesel generators operating in the field. Secondly, PEM fuel cell stacks failed in testing rapidly, and none of the systems tested in the program achieved more than a few hundred hours of run time operating on pure hydrogen. The diesel reformers provided to the program also experienced significant difficulties, with solid carbon formation, materials degradation, and balance of plant and control system issues contributing to the poor performance. Furthermore, costs remained high (well over $10,000 per kW for units operating on natural gas), and no commercial production of these units occurred.

Based on these results, using diesel/PEM residential fuel cell systems in rural Alaska did not appear to be a viable alternative to diesel electric generators. However, Solid Oxide Fuel Cell (SOFC) technology appeared to be advancing rapidly. Preliminary discussions with SOFC suppliers indicated that higher system efficiencies (50% net AC out on large systems operating on natural gas) and longer stack lives (more than 69,000 hours in laboratory tests), as well as the onset of the SECA program, with aggressive price targets for this technology.

Fuel cells are still very much pre-commercial devices, with each of the technologies in the product development stage, with differing technical barriers to success. (Commercial product is defined by several characteristics: fixed product specifications, a fixed delivery date, a fixed delivery price, and a warrantee.) Visiting web sites or booths at industry conferences may give the impression that commercial deployment is imminent, but the only way to determine the true state of product development is to purchase a fuel cell. This exercise can be thought of as an experiment, which in this work will be referred to as a "procurement experiment." Many times, these procurement experiments do not result in the delivery of a product to the purchaser, and can be thought of as failures, but, in fact, this null result contains much information about the state of technology development of the product.

## *Experimental*

By the summer of 2001, experience with PEM fuel cell systems for distributed electrical power production indicated that suppliers of these systems had vastly overstated the capabilities of their product, and near term commercial deployment of these systems for use in rural Alaska was unlikely. Based on this conclusion, a decision was made to abandon further testing of this technology.

**Procurement Experiment #1: The FCT Solid Oxide Fuel Cell**

At a meeting in September 2000, a staff member of NETL stated in a meeting that a 5 kW SOFC operating on propane was scheduled for delivery to the Presidio Trust near San Francisco sometime in the next few months, and that the company that was supplying this unit was intending to market these units starting in late 2001 at a cost of $5,000 per kW, or $25,000 for a 5 kW unit.

Attempts to track down the source of this fuel cell were at first unsuccessful, but eventually it became clear that the supplier of this unit was a company called Fuel Cell Technologies, of Kingston Ontario. This company had entered into an agreement with Siemens Westinghouse for delivery of 5 kW fuel cell bundles, with FCT building the balance of plant and control systems. This agreement was announced in a press release found on the FCT web site. Also on the web site was an announcement on June 11, 2001 of the purchase order for the supply of the unit to the Presidio, as well as a second unit to the National Fuel Cell Research Center at the University of California.

Initial contact was made with FCT during the summer of 2001, when FCT indicated via e-mail on July 23, 2001 that they had "a limited number of field demonstration units available between July and December 2002. These initial units are available at a price of US $5000 / kW, or $25,000 per unit, FOB Kingston, Ontario, and excluding applicable taxes. This does not include any cost for installation. Scheduled maintenance cost will be low due to the very few moving parts in the system. We request a down payment of 20% with the purchase order."

During the fall of 2001, UAF entered into an agreement with the USDOE through NETL to fund the Arctic Energy Technology Development Laboratory. Enabling legislation for this agreement included language indicating that the funds were to be used for research into improving the delivery of electrical power to rural communities in Alaska, with fuel cell technologies specifically named as a technology of interest. A project selection process was created using industry panels to review and select projects, and FCT elected to submit a proposal in this process, in cooperation with the staff at UAF.

During discussions with FCT in the early part of 2002, FCT indicated that the current price for the systems had risen to $50,000 for new orders. However, we also discussed the fact that the University was interested in engaging in cooperative research, and would entertain a proposal in which development costs were included as part of the proposal. After a few weeks, FCT indicated that they would be interested in engaging in this kind of an arrangement, and proposed delivering and installing one of their first systems for a total contract value of $170,000 from DOE, with additional cost share from FCT. This proposal was review and ranked highly by the industry panel, and so was selected as a project to be funded under AETDL. A subcontract was sent to FCT in July, 2002 for this work.

During the summer of 2002, UAF was told that the system would be delivered to Fairbanks in early fall of 2002, in keeping with the announced schedule of FCT. AETDL sponsored a conference titled "Reliable and Affordable Energy for Rural Alaska" on September 17-19, 2002 in Fairbanks, and was hoping to have the fuel cell up and operating for that conference. However, shortly before this event, FCT called with the news that the stacks being supplied to them were failing in early tests, and were being sent back to the supplier. They felt it would be unwise on their part to ship a product they felt was not up to standards.

During the fall of 2002, discussions with FCT indicated that a stack delivered to them in late November was performing well, and that they expected delivery of the stack to FCT in early 2003, with delivery of the system to Fairbanks several weeks after they received it.

In February of 2003, a stack was to be shipped from the supplier to FCT for the UAF system. However, this stack was dropped and broken while being prepared for shipment at the supplier, and it was not clear when another stack would be ready for the system.

At this time, there was also discussion with regards to the fuel to be used in the system. Because our interest in Alaska is primarily to provide power to remote villages, our ultimate interest is to test units operating on fuels readily available in these places. For this reason, we indicated our interest in testing a unit operating on propane initially, followed later by a unit operating on diesel fuel. However, discussions with FCT indicated that they would be more comfortable shipping a unit designed to operate on natural gas. While this fuel is abundant in parts of Alaska (Anchorage and the North Slope, and parts of Fairbanks), it is not readily available in most rural communities. However, UAF was eager to test the operation of the fuel cell, and agreed to operate the unit on natural gas. A site at the Fairbanks Natural Gas Company in Fairbanks several miles from the university was located, and the cooperation of the site owners was obtained.

There were also several other issues that were raised with regards to the installation and operation of this fuel cell. First, the natural gas pressure needed was 40 psig, which is considerably higher than typical line pressure in most natural gas delivery systems. Fortunately, this pressure was available at the Fairbanks Natural Gas site, so we did not need to install a gas compressor to make the system work. The second issue was that the fuel cell needs to be heated before it can be started, and the heating in the alpha units is done electrically. The energy required for this heat-up is significant—about 12kW for a 24 hour period. Once again, since the unit was being installed in an industrial warehouse facility, this power was available, but this is an electrical load significantly higher than most residential loads. The third issue was the need for a 4% hydrogen / 96% nitrogen gas mix needed to maintain a reducing atmosphere in the unit during start-up. All of these changes in specifications--the sole use of natural gas, the pressure of the natural gas feed, the need for electrical power during start-up, and the need for the H2/N2 gas during start up—had an effect on the ability of this unit to meet the intended market needs in rural Alaska.

The good news is that the completed unit was shipped from FCT in late June, 2003, arrived in Fairbanks in mid-July, and was started up on August 1, 2003. The operation of this unit has been nearly flawless, and the project is a real success. The unit is producing both AC electrical power and usable heat, and is operating in a very stable manner. The results of the demonstration project will be covered in the report from that project, and will not be dealt with in detail here.

**Procurement Experiment #2: The Diesel Reformer**

Operating high efficiency fuel cells from diesel fuels is a high priority for military operations, where field deployments are often limed by fuel supply lines. Using logistical fuels for electric power generation would simplify field logistics (in the first Gulf war, small portable generators operating on gasoline were the only devices taken to the field that did not use diesel fuel, and carrying and tracking that fuel was a logistical problem for the soldiers). Use of fuel cells could also reduce noise and heat signatures from operations.

Diesel fuel is also the most common fuel used in rural Alaska, as this is the primary fuel for electrical generation in most remote villages and industrial sites. The high energy content, the relative safety with which the fuel can be handled (a match can be dropped in a bucket of diesel fuel without igniting), and the investment in current infrastructure are all reasons why the continued use of diesel fuel for operating high efficiency electrical generators is desirable. If fuel cells are to be used in these places, the development of a reformer technology for diesel fuel is critical.

In the RAPP program, two different diesel reformer technologies were tested. The first was a steam reformer, based on the design of a methanol reformer, with a palladium membrane to separate the hydrogen, providing pure hydrogen suitable for operation of a PEM fuel cell. However, the efficiency of this reformer (H2 out/ Diesel fuel in) was at best about 35%, leading to an extremely poor overall efficiency. This reformer also experienced significant issues with materials degradation and coking. A second reformer from a different supplier used an Autothermal process to reform diesel. This unit demonstrated a higher efficiency (about 65%) but the gas stream produced was a hydrogen rich stream, also containing significant amounts of CO. This gas stream needed to be purified before a fuel cell could be connected to the system, and the gas purification system never operated properly. Other issues with the system included an unstable auxiliary burner, catalyst substrate breakdown, and oscillations in output.

Fundamental work being done in National Laboratories in the past few years has led to some understanding of the difficulties involved in the reformation of diesel fuels. This include the fact that all components of distillate fuels do not react in reformers at the same rate, with aromatic hydrocarbons breaking down at significantly slower rates than parafins, and the role of sulfur in the nucleation of solid carbon (coking). Another issue has been the need to completely vaporize the fuel before the reaction begins (liquid droplets create local environments rich in fuel, which then thermodynamically favor the formation of solid carbon).

SOFC systems often permit internal reforming of natural gas. However, natural gas is considerably easier to reform than diesel fuel, since this has the most hydrogen per carbon, there are no aromatics in the fuel, and the fuel is a vapor at standard atmospheric conditions. The Siemens technology is designed to do reforming inside the fuel cell stack, taking advantage of the heat generated from the stack as the source of energy for the reformation process. However, heavier hydrocarbons require the presence of additional steam for the reformation to occur, and there is the increased risk of coke formation inside the stack. One possible way to deal with these issues is to separate the fuel cell and the reformer into two separate units. Doing this, however, changes dramatically the heat management of the fuel cell stack, as additional heat must be removed from the fuel cell, and (for steam reforming) supplied to the external reformer.

As part of this program, we attempted to purchase diesel reformers from several suppliers. Most reformer developers indicated to us that diesel reformers were not yet packaged for commercial deployment, and were more than happy to consider cooperative R&D projects in which small scale diesel reformers would be built and tested. However, these R&D projects are expensive, and success is not guaranteed.

One supplier did indicate, in the fall of 2002, that a diesel reformer was being packaged with a PEM fuel cell, and they were willing to provide units for testing for $80,000. However, the longevity of these units was not very good, with a system lifetime of only a few hundred hours expected.

Another party, a reformer developer, indicated a willingness to partner on a R&D effort, using an Autothermal reformer being developed and tested for a Navy program. This reformer was intended to provide a hydrogen rich fuel stream for a 500 kW PEM fuel cell, but no 500 kW PEM fuel cell system is available for testing. The proposed plan was to use a slipstream from the reformer to operate a SOFC stack designed for natural gas. Two issues were identified, however: 1) The energy content of the hydrogen rich gas is 90 BTU/ft of gas, vs 1000 BTU/ft3 of natural gas, and 2) The heat generated in the fuel cell normally absorbed by the natural gas steam reformation needs to be removed from the system in some other way, most likely through an increase in airflow through the stack. Our original intention was to operate the FCT SOFC on this gas, but when we contacted FCT with this proposal, initial permission gradually gave way to a suggestion that we purchase an additional system engineered to handle the new gas stream.

**Experiment #3: Methanol Fuel Reformer with PEM fuel cell**

Methanol is a commonly available industrial substance, usually made in petrochemical refineries from natural gas, used for a variety of uses, most frequently for de-icing applications, including auto fuel tanks and airplane wings. Methanol was also a precursor to MTBE, an oxygenator added to gasoline to reduce air pollution. Due to environmental concerns associated with the rapid transport of MTBE in water tables from leaking fuel tanks, MTBE has been removed from the market, and refineries currently have excess capability for producing methanol.

Methanol is an ideal fuel for use in fuel cell applications due to the fact that it forms hydrogen at much lower temperatures than conventional hydrocarbons, at 350 C rather than at 800 C. This means that the heat required to drive a steam reformer is considerably lower, resulting in less energy loss due to heat leaving the system. Also, the lower temperatures enable the use of less costly materials in the construction of the reformer. Furthermore, since methanol and water a miscible, the fuel can be mixed with water to create a single feedstock, providing both a constant steam to carbon ration, as well as a simplified mechanical system, since only a single pump is required for system operation. In Arctic applications, the fuel mix remains a liquid to -126 F, a temperature 38 degrees colder than the record recorded in Alaska.

Methanol also has significant disadvantages as a fuel. It has a much lower energy density per unit volume or weight (about half that of conventional liquid hydrocarbons), so is more expensive to transport to the final user. Creating a methanol/water premix for fuel only increases this disadvantage. Methanol is hazardous for human consumption, and the miscibility issue with MTBE is also an issue with methanol, where spills could contaminate large groundwater areas quickly. Also, since methanol is a product derived from natural gas, a “well to wheels” analysis of efficiency needs to be done if this fuel is proposed for a dominant fuel. Estimates of the efficiency of producing methanol (heating value of methanol/ heating value of natural gas) vary depending on the plant design where the fuel is produced, but estimates are typically about 65%.

After the difficulties experience with diesel reformers in the RAPP program, this program investigated the feasibility of using PEM fuel cells operating on methanol for powering remote sites, especially applications such as remote communications repeaters. Idatech, from Bend, Oregon, is marketing methanol reformers, and integrated PEM systems. As part of the FY02 funding request, a project was started to create a system designed for Arctic environments using methanol/water premix as the fuel. The details of the performance of that system will be covered in the final report for that project.

The procurement experiment for the methanol/PEM system was quite interesting. First, the suppliers of both sides of the system admitted reliability issues. On the reformer side, the metering pumps used to supply the fuel premix were the weak link in the system, with the expected lifetime of these pumps only about 500 hours. This weakness has been remedied, with a new pump supplier located, with an expected lifetime of at least several thousand hours. (The cost of these pumps is an issue—currently the available price of the pump alone is comparable to the stated target price of the entire reformer.) On the Fuel Cell side, stack longevity remains an issue. While some progress is being made in understanding the failure mechanisms in membrane failure, currently stack life is extended mostly by reducing the maximum power extracted from the stack, limiting the maximum current density to no more than about half the maximum predicted from the polarization curve. While this may extend stack life, it de-rates the system power, thus increasing the cost per unit output of an already expensive system.

Phase 2 of the project, which was not funded, included funds for purchasing a second reformer. However, in the fall of 2002, Idatech announced the commercial launch of a methanol/PEM system based on a Ballard stack. Initial conversations indicated that the cost of these systems would be $30,000 for a 1 kilo-Watt system, which was less than the $40,000 in our budget for the purchase of a second methanol reformer. When UAF requested a formal quote for the system, however, the price had risen significantly, to $45,500 for the base price, plus a charge of $7,900 for spare parts and training. Cost share was listed as a 6 month parts and labor agreement, including a 500 hour warranty, parts, and labor, valued at $14,500, for a total system value of $67,900. This total is more than twice the initial price.

**Experiment #4: The perfect procurement experiment**

My clearest understanding of the level of development of the fuel cell industry came in a brief conversation with an individual who has been working on fuel cell development for more than a decade, in several companies. He announced that he was starting a new company and asked me if I was interested in buying a fuel cell. I said, “sure, but how much does it cost?”, and he replied “how much money do you have?”

## *Results and Discussion*

Fuel Cells have been proposed as an ideal solution for providing efficient electrical power for remote villages in Alaska. However, successful deployment of this technology depends on affordable and reliable commercially available fuel cell hardware.

UAF has used the funding provided by DOE to attempt to purchase small scale fuel cells and reformers from a wide variety of suppliers. The performance of individual products is not covered in this paper, but the attempts to negotiate product delivery is documented.

The first obvious result of this investigation is that fuel cells for residential power are not commercially available. All product currently being produced is available only through cooperative R&D agreements intended as early demonstration projects, and most of the information generated is protected through non-disclosure agreements. No supplier currently meets the requirements of commercial product: fixed product specifications, fixed price, fixed delivery date, and a warrantee. In the Solid Oxide Fuel Cell industry, manufacturing of the cells and stacks in a timely and affordable manner appears to be the fundamental barrier. In the PEM industry, stack lifetime and low system efficiency are major barriers to successful use of this technololgy

The reforming of suitable fuels also remains problematic. Natural gas and methanol are easy to reform, but are not ideal for use in remote areas. Heavier hydrocarbons are more difficult to reform, and reliable reformers are not currently available.

## *Conclusions*

Fuel Cells promise high efficiency, low emissions, high reliability, and low cost. However, these promises have yet to be fulfilled, as all fuel cell technologies are still very much in the product development stage.

Fuel cell developers are under tremendous pressure to produce commercial product from their investors, both private and public. Frequently, optimistic targets are set for product performance and release, and those who promise the most are rewarded with funding for product development.

Obtaining accurate information about the true state of product development is nearly impossible to obtain, unless one attempts to purchase product. This program has purchased several fuel cell systems for pre-commercial testing. While the original intent of these programs was to verify the performance of these fuel cells prior to deployment of these technologies in rural Alaska, the conclusion that we have reached is that none of the systems we have obtained are developed to the point where they would be likely to succeed in a field demonstration in remote areas.

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## *List of Acronyms and Abbreviations*

PEMFC-- Polymer Exchange Membrane Fuel Cell or Proton Exchange Membrane Fuel Cell (the two are different names for the same technology)

SOFC-- Solid Oxide Fuel Cell

RAPP-- Rural Alaska Power Program

UAF-- University of Alaska Fairbanks

DEG—Diesel Electric Generator

Note: SI is an abbreviation for "Le Systeme International d'Unites."