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Final Report

Five Kilowatt Solid Oxide Fuel Cell/Diesel Reformer

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Abstract

Reducing fossil fuel consumption both for energy security and for reduction in global greenhouse emissions has been a major goal of energy research in the US for many years. Fuel cells have been proposed as a technology that can address both these issues—as devices that convert the energy of a fuel directly into electrical energy, they offer low emissions and high efficiencies. These advantages are of particular interest to remote power users, where grid connected power is unavailable, and most electrical power comes from diesel electric generators. Diesel fuel is the fuel of choice because it can be easily transported and stored in quantities large enough to supply energy for small communities for extended periods of time. This project aimed to demonstrate the operation of a solid oxide fuel cell on diesel fuel, and to measure the resulting efficiency.

Results from this project have been somewhat encouraging, with a laboratory breadboard integration of a small scale diesel reformer and a Solid Oxide Fuel Cell demonstrated in the first 18 months of the project. This initial demonstration was conducted at INEEL in the spring of 2005 using a small scale diesel reformer provided by SOFCo and a fuel cell provided by Acumentrics. However, attempts to integrate and automate the available technology have not proved successful as yet. This is due both to the lack of movement on the fuel processing side as well as the rather poor stack lifetimes exhibited by the fuel cells. Commercial product is still unavailable, and precommercial devices are both extremely expensive and require extensive field support.

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Executive Summary

Reducing fossil fuel consumption both for energy security and for reduction in global greenhouse emissions has been a major goal of energy research in the US for many years. Fuel cells have been proposed as a technology that can address both these issues—as devices that convert the energy of a fuel directly into electrical energy, they offer low emissions and high efficiencies. These advantages are of particular interest to remote power users, where grid connected power is unavailable, and most electrical power comes from diesel electric generators. Diesel fuel is the fuel of choice because it can be easily transported and stored in quantities large enough to supply energy for small communities for extended periods of time. This project aimed to demonstrate the operation of a solid oxide fuel cell on diesel fuel and to measure the resulting efficiency.

Results from this project have been somewhat encouraging, with a laboratory breadboard integration of a small scale diesel reformer and a Solid Oxide Fuel Cell demonstrated in the first 18 months of the project. This initial demonstration was conducted at INEEL in the spring of 2005 using a small scale diesel reformer provided by SOFCo and a fuel cell provided by Acumentrics. However, this demonstration was a temporary breadboard integration accomplished in the parking lot of a building, and lasted for only about 4 hours.

This initial demonstration was followed by other activities intended to improve the system integration and verify longer term operation. The fuel cell was shipped to Fairbanks to be operated on natural gas while waiting for the automation of the diesel reformer. The fuel cell operated for less than 40 hours before failure, was returned to the factory, then operated for just under 4000 hours before it failed again. The diesel reformer integration effort was even more problematic, as the proposing company changed management, and the funds requested in the initial proposal (\$250,000) were deemed inadequate for the necessary work by the new management.

Based on the experiences of this project, it appears that reliable, economic fuel cells operating on diesel fuel are still unavailable, and precommercial devices are both extremely expensive and require extensive field support. It is not clear if or when these devices will be developed to a point suitable for use in remote communities in Alaska.

Background

Even at the beginning of the 21st century, much of Alaska remains remote and undeveloped, unconnected to either the road system or to the electric power grid. Those who live in these remote areas of Alaska depend on diesel electric power generators, and their power costs are far higher than those of typical US consumers, with recent rates

exceeding \$1.00 per kW-hr in some communities. Environmental concerns are also an issue, both particulate emissions from the diesel exhaust, and the contamination of water supplies from spilled fuel [1].

In the late 1990's, Polymer Electrolyte Membrane (PEM) fuel cell suppliers (the type of fuel cells used in automobiles and busses) became interested in the rural Alaska energy problem as a possible ideal application for their products[2]. Small scale fuel cells are much quieter than internal combustion engines and could be placed in individual residences, and the waste heat from the fuel cell could be used to supply heat to the residence. However, after testing PEM fuel cell systems provided by several suppliers, it became apparent that these fuel cells were considerably less efficient than promised (22% rather than 40%) [3-5], and that they did not have the desired longevity, lasting a year at best [6]. Diesel reforming also proved problematic, and no long term demonstrations were successfully conducted on these fuels. However, diesel reformers provided by Idatech and by Dias Analytic were delivered and tested, though the performance period from each unit was only about 50 hours [2].

Solid Oxide Fuel Cells have been demonstrated for longer periods of time and have been shown to have better performance [7], with lifetimes of 68,000 hours (8 years) and efficiencies of 49% on natural gas. The DOE SECA program was designed to help the industry to develop commercial product and address basic research and development issues [8]. A demonstration was conducted in Fairbanks on a 5 kW SOFC provided by Fuel Cell Technologies of Kingston Ontario, with a successful run of 9200 hours on natural gas [9]. Conversations with industry representatives indicate that hydrocarbon reforming was proceeding, and that integrating a SOFC fuel cell and diesel reformer into a single unit could be done, but that the best fuel cell technology and reforming technology might not from the same suppliers.

Goals and objectives

The goal of this project was to advance the state of the art in fuel cells that could operated on logistical fuels. Solid Oxide fuel cells appeared to be more attractive than lower temperature fuel cells due to the high operating temperatures, so that the heat provided from the fuel cell would be of use for the reformation reaction. The project was proposed to proceed in three phases:

1. Demonstration of a 5 kW SOFC operating on diesel reformat provided by the INEEL 500 kW diesel reformer (funded by the US Navy)
2. Development of a diesel reformer appropriately sized for use with the 5 kW SOFC .
3. Breadboard integration of the fuel cell and reformer.

While the ultimate goal of any program of this kind would seem to be the complete integration of the fuel cell and diesel reformer, it was quite apparent from discussions with suppliers that this integration required considerable attention to the details of integration to allow for proper heat and mass transfer to occur. Given the fact that the best reformer technology and the available fuel cells were not from the same company,

and that intellectual property issues were involved in the integration of the two, this project moved forward with more modest expectations, with the integration of the two parts only at a laboratory breadboard integration. This was intended to be a proof of concept, and allow information to be collected on the operation of the fuel cell and reformer, but not to be a finished product. One thing of interest was the heat management of the fuel cell, as SOFCs operating on natural gas use steam reforming, which is an endothermic reaction, cooling the system. In the proposed diesel reformer/fuel cell breadboard test, the reformation reaction occurs outside the fuel cell envelope, which means that additional air flow is required to maintain fuel cell temperature.

Selection of Fuel Cell Company

There are several potential suppliers of solid oxide fuel cells, but there are no solid oxide fuel cells that could currently be considered commercial devices (fixed price, fixed delivery date, fixed specifications and a warranty). The DOE SECA program[8] focusing on the development of solid oxide fuel cell systems was promoting the basic R&D of small scale SOFC systems, and their integration into 5 kW test packages, and so the participants in that program seemed to be the most likely sources for fuel cells.

UAF had previous experience with the products from Fuel Cell Technologies (FCT) of Kingston, Ontario, and was quite impressed with the system quality, efficiency and operating reliability of those systems. At the beginning of this program, however, FCT was experiencing difficulties in obtaining fuel cell stacks from their supplier to integrate into their system, and found itself unable to meet its commitments to its customers. When asked to provide a quote for a system for this program, the number given was about \$300,000—quite a handsome sum for a 5 kW power generator.

A second supplier, Acumentrics, of Westwood, Massachusetts (near Boston) actively pursued this proposed project, and was willing to provide a fuel cell at \$200,000 (quite a bit lower than FCT, but still a lot of money for a small generator). Acumentrics was a small electronics firm providing ruggedized uninterruptible power supplies to the military, but purchased SOFC technology from a group of New Zealand developers. The technology being developed at Acumentrics focused on low cost manufacturing techniques using small scale tubes, deposition of material layers with ceramic slurries, and slightly lower operating temperatures than some other SOFC systems.

Other fuel cell suppliers were also considered, including SECA participants such as Delphi, who is developing a planar SOFC. Rolls Royce Fuel Cell division was also approached. However, these companies were unwilling to provide a quote for a small scale unit for this program.

Based on cost and availability, Acumentrics appeared to be the best supplier for the SOFC, and was included in the original proposal.

Selection of Reformer Company

UAF has had some experience with diesel reforming in the past, and has developed a healthy respect for the difficulties in this task. While the transformation of natural gas to syngas is a routine operation in many petroleum refineries, and, in theory, any carbon source including coal or biomass can be converted to syngas, the development of small scale diesel reformers has proved problematic. The main issues is the complete vaporization and mixing of the diesel fuel with the reacting air or steam. In small scale reactors sized to match small fuel cells, the surface to volume ratio is large, and the probability of developing cold spots on walls is high, resulting in localized carbon deposition, which in turn nucleates the formation of more carbon. Once solid carbon forms, it is difficult to remove, as it is thermodynamically stable in the reducing environment of the reformer. Once it begins to form, it grows to cover the catalytic surfaces of the reactor bed, and eventually plugs the flow channels, stopping the reactor.

The US DOE Energy and Efficiency division spent considerable effort in 2001-2004 attempting to develop an on-board gasoline reformer for fuel cell powered vehicles. This strategy had the advantage of being able to use the conventional fueling infrastructure currently available in the US while also enabling the transition to hydrogen fuel cell power. However, entry into this market required that the resulting vehicles perform in ways similar to conventional automobiles, including rapid starts, reasonable fuel economy, and packaging of the systems within the expected envelope of a normal automobile. This effort was reviewed in 2004 and the program was canceled as the issues identified were deemed beyond the resources of the program at that time, and the focus shifted to on board hydrogen storage for automotive use.

One of the participants in the DOE EE program was SOFCo EFS, a division of McDermott, located in Alliance, Ohio. This company had been working on the problem of diesel reforming since the 1994, and had invested about \$60M in research in this area. During a site visit to the facility in March of 2002, a 50 kW gasoline reformer was installed in the laboratory for evaluation. Discussions indicated that this reformer worked well on gasoline, but the start-up times and the volume constraints required by the DOE were not met. However, it was indicated that operation on diesel fuel for stationary applications would be possible.

During the Fuel Cell Seminar in November, 2002, Lyman Frost from SOFCo and Robert Carrington from INEEL indicated interest in testing a SOFC on a slipstream from the diesel reformer currently being built at INEEL. This device was intended to operate a 500 kW PEM fuel cell, but that fuel cell had proved to be unobtainable.

Description of the INEEL Diesel Reformer

Phase 1 of this project was intended to show that a fuel cell system could operate on a reformat stream from diesel fuel. The original plan was to use a slipstream from a 500

kW diesel reformer being built at Idaho National Engineering and Environmental Laboratory, with funding from SOFCo and the Navy in October, 2004.

The development of this reformer was funded largely through a Navy program intended to demonstrate fuel cells for use on board ships. The Navy is particularly interested in providing auxiliary power to their ships for several reasons, both for use in port, and as a backup system to decrease vulnerability during battle. This project began in the late 1990s when PEM fuel cell manufacturers were promising compact, inexpensive fuel cells to be used in transportation applications[10]. A 500 kW fuel cell was proposed as being of the right size for urban bus applications, so the diesel reformer was sized to match.

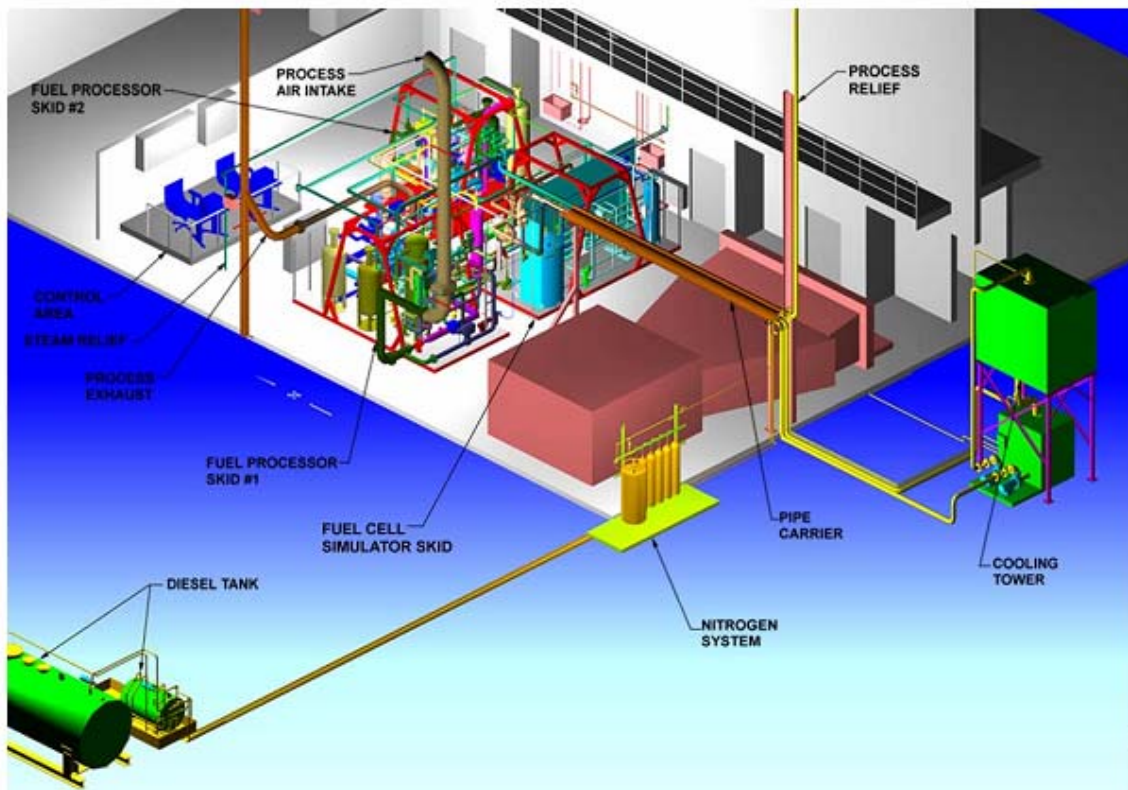


Figure 1 Schematic of the 500 kW reformer at INEEL.

By the time AETDL became involved with this project, the actual PEM fuel cell intended for the demonstration had been replaced with a simulated fuel cell—a reactor chamber that converted the reformat into heat and an exhaust stream similar to that from a fuel cell.

INEEL expressed interest in using a slipstream from the reformer to supply the 5 kW SOFC to demonstrate that the reformer could work with a fuel cell. The SOFC is actually an easier match with the diesel reformer, as SOFCs are more tolerant of carbon monoxide (SOFCs will convert CO and steam to Hydrogen and CO₂ in a spontaneous reaction inside the fuel cell stack, while PEM fuel cells are poisoned by CO levels above a few parts per million).

First demonstration attempt, October, 2004

The first attempt to demonstrate the operation of the Acumentrics Solid Oxide fuel cell operating on a slipstream of the INEEL 500 kW diesel reformer was conducted in October 2004. This date was chosen as it coincided with the time scheduled for a 100 hour test (approximately 1 working week) to demonstrate the stable operation of the diesel reformer as an important milestone in the Navy program.

The Acumentrics fuel cell was shipped to Idaho Falls in anticipation of the demonstration, and UAF personnel traveled to witness the demonstration and collect data.

Upon arrival at the INEEL facility, it became apparent that the expected level of progress had not been achieved. The reformer had been assembled, and filled a large bay of a building with hundreds of feet of piping and insulated reactor beds. A computerized control system had been built for both control and data acquisition. The fuel cell feed was installed as a port in the piping system at the appropriate point to divert about 1% of the total gas stream to the fuel cell.

However, this reformer failed to operate in a stable manner, and we were unable to demonstrate operation of the fuel cell from this reformer. The major reason for this appeared to be the instability created by dynamic issues related to the separation of the compressor and turbine used to move gasses through the system. In a typical turbine engine, there is a very small volume and no restrictions in the combustor zone, so increasing the fuel flow to the engine results in a very rapid increase in power delivered to the turbine, increasing the air flow into the system. This results in a stable acceleration of the engine. In the INEEL diesel reformer, a total of 200 feet of large diameter piping and 6 packed reactor beds had been installed between the compressor and the combustor. This created a large lag time between the addition of fuel to the system (into the first packed bed) and the subsequent arrival of this energy at the turbine. In fact, when diesel fuel was initially injected into the system, this fuel needed to be vaporized, increasing the backpressure on the compressor, but the fuel value of the fuel did not appear at the turbine until much later, perhaps minutes later. This made the reformer almost impossible to control (at a public meeting, one of the operators described running the system “like juggling snakes”, and when asked who designed the turbine he replied “Satan himself.”) Also contributing to the difficulty in controlling the system was the use of pneumatic valves for control (for safety reasons), which resulted in sluggish controls.

The fuel cell fared slightly better in this initial start-up attempt, with some shipping damage to the insulation package around the fuel cell stack noted. Also, during fuel cell start-up on natural gas, CO was detected inside the laboratory that was traced to the exhaust from the fuel cell (about 60 ppm was measured in the exhaust).



Figure 2 Acumentrics Fuel Cell at INEEL, October, 2004. Energy Alternatives Jim Buckley is standing next to fuel cell unit.

The attempt to run the fuel cell on a slipstream from the 500 kW reformer were abandoned after three days. The fuel cell was put back in the shipping crate and returned to the Acumentrics factory for repairs.

Attempts were made to operate the reformer for several weeks after the attempt to run the fuel cell, but the longest sustained run of the reformer was for 40 minutes.

Second Attempt

During a meeting at the Fuel Cell Seminar in November, 2004, a new demonstration strategy was developed, using a smaller 20 kW diesel reformer built by SOFCo at their Alliance OH facility, which would be shipped to INEEL for a demo. This was planned for early in January, 2005.

The Acumentrics fuel cell was returned to the factory, repaired, and a factory acceptance test was conducted during the last week in December, 2004 to verify that the fuel cell was operating properly.

SOFCo delayed shipping the diesel reformer, however, and so the demonstration was planned for mid March, with all participants being on site between March 14-16, 2005.

The diesel reformer and fuel cell were installed just outside the building at INEEL where the large diesel reformer was operating, in order to make use of some of the instrumentation installed for the larger unit.

Initial startup of the fuel cell and diesel reformer were attempted on Monday, March 14, with much of the day occupied with calibrating the mass flow lines needed for the diesel reformer. On Tuesday March 15, both the diesel reformer and the fuel cell were operational by mid afternoon, the fuel cell operating on natural gas, and the diesel reformer operating on low sulfur diesel, and a short test of about 45 minutes was conducted, with operation continuing long enough to approach thermal equilibrium.

On Wednesday, March 16, the fuel cell and diesel reformer were both started early, with the fuel cell operating on natural gas during the warm up (to baseline the fuel cell at the altitude) and the diesel reformer started on Syntroleum S2 fuel (no lubricity additive). After about 2 hours of independent operation, the reformat stream was directed into the fuel cell, and the system was operated on this fuel for about 2 hours. The feedstock for the diesel reformer was then switched to the low sulfur diesel fuel, and the system operated for another 2 hours to collect equilibrium data in this configuration.



Figure 3 Setup in the parking lot at INEEL. Acumentrics fuel cell at left, SOFCo reformer at right. Natural gas supply in tank with wheels, the insulated line at the top is for the steam supply.

It must be noted that there were some issues of concern in this demonstration. First, while the reformer was identified as a CPOX (Catalytic Partial Oxidation) device, these normally operate without the addition of steam, this reformer required steam for fuel vaporization. The addition of steam is also beneficial for the prevention of coking in reformers. However, requiring steam makes the technology less desirable from a remote field application viewpoint, as pure water is difficult to provide. This issue may disappear in a final version of the system where water vapor from the fuel cell exhaust could be used, as long as the mass flow balance could be shown to work.

A second issue is the efficiency demonstrated—the reformer was sized a bit bigger than the fuel cell, with about 9kW of diesel fuel flowing into the system, while the fuel cell was providing about 1.5 kW electrical energy out. This means that the fuel utilization during the demonstration was quite low, and further development is required if higher efficiencies are to be achieved.



Figure 4 Low Sulfur diesel label for fuel used at INEEL demonstration. Maximum sulfur content of 15PPM.

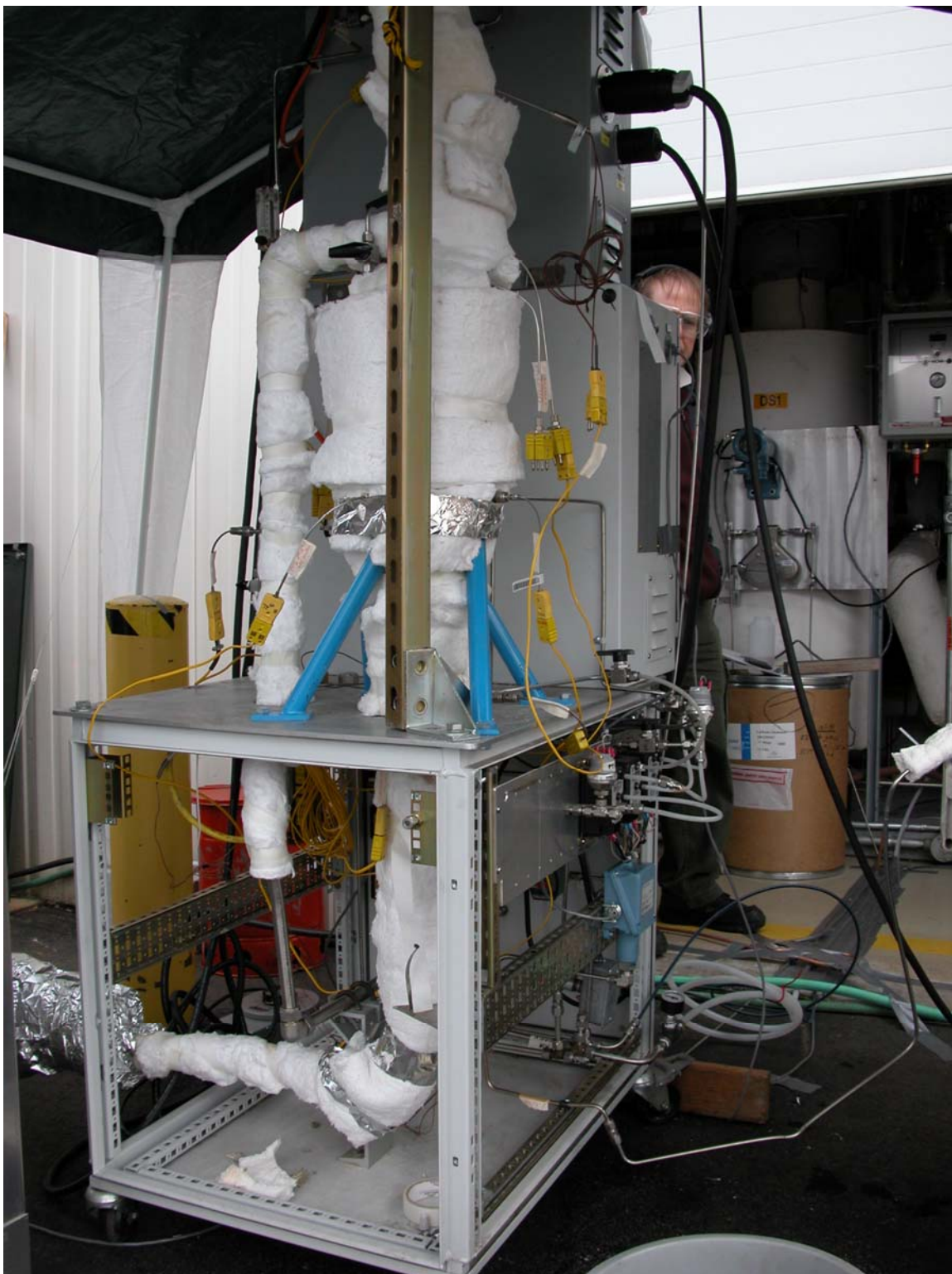


Figure 5 SOFCo Diesel reformer, as installed at test at INEEL. Note the control system (named Mark) at the back end of the machine.

Also, during the demonstration, the carbon monoxide detectors inside the building adjacent to the fuel cell and reformer indicated higher than normal readings. A portable detector was used to locate the source of this gas, (the reformer produces large amounts of CO during its normal operation, but this should be consumed in the fuel cell and converted to CO₂, but a leak could result in large amounts of CO being released into the atmosphere), and was found to be coming from the exhaust of the fuel cell. This was not expected, as the fuel cell should have been converting all the CO into CO₂ in the combustion zone after the fuel cell. (Later testing showed that the CO was actually leaking from the fuel cell stack area, due to incomplete sealing of the hot zone of the area).

However, the good news during this demonstration was that the fuel cell operated as expected, meaning that a steady output was obtained from the fuel cell during operation on both natural gas and the reformat stream from the small SOFCo reformer. The fuel cell was operated for a total of nearly six hours, with initial start up on natural gas, followed by stable operation on low sulfur diesel fuel and Syntroleum synthetic diesel fuels. The operation on the reformat gas required some adjustments in the air flow to the fuel cell, as internal reforming was not being done inside the fuel cell boundary, but these adjustments were made without difficulty. [11]

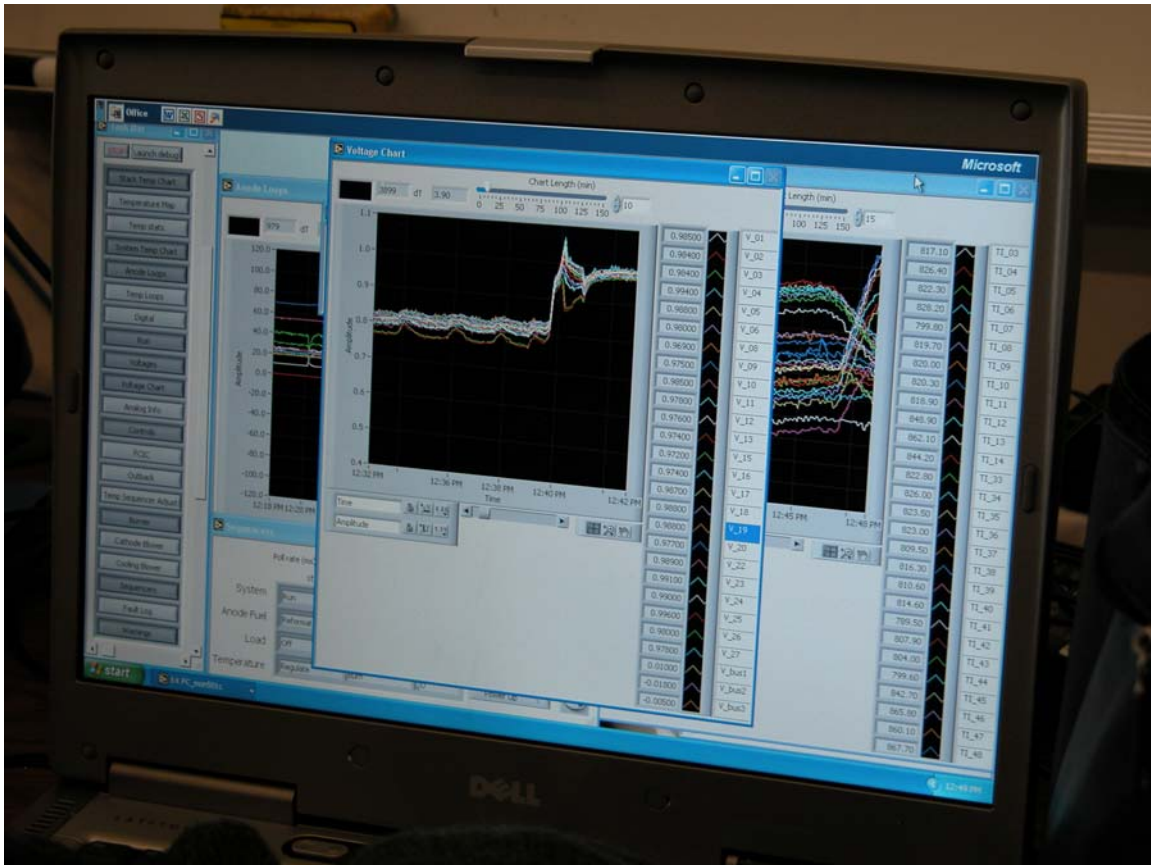


Figure 6 Transition between natural gas and diesel reformat, showing transitions in temperature and mass flow signals.

A press release was generated that very carefully stated that a successful demonstration had occurred:

Press Release Language

The US Department of Energy, The Arctic Energy Technology Development Laboratory (AETDL) , the Department of the Navy, the Idaho National Engineering and Environmental Laboratory (INEEL), Acumentrics Corporation, and SOFCo Corporation successfully demonstrated the operation of a Solid Oxide Fuel Cell on reformat from diesel fuel on March 16, 2005 at INEEL in Idaho Falls, ID. This demonstration was part of a continuing effort to use readily available fuels to create electricity using highly efficient fuel cell technology.

During the demonstration, operation on two fuels was demonstrated, including conventional diesel fuel manufactured to the new EPA 2007 low sulfur spec, and a Fischer Tropsches synthetic fuel made by Syntroleum Corporation of Tulsa, Oklahoma. Both the fuel cell and reformer were stable on these fuels.

The efficiency measured during this demonstration was not at a desirable level—the reformer was sized a bit bigger than the fuel cell, with about 9kW of diesel fuel flowing into the system, while the fuel cell was providing about 1.5 kW electrical energy out. This means that the fuel utilization during the demonstration was quite low, and further development is required if higher efficiencies are to be achieved. In addition, some parasitics in the system (most notably the need for external steam for the reformer) were not accounted for in the demonstration evaluation (this function was intended to be incorporated into the final reformer design).

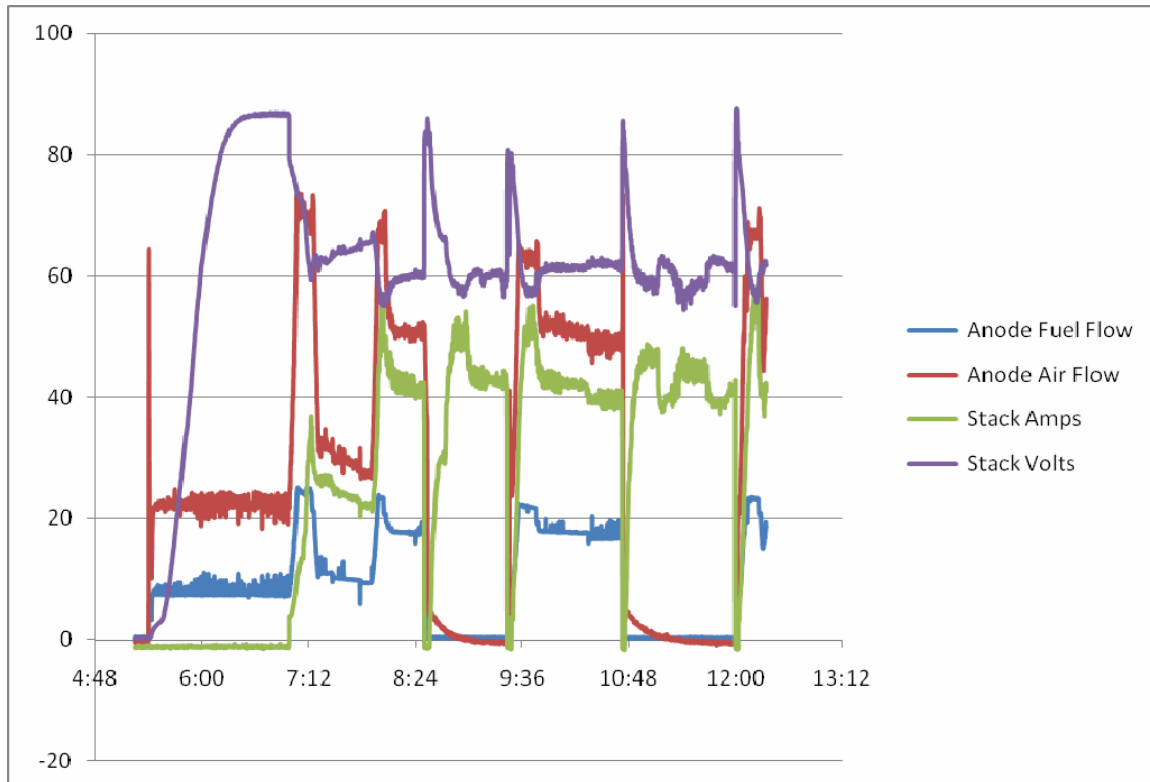


Figure 7 Graph showing some of the data collected during the run at INEEL. Here the fuel and air flows can be seen, showing the natural gas flow is shut off during the Syntroleum and ULSD runs, and the air flows are adjusted to maintain constant voltage and amperage.

In one sense, this demonstration met the “laboratory breadboard” demonstration goal listed as the end result in our initial proposal. However, there was also ample evidence of the need for additional work. The outstanding issues included automating the reformer to allow for continuous operation without the presence of an experienced operator, and conducting a long term test of at least 1000 hours to verify stable operation of the fuel cell stack on diesel reformat.

The project team then proposed continuation of the project towards a longer term demonstration of the reformer and fuel cell, to occur in Fairbanks. This proposal included two major pieces: development of the control system for the diesel reformer, and long term demonstration of the operation of the SOFC.

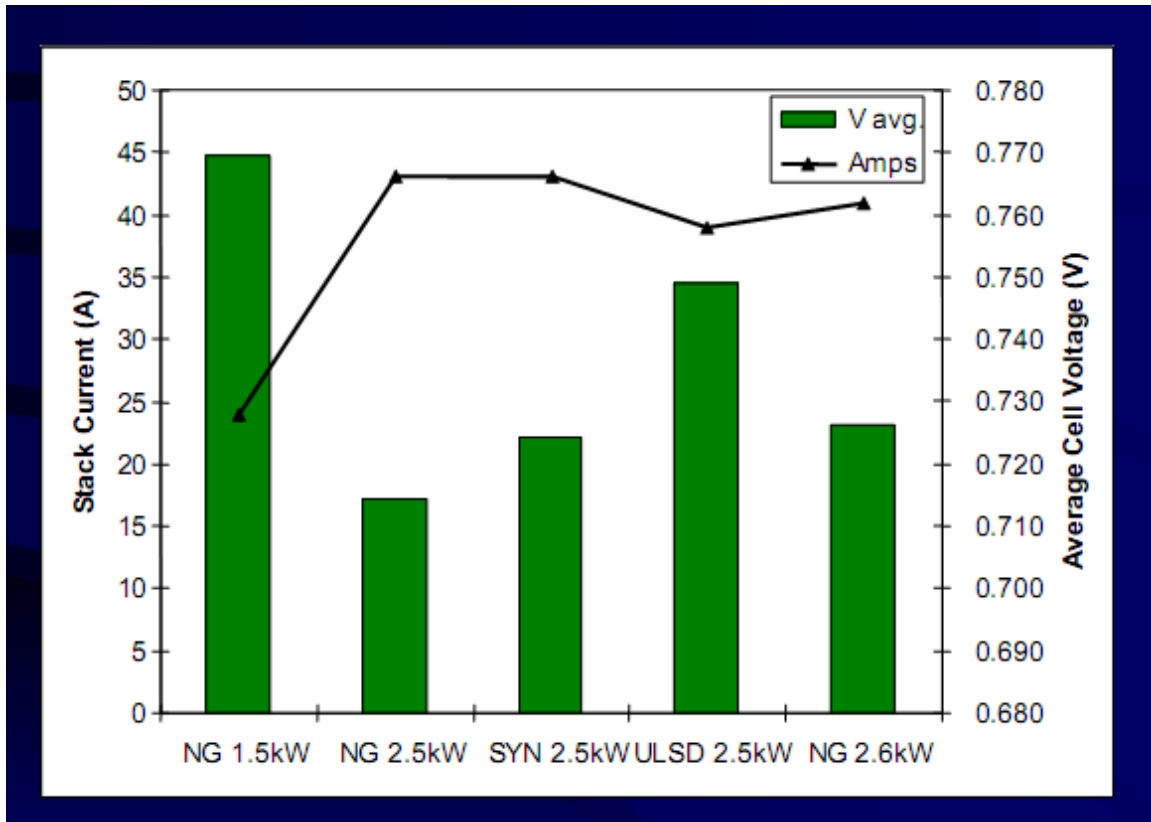


Figure 8 Stable operation of the Acumentrics fuel cell on Natural gas, Syntroleum Fuel, Low Sulfur Diesel fuel, and returning to natural gas, from the March 16, 2005 run at INEEL.

Development of the control system for the diesel reformer at SOFCo

In the initial proposal to the USDOE through the Arctic Energy Office at UAF, phase 1 of the demonstration was intended to be operation of the fuel cell on a slipstream from the 500 kW diesel reformer at INEEL, and phase 2 was for the development of a small scale diesel reformer by SOFCo, of Alliance Ohio.

After the successful operation of the small diesel reformer at INEEL, discussions were held with SOFCo about the scope of work for the development of the small diesel reformer. SOFCo has been involved in liquid hydrocarbon reforming for many years, and was a major participant in the US DOE EE program to develop on board reforming of gasoline for fuel cell powered vehicles in the early part of this decade. However, this program was abandoned when it became apparent that on board reforming was unlikely to meet some of the stringent requirements for operation on a vehicle, including weight, start up times, and gas purity.

SOFCo was also involved with the state of Ohio in developing an small SOFC system intended to provide auxiliary power to large trucks, especially for operation when the

trucks are not on the road (many truckers simply leave the engine at idle to provide power electrical power to the truck cab while the driver rests). Initial discussions with SOFCo centered on ways to combine the goals of these two projects so that a single development effort could result in deliverables for both programs, leveraging funding on both sides.

A sub-award document was prepared by UAF contracting with a \$250,000 budget and a performance period of 14 months, beginning in January, 2006, with delivery of the completed reformer to UAF for testing in the spring of 2007. Based on preliminary discussions between contracting groups, it was expected that this subaward SOW would be signed and returned quickly. However, this did not occur.

After several months, it became clear that SOFCo was not able to sign the subaward due to negotiations over the sale of the company. The existing management was unwilling to sign documents committing the company to the deliverables, but did indicate that the funds available in this award were part of the negotiations.

In April of 2007, it was announced that the new purchaser of SOFCo was Rolls Royce Fuel Cells. Given the interest that this company indicated in diesel reforming, it was expected that the sub-award would quickly be signed and returned to UAF. However, this did not occur. After several phone calls and discussions with the new management, it became clear that the issue was the new management considered the level of funding inadequate for completion of the proposed work. Rolls Royce proposed a budget requiring more than double the previously negotiated funding levels. Since this amount was considerably more than the funding available in the project, discussions were held with the USDOE Arctic Energy Office and NETL over a possible increase in the project budget to fund this effort. No funds were approved for this increase, so the sub-award documents were never signed.

Fuel cell demonstration program at UAF

After the successful completion of the operation of the Acumentrics fuel cell on diesel reformat in the INEEL parking lot, the fuel cell was put back into the shipping crate and shipped to Fairbanks. At this point in time, it was fully recognized that the delivery of the diesel reformer was some time away, but Acumentrics stacks had only been demonstrated for a maximum of 1500 hours. A decision was made to attempt to operate the fuel cell on natural gas while waiting for the delivery of the diesel reformer.

The fuel cell was installed at the Fairbanks Natural Gas facility in south Fairbanks, as the required utilities (natural gas, electrical supply, internet connections, exhaust lines, and waste heat recovery systems) were already installed, but the test site was vacant due to the recent failure of the FCT unit.

The unit was started on March 30, 2005, but ran for only 12 hours before it experienced a shutdown. A restart of the unit was attempted on April 6, but the unit did not start. Examination of the unit resulted in the discovery of a failed air supply fan, which was

replaced. A new fan was shipped, and a restart attempt occurred on May 5, 2005. During this attempt, a backfire occurred traceable to backpressure in the exhaust line, which caused instabilities within the fuel cell unit and a backflash of hot gases through fans designed only for ambient air. These fans melted, and needed to be replaced. In addition, a fan was placed in the hot exhaust line to lower the backpressure at the unit.

On May 16, the unit was restarted again. During start-up, it was noted that the fuel control valve was not functioning properly, but Acumentrics reps suggested that we open the valve full throttle and run anyway. The unit operated for about 12 hours before a voltage instability developed on one row of cells, indicative of a stack failure. Acumentrics did not seem particularly interested in repairing the stack.

In the fall of 2005, Acumentrics contacted UAF proposing to rebuild the fuel cell with a newly designed stack configuration. This new design was intended to shorten the electrical path between cells, reducing the ohmic losses in the stack, improving the efficiency of the system.

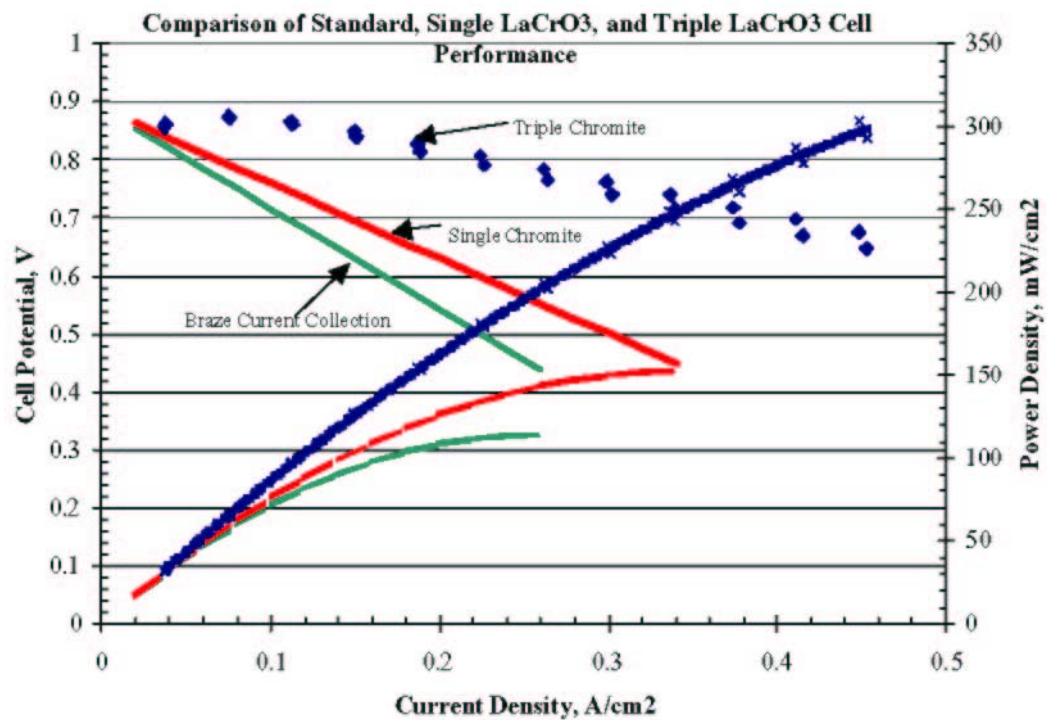


Figure 9. Performance of new stack design, Acumentrics. Graph shows improved voltage performance and higher achievable maximum current density for "triple chromite" configuration.

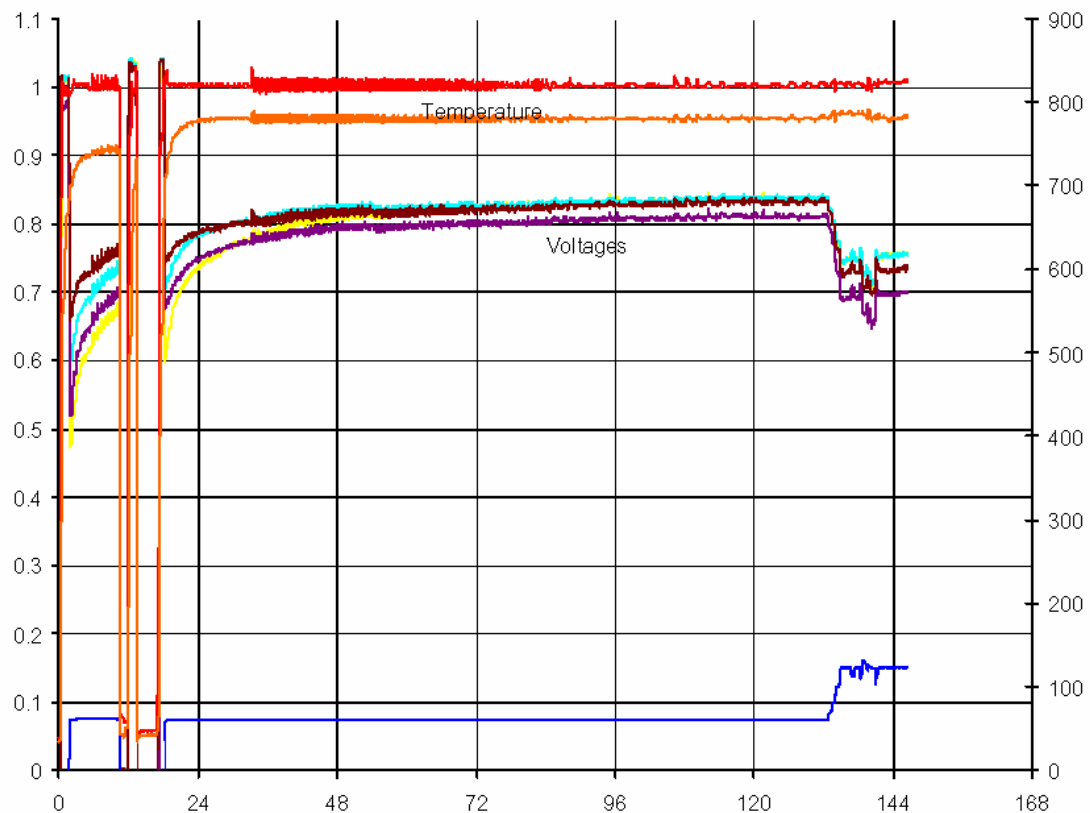


Figure 10. Operation of test stack at Acumentrics, showing stable operation. X axis is time in hours, Y axis is single cell voltage in volts. Temperature is in degrees C.

After some discussions and approval from DOE, the unit was shipped back to the factory for the rebuild in the Spring of 2006. The unit was rebuilt during the fall of 2006 and returned to Fairbanks in December of 2006 after a factory acceptance test.

The unit was started again on January 2, 2007. The details of this run are included in Appendix A. However, some general comments can be made.

First, the efficiency of the fuel cell operating on natural gas was much lower than expected—during the best run, near the beginning of the life of the fuel cell, the efficiency (based on total natural gas in to AC electricity out to the building) was 19.8%. During the longest run of 2700 hours, the efficiency was measured at 17.8%. Secondly, the fuel cell operated for a total of 3968 hours before the stack failed. While this is a considerable improvement from previous fuel cells developed by Acumentrics, it still falls far short of the 40,000 hour goal frequently stated as necessary for commercial markets.

After the stack failure in October 2007 discussions were held with the Acumentrics staff about what should be done with the unit. The AETDL process was nearing an end so additional funds were not available. It was apparent that operating a fuel cell on diesel fuel was not likely to happen. Also, the Acumentrics unit at Exit Glacier operating on propane experienced a stack failure, and could not be operated, and the Acumentrics factory was no longer supporting the cell design used in that stack. There were some funds left available for continued work, but not enough to support both projects. The decision was made to repair the stack in Fairbanks, but to operate it at Exit Glacier during the summer of 2008 on propane. The results from that demonstration can be found in the final report on that project. [12, 13]

Discussion and Conclusions

This results of this program can be best described as a mixed success. A solid oxide fuel cell was delivered to the program, and it operated on reformat from low sulfur diesel products for a few hours. A run of about 4000 hours was achieved on a small scale SOFC operating on natural gas.

However, the inability to achieve many of the aims of the program should also be noted: the initial attempt to operate fuel cell on the 500 kW diesel reformer failed because the reformer did not operate in a stable manner. The successful diesel demonstration lasted only a few hours. The fuel cell failed quickly after the initial demonstration when operated on natural gas. The reformer was not automated due to changing requirements for funding of this task. The rebuilt fuel cell achieved only about half the advertised efficiency (20% achieved compared to the 40% promised). These results demonstrate that the fuel cell industry has a long way to go before fuel cells will be inexpensive, reliable, and capable of replacing other technologies in commercial markets.

These results are consistent with others in the industry. Diesel reforming with Solid Oxide fuel cells was the focus of sponsored research during the early parts of this decade [14-17], but a web search at the time of this writing did not indicate much recent activity in this field. The waning enthusiasm for fuel cells in general and diesel reforming in particular is unfortunately traceable to the results obtained from programs such as this one.

The inability of the industry to develop commercial products is perhaps best indicated by the public announcement in June 2007 of the attempted sale of the Siemens Fuel Cell division. This group has been active in SOFC R&D since the mid 1970s, and has achieved many scientific and technical demonstration successes, and total corporate and government investment in this company is rumored to be well over one billion dollars. In 2000, they announced the building of a factory to produce hundreds of fuel cell systems per year for commercial deployment.

The reasons for this slow progress towards commercialization are many, but it is worth considering the differences between fuel cells operating on hydrocarbon fuels as compared to conventional combustion technologies.

For a combustion device such as a diesel generator or a gas turbine, the combustion reaction is a homogenous gas phase reaction that occurs when fuel and air are mixed and ignited. If one of these components is removed, the reaction stops, but usually the system simply stops with no permanent damage to the hardware. The engines are self aspirating, meaning that they pull in their own air supply by creating a vacuum by mechanical means. And the systems are robust with respect to the presence of impurities: the worst that usually happens if minor impurities are put into the system is that environmentally unfriendly products may result (think of acid rain caused by sulfur in fossil fuels), but the system continues to operate (an important safety feature in aircraft engines). The thermodynamic efficiency depends on the maximum temperature achieved, but this occurs in the gas phase, and the containing structures (the piston and cylinder walls in a diesel engine) remain much cooler, allowing the use of ordinary engineering materials (steel, cast iron, or even aluminum). And the combustion systems are compatible with a wide variety of naturally occurring hydrocarbon fuels, from natural gas to coal.

Fuel cells are electrochemical reactors, where air and fuel need to be supplied to reacting surfaces under carefully controlled conditions of temperature and pressure. The entire fuel cell stack must be maintained at temperature, so all materials used in the system must be capable of surviving on a long term continuous basis (at 800 degrees C, the temperature of solid oxide fuel cells, most metals experience rapid high temperature oxidation corrosion). The system is not self aspirating, so air must be supplied through an external blower or compressor (so much for the myth of no moving parts), and even short term interruptions in fuel or air can result in major damage to the system through chemical attack or thermal shock. Impurities are a major problem, as these impurities may block catalytic sites necessary for the gas-solid phase reactions. Small defects in the individual cells may create shorts, and the failure of a single cell is sufficient to stop the operation of the entire system. Care must be taken in starting and stopping the system to avoid thermal shock, although thermal cycling itself is somewhat damaging to the system. Hydrocarbon fuels do not react directly in fuel cell systems, so naturally occurring fuels must be reformed into hydrogen and carbon monoxide (syngas) in order to be used by the fuel cell.

The reforming reactions are complex, involving a mixture of a hydrocarbon, oxygen, and steam, but the exact reaction products are a complex function of temperature, pressure, flow rate, mixture ratios, hydrocarbon structures, and impurities. Natural gas is by far the easiest fuel to reform, but even this fuel in commercial purities contains sulfur in levels sufficient to contaminate many fuel cell systems. Heavier hydrocarbons, especially diesel fuels containing aromatic compounds, are especially difficult to reform, as the heavier molecules may condense out on cold wall surfaces and nucleate the formation of solid carbon particles, otherwise known as soot formation. This soot can quickly plug the channels in the reformer, stopping the reaction and the fuel cell. Soot formation can be suppressed by adding additional steam to the system, but creation of the steam is an energy parasitic on the system. In order for diesel reformers to be usable, they must be compact and cheap as well as efficient, but successful operation of diesel reformers to date have not included these attributes.

The successful commercial use of fuel cells requires that all these issues be addressed in a single system. There are no fundamental chemistry or physics laws preventing success, but the engineering challenges are daunting. In particular, the use of high purity exotic materials in fuel cells and reformers, the complex manufacturing processes needed to fabricate them, the intolerance of these systems to impurities, and the long lead time needed to prototype and test these systems all drive the development costs to very high levels. Given the billions of dollars that have been invested to date, it seems appropriate to evaluate the progress achieved and the cost, and compare to the future investments that need to be made if this technology is to succeed.

The goal of the Alaska Arctic Energy Technology Development Program was to determine if fuel cells are of use to the people living in remote communities as a more reliable and economic way of providing energy to residents of these communities. Based on the activities in this project, it appears that the answer to this question is—not yet.

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Rolls Royce Fuel Cells: Mark Fleiner

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APPENDIX

Acumentrics Fuel Cell Demonstration Fairbanks

Run number: 1

start	1/4/2007 2:04:00 PM	Hours	48.816666	Efficiency:	10.78%
stop	1/6/2007 2:53:00 PM	Cumulative Hours	48.816666		
Electric start:	17335	Electric Meter end:	17410	Total kW hours	75
Gas meter start:	0	Gas meter end:	24	Gas x 100 tt3	24
Start up					

Jim Buckley here for start up. Unit experienced rapid on-off cycling of start-up burner, issue solved by changing low temperature set point for burner start up. Significant odor detected from unit during start up.

Running notes:

Unit continued to give off a significant amount of irritating fumes during operation, CO sensors in room gave readings of up to 60 PPM CO during operation. Also, heat recovery coil was plugged, but the decision was made to deal with this issue during the next shutdown. Unit was not visible on the internet, Acumentrics personnel had no access to unit while running.

Shut down notes:

Unit shut down due to erratic cell voltage on two adjacent cell voltage taps. Data set revealed one cell at a negative voltage, the adjacent at nearly 2 volts, most likely due to loss of contact on lead.

Repair notes:

Cell voltage issue discovered to be incomplete crimping of lead to voltage tap. Wire was reattached with new crimp fitting, all other fittings checked for adequacy of crimping. Also installed internet access lines for communications, and attempted to rearrange insulation to prevent carbon monoxide from getting into building. Also replaced heat exchanger on top of fuel cell.

Planned Routine maintenance
Manufacturing defect

Control System
Balance of plant failure

Stack failure
Low Cell Voltage

Acumentrics Fuel Cell Demonstration

Fairbanks

Run number: 2

start	1/31/2007 3:14:00 PM	Hours	502.41666	Efficiency:	19.82%
stop	2/21/2007 1:39:00 PM	Cumulative Hours	551.23333		
Electric start:	17410	Electric Meter end:	18479	Total kW hours	1069
Gas meter start:	24	Gas meter end:	210	Gas x 100 tt3	186

Start up

Make up air line installed in building near fuel cell, and significant airflow was entering the building through this. Unit failed to start on first several attempts--turned out that the igniter was not in proper position--unit started promptly when this was installed properly. CO measurements were much lower in the building. Coolant leak on heat recovery system discovered, patched with a clam type repair kit. Flammable gas detector inside the unit started beeping, adjusted cover to allow more air flow inside the unit.

Running notes:

2/1/07 Flammable gas detector beeping again, covers adjusted. Data computer shut down for several days after Windows automatic upgrade caused restart--lost data from 3 days. Fortunately the fuel cell was working fine through this event.

Shut down notes:

Cause of fuel cell shut down appeared to be low battery voltage--data set showed battery voltage sinking over last two or three days of run. System attempted to charge batteries, but could not meet building load at the same time, eventually shut off system at 42 volts on battery system.

Repair notes:

Batteries took charge, returned to normal state. Additional instrumentation placed on battery by UAF personnel. Measure battery currents, in and out, as well as voltage. Should allow for better observation of batteries in power management.

Planned Routine maintenance
Manufacturing defect

Control System
Balance of plant failure

Stack failure
Low Cell Voltage

Acumentrics Fuel Cell Demonstration

Fairbanks

Run number: 3

start	3/8/2007 1:30:00 PM	Hours	251.15000	Efficiency:	11.28%
stop	3/19/2007 12:39:00 AM	Cumulative Hours	802.38333		
Electric start:	18596	Electric Meter end:	19090	Total kW hours	494
Gas meter start:	233	Gas meter end:	384	Gas x 100 tt3	151

Start up

Restart attempted after additional battery instrumentation added to system. Replaced main igniter after failed start attempt--unit started. At time of unit start-up, CO sensor reading 30 ppm.

Running notes:

Power logging system set up on 3/14/07. On 3/15/07, building smells acrid again, but CO sensors are reading 0 (discovered that they always read 0 when actual level is below 30 ppm)

Shut down notes:

Error log indicated fuse failure.

Repair notes:

Repair was complicated by lack of a bad fuse--required a lot of electrical system troubleshooting. Found a small diameter wire on fuse box burned off at fuse number 7. Repaired. Unit still did not start. Replaced control board with new board when heat damaged component discovered, but new board did not work due to changes in board design. Then a group of wires with burned insulation were found, turned out not to be the problem. Then discovered that one fuse had been moved by a single slot, most likely during troubleshooting. When fuse was placed in proper slot and old control board put back in unit, it started again.

Planned Routine maintenance
Manufacturing defect

Control System
Balance of plant failure

Stack failure
Low Cell Voltage

Acumentrics Fuel Cell Demonstration

Fairbanks

Run number: 4

start	3/30/2007 11:30:00 AM	Hours	0	Efficiency:	0.00%
stop	3/30/2007 11:30:00 AM	Cumulative Hours	802.38333		
Electric start:	19090	Electric Meter end:	19090	Total kW hours	0
Gas meter start:	384	Gas meter end:	386	Gas x 100 tt3	2

Start up

Failed start due to installation of new control board, with different jumper configuration than previous board, causing a misread of the cell voltages. Stack got hot, but failed to take a load.

Running notes:

Shut down notes:

Repair notes:

Planned Routine maintenance
Manufacturing defect

Control System
Balance of plant failure

Stack failure
Low Cell Voltage

Acumentrics Fuel Cell Demonstration

Fairbanks

Run number: 5

start	4/2/2007 1:37:00 PM	Hours	2767.0166	Efficiency:	17.81%
stop	7/26/2007 8:38:00 PM	Cumulative Hours	3569.3999		
Electric start:	19090	Electric Meter end:	24601	Total kW hours	5511
Gas meter start:	386	Gas meter end:	1453	Gas x 100 tt3	1067

Start up

4/2/07 Unit started after several failed attempts. These failed attempts resulted in either a complete failure of the ignition cycle, or erroneous voltage readings during start-up. Eventually the system was restored to proper electrical configuration, and it started.

Running notes:

Factory suggested that we increase the load to allow more heat to be generated by unit. However, when additional load was placed on the unit, battery voltage began dropping. Contact with factory, indicated that stack is limited to 80 amps, needed to reset current limit on unit to allow stack to supply additional current. Fuel utilization number very low.

5/4/07 As weather warms, fuel cell is starting to overheat the building. Temporary cooling done by opening garage door slightly.

5/17/07 Appears that a couple of the individual cell voltages are starting to drop out of the pack, going down to about .7 volts.

On Sunday, 6/17/2007. the load on the unit was increased by several hundred watts by turning on the building outside light. This caused a drain on the battery, and the fuel cell disconnected from the building load. After the battery was charged, the unit picked up the building again, and went through several cycles like this. On Tuesday, 6/19 the additional load was removed. This exercise seemed to damp out the low level cycles noted previously.

6/25/07 Noted that lowest 2 cell voltages have dropped to about .66 volts. Jim Buckley suggested running fuel cell at idle for two or three days.

7/11/07 Noted that voltages have dropped, with the lowest voltages going below 0.6 volts. E-mail from Stephan Worth at Acumentrics indicated that temperature of stack has changed due to a load change, and that they are working to get the temperatures and voltages back up.

Shut down notes:

On 7/25/07, the fuel cell appeared to be having problems with several cells. A discussion on 7/26/07 led to the decision to remove the load on the fuel cell for a few days to see if we could get the cells to recover. This strategy has apparently worked in the past for other fuel cell stacks. This was planned for implementation on July 27. However, when UAF personnel showed up to implement this plan, it was discovered that the fuel cell had faulted on a low cell voltage trip.

Low Cell voltage caused fault, probably cell 35.

Repair notes:

Plan to examine all voltage tap contacts to assure that voltage measurements received by the control system are accurate.

8/7/07 Attempt to restart fuel cell failed due to thermocouple located near heat exchanger fan. Disassembly of unit revealed that several thermocouple wires were heat damaged--hot gasses had melted fiberglass insulation, resulting in

Acumentrics Fuel Cell Demonstration

Fairbanks

Run number: 5

bare wires that crossed. Discussion with Acumentrics on 8/20/07 revealed that shutdown on July 27 was the result of voltage tap contact issues, as one row of cells dropped below .4 volts, while an adjacent row was climbing in voltage. Acumentrics recommended using silver paste to assure better contact between crimped connector and nickel voltage tap. Also repack insulation to assure less gas leakage.

8/28/07 On disassembly of the fuel cell insulation package, a gap between the recuperator and the downcommer was observed. This may be the source of leakage that caused the CO problems and the overheating inside the cabinet. Acumentrics recommends either removing shims to lower the recuperator, or to plug the gap with insulation.

8/22/07 Jim Buckley called--Exit Glacier stack row from failure in June ran fine back at the factory after the fuel lines were cleaned with a vacuum cleaner. Source of blockage unknown. Recommended that a forensics filter be used on the vacuum system to identify source of blockage.

Tom Johnson repaired unit, by removing insulation from left side of fuel cell unit, plugging leak noted, and replacing thermocouples affected by heat. Also recrimped voltage taps to hopefully prevent future issues with loose voltage taps.

Planned Routine maintenance
Manufacturing defect

Control System
Balance of plant failure

Stack failure
Low Cell Voltage

Acumentrics Fuel Cell Demonstration Fairbanks

Run number: 6

start	10/2/2007 11:00:00 AM	Hours	398.68333	Efficiency:	7.79%
stop	10/19/2007 1:41:00 AM	Cumulative Hours	3968.0833		
Electric start:	24601	Electric Meter end:	25012	Total kW hours	411
Gas meter start:	1453	Gas meter end:	1635	Gas x 100 tt3	182

Start up

Unit started up, but did not come up well. Appears that unit is starved for fuel, suspect that the problem may be fusing of the catalyst in the reformer section, as noted at the factory. Low voltage fault, cleared, unit continued to operate. Unit did not come up to full power level--unable to fully power the building lights--unit currently running a reduced power load, DC load of about 1500 watts, heater is cycling.

Running notes:

Unit seems starved for fuel. Not operating at full power.

10/12/07 unit doing funny oscillations, perhaps due to Acumentrics fooling with the unit... Low voltages on

Shut down notes:

10/20/07 Unit discovered non-operational by Jack Schmid.

Repair notes:

Plan to replace catalyst in pre reformer, but disassembly revealed no obvious damage to the reformer catalyst. No significant coking observed. It is not clear why the system is operating so poorly, but two cells are at very low voltage.

Unit not restarted. Eventually shipped to Exit Glacier to operate on propane in summer 2008 after an in-field stack repair.

Planned Routine maintenance
Manufacturing defect

Control System
Balance of plant failure

Stack failure
Low Cell Voltage

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