Propane Fuel Processing for Solid Oxide Fuel Cells (SOFCs)
Project 10547

FINAL REPORT

Prepared for: Propane Education & Research Council

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1. Executive Summary

Global Thermoelectric is developing 2 kW to 10 kW planar solid oxide fuel cell (SOFC) systems which are designed to operate on propane or natural gas. This creates the need for a propane fuel processing system which can remove excess sulfur compounds from the fuel and break the propane fuel into a reformate suitable for use in the SOFC. Given that SOFC systems can use both hydrogen and carbon monoxide as fuels, the reforming process is relatively simpler and less costly than reforming for low temperature fuel cells (eg. PEMFC).

Global received a grant of USD 500,000 from the Propane Education and Research Council (PERC) to develop and test a low cost, reliable design for a partial oxidation (POx) propane fuel processor for use with a 5 kW SOFC system. The project consisted of the following five activities: Proof of Concept, Advanced Modeling, Catalyst Development / Desulfurization, Alpha Development, and Beta Development.

The Proof of Concept testing showed that the proposed system could be started from room temperature and operated continuously for 100 hours with very stable performance, while also demonstrating the ability to run efficiently to a turn down ratio of 8.3:1. The advanced modeling activity proved extremely useful by providing design suggestions for the partial oxidation reactor that ensured a very low pressure drop of less than 0.5 psi through the reactor.

Significant analysis and characterizing of multiple catalysts was conducted for both desufurizing and partial oxidation catalysts. A desulfurization system was developed that reduced the sulfur levels to the desired 0.1 ppm level, and that this could be done in a relatively small system of less than 4 litres for sulfur contents in the 120 ppm range. The final design for the POx reactor was allowed for a very small (0.11 litre) reactor suitable for a 5 kW SOFC system.

In the Alpha tests, the output from the fuel processing system (consisting of the de-sulfurizer and the POx reactor) was fed to Global's standard SOFC cell membranes and stacks. The results showed that both cells and stacks can operate on processed propane with relatively little impact (approx. 7% compared to pure hydrogen) on performance.

The Beta test confirmed the operation of a multi-kW SOFC stack system operating on fuel supplied by a full size fuel processing system inclusive of fuel desulfurization

As a final conclusion, a commercially viable propane fuel processor design, consisting of a multi-stage desulfurizer and a partial oxidation reformer, for a 2kW to 10kW solid oxide fuel cell system has been successfully developed and tested.

2. Introduction

2.1 Background

Fuel cells are poised to offer significant advantages to the power generation industry. Although still in the commercialization phase, fuel cells are rapidly developing towards commercial viability, and when the potential of the technology is realized, they will provide unprecedented efficiency and reliability to distributed power generation for a wide variety of applications.

Global Thermoelectric Inc. is developing 2 kW to 10 kW planar solid oxide fuel cell (SOFC) systems which are designed to operate on propane or natural gas. Although SOFC systems are well matched to hydrocarbon fuels, and are fundamentally simpler in design than proton exchange membrane (PEM) fuel cells operating on hydrocarbons, there is a requirement for some fuel processing, inlcuding removal of sulfur compounds from the fuel. Therefore the successful commercialization of SOFC systems is reliant on development of low cost fuel processors for propane. This project, sponsored by the Propane Education and Research Council (PERC), was undertaken to deliver and test a design for a commercially viable propane fuel processing system. This project is therefore a key enabling activity to ensure commercially viable fuel cell systems operating on propane.

2.2 Project Benefits

As noted above, small-scale SOFC systems offer fundamental advantages over other fuel cell systems, and over conventional power generating systems. With highly efficient power generation, nearly solid state operation, and relative ease of operation on hydrocarbon fuels compared to other fuel cell technologies, SOFC systems are best able to utilize propane fuel for small scale localized power generation. Development of a commercially viable fuel processing system, as Widespread use of these systems will bring numerous advantages to the propane industry including:

- Increased Fuel Consumption: Widespread use of SOFC systems for residential and commercial use will provide a significant increase in propane fuel consumption – expected to be in the hundreds of millions of gallons per year.
- Improved Summer Loading: Since the SOFC systems will be used for electrical supply, the loading will be similar in summer and winter, therefore assisting the propane industry to even out traditional seasonal loading cycles caused by over weighting to heating loads.
- Increased Customer Base: The SOFC product, which provides on-site electrical generation, is a new application for propane use, and therefore it can be expected that this product will bring new customers to the propane industry.
- Reduced Emissions: SOFC systems offer high efficiency electrical generation which therefore offers reduced CO_2 emissions. In addition, SOFC systems have extremely low noxious emissions compared to existing central and distributed power generation technologies.

2.3 Objectives

The overall objective of the project was to develop and test a low cost, reliable design for a partial oxidation propane fuel processor for use with a 5 kW solid oxide fuel cell system.

Most work done to date on fuel processing systems for small scale (2kW to 10kW) fuel cells has been to meet the specific requirements of PEM fuel cells. The objective of this project was to develop a simplified fuel processing system that is designed to meet the less demanding requirements of an SOFC system. By focussing specifically on SOFC requirements, the intent of the development was to provide a simpler, lower cost, more reliable, propane fuel processing system than is presently available.

2.4 Scope

The scope of work for the project was been broken down into five activities as noted below:

2.4.1 Activity 1 – Propane Fuel Processor Proof of Concept

- Global's existing partial oxidation reformer (designed for use with natural gas) was adapted to operate on unodorized propane. The design was then tested to give initial design feedback to assist with advanced modeling and detailed design of the Alpha propane partial oxidation reformer.

2.4.2 Activity 2 – Advanced Modeling

- The modeling was done in 2 phases. In Phase 1, the focus was on the basic model with validation through the proof of concept reformer. Phase 2 focused on design improvement, understanding the detailed reaction engineering and combustion/fuel processing processes, and reviewing design alternatives.

2.4.3 Activity 3 – Catalyst Development / Desulfurization

- Testing, characterization, and selection of appropriate catalysts for both the partial oxidation reforming, and the sulfur removal components of the fuel processing system. Key measures include: catalyst life, hydrocarbon conversion, cost, application suitability, and sulfur tolerance.

2.4.4 Activity 4 – Alpha Development

- The Alpha development incorporated the initial learnings from Activities 1 through 3, culminating in the design and test of a scaled Alpha propane fuel processing system. The Alpha system operated with a commercial propane input, and the output was used to supply a standard Global SOFC single cell, as well as a standard Global SOFC fuel cell stack. The output of the fuel processor (composition, temperature, pressure etc.) was monitored, and performance results from the cell and stack were baselined against cell and stack performance operating on hydrated hydrogen.

2.4.5 Activity 5 – Beta Development

- The Beta system was a refinement of the Alpha fuel processor design, which was scaled up to meet the requirements of a multi-kW SOFC system. The Beta system utilized an input of commercial propane and provided the processed fuel output to a multi-kW SOFC stack configuration. The output of the fuel processor (composition, temperature, pressure etc.) was monitored, and performance results from the stack assembly.

3. Project Results and Discussion by Activity

3.1 Activity 1 – Propane Fuel Processor Proof of Concept

3.1.1 Objectives and Scope

Objectives:

- Successful startup and a continuous run of 100 hours
- Characterize transients between standby, 50%, 75%, and 100% power
- Verification of gas compositions, and hydrocarbon conversion near equilibrium expectations

Scope: Global's existing partial oxidation reformer (designed for use with natural gas) was adapted to operate on unodorized propane, and tested to give initial design feedback to assist with advanced modeling and detailed design of the Alpha propane partial oxidation reformer. Activity #1 was broken into 4 main topics:

- Start-up Test
- Conversion
- 100 Hour Steady State Test
- Transient Test – Turndown

3.1.2 Test Procedure

All testing for Activity #1 was carried out on Global's reformer test station which is a fully integrated test stand. The fuel supply for the tests was HD-5 Propane.

3.1.3 Results

3.1.3.1 Start-up Test

Start-up was accomplished through the manual control of the propane and air flow rates, while monitoring the oxygen to carbon ration (O_2 / C) to ensure equilibrium of the partial oxidation reaction.

The startup test was the first process tested on propane. The temperature profiles and response were similar to a startup on natural gas with only one exception. The startup burner had greater stability (less fluctuations in flame temperature). This may be attributed to the higher density of the propane or to better mixing phenomenon, although the true mechanism may be a combination of factors.

3.1.3.2 Conversion

The measured gas compositions were very close to expected equilibriums and are very well suited to operating an SOFC stack. It should be noted that the gas composition readings were taken from a gas chromatograph, which required the gas to be cooled to approximately 80 C. Therefore the gas did go through a water-gas-shift during the cooling, however the actual composition measured is as would be expected at the higher operating temperature of approximately 750 C.

3.1.3.3 100 Hour Steady State Test

Both the temperature profile, and the species concentration measured during the 100 hour test were extremely stable, indicating that the fuel processor is well suited to use with propane.

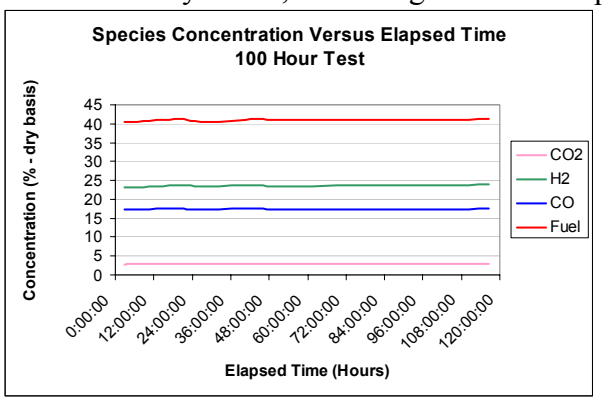

Fig. 7. Species Concentration Over Time

3.1.3.4 Transient Test – Turndown

The purpose of the turndown test was to push the reformer to an undesirable performance condition by lowering the flows to lowest sustainable operating point. At some point it was expected that the temperature would drop sufficiently to cause the reaction to cease. The reactor achieved a turndown ratio of 8.3:1.

3.1.4 Conclusions

The testing was very successful, with all of the stated objectives having been satisfied.

The following can be concluded regarding the proof-of-concept test series:

- A startup from room temperature to operating temperature was conducted without any major failure mechanisms
- Conversions were consistent with expected equilibrium values both during startup and at operating flow rates
- Over the course of 100 consecutive uninterrupted hours the reformer produced near equilibrium compositions with no measurable degradation in a thermally stable manner
- Turndown was successfully quantified at a ratio of 8.3:1 with a fuel composition penalty of approximately 2%

Future reformer designs can be quantified against this data.

3.2 Activity 2 – Advanced Modeling

3.2.1 Objectives and Scope

Objective:
To demonstrate and facilitate the use of advanced modeling in the design of a novel propane POx reformer for a 5 kW SOFC system.

Scope:
Stage 1: Develop a CFD model to analyze the preliminary POx reformer design. The model was not intended to provide information regarding the species concentration or the temperature inside the POx reactor, but its intention was to provide predictions of the flow distribution inside the reformer, and overall pressure drop. Specifically, the model was intended to determine maximum pressure drop (.5 psi design criteria), and to provide a plug velocity profile in the packed catalyst bed to ensure a constant residence time through the catalyst region.

Stage 2: An actual prototype of the POx reformer was to be built, and the CFD model was to be modified to accurately reflect the as-built geometry. Flow and pressure measurements were to be made on the prototype, and the CDF model was to be validated against these measured values.

3.2.2 Test Procedure

Preliminary design calculations were made to determine air and propane flow rates, and catalyst volume. The model was then created using Fluent v6.0, a commercial CFD package.

3.2.3 Results

3.2.3.1 Stage 1 – CFD Analysis

The Model predicted a pressure drop in excess of 7 psi based on the original POx reformer design; well above the required 0.5 psi pressure drop. Based on the Model's results, the POx reformer was re-designed with a new dimensional layout, and new packing for the catalyst. The Model simulated the new design prior to building a physical prototype. The model simulation predicted an expected overall pressure drop of 0.3 psi, which is within the design parameters. The model also predicted a uniform gas velocity through the catalyst bed, which helps to reduce carbon buildup.

3.2.3.2 Stage 2 – Model Validation

Based on the data generated by the CFD model, a revised 5 kWe POx reformer prototype was built and tested. The prototype was built as per the CDF model design, with the exception of some of the external supply tubing sizes, and the use of support and exit screens for the catalyst bed (not contemplated in the CFD Model).

Pressure differentials were measured at 8 different locations on the reformer, and results were taken at 5 different air flow rates. There were some discrepancies between the CFD model and the measured results. For instance, the pressure gradient in the catalyst bed was under predicted

by about 30%. This can be explained by uncertainty in the bed pressure drop data provided by the catalyst manufacturer, and the model can easily be adjusted in the future to account for this discrepancy. Overall the CFD predictions were close, and the prototype did provide a pressure drop of less than 0.5 psi, thereby meeting the design requirement.

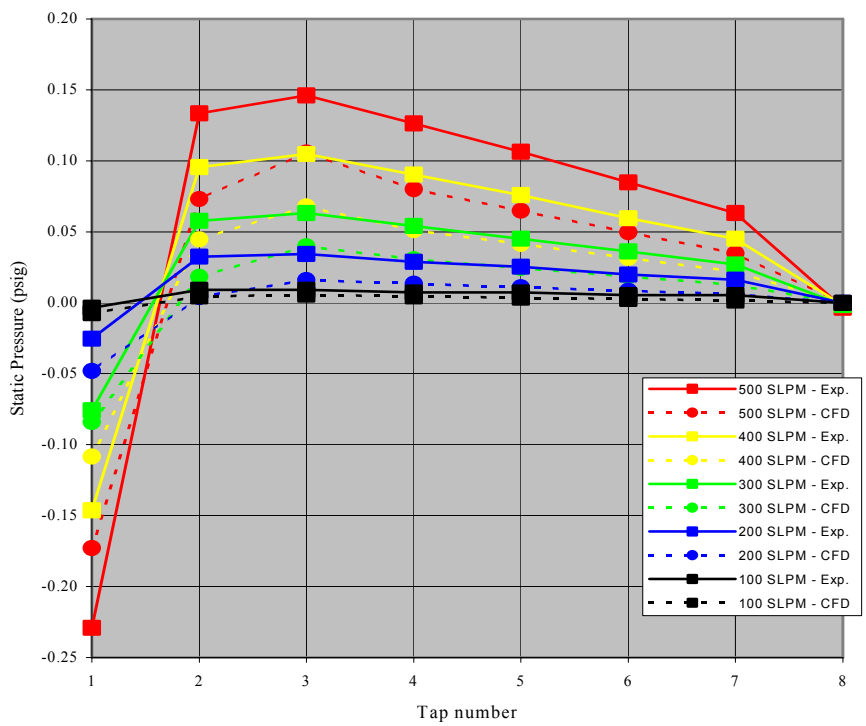

Fig. 10. Predicted (CFD) and Measured (experimental) Static Pressure Variation along the POx Prototype at 5 Different Air Flow Rates

3.2.4 Conclusions

Based on predictions from the CFD, the total pressure drop across the reformer was reduced to less than 0.3 psi, well within the pressure drop specification, and the velocity distribution in the catalyst bed is very uniform, i.e. close to an ideal plug flow reactor.

The CFD model of the POx reformer was validated against experiments performed on an actual prototype. The CFD model generally underpredicts the pressure drop compared to the experimental values, particularly in the packed catalyst bed where the predicted pressure gradient is 30% below the measured value. The discrepancy in the bed can easily be attributed to the uncertainty in the empirical bed pressure-drop data supplied by the catalyst manufacturer, and can be corrected for in future models. Overall, the CFD model does a good job of reproducing the variation in static pressure along the length of the reactor at the various flow rates.

3.3 Activity 3 – Catalyst Development / Desufurization

3.3.1 Objectives and Scope

Objectives: To develop a de-sulfurizer for propane fuel suitable for use with a solid oxide fuel cell system (ie. total concentrations of sulfur < 0.1 ppm), to select a catalyst suitable for catalytic partial oxidation reforming of propane, and to define the reforming reactions for the same.

Scope:
De-Sulfurization:

- Identify and test potential catalysts
- Determine appropriate method for de-sulfurization (eg. High temperature vs low temperature systems)
- Analyze sulfur composition and content of commercial propane

Partial Oxidation Reforming:

- Identify and test potential catalysts
- Analyze POx reaction points, and recommend operating conditions

3.3.2 Test Procedure

Activity 3 included a wide range of tests and procedures for analyzing and testing various materials and systems. Details are available in the reports specific to this activity.

3.3.3 Results

3.3.3.1 De-Sulfurization

The sulfur composition of commercial propane was analyzed to determine existing levels of various types of sulfur containing compounds – essentially the following: methyl, ethyl, and tert-butyl mercaptan, ethyl methyl, dimethyl, hydrogen, and carbonyl sulfide. Testing of all sulfur removal methods and catalysts was then measured against the ability to remove the noted sulfur constituents. It may be noted that both the variety and quantity of sulfur compounds in propane is much higher than in natural gas, and therefore alternative means of sulfur removal are required for propane systems.

Final design criteria provide a de-sulfurizer with a size of 3.76 litres which would be suitable for 30 day operation of a 5 kW SOFC system utilizing a propane supply with an average 120 ppm of sulfur. Longer run times would be possible with lower sulfur levels.

3.3.3.2 Partial Oxidation Reforming

A number of commercial catalyst types were tested to determine suitability for supply of propane reformate to SOFC systems. The selection process was based on optimization of the following key criteria:

- Maximize catalytic activity to ensure full conversion of propane fuel to H2 and CO.
- Operate at an appropriate temperature to minimize carbon buildup and remain below the light-off temperature (the point where the temperature of the catalyst changes dramatically due to the heat generation from the oxidation reaction.

- O_2/C ratio selected to ensure stability of reaction to minimize carbon buildup
- Operation at high fuel velocity as measured by Gas Hourly Space Volume (GHSV) to allow for the smallest physical design, while maintaining minimal pressure drop.

The final POx reformer design has physical size of 0.11 litres, and can provide reformate to a 5 kW electrical SOFC system assuming a GHSV of 80,000/hour.

3.3.4 Conclusions

It was determined that by using a multi-stage desulfurizing system, all of the constituent sulfur species in propane can be stripped out to a level suitable for supply to a solid oxide fuel cell system. The propane de-sulfurizer can be relatively small at 3.76 litres (dependant on sulfur content levels). The de-sulfurized propane can be fully reformed utilizing a very compact (0.11 litres for a 5 kW system) partial oxidation reformer using a monolith design with the preferred catalyst tested by Global.

In summary, commercially viable materials and component designs have been combined into a propane fuel processing system suitable for use with solid oxide fuel cell systems. Long term life testing, and integration into full SOFC systems will be the next steps in commercializing this technology.

3.4 Activity 4 – Alpha Development

3.4.1 Objectives and Scope

Objective: The overall objective was to gain an understanding of the solid oxide cell and stack performance issues and benefits when operating on commercial propane.

Scope:
Stage 1: Single Cell Tests

- The tests compared the performance of a standard Global Thermoelectric Inc. solid oxide fuel cell membrane running on propane reformate versus humidified hydrogen as fuel. Tests were conducted on 3 standard cells running at standard operating conditions.

Fig. 12. SOFC Cell

Stage 2: Stack Tests

- The test compared the performance of a standard Global Thermoelectric Inc. solid oxide fuel cell 16 cell stack running on propane reformate versus humidified hydrogen.

Fig. 13. SOFC Stack

3.4.2 Test Procedure

All tests were conducted with Global's standard 10cm x 10cm SOFC cells, and standard 16 cell stacks. The baseline fuel for all tests was humidified hydrogen, and the propane supply was desulfurized, and reformed HD-5 propane. The desulfurizer was a low temperature adsorption-based system designed by Global with capability to reduce the sulfur level to below 1 ppm. The reformer was a partial oxidation propane reformer designed by Global to provide a reformate mixture containing H2, CO, CO_2, and H_2O.

The tests were conducted in Global's fuel cell test stands which are comprised of; an electric furnace to house the cell or stack assembly, a fuel and air supply module, an electronic load bank, and a computer control system.

3.4.3 Results

3.4.3.1 Single Cell Tests

Both the desulfurizer and the POx reformer functioned very well, with the desulfurizer eliminating virtually 100% of the sulfur compound for the entire test, and the reformer converting 100% of the propane to reformate, with a composition as shown below.

Table 1: The Composition of Reformate (dry basis).

	N_2	H_2	CO	CO_2	CH_4	C_3H_8
Vol%	49.0	26.1	15.2	1.6	0	0

The results demonstrated that Global's SOFC cells can run on propane reformate from a POx reformer. The performance on reformate was slightly lower than on humidified hydrogen, but the margin is small and is not a detriment to the commercial viability of propane fueled SOFCs.

The results suggest that this performance difference is a direct impact of the fuel composition, in particular the slightly increased water content in reformate. When the average performance of the cells on hydrogen and reformate were compared (Figure 14) several behavioral aspects of the cell became evident. Firstly there was a slightly lower open circuit voltage exhibited when the cells were run using reformate, and secondly the activation loss was lower when the cells utilize reformate. Both of these aspects are consistent with slightly higher water content in the fuel stream as the increased levels of water can increase the oxygen partial pressures in the anode chamber leading to the reduced open circuit voltage.

Another important aspect of cell performance is the area specific resistance (ASR) of the cell. This is the drop in cell voltage due to the ohmic losses within the cell. Comparisons of the area specific resistances of the cells when running on hydrogen versus reformate show there to be a slight increase in the cell ASR when running on reformate. However this increase is small and

variable, and may be due to effects of the fuel change over rather than a fuel issue, more research would be required to confirm this. It must be emphasized that this is not seen as a major issue, as in all cases the cells are below 0.35Ωcm2, which is considered excellent performance for SOFCs at 750°C with realistic current collection.

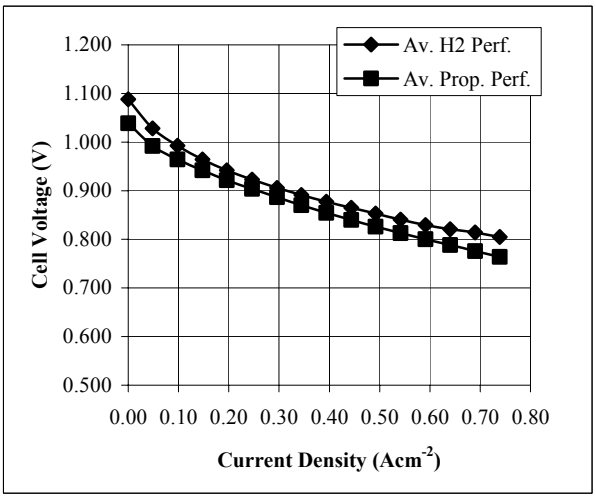

Fig. 14. Comparison of Average Cell Performance On Hydrogen and Propane Reformate

3.4.3.2 Stack Tests

Two fuel cell stacks were tested on both hydrogen and propane. In both cases the propane and hydrogen power curves had identical patterns, with the propane fueled tests yielding lower power output by 5.7% in one stack, and 9% in the other stack. It can be inferred that the propane reformate did not have any significant performance issues relating to pulling power, but had lower open circuit voltage attributable potentially to higher steam content, impurities, lower fuel energy content, slower reaction kinetics, or other mechanisms.

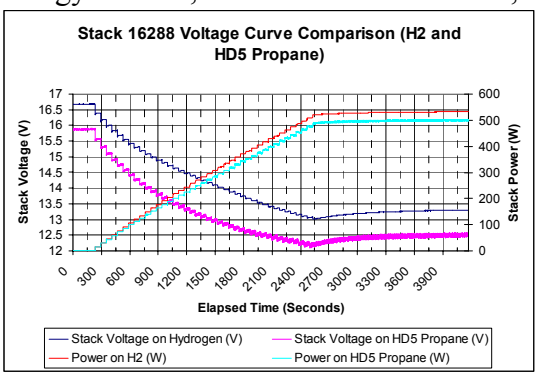

Fig. 15. Power Curve for Stack 16288

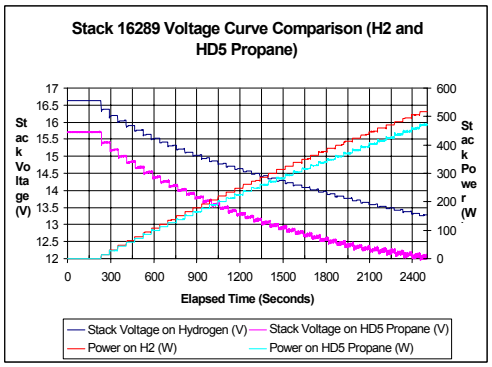

Fig. 16. Power Curve for Stack 16289

3.4.4 Conclusions

This series of experiments have shown that single cells and fuel cell stacks can utilize propane reformate using a partial oxidation reformer with low impact on performance. Results suggest that the performance drop exhibited is most likely due to the increased levels of humidity in the reformate fuel stream. Initial results suggest that the cells may be stable in steady state operating conditions, however, longer duration testing is required to fully characterize long-term behavior.

As noted above, the performance difference on propane is not large, and will not affect the commercial viability of propane fueled SOFC systems.

3.5Activity 5 – Beta Development

3.5.1 Objectives and Scope

Objective: The overall objective is to gain an understanding of a multi-kW scale propane fuel processing system in a multi-kW SOFC stack system. Specifically:

- To develop and execute safe and reliable start-up and shut-down procedures for a propane fuel processing system supplying a multi-kW SOFC stack system.
- To demonstrate operational capability of the fuel processor and stack system

Scope:
Activity 5 included start-up, operation at a steady state fuel cell stack loading condition, and shutdown. The baseline test included a 34 Amp polarization curve of the fuel cell stacks, followed by a steady state run time that was to be maintained while stack output was above 0.64 Volts per cell, or for 24 hours. The tests were based on the following main subsystems:

- Propane desulfurizer
- Fuel-air equalization heat exchanger
- Propane partial oxidation reformer
- Air heat exchanger
- 8 x 16-cell SOFC stacks
- Afterburner
- Electronic Load Bank
- PC based control system

3.5.2 Test Procedure

The demonstration of propane as a fuel in a multi-kW system was undertaken using a brassboard test apparatus. Although the individual components are not fully thermally integrated, the brassboard does allow for testing of a complete system. This approach provides high flexibility when testing individual components. A custom designed control computer was used for data acquisition, monitoring and control during the test. Figure 17 provides a block diagram of the test set-up.

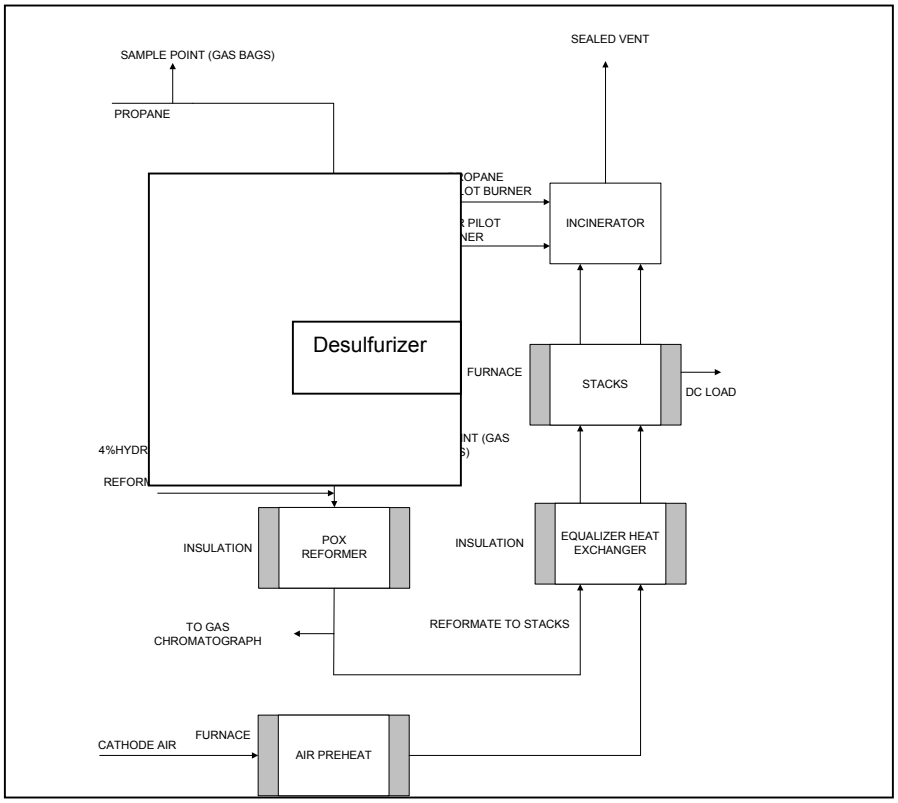

Figure 17: Block Diagram of Multi-kW Propane Fuel Cell System

Process Flow:
The desulfurizer components were sized to accommodate up to 30 days of continuous propane flow equivalent to generating 5 kW net ac power output. To facilitate gas sample collection, sampling ports were installed at the inlet to the system, as well as between the desulfurizers components, and at the outlet prior to the partial oxidation reformer. A total sulfur level in the propane fuel below 0.1 ppm by volume, the detectable limit of sulfur GC equipment, is considered a safe level for Global's SOFC stacks. The total organic sulfur content of the facility propane supply was determined to be between 38ppm/v and 130ppm/v, fluctuating in correlation with the change in outside temperature (ie. temperature of the supply propane tank). Typically, the organic sulfur content of propane is in excess of 120ppm/v, which is the condition for which the desulfurizer was designed.

After the desulfurizers, the reformer air was mixed with the desulfurized propane before the mixture was fed into the partial oxidation or POx reformer. Cold start of the POx was initiated with a hot surface ignitor. Once ignition was established and the temperature of the catalyst was stabilized above 550°C. The reformate out of the POx reformer, along with the cathode air, was supplied to an equalizing heat exchanger which fed the hot gases to the stacks. The stacks were mounted in a furnace with electric resistance heating to help maintain the stacks at 750 C operating temperature. The stacks were split into two electrically parallel strings, each consisting of four series connected stacks. The positive and negative terminals for each of the two parallel strings were connected to a DC load bank. After traveling through the stacks, the

residual fuel in the anode stream and the oxygen-depleted air in the cathode stream entered an incinerator and were burnt before being exhausted to the atmosphere.

Start-up and Shutdown:
Detailed procedures for both start-up and shut-down were developed to ensure proper operation of each component and to ensure safety during the test.

3.5.3 Results

3.5.3.1 Performance of the Desulfurizer:

Samples were taken during the course of the testing to verify the operation and effectiveness of the multi-stage desulfurizer process. The system was sampled at each of the operating scenarios listed below:

Scenario 1: Approximately one hour after the load was applied to the fuel cell stacks through the use of the DC load bank.

Scenario 2: Approximately one half of an hour before the load was removed from the fuel cell stacks, samples were taken to determine the characteristics after approximately 24 hours of continuous operation.

	Scenario 1		***Scenario 2***	
	Point #1	*Point #3*	*Point #1*	*Point #3*
Hydrogen Sulphide	0.2	<0.1	0.2	<0.1
Carbonyl Sulphide	35.8	<0.1	47.6	<0.1
Methyl Mercaptan	0.4	<0.1	0.7	<0.1
Ethyl Mercaptan	1.5	<0.1	2.6	<0.1
Dimethyl Disulphide	<0.1	<0.1	<0.1	<0.1
Carbon Disulphide	<0.1	<0.1	<0.1	<0.1
iso-Propyl Mercaptan	<0.1	<0.1	<0.1	<0.1
tert-Butyl Mercaptan	<0.1	<0.1	<0.1	<0.1
n-Propyl Mercaptan	<0.1	<0.1	<0.1	<0.1
Methyl Ethyl Sulphide	<0.1	<0.1	<0.1	<0.1
sec-Butyl Mercaptan	<0.1	<0.1	<0.1	<0.1
Thiophene	<0.1	<0.1	<0.1	<0.1
iso-Butyl Mercaptan	<0.1	<0.1	<0.1	<0.1
Diethyl Disulphide	<0.1	<0.1	<0.1	<0.1
n-Butyl Mercaptan	<0.1	<0.1	<0.1	<0.1
tert-Butyl Methyl Sulphide	<0.1	<0.1	<0.1	<0.1
Dimethyl Sulphide	<0.1	<0.1	<0.1	<0.1
Diethyl Sulphide	<0.1	<0.1	0.4	<0.1
Unidentified Sulfur Components	0.1	<0.1	0.4	<0.1
Total Organic Sulfur	**38.0**	**<0.1**	**51.9**	**<0.1**

Table 2: Summary of Organic Sulfur Content

In summary, there is no evidence that any organic sulfur was present in the propane flow entering the POx reformer and eventually the fuel cell stacks. The total sulfur level at the outlet of the desulfurizer was well below the 0.1 ppm by volume requirement.

Upon completion of the tests, the desulfurizer components were inspected and it was determined that a very small portion of the catalyst (< 1%) appeared to be crushed, likely the result of thermal cycling, which therefore is useful knowledge in determining the optimal operating temperature of the system.

3.5.3.2 Performance of the Partial Oxidation (POx) Reformer:

Startup:
The ability to successfully and repeatably light the POx reformer was demonstrated through numerous system ignition attempts. Control of temperature during startup was critical to ensure that the POx reformer did not overheat given its natural exothermic reaction. Control of the O_2 / C was also critical to ensure full combustion during the start-up phase and migration to partial oxidation during the run phase.

Run Phase:
The gas composition of the reformate exiting the POx was analyzed by a gas chromatograph on a routine basis throughout the course of the test. Based on previous GC testing, it is known that propane fully decomposes at these operating conditions. This, coupled with the fact that there is very little methane (CH_4) represented in the results, indicates that the reformer maintained a conversion rate above 95% for the duration of the time that the system was producing power. The actual GC compositions obtained are summarized in Figure 18 below:

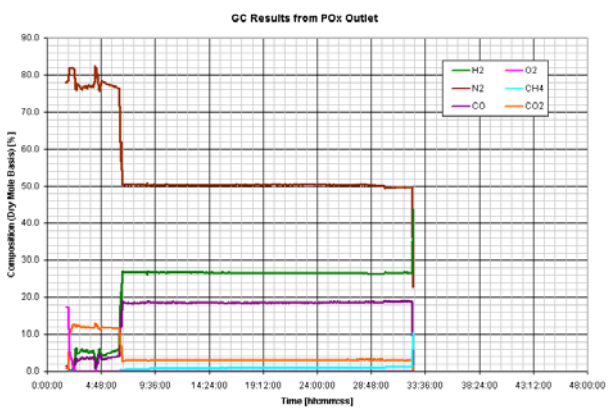

Figure 18: GC Results from POx Reformer Outlet

Factors that affect the equilibrium of the POx reformer include the propane and process POx air flow rates, and the POx operating temperature, all of which remained reasonably constant throughout the duration of the time that the system was producing power. This is shown in Figure 19 below. Therefore, as shown in Figure 20, the gas composition obtained from the time period over which the system was producing power was very close to the equilibrium concentration.

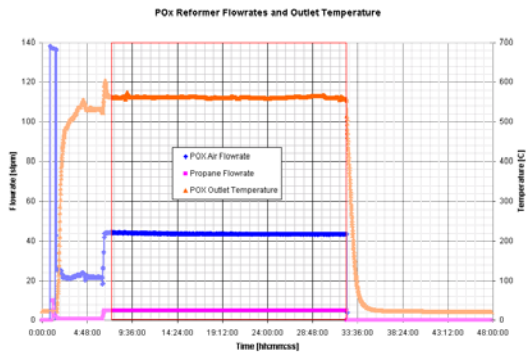

Fig. 19: POx Reformer Flowrates and Outlet Temp.

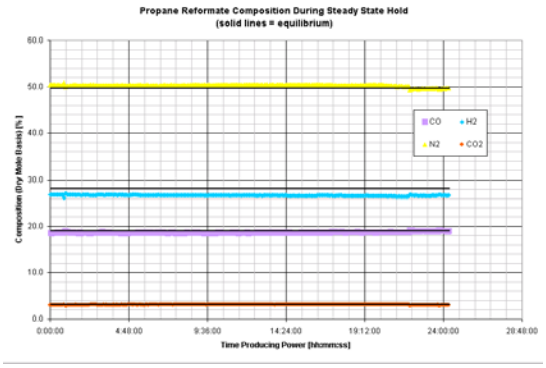

Fig. 20: Propane Reformate Composition (stdy state)

Based on the fact that the POx reformer was operating at a conversion rate in excess of 95% and that the measured composition of the reformate for the duration of the test was very close to the predicted equilibrium concentration, the reformer used in this test proved to be a more than adequate means for producing the required reformate for the fuel cell stacks.

Upon disassembly and inspection of the POx reformer vessel and catalyst, it was determined that there had not been any carbon deposited on either the catalyst or walls of the vessel. This again, is a positive result.

3.5.3.3 Performance of the Fuel Cell Stacks:

Once the system was up and running and the eight SOFC stacks had reached an operating temperature of approximately 750°C, the first power curve was generated. After the initial 34A powercurve, the stacks were held at steady state for a period of approximately 24 hours and then a shut-down power curve was generated (See Figures 21 and 22)

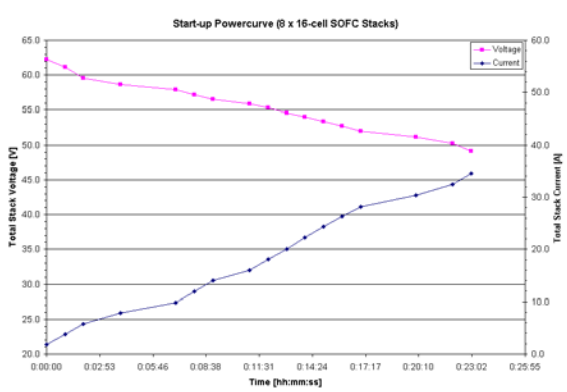

Fig. 21: Start-up Powercurve (Total Stack Voltage)

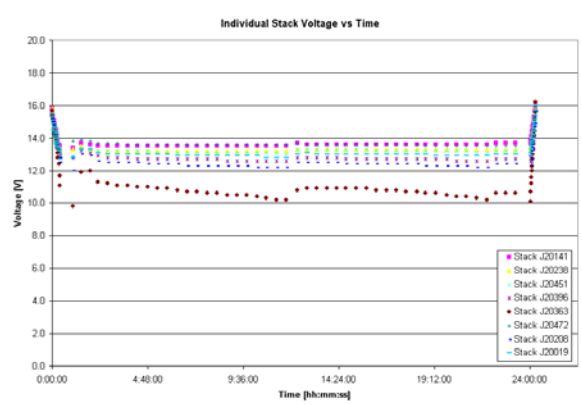

Fig. 22: Individual Stack Voltages (Steady State Hold)

All of the stacks did not perform equally due to different wear characteristics on the stacks prior to the test. This affected the total power output level, but did not affect the overall performance

of the system. Overall the stack performance was as expected, and indicated that the fuel supplied was highly compatible with the SOFC stacks.

3.5.4 Conclusions

Overall, the objectives of this final activity, and therefore the project, were met successfully. A standard GLE multi-kW SOFC stack configuration was successfully coupled with a multi-kW propane fuel processing system. Safe and relatively simple start-up and shut-down procedures for the system were designed and executed. The stacks generally performed well with the exception of one, which had been previously thermally cycled. Two of the stacks showed no signs of degradation over the course of the test, which again proves that GLE's SOFC technology is compatible with commercial propane fuel. The work had demonstrated that commercial propane is an excellent fuel for SOFC systems, and that the fuel processing required for operating a multi-kW SOFC system on propane fuel can be accomplished through known technology as was demonstrated in this project.

4 Acknowledgements:

We gratefully acknowledge the financial and public support from the Propane Education and Research Council; which, with the dedication and skilled efforts of the Global Thermoelectric development team, has dramatically accelerated the understanding and capability to introduce propane fueled solid oxide fuel systems to the market.