# HYDROGEN PRODUCTION FOR FUEL CELLS VIA REFORMING COAL-DERIVED METHANOL

## 41850R12.pdf

Quarterly Technical Progress Report
Reporting Period Start Date: July 1, 2006
Reporting Period End Date: September 31, 2006
Principal Author: Paul A. Erickson
Report Issue Date: November 2006
DOE Award Number: DE-FC26-03NT41850
Submitting Organization:
The Regents of the University of California, Davis
One Shields Avenue
Davis, California 95616

# DISCLAIMER

# ABSTRACT

Hydrogen can be produced from many feedstocks including coal. The objectives of this project are to establish and prove a hydrogen production pathway from coal-derived methanol for fuel cell applications.

This progress report is the 12th report submitted to the DOE reporting on the status and progress made during the course of the project. This report covers the time period of July 1 – Septmeber 31, 2006. This quarter saw progress in six areas. These areas are:

1. Autothermal catalyst degradation due to start-up and shutdown,
2. Gas chromatography of reformate via steam reforming,
3. Gas chromatography of reformate via autothermal reforming,
4. Fuel cell testing with reformate via steam reforming,
5. Fuel Cell load bank system,
6. Hydrogen storage.

High purity hydrogen from coal-derived methanol has been produced and testing with a Nexa system (PEM Ballard Fuel Cell) has been completed. The Hydrogen Production and Utilization Laboratory achieved the main objectives of this project: to establish and prove a hydrogen production pathway from coal-derived methanol for fuel cell applications. In addition, the hydrogen produced from both coal-derived and chemical grade methanol has been analyzed for impurities that could harm a PEM fuel cell. In the last quarter, the research focus shifted to hydrogen purity. PEM fuel cells operating on pure hydrogen is a proven technology, and if hydrogen produced from coal-derived methanol is of equal purity, no problems would exist when using the hydrogen for such purposes.

The gas chromatography tests results show that there is no significant difference between the supplied industrial hydrogen, and the hydrogen produced from chemical grade and coal-derived methanol. This result is great news for those looking to use coal-derived methanol as a feedstock for hydrogen production for use in fuel cells. As no apparent difference between the three hydrogen samples exists, the hydrogen produced from coal-derived methanol could be used interchangeably with hydrogen used for PEM fuel cells.

A graduate student presented his research at the Pittsburg Coal Conference

## TABLE OF CONTENTS

# EXECUTIVE SUMMARY

Hydrogen can be produced from many feedstocks including coal. The objectives of this project are to establish and prove a hydrogen production pathway from coal-derived methanol for fuel cell applications.

This progress report is the 12th report submitted to the DOE reporting on the status and progress made during the course of the project. This report covers the time period of July 1 – September 31, 2006.

Much progress has been made on the project funded by the Department of Energy during this reporting period and the project goals have been successfully met. This quarter saw specific progress in six areas. These areas are:

1. Autothermal catalyst degradation due to start-up and shutdown,
2. Gas chromatography of reformate via steam reforming,
3. Gas chromatography of reformate via autothermal reforming,
4. Fuel cell testing with reformate via steam reforming,
5. Fuel Cell load bank system,
6. Hydrogen storage.

To minimize autothermal catalyst degradation the start-up and shutdown cycles were analyzed. Based on the different start-up and shutdown cycles, the top surface could be the primary region catalyst degradation can initially take place. When examining the steady state methanol conversion for both fuel cell rich and lean start-up and shutdown cycles, the fuel lean catalytic oxidation was shown to have a degradation rate greater than fuel rich catalytic combustion. Consequently, the major factor of catalyst degradation during start-up and shutdown cycles is sintering.

The final quarter research focus has shifted slightly towards determining the hydrogen purity produced. If pure hydrogen is produced with no impurities, then the hydrogen can be used on any PEM fuel cell, or other type of fuel cell using pure hydrogen. The GC test results show that there is no significant difference between the supplied industrial hydrogen, and the hydrogen produced from chemical grade and coal-derived methanol. As no apparent difference between the three hydrogen samples exists, the hydrogen produced from coal-derived methanol could be used interchangeably with hydrogen used for PEM fuel cells.

The maximum stable pressure attainable with the current setup was 70 psi during simultaneous autothermal reformation and palladium membrane separation. Nitrogen and methane permeation for the palladium membrane decreased approximately 90% and 72% respectively as both membrane temperature and differential pressure increased from 300 $C^o$ to $400C^o$ and from 50psi to 70 psi. Carbon monoxide, a poison to PEM fuel cells, could not be found. Increasing the pressure of the reformer to 200 psi, the manufacturer's requested operating temperature, the impurity peaks present should vanish.

The polarization curve obtained from testing a 1.2 kW PEMFC with hydrogen from chemical grade (CGM) and coal-derived (CBM) methanol was completed this quarter. An industrial hydrogen source was analyzed as a control for comparison to hydrogen from CGM and CBM. When comparing the CGM and CDM polarization curves, these two different hydrogen feedstock sources have similar performances in the PEMFC and have no significant differences. As no apparent difference between the three hydrogen samples exists, the hydrogen produced from coal-derived methanol could be used interchangeably with hydrogen used for fueling PEM fuel cells.

The fuel cell load bank system was completed and used for fuel cell testing. The system worked well and provided a load up to 1.2 kW in 12 increments. The system provided an instantaneous response, and the fuel cell could handle the power-draw increase steps. The system provided a relatively fast and inexpensive solution to providing a load to the fuel cell.

The ideal maximum hydrogen pressure attainable in the storage tank is 150 psi when reformate gas is at 200 psi. In practice, when the collected hydrogen pressure approached 100 psi, the positive hydrogen pressure gradient inside the tank graduately dropped due to the decrease in difference between hydrogen partial pressure in the gaseous reformate and pure hydrogen side across the membrane. A 20-hour hydrogen production time was required to reach a 110 psi gage pressure (827 kPa) inside the one gallon tank. The equivalent hydrogen mass of 2.855x10-3 kg has an available energy of 342.6 kJ (LHV) when assuming a temperature of 25˚C inside the tank. The small amount of collected hydrogen can sustain three data sets when testing the fuel cell system. Scale up of the purification system should take place to achieve a more realistic power system but the results acquired positively prove the coal to hydrogen pathway through coal-derived liquids.

# Experimental

The following section describes the experimental methods used and developed during the reporting period for the following areas: autothermal catalyst degradation due to start-up and shutdown, gas chromatography of reformate via steam reforming, gas chromatography of reformate via autothermal reforming, fuel cell testing with reformate via steam reforming, fuel cell load bank system, and hydrogen storage.

## Autothermal Catalyst Degradation due to Start-up and Shutdown

Previous reports have quantified catalyst degradation during steam reformation, which presents the issue of limited catalyst lifetime. To determine the lifetime of the autothermal catalyst, degradation tests similar to the ones performed for steam reformation were completed. It was confirmed in the ninth quarterly report (October-December 2005) that autothermal reforming of coal-derived methanol has lower degradation rates than steam reforming of coal-derived methanol due to the higher operating temperatures attained in autothermal reformation. Some of problematic chemical compounds found in coal-derived methanol can react with oxygen and be volatized rather than deposited on the catalyst surface.

An autothermal catalyst degradation test composed of 13 separate cold start-up and full shutdown cycles was completed using coal-derived methanol. In the case of fuel lean start-up, premix vapor (~250ºC) flows into the reactor one minute after hot air (~250ºC) was introduced so fuel can be oxidized in an air rich environment. On the other hand, in the case of fuel rich start-up, air was introduced into the reactor one minute after vapor premix fuel enters the reactor so oxidation takes place in a fuel rich environment. Fuel rich start-up and shutdown processes are controlled by manipulating air fuel equivalence ratio. During the start-up and shutdown processes, catalyst surface temperature suddenly increases and decreases, which can potentially result in catalyst degradation due to thermal stress on the catalyst. The effect of oxygen and carbon ratios variation on the catalyst surface is shown in Figure 1.

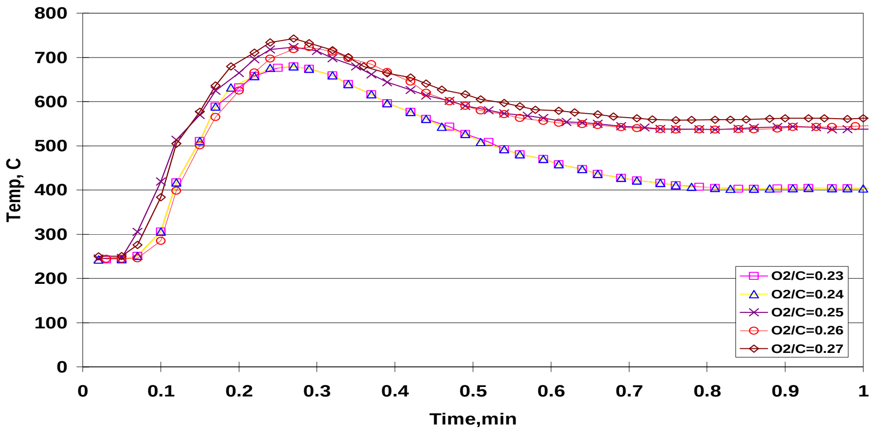

**Figure 1: Top Surface Catalyst Temperature Change at Different Oxygen Carbon Ratio during Start-up**

In this study, fuel lean start-up and shutdown processes have been chosen due to the higher temperatures experienced during start-up and shutdown. This corresponds to a worst case scenario for catalyst degradation due to thermal stresses. For each experiment, great attention and effort was spent to have uniform independent conditions such as $O_2$/C, S/C and inlet temperature, etc during the degradation test. In this study, 0.27 $O_2$/C and 1.5 S/C were used. The reactor was preheated to 250$^o$C before the experiment started and the reactor heaters turned off after catalyst light-off. Air inlet and premix fuel temperature were maintained constant at 250$^o$C. At lower oxygen and methanol ratios, initiated light-off temperature could not be maintained because the energy generated from oxidation was not large enough to sustain the endothermic steam reforming reaction and maintain catalyst temperature. As shown in the figure, ratios larger than 0.27 $O_2$/C would sustain the oxidation reaction and maintain a catalyst temperature closer to 550 $^o$C on the 1.5" catalyst. This ratio should be minimized such that the energy from oxidation goes to sustain the steam reforming reaction. Excessive oxidation would start to decrease fuel available for steam reformation. Ratios of 0.27 $O_2$/C and 1.5 S/C were selected for all experiments to isolate changes in fuel rich and lean start-up and shutdown procedures.

Fuel rich start-up could increase the possibility of fouling as well as poisoning. However, it could decrease the possibility of catalyst degradation caused by sintering due to relatively low temperatures experienced during transients for both start-up and shutdown. By contrast, fuel lean start-up and shutdown processes with excess air could increase the possibility of catalyst degradation from catalyst sintering as a result of higher operational temperatures. However, the possibility of fouling and poisoning is relatively low compared with fuel rich oxidation. To verify the start-up and shutdown in relatively short time duration, two 0.25" thick monolithic wash coated catalyst samples were used for both tests.

## Gas Chromatography of Reformate Via Steam Reforming

Purified hydrogen from coal derived methanol and chemical grade methanol was fed to gas chromatography (GC) equipment for hydrocarbon impurity analysis with a thermo-conductivity detector and Helium-ionized detector. Also, an industrial $H_2$ with 99.99% purity was analyzed as the base of the two samples. For industrial $H_2$ and chemical grade MeOH, the GC operating time was 7.20 minutes. For coal derived MeOH, the operating time was 17.05 minutes.

## Gas Chromatography of Reformate Via Autothermal Reforming

Autothermal reforming produces reformate with nitrogen, methane and small amounts of unconverted methanol. The palladium membrane operating temperature and pressure for hydrogen separation should be different from steam reforming methanol due to the nature of the Cu/ZnO catalyst. Previous research confirmed that nitrogen, methane and methanol can permeate through a palladium membrane at low pressure. In the case of steam reforming methanol with Cu/ZnO catalyst, nitrogen and methane are not present in the reformate. However, there should be unconverted methanol which can pass through the palladium membrane during certain operating conditions.

To perform hydrogen separation using a palladium membrane, high operating temperature and pressure are required. The palladium membrane required periodic regeneration to remove carbonaceous compounds, especially when hydrocarbon gases flow through the retentate side of the membrane. The regeneration was performed with air and small amounts of hydrogen at approximately 500°C. Afterword, the palladium membrane separation unit was checked for leaks using gaseous nitrogen at 350°C and 50 psi. Blank runs of gas chromatography took place to ensure gaseous compounds were not present in the columns.

## Fuel Cell Testing with Reformate Via Steam Reforming

Purified hydrogen reformed from chemical grade MeOH and coal derived MeOH were fed to a 1.2 kW PEMFC to test and analyze the performance of the fuel cell via collecting polarization curves. Industrial $H_2$ purchased from a gas supplier was used as a reference and for comparison. The hydrogen cylinder pressure was regulated to 30 psi. The hydrogen pressure delivered to the fuel cell can range from 10 psi to 250 psi. To start-up and shutdown the fuel cell, 24 volts must be supplied and the power supply must be capable of supplying a maximum of 6 Amps during load spikes. Typically only 1-2 Amps are required during start-up, after which the power supply can be disconnected if desired. Fuel cell output power, voltage, current, and stack temperature can be monitored and recorded through the data acquisition system.

## Fuel Cell Load Bank System

The Nexa system (PEM Ballard Fuel Cell) provides up to 1200 Watts of unregulated DC power at a nominal output voltage of 26 VDC. The load will be provided by a series of commercial 1.5 kW electrical resistance heaters wired in parallel. As each resistor is switched on, the load will increase proportionally. Figure 2 shows the wiring schematic of three resistors in parallel. Each resistor is approximately 9.6 Ω, which roughly corresponds to a 160 W electrical load per resistor. The power dissipated by each resistor will change proportionally as the fuel cell voltage changes along the polarization curve.

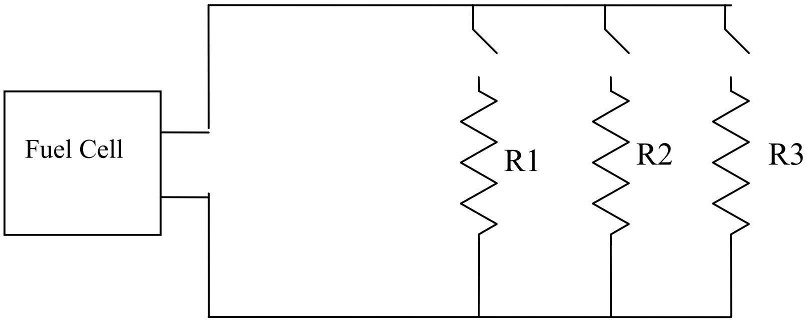

**Figure 2: Load Bank Schematic**

The household electric resistance heaters were chosen as the resistive load due to the low cost and high availability. Cooling of the heaters is provided by the internal electric fan located inside each unit. The electric fan requires a standard 120 VAC power supply.

## Hydrogen Storage

In this quarter, a hydrogen storage tank was set up and connected to a purifying system to collect and store purified hydrogen to fuel a 1.2 kW PEM fuel cell. A Ballard NEXA 1.2 kW PEMFC with LabView monitoring program was integrated into the reformer system to investigate the system's performance. Twelve electrical heaters were internally circuited into a load bank unit. The unit can handle for a maximum 16.7kW power-draw with single phase and three phase operation with 12 increments of power-load for fuel cell testing. A simple schematic of the overall system is shown in Figure 3.

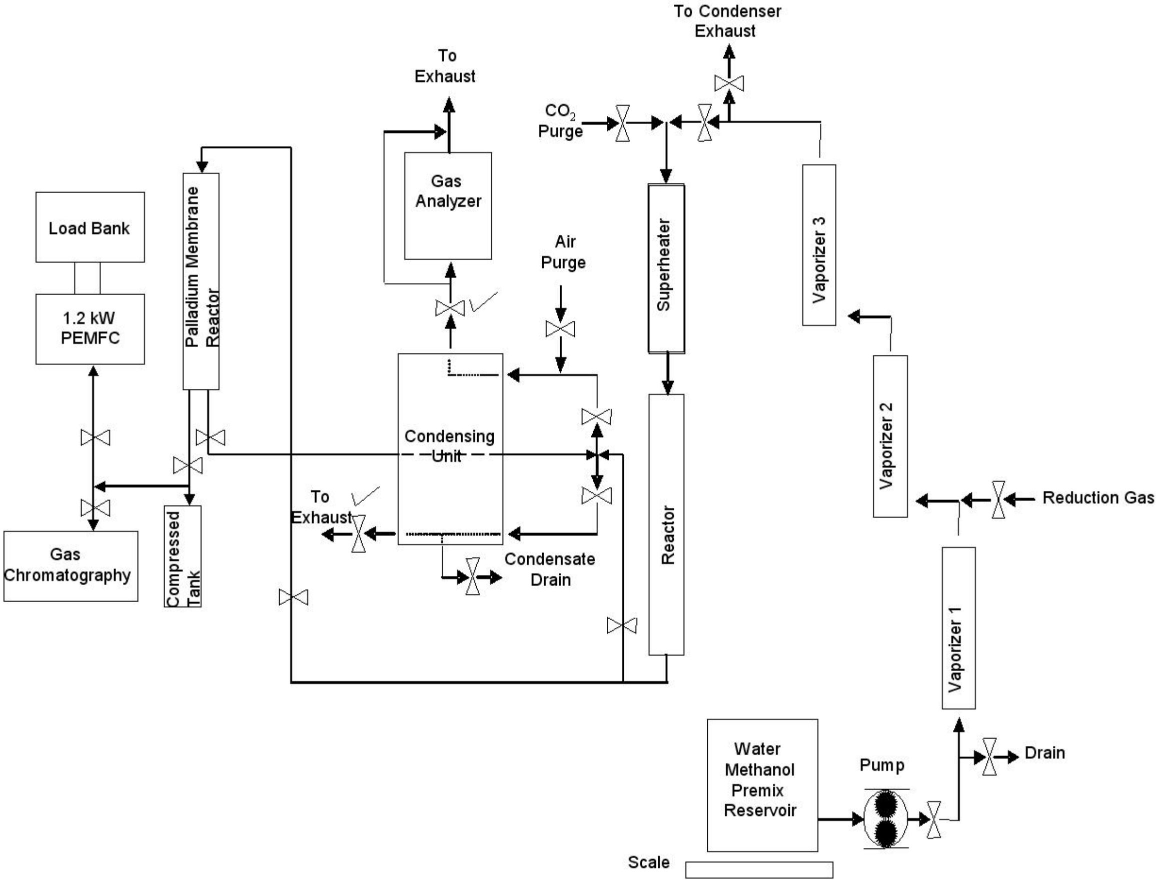

**Figure 3: Schematic of Overall System**

Limited by the output capacity of the palladium membrane reactor (maximum 1.0 SLPM pure hydrogen) the overall fuel processing system cannot provide enough hydrogen production for the fuel consumption rate for simultaneous fuel cell testing. The pure hydrogen was collected in a Swagelok 316 stainless steel cylindrical tank with one gallon (3.78L) capacity. The pure hydrogen tank was pressurized by the pure hydrogen output backpressure of the palladium membrane reactor when operating the purifying system at steady state and a pressure of 200 psi. When the palladium membrane operates at 200 psi and reformate gas is at the same pressure, the hydrogen partial pressure is 150 psi when 100% fuel conversion is assumed (75% hydrogen concentration in reforming products). In other words, the ideal maximum hydrogen pressure attainable in the storage tank is 150 psi when reformate gas is at 200 psi.

# RESULTS AND DISCUSSION

The following section presents results from the reporting period from the following areas: autothermal catalyst degradation due to start-up and shutdown, gas chromatography of reformate via steam reforming, gas chromatography of reformate via autothermal reforming, fuel cell testing with reformate via steam reforming, fuel cell load bank system and hydrogen storage.

## Autothermal Catalyst Degradation due to Start-up and Shutdown

An autothermal catalyst degradation test composed of 13 separate cold start-up and full shutdown cycles was completed using coal-derived methanol. In the case of fuel lean start-up, premix vapor (~250ºC) flows into the reactor one minute after hot air (~250ºC) was introduced so fuel can be oxidized in an air rich environment. On the other hand, in the case of fuel rich start-up, air was introduced into the reactor one minute after vapor premix fuel enters the reactor so oxidation takes place in a fuel rich environment. During the start-up and shutdown processes, catalyst surface temperature suddenly increases and decreases, which can potentially result in catalyst degradation due to thermal stress on the catalyst.

As shown in Figure 4, the top catalyst surface temperature during both fuel rich and lean start-up are nearly equivalent, except for the amount of heat generated by means of methanol oxidation. Hence, the transient time for the fuel lean start-up process was less than the fuel rich start-up process, as shown in Figure 5.

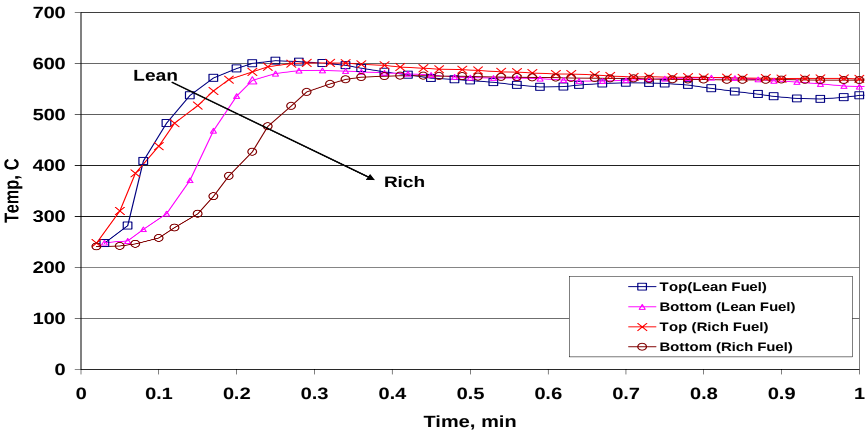

**Figure 4: Temperature Profile for Fuel Lean and Rich Start-up in Case of 0.25” Catalyst during Start-up**

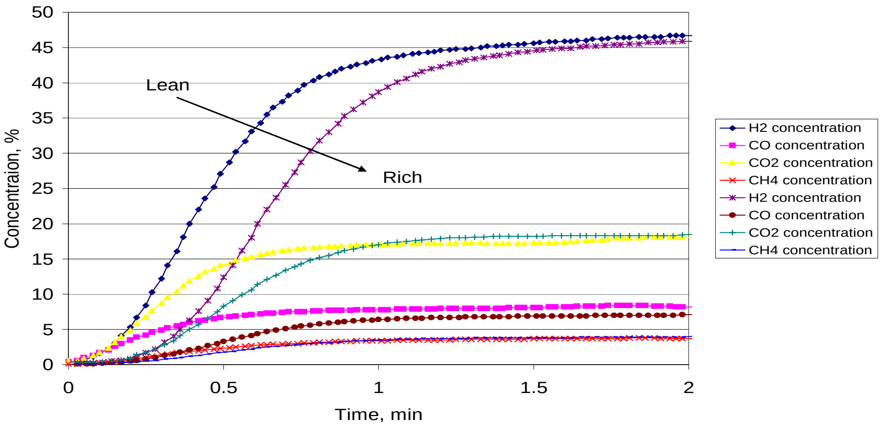

**Figure 5: Dry Reformate Gas Concentration for Fuel Lean and Rich Start-up in Case of 0.25” Catalyst**

As shown in Figure 6, the top surface catalyst temperature suddenly increased for the fuel lean shutdown cycle. By contrast, the top surface catalyst temperature decreased in case of the fuel rich shutdown cycle due to the endothermic reaction present. Based on the different start-up and shutdown cycles, the top surface could be the primary region catalyst degradation can initially take place.

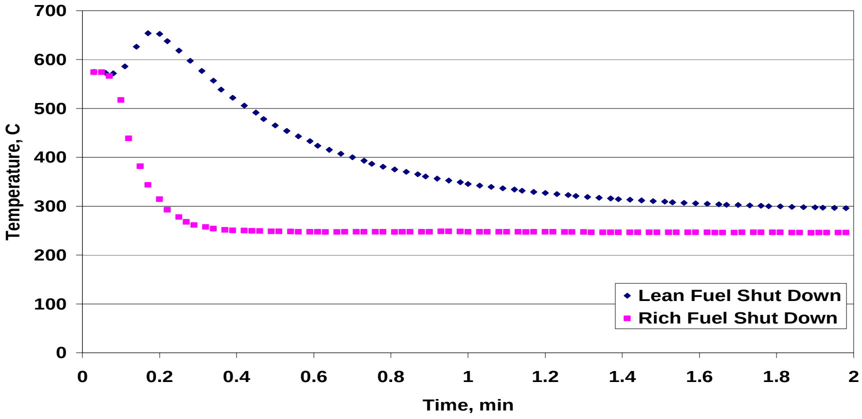

**Figure 6: Temperature Profile for Fuel Lean and Rich Start-up in case of 0.25” Catalyst during Shutdown**

Figure 7 represents the methanol conversion for both fuel rich and lean start-up and shutdown cycles. The shown conversions were measured during steady state. The fuel lean catalytic oxidation was shown to have a degradation rate greater than fuel rich catalytic combustion. Consequently, the major factor of catalyst degradation during start-up and shutdown cycles is sintering.

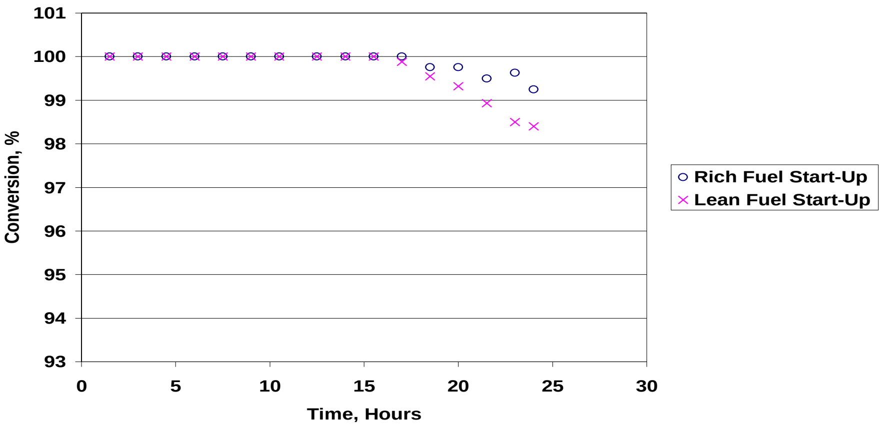

**Figure 7: Methanol Conversion after Fuel Rich and Lean Start-up for 24 Hours**

These results show that simple manipulations in equivalence ratio can extend catalyst life. Any preventable degradation would be useful without changing any physical element of the setup is very useful. Further research could include looking into when fuel lean start-up and shutdown would be beneficial, or a lean start-up and rich shutdown would be a preferred method.

## Gas Chromatography of Reformate Via Steam Reforming

Purified hydrogen from coal derived methanol and chemical grade methanol was fed to gas chromatography (GC) equipment for hydrocarbon impurity analysis with a thermo-conductivity detector and Helium-ionized detector. Also, industrial $H_2$ with 99.99% purity was analyzed and established as the baseline test for the two samples. For industrial $H_2$ and chemical grade MeOH, the GC operating time was 7.20 minutes. For coal derived MeOH, the operating time was 17.05 minutes.

Figure 8Figure 10 are HID analysis graphs of industrial $H_2$, chemical grade MeOH (CGM), and coal derived MeOH (CBM) respectively. The split of the first wide peak was due to an extreme high concentration of hydrogen. With a y-axis magnitude range of –80 to 800 mV, the comparison of the three HID analysis cases show only hydrogen specie existing in the sample and the results are similar.

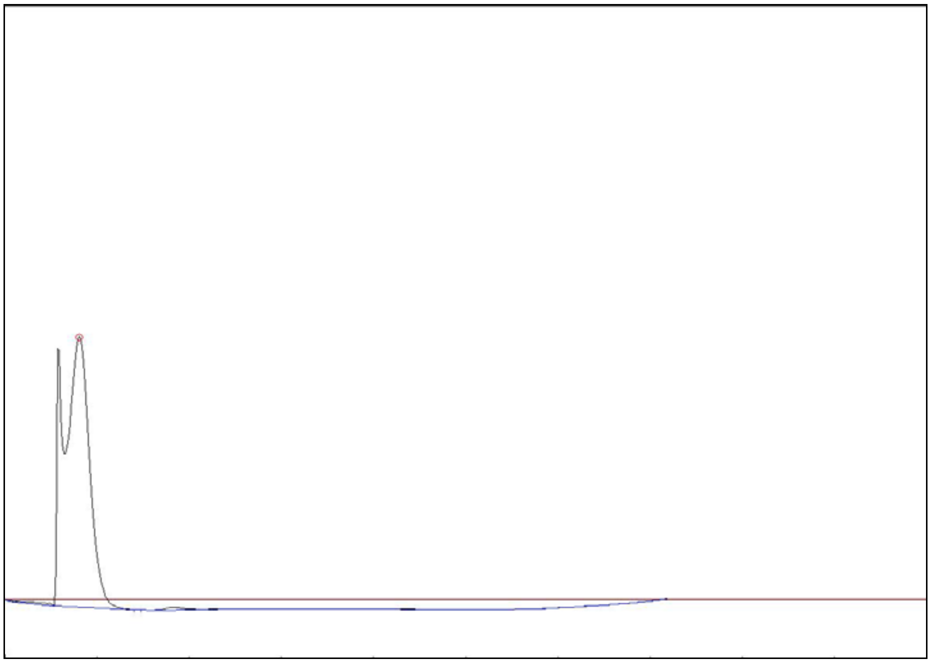

Figure 8: Industrial $H_2$ HID Analysis after 7.20 Minutes

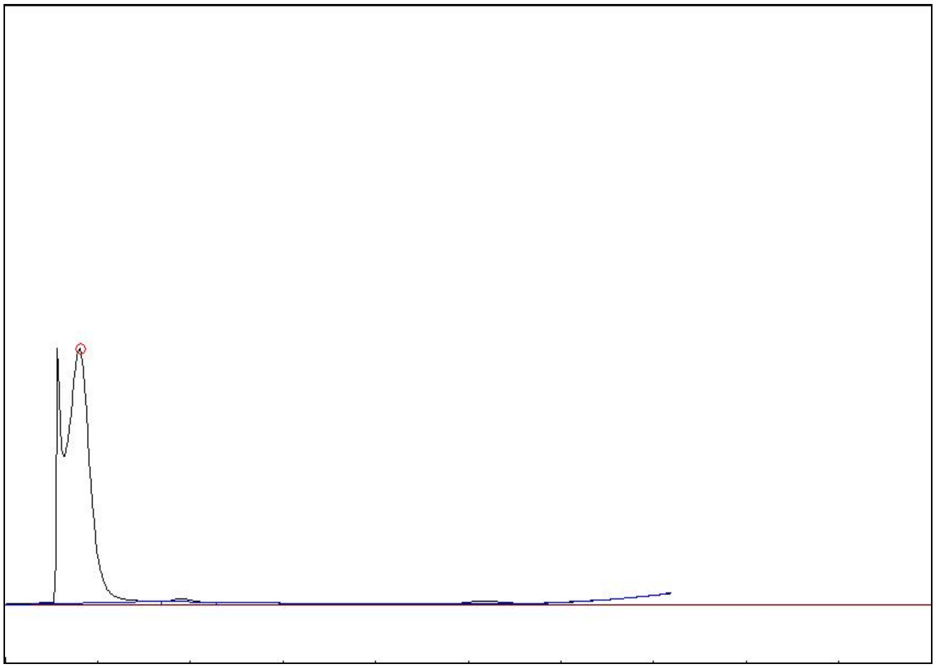

Figure 9: CGM $H_2$ HID Analysis after 7.20 Minutes

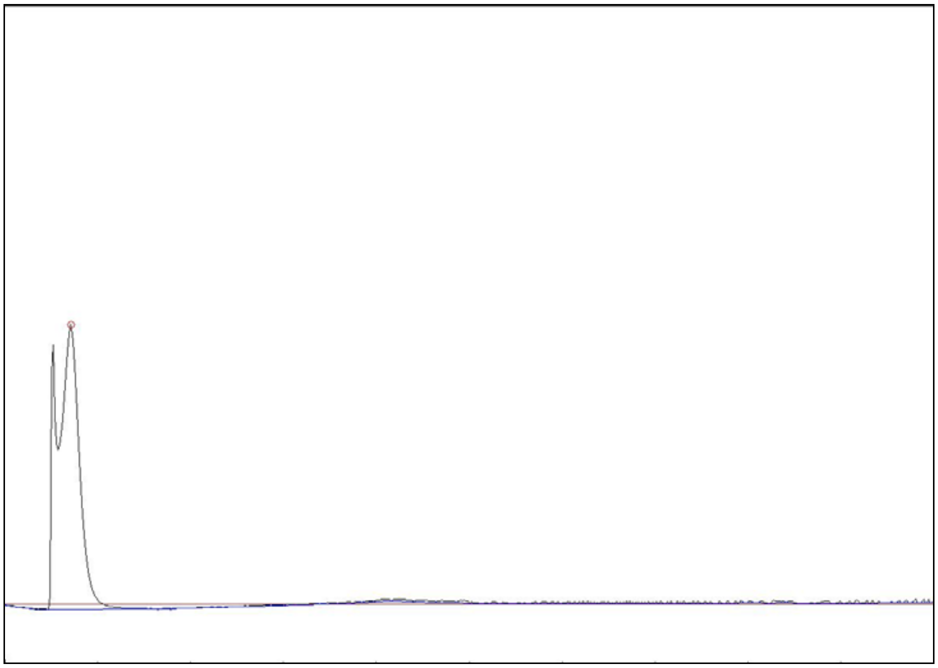

**Figure 10: CBM $H_2$ HID Analysis after 17.05 Minutes**

Figure 11-Figure 13 are the TCD analysis of the three samples. The y-axis range is –1.25 to 12.5 mV. Under this resolution, TCD analysis shows an impurity is present in all the samples, except the pure hydrogen reference case. More research is underway to determine the concentration, and identity of the impurity.

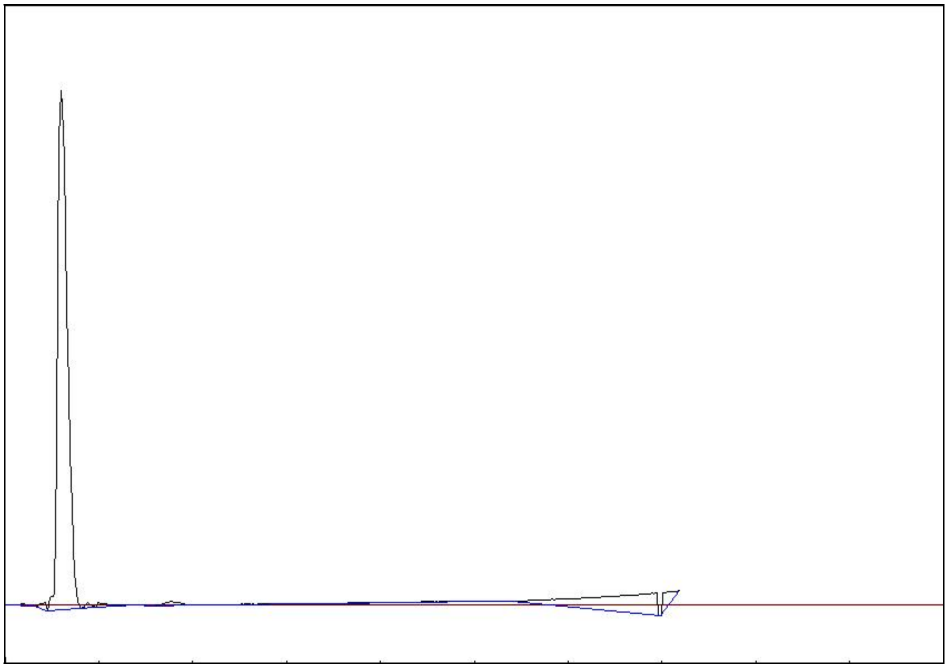

**Figure 11: Industrial $H_2$ TCD Analysis after 7.20 Minutes**

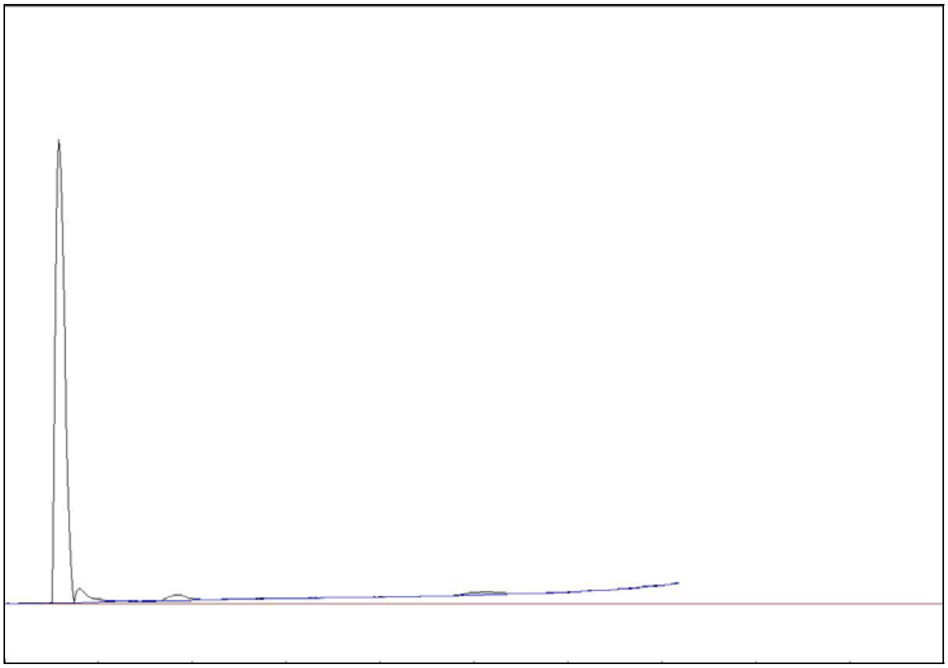

Figure 12: CGM $H_2$ TCD Analysis after 7.20 Minutes

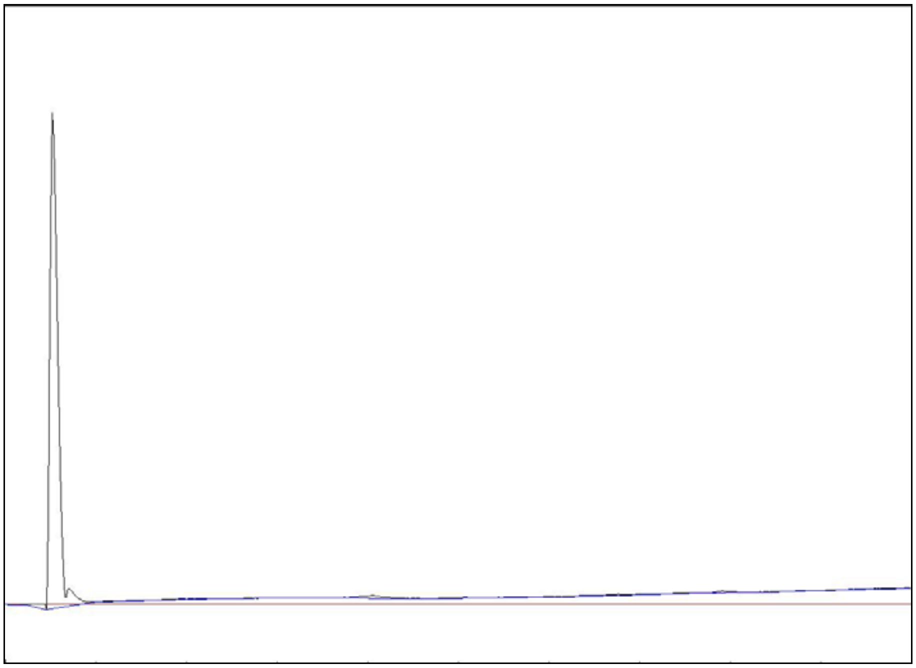

Figure 13: CBM $H_2$ TCD Analysis after 7.20 Minutes

## Gas Chromatography of Reformate Via Autothermal Reforming

To perform hydrogen separation using a palladium membrane, high operating temperature and pressure are required. The palladium membrane required periodic regeneration to remove carbonaceous compounds, especially when hydrocarbon gases flow through the retentate side of the membrane. The regeneration was performed with air and small amounts of hydrogen at approximately 500$^o$C. Afterwards, the palladium membrane separation unit was checked for leaks using gaseous nitrogen at 350$^o$C and 50 psi. Blank runs of gas chromatography took place to ensure gaseous compounds were not present in the columns.

When attempting to pressurize the system to 200 psi during autothermal reformation, difficulties with the mass flow controllers arose. The mass flow controllers are used to control the mass flow rate of air. The maximum stable pressure attainable with the current setup was 70 psi during autothermal reformation. Although 70 psi is far below the ideal 200 psi desired for the palladium membrane, it was confirmed that a palladium membrane could be used to produce ultra high purity hydrogen from the reformate produced during autothermal reforming of coal-derived methanol at a pressure of 70 psi. In literature, increasing both temperature and pressure would highly increase the permeation of only hydrogen through the membrane and suppress the permeation of nitrogen and methane as well. Nitrogen and methane permeation for the palladium membrane decreased approximately 90% and 72% respectively as both membrane temperature and differential pressure increased from 300$^o$C to 400$^o$C and from 50 psi to 70 psi. The results are shown in Figure 14 and Figure 15. Carbon monoxide, a poison to PEM fuel cells, could not be found.

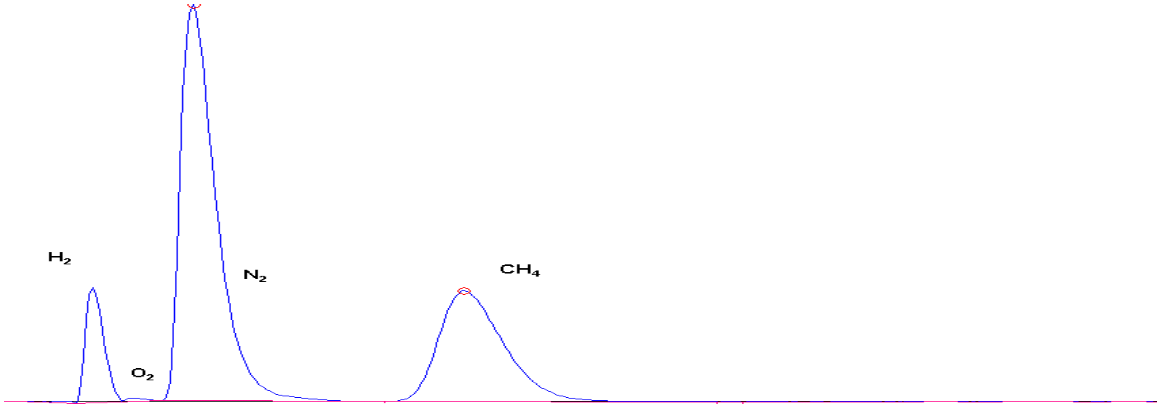

**Figure 14: Gas Chromatography for the Permeated Gases from Palladium Membrane at 50 psi and 300 $^o$C**

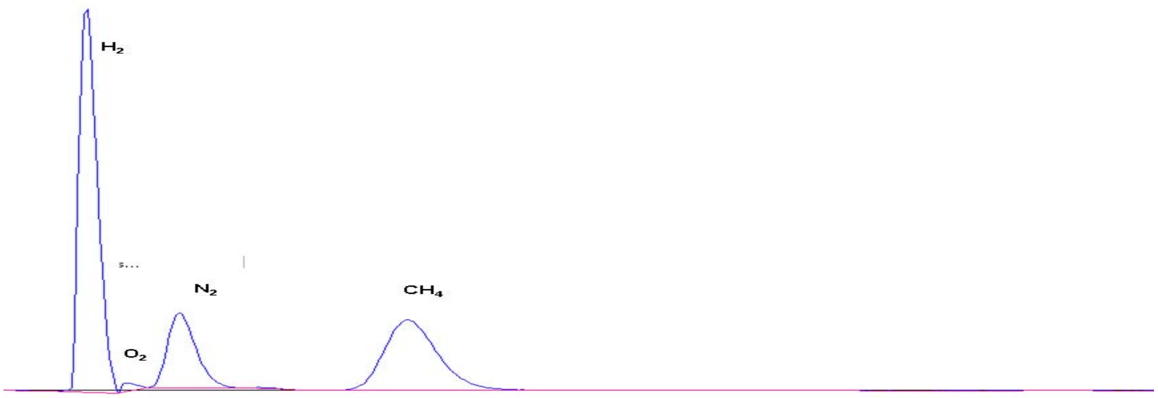

**Figure 15: Gas Chromatography for the Permeated Gases from Palladium Membrane at 70 psi and 400 °C**

## Fuel Cell Testing with Reformate Via Steam Reforming

Figure 16 shows the polarization curve of the NEXA PEM fuel cell using the three hydrogen sources, industrial hydrogen, reformed from chemical grade (CGM) and coal-derived (CBM) methanol. Each curve in the chart represents the average of three data sets. The industrial hydrogen was tested three times and each resulting average is plotted in the figure. Each data set is composed of seven increasing net power-draws from the stack from no load to maximum load tested. The seven power-draws were caused by incrementally increasing the load bank power-draw from Level Zero (30W output power from the stack) to Level Six (around 670W to 740W net power depending on test configurations). Limited by the hydrogen capacity in the tank, only seven power-draw increments were used in each data set to get a total net power between 670 and 740 W. The error bar shown in the figure is one standard deviation of the three data sets at each power-draw state.

The chart shows that the averages of the three industrial $H_2$ tests have a higher curve than CGM curve and CDM curve, which might be caused by the different hydrogen supply pressures to the fuel cell. During testing, the industrial hydrogen was maintained at a constant fuel purging pressure, but during the CDM and CGM tests, the fuel purging pressure at the tank decreased rapidly as the tank emptied and thus affected the fuel cell's performance as shown in the polarization curve. When comparing the CGM and CDM polarization curves, these two different hydrogen feedstock sources have similar performances in PEMFC and have no significant differences.

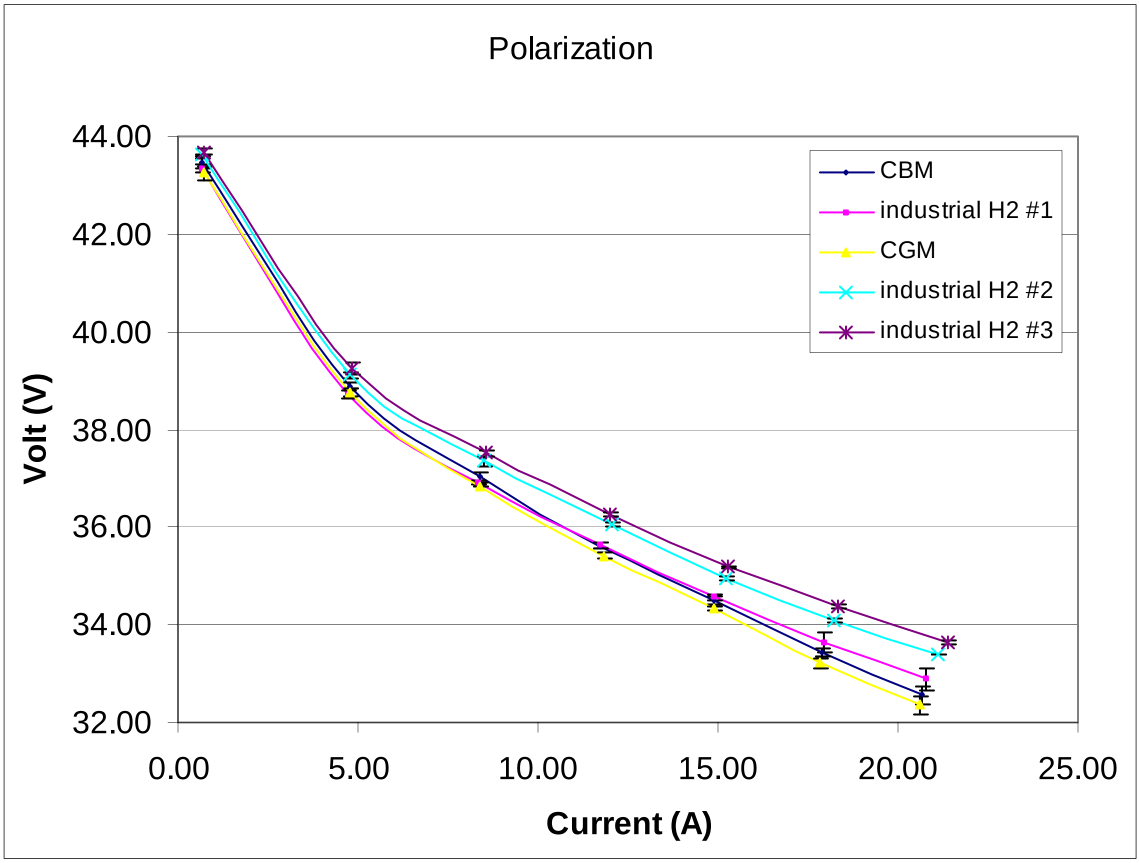

**Figure 16: Polarization Curve of Fuel Cell Performance using Industrial Hydrogen, CGM and CBM Hydrogen**

## Fuel Cell Load Bank System

The fuel cell load bank system was completed and used for fuel cell testing. The system, shown in Figure 17, worked well and provided a load up to 1.2 kW in 12 increments. The system provided an instantaneous response, and the fuel cell could handle the power-draw increase steps. The system provided a relatively fast and inexpensive solution to providing a load to the fuel cell. A system with complete control over the load would be ideal.

**Figure 17: Completed Fuel Cell Load Bank**

## Hydrogen Storage

Limited by the output capacity of the palladium membrane reactor (maximum 1.0 SLPM pure hydrogen) the overall fuel processing system cannot provide enough hydrogen production for the fuel consumption rate for simultaneous fuel cell testing. The pure hydrogen was collected in a Swagelok 316 stainless steel cylindrical tank with one gallon (3.78L) capacity. The pure hydrogen tank was pressurized by the pure hydrogen output backpressure of the palladium membrane reactor when operating the purifying system at a steady state pressure of 200 psi. When the palladium membrane operates at 200 psi and reformate gas is at the same pressure, the hydrogen partial pressure is 150 psi, when 100% fuel conversion is assumed (75% hydrogen concentration in reforming products). In other words, the ideal maximum hydrogen pressure attainable in the storage tank is 150 psi when reformate gas is at 200 psi.

In practice, when the collected hydrogen pressure approached 100 psi, the positive hydrogen pressure gradient inside the tank gradually dropped due to the decrease in difference between hydrogen partial pressure in the gaseous reformate and pure hydrogen side across the membrane. As the cylinder pressure increased, the cylinder pressure began to approach the partial pressure of hydrogen in the reformate side of the membrane, which decreases the hydrogen output flow rate from the palladium membrane. A 20-hour hydrogen production time was required to reach a 110 psi gage pressure (827 kPa) inside the one gallon tank. The equivalent hydrogen mass of 2.855x10-3 kg has an available energy of 342.6 kJ (LHV) when assuming a temperature of 25˚C inside the tank. The small amount of collected hydrogen can barely sustain three data sets when testing the fuel cell.

# CONCLUSION

To minimize autothermal catalyst degradation the start-up and shutdown cycles were analyzed. The top catalyst surface temperature during both fuel rich and lean start-up are nearly equivalent, except for the amount of heat generated by means of methanol oxidation. Hence, the transient time of fuel lean start-up process was less than the fuel rich start-up. The top surface catalyst temperature suddenly increased for the fuel lean shutdown cycle. By contrast, the top surface catalyst temperature decreased in case of the fuel rich shutdown cycle due to the endothermic reaction present. Based on the different start-up and shutdown cycles, the top surface could be the primary region where catalyst degradation can initially take place. When examining the steady state methanol conversion for both fuel cell rich and lean start-up and shutdown cycles, the fuel lean catalytic oxidation was shown to have a degradation rate greater than fuel rich catalytic combustion. Consequently, it is believed that the major mechanism of catalyst degradation during ATR start-up and shutdown cycles is sintering.

Current PEM fuel cell technology shows that with pure hydrogen, a fuel cell will function properly and experience minimal degradation. The focus of the research has shifted slightly towards determining the hydrogen purity produced. If pure hydrogen is produced with no impurities, then the hydrogen can be used on any PEM fuel cell, or other type of fuel cell using pure hydrogen. The goal of the gas chromatography was to determine the purity of hydrogen being produced, and to determine if any hydrocarbons, or CO was passing through the membrane. The PEM membrane can be easily damaged due to impurities. In this report, it was shown that coal derived methanol can be reformed into pure hydrogen. An industrial hydrogen source was analyzed as the control sample to test the hydrogen output from the purifying subsystem for impurities. The GC test results show that there is no significant difference between the supplied industrial hydrogen, and the hydrogen produced from chemical grade and coal-derived methanol. This result is great news for those looking to use coal-derived methanol as a feed stock for hydrogen production for use in fuel cells. As no apparent difference between the three hydrogen samples exists, the hydrogen produced from coal-derived methanol could be used interchangeably with hydrogen used for PEM fuel cells.

The maximum stable pressure attainable with the current setup was 70 psi during autothermal reformation. In literature, increasing both temperature and pressure would highly increase the permeation of only hydrogen through the membrane and suppress the permeation of nitrogen and methane as well. Nitrogen and methane permeation for the palladium membrane decreased approximately 90% and 72% respectively as both membrane temperature and differential pressure increased from 300 $C^o$ to 400$C^o$ and from 50psi to 70 psi. Carbon monoxide, a poison to PEM fuel cells, could not be found. Increasing the pressure of the reformer to 200 psi, the manufacturer’s requested operating temperature, the impurity peaks present should vanish. A secondary hydrogen filter could be used to ensure the purity of hydrogen is high.

The polarization curve obtained from testing a 1.2 kW PEMFC with hydrogen from chemical grade (CGM) and coal-derived (CBM) methanol was completed this quarter. An industrial hydrogen source was analyzed as a control for comparison to hydrogen from CGM and CBM. The polarization curve shows the averages of the three industrial $H_2$ tests have a higher curve than the CGM and CDM curves. This might be caused by the different hydrogen supply pressures to the fuel cell. During testing, the industrial hydrogen was maintained at a constant fuel purging pressure, but during the CDM and CGM tests, the fuel purging pressure at the tank decreased rapidly as the tank emptied and thus affected the fuel cell's performance as shown in the polarization curve. When comparing the CGM and CDM polarization curves, these two different hydrogen feedstock sources have similar performances in PEMFC and have no significant differences. The GC test results show that there is no significant difference between the supplied industrial hydrogen, and the hydrogen produced from chemical grade and coal-derived methanol. This result is great news for those looking to use coal-derived methanol as a feed stock for hydrogen production for use in fuel cells. As no apparent difference between the three hydrogen samples exists, the hydrogen produced from coal-derived methanol could be used interchangeably with hydrogen used for PEM fuel cells

The fuel cell load bank system was completed and used for fuel cell testing. The system worked well and provided a load up to 1.2 kW in 12 increments. The system provided an instantaneous response, and the fuel cell could handle the power-draw increase steps. The system provided a relatively fast and inexpensive solution to providing a load to the fuel cell. A system with complete control over the load would be ideal.

The ideal maximum hydrogen pressure attainable in the storage tank is 150 psi when reformate gas is at 200 psi. In practice, when the collected hydrogen pressure approached 100 psi, the positive hydrogen pressure gradient inside the tank graduately dropped due to the decrease in difference between hydrogen partial pressure in the gaseous reformate and pure hydrogen side across the membrane. As the cylinder pressure increased, the cylinder pressure began to approach the partial pressure of hydrogen in the reformate side of the membrane, which decreases the hydrogen output flow rate from the palladium membrane. A 20-hour hydrogen production time was required to reach a 110 psi gage pressure (827 kPa) inside the one gallon tank. The equivalent hydrogen mass of 2.855x10-3 kg has an available energy of 342.6 kJ (LHV) when assuming a temperature of 25˚C inside the tank. The small amount of collected hydrogen can barely sustain three data sets when testing the fuel cell. The whole system is limited by the palladium membrane, and tank pressure. A pump could increase tank pressure, and increase storage, to allow for longer fuel cell testing. The pump could pressurize the hydrogen output at ambient conditions to a pressurized tank. This configuration would allow the greatest pressure difference across the palladium membrane, which would maintain the greatest possible pure hydrogen flow rate.

## REFERENCES

[1] Beerman, M.J., Evaluation Of The Use Of Acoustic Waves For Improving The Transient Response Of Steam Reformers, masters thesis, University of California, Davis, CA, 2005

[2] Erickson, P.A., Enhancing the Steam-Reforming Process with Acoustics: An Investigation for Fuel Cell Vehicle Applications, doctoral dissertation, University of Florida, Gainesville, FL, 2002

[3] Davieau, D.D., An Analysis of Space Velocity and Aspect Ratio Parameters in Steam-Reforming Hydrogen Production Reactors, masters thesis, University of California, Davis, CA, 2004

[4] Dorr, J.L., Methanol Autothermal Reformation: Oxygen-to-Carbon Ratio and Reaction Progression, masters thesis, University of California, Davis, CA, 2004

[5] Dorr, J.L., and Erickson, P.A., Preliminary Modeling and Design of an Autothermal Reformer, 2004 International Mechanical Engineering Congress and Exposition, Anaheim, CA, November 2004, IMECE2004-5989