Production of hydrogen driven from biomass waste to power Remote areas away from the electric grid utilizing fuel cells and internal combustion engines vehicles

Final Report

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EXECUTIVE SUMMARY

Recent concerns over the security and reliability of the world's energy supply has caused a flux towards the research and development of renewable sources. A leading renewable source has been found in the biomass gasification of biological materials derived from organic matters such as wood chips, forest debris, and farm waste that are found in abundance in the USA. Accordingly, there is a very strong interest worldwide in the development of new technologies that provide an in-depth understanding of this economically viable energy source. This work aims to allow the coupling of biomass gasification and fuel cell systems as well as Internal Combustion Engines (ICE) to produce high-energy efficiency, clean environmental performance and near-zero greenhouse gas emissions. Biomass gasification is a process, which produces synthesis gas (syngas) that contains 19% hydrogen and 20% carbon monoxide from inexpensive organic matter waste. This project main goal is to provide cost effective energy to the public utilizing remote farms' waste and landfill recycling area.

Project Objective

The objective is to produce ultra-pure hydrogen derived from biomass waste to power high and low temperature Proton Exchange Membrane (PEM) fuel cells as well as Internal Combustion engines (ICE). These systems can generate relatively clean and cost effective Combined Heat and Power (CHP) that can potentially reduce our national dependence on foreign oil and the utility grid during peak hours. This newly developed and integrated hydrogen generation system with fuel cell units are designed to power homes, electric vehicles and farms machinery located away from the utility grid.

The completion of the project is summarized according to the following tasks included in the Statement of Project Objectives (SOPO) that was approved by the DOE in the beginning of the project:

Task 1 - Project Design and Construction:

The system was designed and constructed, as shown in Figure (1), to cost effectively produce ultra-pure hydrogen from biomass that is capable of energizing low temperature MEA (80^{o}C) for a Proton Exchange Membrane (PEM) fuel cell to generate combined heat and power. Ultra-pure hydrogen with carbon monoxide (CO) content of 10 parts per million (ppm) is to be fed to the PEM fuel cell to prevent the poisoning of its platinum catalyst. However, for High Temperature PEM fuel Cells (180^{o}C) the MEA catalyst can tolerate 2% to 3% CO. The WGS (WGS) system is the initial CO cleanup process in which the syngas will flow through a system that consists of a relatively low temperature (250^{o}C) shift catalyst reactor. The CO and steam (H_2O) mixed with hot syngas will flow through our newly designed reactor, in the presence of the catalyst, will chemically react and form additional hydrogen (H_2) and carbon dioxide (CO_2). The amount of H_2 originally existed in the syngas system will increase meanwhile the CO percentage will be reduced to a much smaller amount. The chemical reactions taking place inside the WGS reactors represent the first step of the hydrogen cleanup and purification processes. Standard catalysts are commercially available for WGS, with various compositions of copper and zinc for a temperature shift between (120–250 °C). In the present work, this catalyst has been tested and efficiently maximized the H_2 content in the syngas from 20% to 38.6% and considerably reduced the CO content from 20% to 1.4% in the produced SYNGAS.

Hydrogen PEM fuel cell performance was also tested under small amounts of CO impurities, evaluation of hydrogen purification using electrochemical hydrogen separation was performed, and overall evaluation of the system economic validity are also an integral part of the current research and developmental work. A new and innovative technique for CO removal such as the utilization of Copper Chloride, dissolved in methanol, is our final choice combined with the electrochemical separation process to produce Ultra-pure Hydrogen. The power conditioning of the 5 kW PEM Fuel Cell that safely powers home appliances and electronics as well as electric vehicles represents the final stage of this project. The present research work for this project has produced intellectual properties that were protected by a provisional application followed by a patent application to secure our Intellectual Property (IP) through a patent filing with the U.S. Patent and Trademark Office (USPTO)

The production of hydrogen rich gas from biomass waste is directly used to energize Internal Combustion Engine (ICE) Vehicles and powering (high & low Temperature) Proton Exchange Membrane (PEM) fuel cells, after further CO purification, to produce useful Combined Heat and Electric Power (CHEP) as discussed earlier under this task.

The system under consideration is uniquely designed to produce very useful ultra-pure hydrogen derived from biomass waste and synthesis gas (syngas). Figure (1) demonstrates our final system integration of our research and development work performed in this research project to produce cost effective energy from biomass.

Figure (1) the Outdoor Integrated System

Task 1: Conclusions

- The integrated system was designed and constructed
- The system can produce Hydrogen Rich Gas with about 1.4% CO, right after the WGS, much lower levels of CO concentrations could be achieved using additional purification techniques, as will be discussed later, to power low temperature (80^{o}C) PEM fuel cells with Ultra-pure Hydrogen
- High temperature PEM fuel cells (180^{o}C) can be directly powered by the system, so as an Internal Combustion Engines (ICE)
- The system's Intellectual Property (IP) was protected through a patent filing with the U.S. Patent and Trademark Office (USPTO) with headquarters in Alexandria, Virginia

Task 2 – Testing of 20 kW Gasifier and its system components

Figure (1) shows an overall view of the outdoor integrated system including the recently installed Auger Motor and Coupling for protecting the motor against Auger jamming with wood chips and power overload.

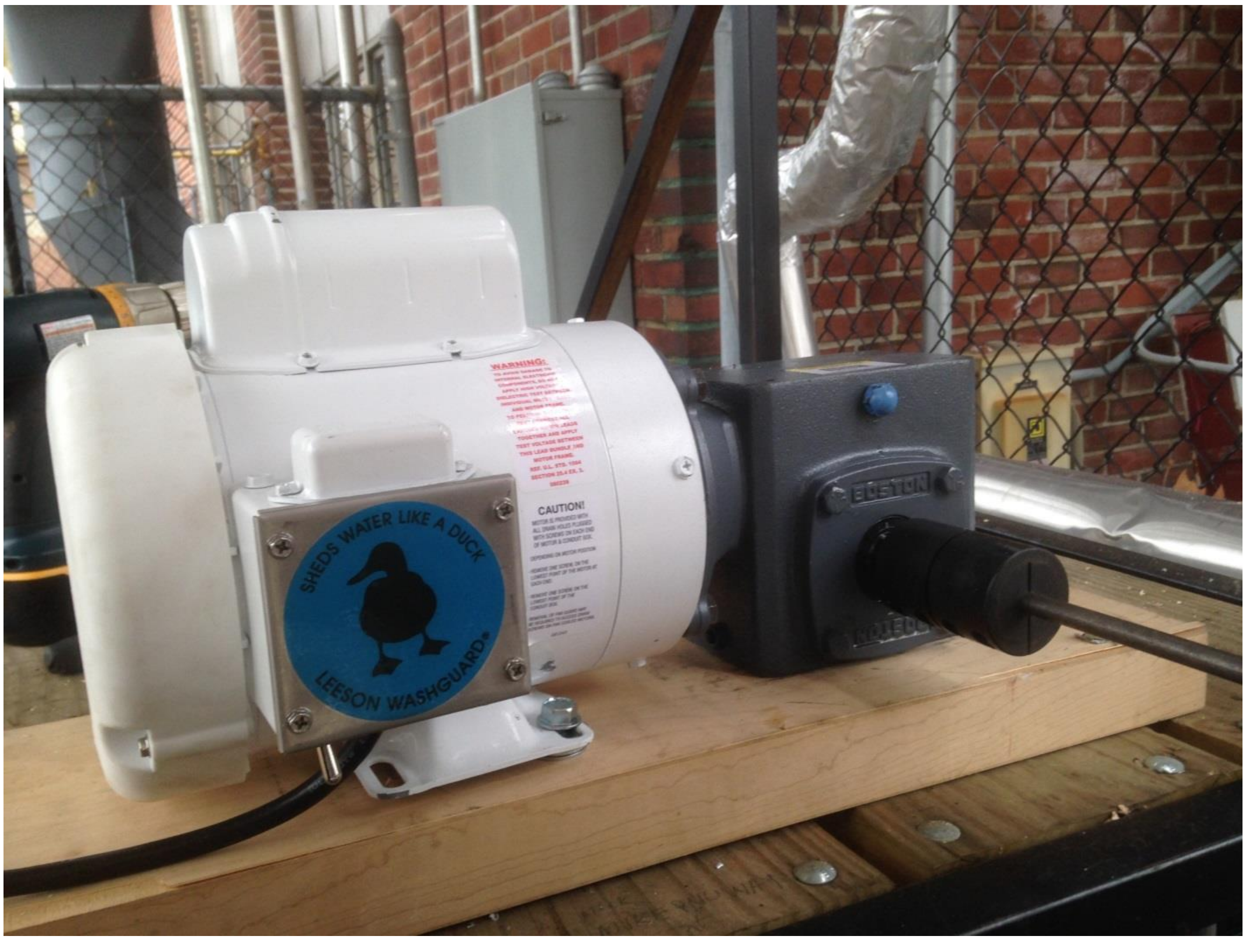


Figure (2) Close up picture of New 0.75 HP Electric Motor to power the Gasifier Auger and replace the old damaged Motor due to jammed Auger with the woodchips and exposure to electric power overload

The driving shaft from the electric motor to the Auger is fitted with couplings to turn loose when the Auger gets jammed with the woodchips and protect the electrical motor from damage, as shown in Figure (3). The functionality of the coupling was successfully tested and proved its damage protection of the electric motor.

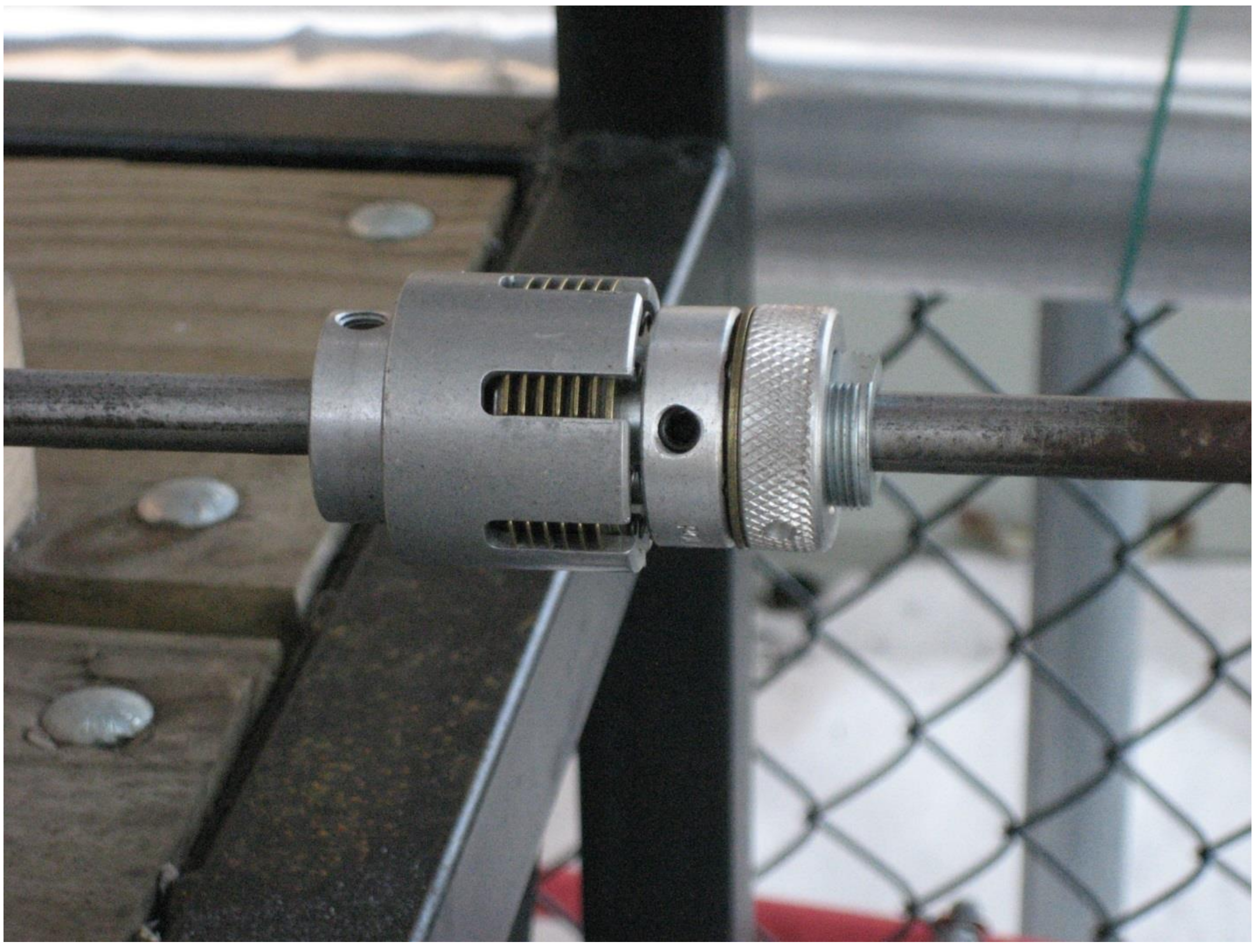


Figure (3) Safety Coupling

Figure (4) Two phase separation system performing in subfreezing condition

Moreover, separator system performance was tested at one extreme condition “subfreezing condition”, also at the worst possible operation condition when the maximum amount of steam produced from the steam generator was directly fed to the two phase separation system. As a first test trial air at room temperature was used in this test to simulate the syngas. Careful examination of the test results indicated that 91.36% of the steam was condensed into water and separated from the gases for recycling. A possible augmentation to the separator system is to increase its condensation capability by changing its fan to a larger size. It would be possible to put a larger fan in place of the current one to draw more air over the cooling fins of the radiator. Another possible improvement would be to place a second radiator connected in series with the first radiator shown in Figure (4A). A second radiator would ensure complete vapor condensation and would help with the complete splitting of the two-phase flow into more defined phases.

Figure (4A) Two phase separation system with cooling radiator and fan system performing in subfreezing condition

The WGS shown in Figure (1) was also tested on a regular basis and the results were very favorable. It is expected, by design, that the produced Syngas will contain extra amount of humidity since the amount of steam used in the WGS process is 5:1 the amount of CO by weight. Therefore, it is expected that the WGS process will produce two-phase flow (gases, and steam) and we need to condense the steam to water and separate the gases from the water. This separation process has been accomplished through the condenser/radiator and fan system shown in figures (4 & 4A). This system testing was successfully accomplished and the ability of the radiator to condense approximately 90% of the steam was proven. It should be noted that some humidity is required to be retained in the syngas as it proceeds for the following operations including the CO removal and hydrogen purification processes.

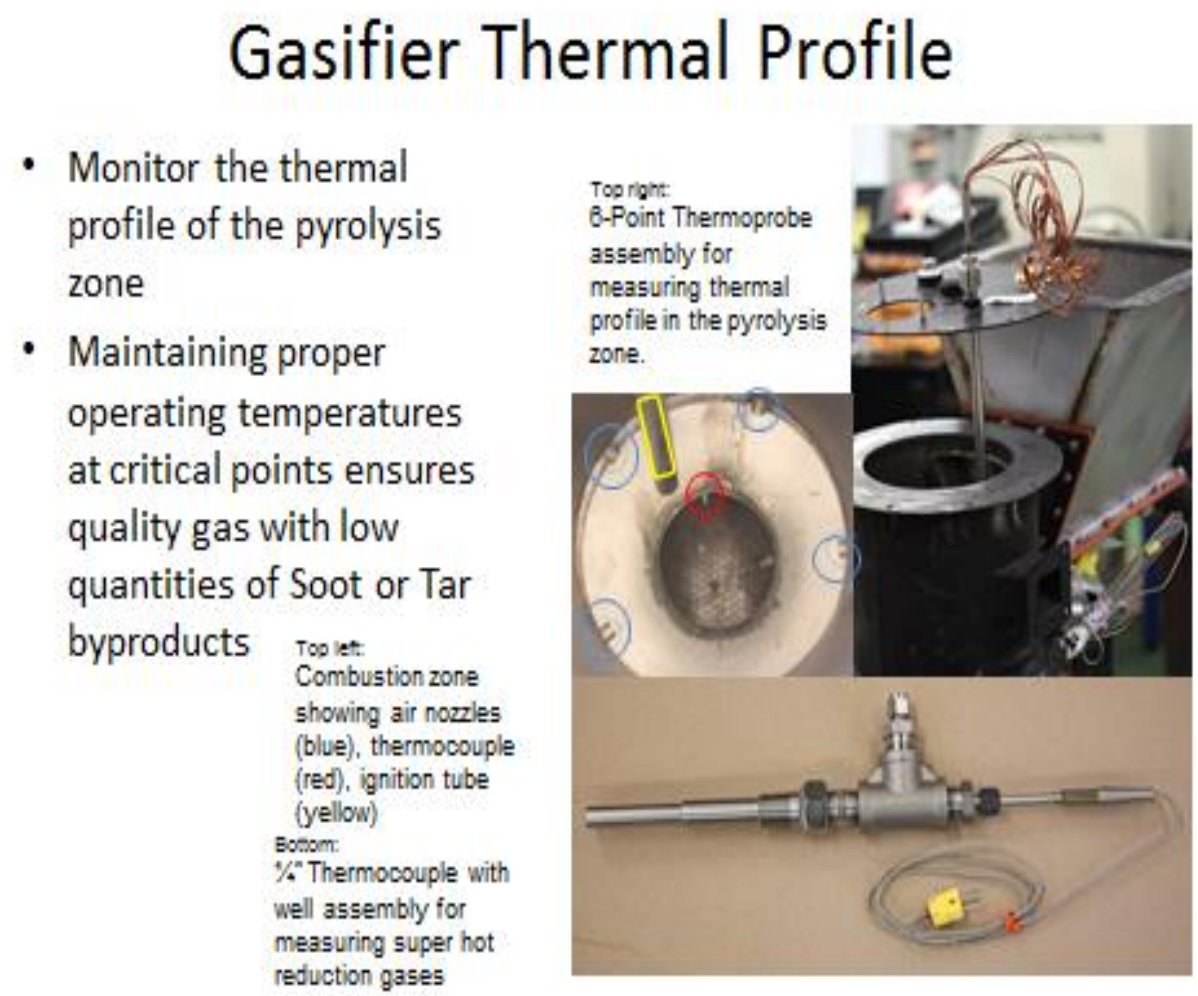


Figure (5) Sensors for Monitoring the Temperature Profile inside the Gasifier

Since our gasifier operates as a downdraft system under vacuum, this necessitates the fabrication of woodchips powered steam generator. The weight ratio of steam H_2O to the CO in syngas of 1:5 is required; therefore a mixer/conveyer system was acquired. The woodchips are the selected biomass fuel for this gasification system; the syngas will contain about 1% tar that could contaminate the WGS and the fuel cell catalysts. A reliable tar filter made of activated carbon has been acquired and added to the inlet section of the WGS reactor to capture any tar produced through the gasification process and prevents tar from reaching the WGS catalysts. Testing insured that 100% of the tar has been captured by the filter and absolutely no tar has been admitted to the WGS.

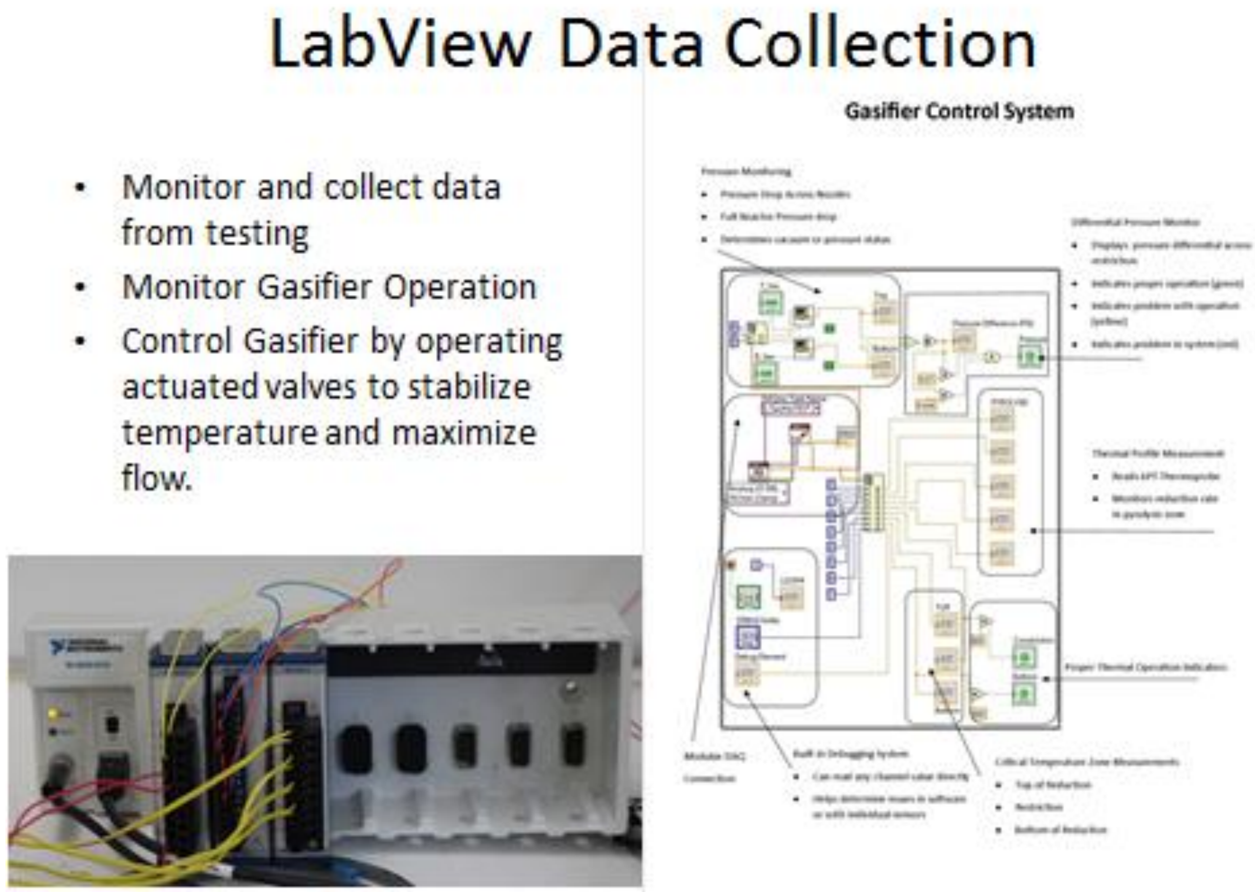


Figure (5A) Sensors Data Collection System

To ensure optimum operation of the Gasifier, numerous thermocouples installed inside the Gasifier as shown in Figures (5, 5A &6) are monitored through wireless communication between the sensors and the data acquisition system entitled ”Lab View” loaded on desktop computer Figure 5A.

Figure (6) shows five thermal probes are installed at various locations inside the gasifier pyrolysis zone to provide thermal profile measurements – These probes are connected wirelessly to a desktop computer inside the IRTT

Figure (6) shows five thermal probes installed at various locations inside the gasifier pyrolysis zone to provide thermal profile measurements during the testing and operation of the gasifier.

In addition, hard wire communication was successfully tested in a previous work. However, despite this successful testing hard wire communication was proven impractical and in many cases is considered unreliable. Wireless communication is more convenient and practical. Therefore, a wireless communication system was developed and established communication between the sensors installed inside the outdoor gasifier and the computer station remotely located indoor. As indicated earlier, the computer station is fitted with LabView software as the data acquisition system. Field-testing of this system under normal operating condition constituted the final step towards the completion of this task.

Task 2: Conclusions:

- The gasifier is instrumented with thermocouples, pressure transducers and humidity sensors connected wirelessly to a computer to monitor and optimize the gasifier performance.

- The two phase separation system showed about 90% steam condensation and water separation from the syngas utilizing the weight difference between liquid and water in a centrifugal process

Task 3 - Testing of a Full Scale Water Gas Shift (WGS) reactor for H_2 Cleanup from Biomass Synthesis Gas impurities such as CO

Figure (7) WGS Reactor with three added couplings to simplify maintenance process

These couplings were proven useful as they considerably simplified the process of changing the old catalyst by a fresh batch as well as replacing the dirty tar filter by a clean one. Tar can easily tarnish the catalyst and greatly reduce or eliminate the catalyst activity in the WGS process.

The field-testing of WGS system showed repeatable and consistent results that indicated a sound design of the WGS reactor. The scrubbing process demonstrated by the WGS process reach the saturation stage at 93% CO conversion and therefore will not completely remove the CO to the required amount of <10 ppm. A different complementing purification method was found necessary to bring the CO ratio to < 10 ppm. An extensive literature survey has shown that modern techniques have excellent potential to convert CO to CO_2, which is a more stable gas than CO. In this project copper chloride provided the initial step of the purification process followed by the electrochemical separation of hydrogen to achieve the ultrapure grade of hydrogen. As indicated earlier, two carbon filters were designed and installed between the gasifier and the WGS to clean up the syngas from tar and protect the system catalysts from tarnishing with tar that will reduce or eliminate their functionality.

Task 3 Conclusions:

- The field testing indicated the robust design and sound performance of the WGS reactor
- The WGS Reactor was designed with three couplings to simplify maintenance process
- The tar filters showed excellent functionality in sieving the tar out of the syngas
- Copper chloride provides the initial step of the ultra-purification process
- The electrochemical separation of hydrogen is the secondary and final process to achieve the ultrapure grade of hydrogen 99.9999% purity.

Task 4 - Design, Development, Fabrication and Testing of Hydrogen Purification Systems

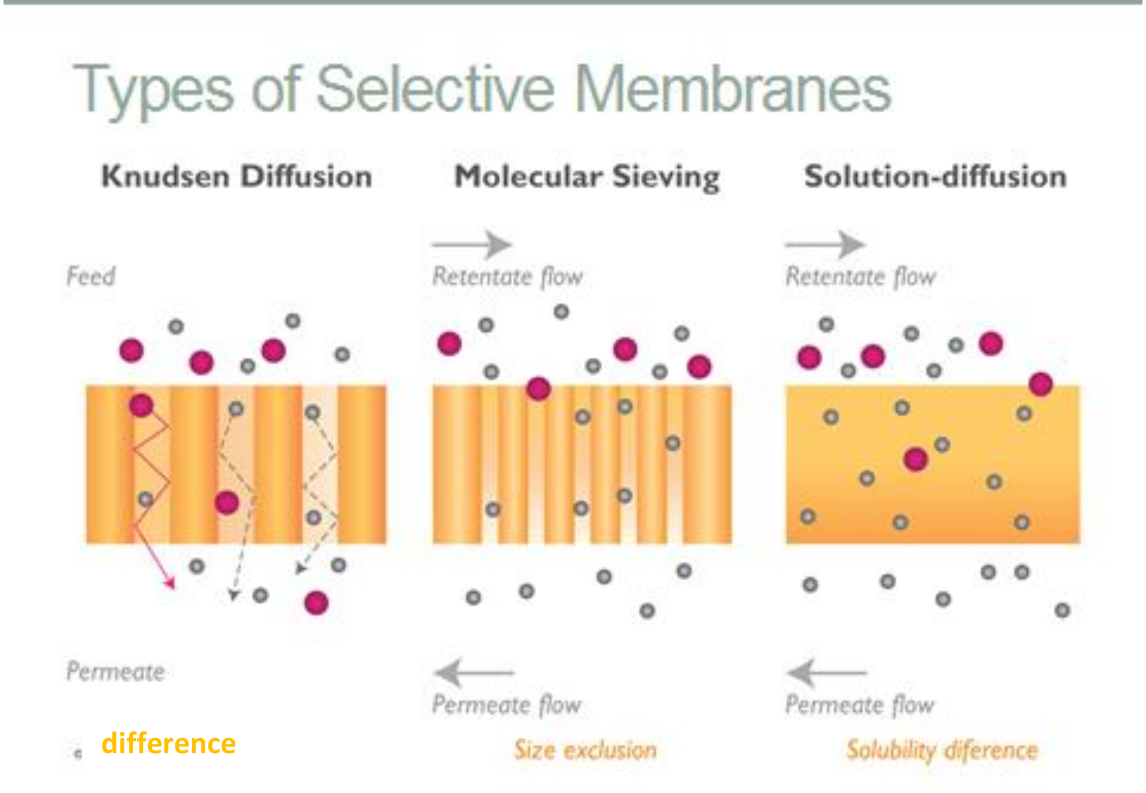


Figure (12): Shows different types of selective membrane for hydrogen purification systems

After reviewing, evaluating and testing of different types of selective membranes Figure (12) for hydrogen purification, two systems perform using the proton sieving principle are tested in this project, and they are as follows:

- Palladium Membrane
- Electrochemical H_2 Pump / Separation System

Figure (13) demonstrates the theory of operation of electrochemical separation system. Initial research work was conducted under this task to examine the electrochemical separation/purification of hydrogen from biomass synthesis gas (syngas) and evaluate the performance and cost effectiveness of this technique versus the palladium membrane system.

It must be noted that a small percentage of carbon monoxide mixed with hydrogen inhibits hydrogen permeation through the palladium membrane. The cause of the inhibition is because of the adsorption energy of CO at the Palladium surface and blocking available hydrogen dissociation sites. Similarly, it is well known that CO will also tarnish the platinum catalyst of the electrochemical hydrogen purification system causing reduced hydrogen interaction or catalytic sites, as will be discussed later in this report.

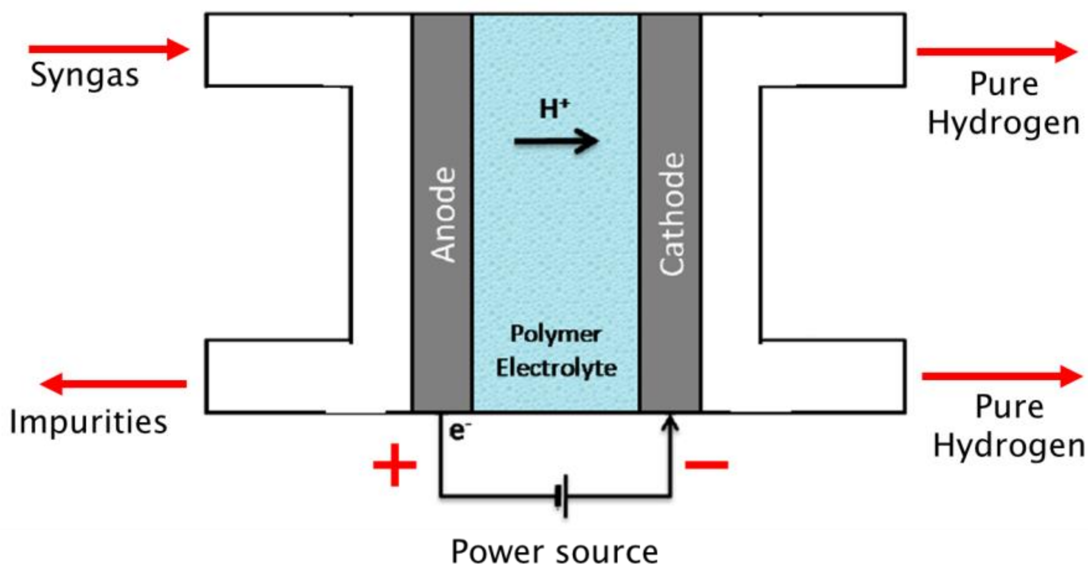


Figure (13) Purification of H_2 using a Polymer Electrolyte Membrane Fuel cell as an Electrochemical Pump

The operation of a PEM electrochemical separation or hydrogen pump is different than a regular PEM fuel cell.

- The feed to the electrochemical separation device/hydrogen pump is hydrogen gas mixed with other usually undesirable gases such as CO_2 and N_2.
- This feed must be humidified, the humidification is necessary for the Nafion's proton conductivity.
- A power source is necessary to operate the hydrogen pumping by the PEM fuel cell.
- The power source is an external circuit required for the transport of electrons and the transport of protons across the membrane.
- The H_2 is transported as an ion across the membrane, leaving the CO_2 and possibly other gasses behind as impurities. The CO_2 can be sequestered, concentrated and stored in tanks

- The purification of the hydrogen used in this method is directly proportional to the current level flowing in the circuit

EXAMINING THE HYDROGEN PURIFICATION PERFORMANCE OF A LABORATORY ELECTROCHEMICAL SEPARATION SYSTEM:

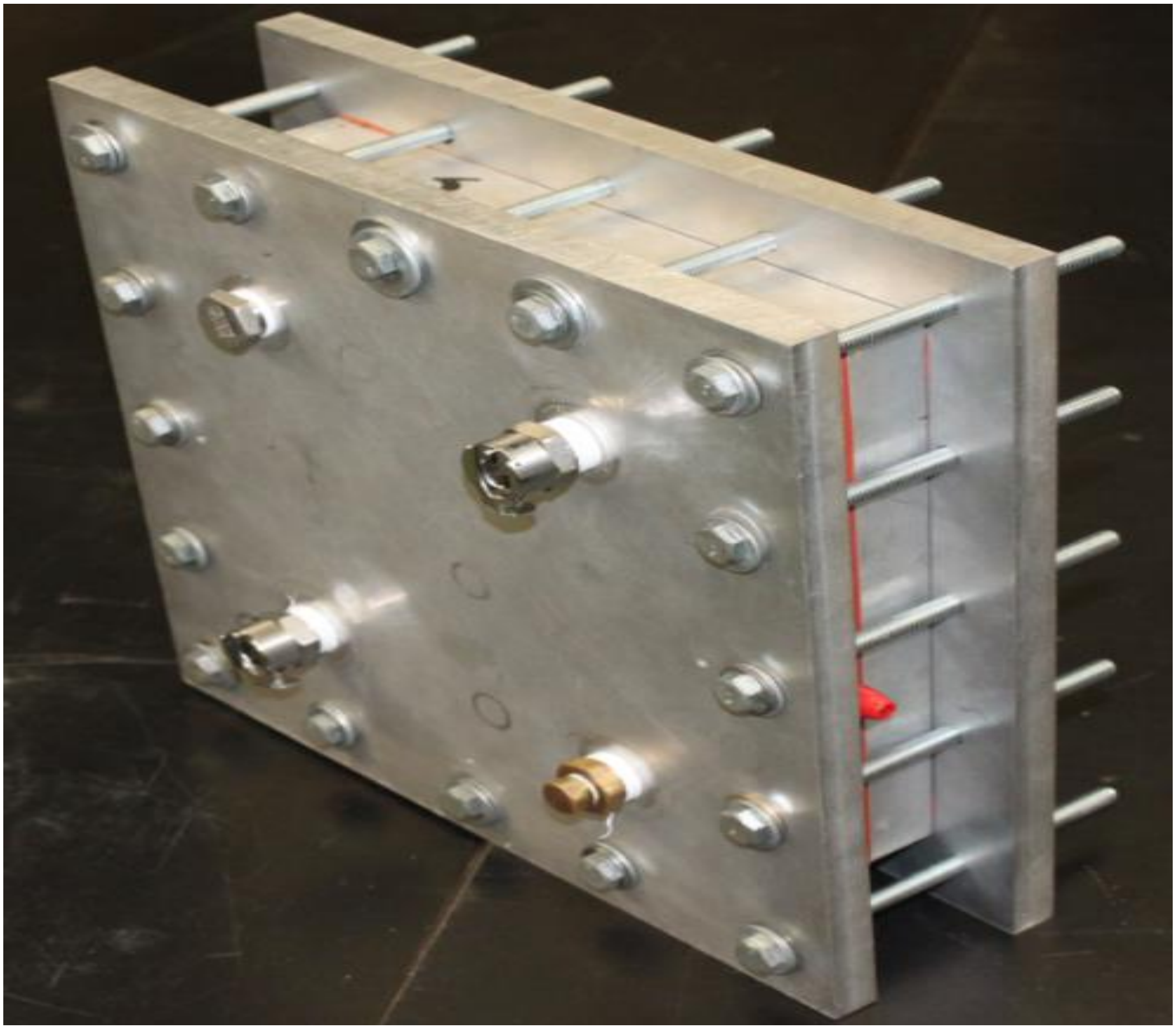


Figure (14) Full Scale Electrochemical Hydrogen Purifier

Due to the economic advantages of the electrochemical hydrogen purification in relation to the palladium membrane, we have decided to advance this technique forward to a full industrial scale in this project. As shown in Figure (14), the full scale electrochemical separator has an active area 10X10 cm i.e. 100 cm^2 per cell

The advantages of this system are as follows:

- The Hydrogen pump is a viable option for hydrogen purification
- Low power requirements in comparison to other purification methods
- Along with purifying hydrogen, it can act as a hydrogen compressor
- Doesn’t rely on pressure differentials or extremely high temperatures like the palladium membrane

The electrochemical full-scale device is shown as complete system setup Figure (14). In this system syngas that consists of hydrogen and possible other gas impurities are fed at a relatively low pressure, of about 3 psi, to the anodic side of the electro-chemical device/hydrogen pump. At the delivery side of the pump which is the cathodic side the pressure of the purified hydrogen could reach higher pressure levels such as 40 psi and higher. Stainless steel fittings and valves were installed onto the module to incorporate a pressure gage on both the anode and cathode side of the electrochemical cell.

Figure (15) indicates a) at certain power value such as 0.075 W/cm^2 hydrogen production is about 13.5 SCCM for single cell, about 17 SCCM for two cells and about 25 SCCM for three cells that as the power density increases the deviation between the 1 cell, 2 cells and 3 cells performances and the difference in hydrogen flow rate become more pronounced. For example at power density 0.1 W/cm^2 the 1 cell produces 15 SCCM, the 2 cells produce 20 SCCM and three cells produce close to 30 SCCM (using extrapolation). This represents about 33% difference between the two setups. However, at 0.15 W/cm^2 power density, 1 cell produces 17.5 SCCM and the 2 cells produce 24 SCCM. This represents a difference of 37.14% the two setups.

Further experimental work was performed to examine the effect of the cell number on the hydrogen purifier flow rate. The flow rate of one, two, and three cells was monitored and plotted versus the power density indicating a clear increase in the hydrogen flow rate and pressure output with the increase in the number of cells.

Therefore, in this report, more stainless steel separator plates were manufactured and spray coated with carbide-based coating using High Velocity Oxygen Fuel System (HVOF) to increase the purifier size and enhance its performance and achieve the full-scale stack performance for the current application.

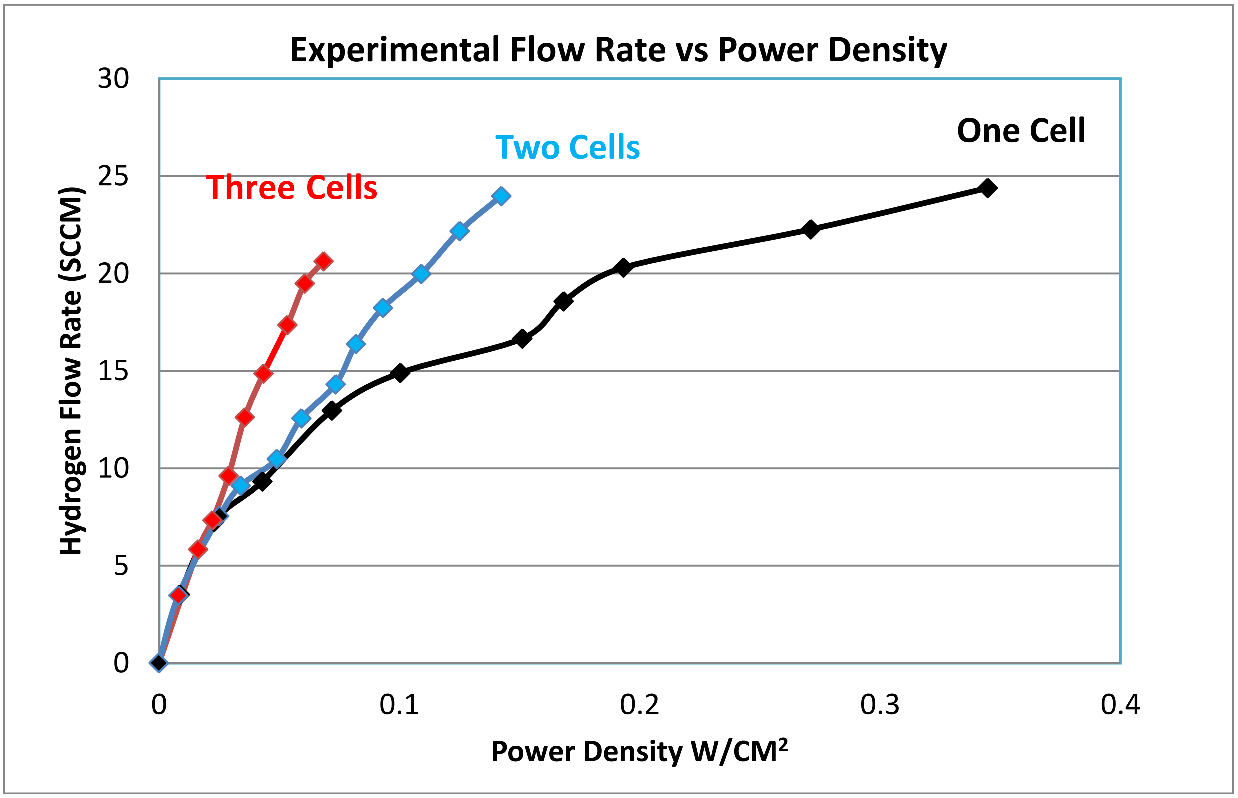


Figure (15): Performance of full-scale single cell, two cells and three cells evaluated by hydrogen purifier power density vs. hydrogen flow rate per unit area, of the active area of the membrane.

Further analysis of Figure (15) above indicates that at the same power density as the number of cells increases the productivity of the stack also increases so as its efficiency. As shown in Figure (15A)

Therefore, stamping and/or coining of the separator plates were considered for manufacturing hydrogen stack separators cost effectively.

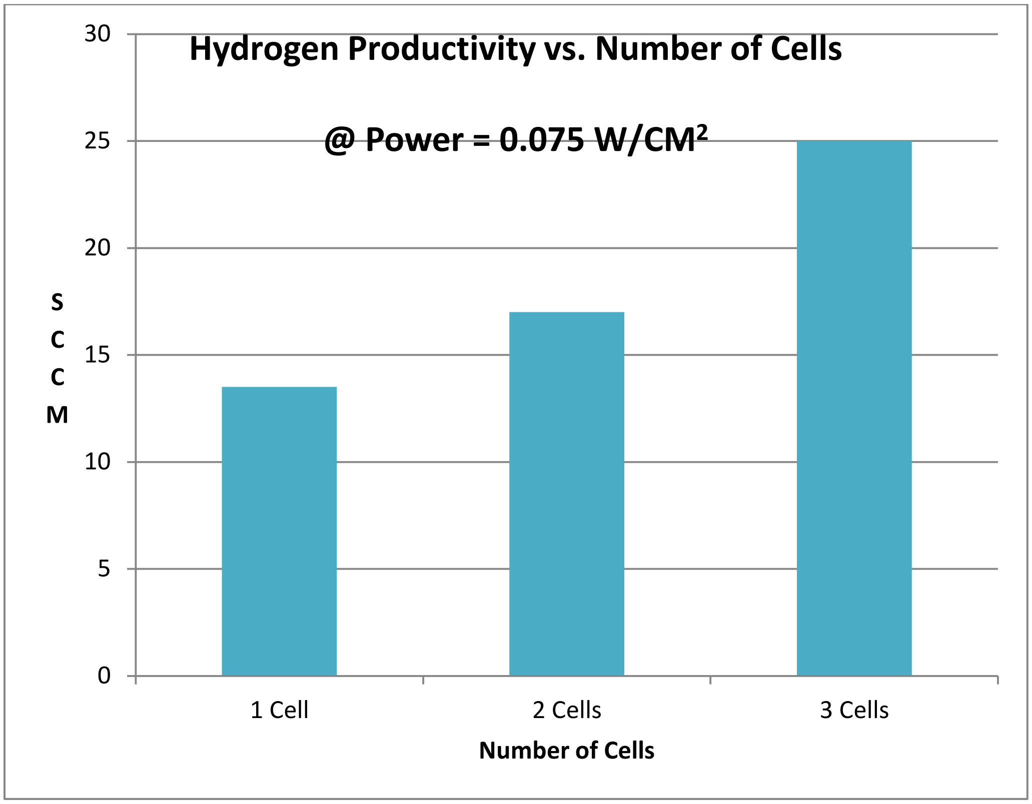


Figure (15A) Effect of number of cells on Hydrogen Productivity

Task 4: Conclusions

- As the power density increases the deviation between the 1 cell and 2 cells stack performance and the difference in hydrogen flow rate becomes more pronounced.
- The compression rate will continue to increase with current because the applied current is the ultimate driving force on the hydrogen ion (proton) through the Proton Exchange Membrane (PEM) in the electrochemical separation system.
- This system can be used to compress pure hydrogen in a tank for storage when hydrogen is not directly consumed by fuel cells.
- The hydrogen flow rate increases with the increase in the number of cells as well as power density.

Task 5- Design and development of 5 kW PEM Hydrogen Fuel Cell, utilizing IRTT's patented bipolar plate technology

In this task considerable attempts were performed to optimize the thermal spray coating quality applied to the Fuel Cell Stainless Steel bipolar plates to produce the lowest possible Interface Contact Resistance (ICR) and the highest possible Corrosion Resistance. The design of experiment technique was performed on the thermal spray parameters to achieve the optimum coating quality and reduce the possibility of surface wrinkling of the plates due to Internal Thermal Stresses. Also, we have nitrated the Chromium Carbide Powder to improve its ICR performance as shown in Figure (16)

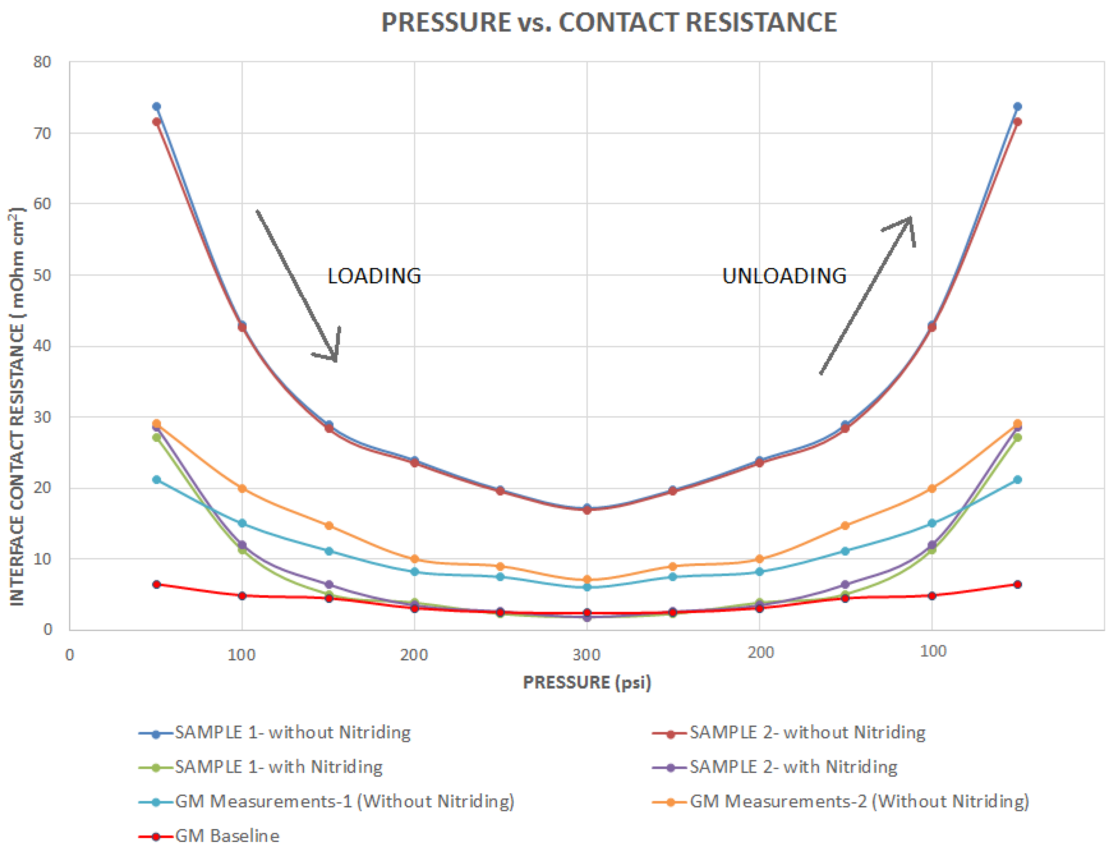


Figure (16) IRTT's 2006 patented thermal spray coating superimposed with treated powder coating

Thin Stainless Steel plate–shows wrinkling due to internal thermal stress as shown in Figure (16A) - To mitigate the surface wrinkling problem caused by thermal stresses, a number of technical approaches were utilized as shown in Figure (17)

Figure (16A) Sample coated plate with excessive wrinkling- Optimization of the spray parameters is required

- The first technique is to apply tension on the bipolar plates using springs during the spraying process as shown in Figure (17) below

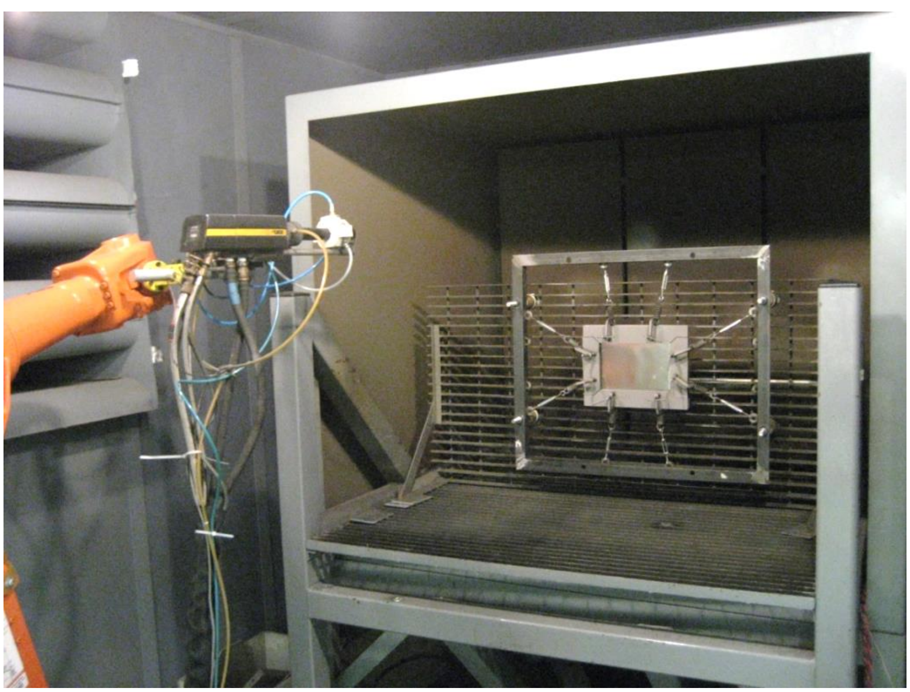


Figure (17) Spray hood with spring supported Frame to minimize wrinkling due to internal thermal stresses

Figure (17A) 55 ton compression with heat to flatten the plate, relieve stresses and eliminate wrinkling produced by the combination of internal thermal stresses and the mismatch in the thermal expansion coefficients between the substrate and the coating materials

Figure (18) Sample coated plate with the least wrinkling- Optimized run #10 Table (1)

Table (1) Spray Parameters for thermal coating

RUN NO	COATING SPEED (mm/sec)	STAND OFF DISTANCE (in)	Z DEPTH (mm)	INTITIAL TEMPERATURE (°C)	WRINKLES/IN2	RESISTIVITY (mΩ)
1	1100	18.5	-4.5	27	1.577	
2	1100	20	-3.5	60	1.11	
3	1100	21.5	-2.5	93	1.088	
4	1200	18.5	-3.5	93	0.911	23.928
5	1200	20	-2.5	27	1.155	
6	1200	21.5	-4.5	60	1.2	
7	1300	18.5	-2.5	60	1.422	
8	1300	20	-4.5	93	0.866	22.4795
9	1300	21.5	-3.5	27	1.177	
10	**1300**	**21.5**	**-4.5**	**93**	**0.644**	**11.5145**
11	1300	21.5	-4.5	20	1.2	
12	1300	21.5	-4.5	150	0.8	14.95
13*	1300	21.5	-4.5	93	0.95	17.1587

*Corners were not cut

In table (1) above the optimized spray parameters are shown in **run number 10.** The lowest Interphase Contact Resistance (ICR) with a value of 11.5 mOhm.cm.

In this task the coated metallic bipolar plate's technology was developed at the IRTT of Farmingdale State College. Short Metallic bipolar PEM stacks were developed and tested using the fuel cell testing station, which showed very favorable results. These short stacks didn't have the sufficient power to produce 5 kW of power but were sufficient to prove the concept of metallic bipolar plate technology. To develop a 5 kW DC/AC micro-grid to power homes away from the utility grid, a 5kW fuel cell was acquired and connected to a converter and inverter to produce 110 volts AC. This micro-grid is capable of covering the electric demand of an average size house away from the utility grid as shown in Figure (19).

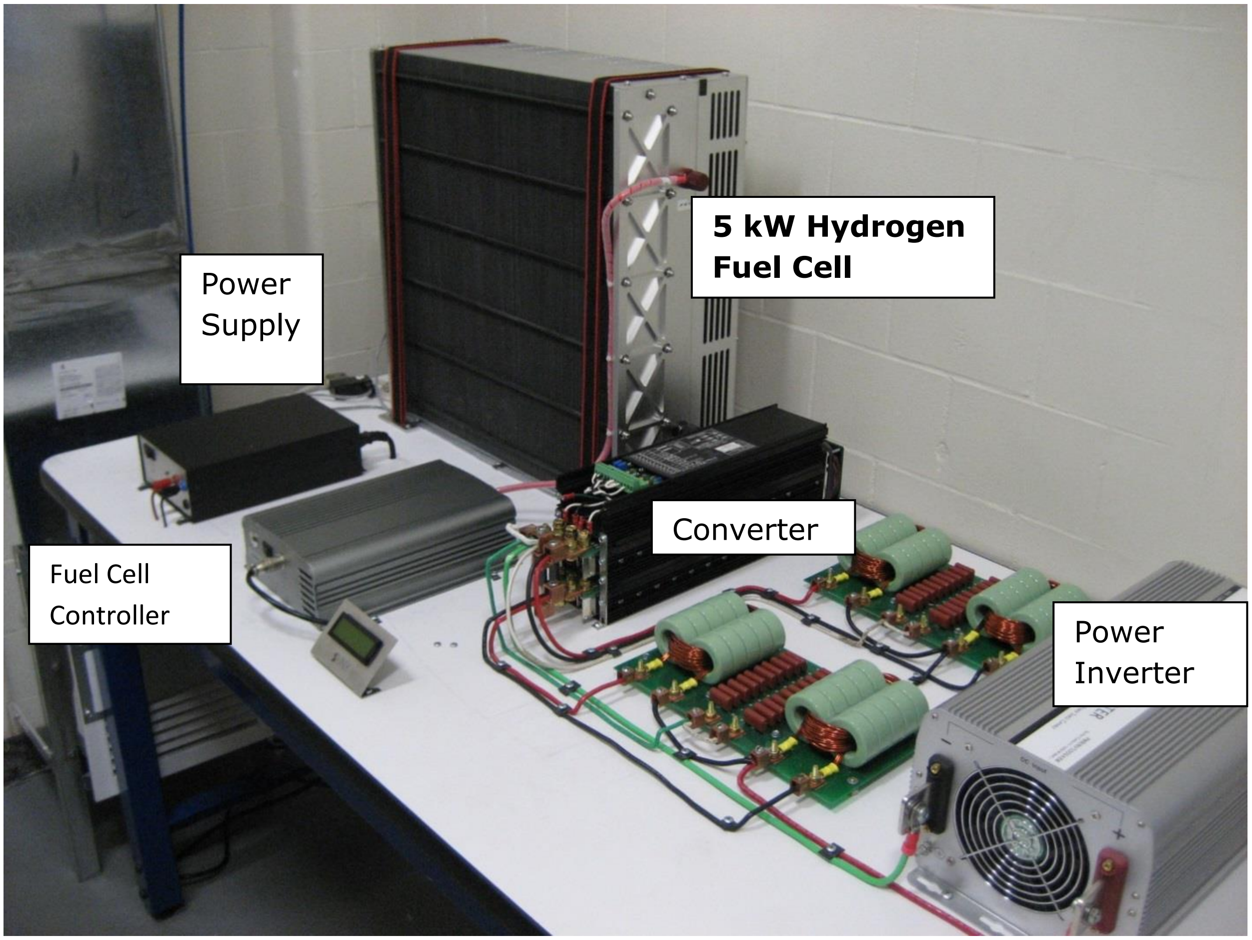


Figure (19) Electric power conditioning system for the 5 kW Hydrogen Fuel Cell

Task 5 conclusions:

- The metallic bipolar plates coating technology was optimized and successfully tested.
- Proton Exchange Membrane (PEM) stack technology was also started
- The 5 kW Hydrogen Fuel Cell with converter and inverters for power conditioning was completed as shown in figure (19) above and is able to energize average size home appliances and electronics systems as well as charging electric cars.

Task 6: Final system Integration and Field Testing:

A new and innovative technique for CO removal such as the utilization of Copper Chloride, is our final choice combined with the electrochemical separation process. The power conditioning of the 5 kW PEM Fuel Cell that safely power home appliances and electronics as well as charging electric vehicles represents the final stage of this project. The present research work for this project has produced additional intellectual properties that were protected by a provisional application followed by a current patent application that establishes our Intellectual Property (IP) patent filing with the U.S. Patent and Trademark Office (USPTO) to protect our newly developed technology.

The production of hydrogen rich gas from biomass waste is directly used to energize ICE Vehicles and powering (high & low Temperature) Proton Exchange Membrane (PEM) fuel cells, after further CO purification, to produce useful Combined Heat and Electric Power (CHEP).

The system under consideration is uniquely designed to produce very useful ultra-pure hydrogen derived from biomass waste and synthesis gas (syngas). Figure (20) demonstrates our final system integration of our research and development work performed in this research project to produce cost effective energy from biomass.

The system was completely integrated and successfully tested to produce two types of syngas A) Syngas with 2% to 3% Carbon monoxide that could be directly utilized to power Internal Combustion Engines B) Ultra-pure hydrogen that is further processed and bubbled through copper chloride followed by the final purification stage using electrochemical separation system.

Our subcontractor Stony Brook University has independently conducted testing on various WGS types of catalysts and confirmed the utilization of our catalyst as an independent third party.

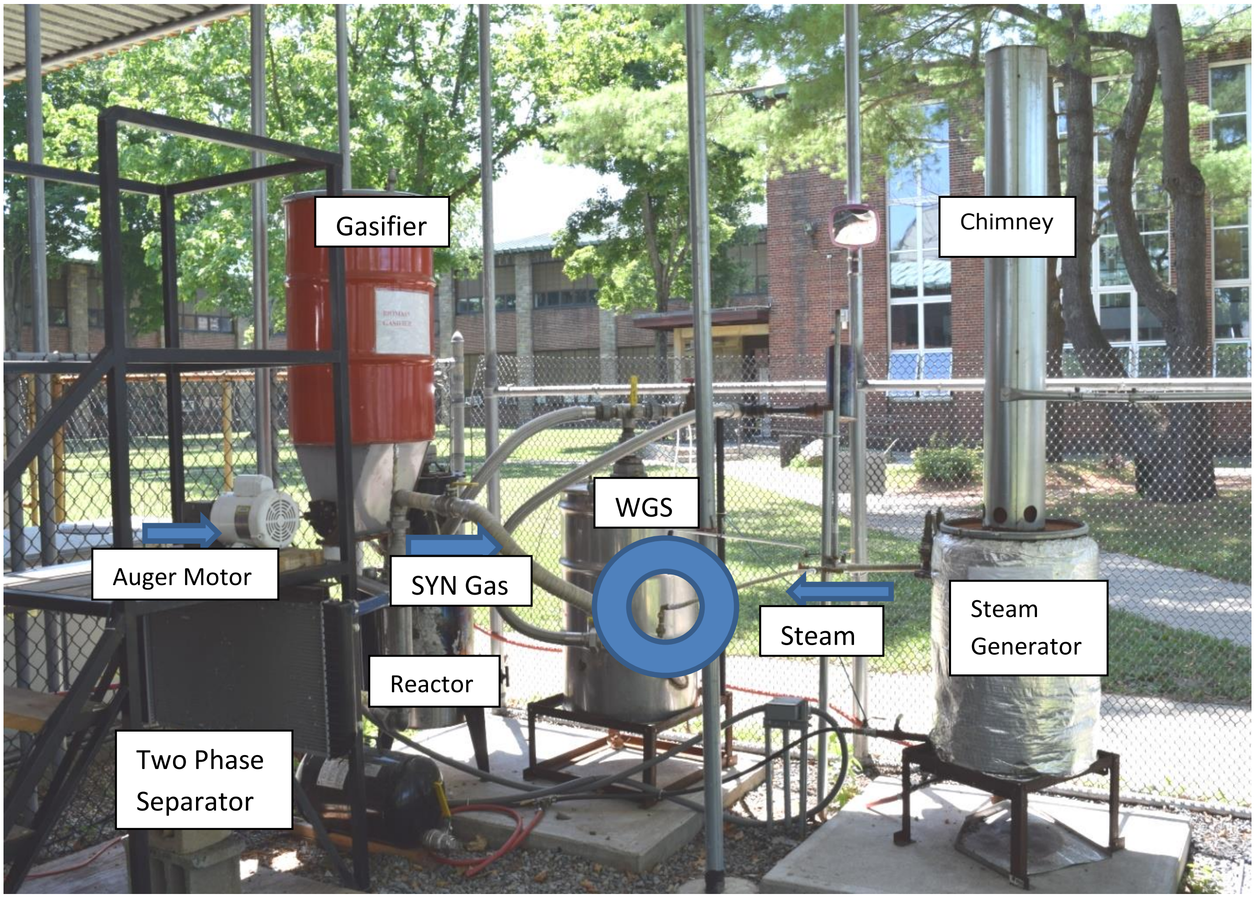


Figure (20) Final system integration for Cleanup/Scrubbing process of Carbon monoxide from syngas

After the WGS process, shown in figure (20) above, the output syngas will contain 2% to 3% carbon monoxide and about 40% hydrogen sufficient to energize internal combustion engines. Further purification of the carbon monoxide (CO) using copper chloride followed by electrochemical separation process will reduce CO to > 10 ppm and will render the syngas capable of powering fuel cells.

Task 6: Conclusions:

- The system is completely integrated and tested
- The system is capable of producing syngas with about 40% hydrogen and 2% to 3% CO

Task 7: Final Field and Performance testing and Evaluation:

In the final quarter, a number of field-testing was conducted in this final stage of the project as shown in the following:

1) Testing the overall performance of the complete system assembly to examine its performance, integrity and durability:

The final testing results clearly showed the system's excellent durability and the reliability of all its integrated sub-systems and components. The tar filters should be changed periodically using activated carbon granules. All tar must be removed from the system's syngas because of its harmful effect on the WGS (WGS) and the fuel cells catalysts.

2) Testing critical aspects of the project including the following:

a) Tar purification sub-systems:

To protect the system catalysts for both the WGS and the fuel cells (high and low temperatures) from tar that exists in the syngas, two tar filters were made of packed fresh activated carbon to absorb tar from the system and prevent it from poisoning these catalysts. One filter is located at the exit from the gasifier reactor and the second is located at the entrance of the WGS to prevent any tar from reaching and tarnishing the catalyst inside the WGS.

The first filter located by the gasifier was able to reduce the tar amount by 40% this gives a clear indication that the larger filter located by the WGS will absorb the remaining 60% tar in the syngas.

b) Verifying the cost effectiveness of a PEM fuel cell metallic bipolar plate coating – Based on One Cell Short Stack:

This verification study was conducted to evaluate the cost savings resulting from the carbide-based coating on stainless steel PEM bipolar plates. The current experimental work consisted of ten repeatable measurements of the power output from coated power stack and another similar measurements of uncoated Proton Exchange Membrane (PEM) fuel cell stack made of 304 stainless steel bipolar plates. The comparison of the power output for the coated and uncoated clearly show extensive savings amounts to $1.16M over five years of operation Figure (27) for carbide-based coating vs uncoated stack.

Bipolar plates serve as the backbone of a Proton Exchange Membrane (PEM) fuel cell stack. They isolate the individual cells, conduct current between cells, facilitate water and thermal management through the cell, provide conduits for reactant gases and facilitate the removal of reaction products [1,2]. Therefore, bipolar plates must be made of materials with high corrosion resistance, low interfacial contact resistance, high electrical conductivity, high mechanical strength, low permeability, no brittleness, hydrophobic and low cost. In addition, these bipolar plates must have excellent manufacturability and suitable for cost-effective high volume production [3-7].

Cincinnati Milacron SABRE 850 Machining Center Figure (21) of the Institute for Research and Technology Transfer (IRTT) was utilized to fabricate bipolar plates made of 304 stainless steel with 6x6 inches width and height and 3.94 x 3.94 inches (10x10 cm) active area as Figure (22) depicts. A small one-cell stack as shown in Figure (23) was also fabricated and tested at room Temperature (68^{O}F) and 65% relative humidity using the Electronic Load shown in Figure (24).

Figure (21) Cincinnati Milacron SABRE 850 Machining Center

Each plate in the power stack is sprayed with carbide-based coating using the IRTT High Velocity Oxygen Fuel (HVOF) shown in Figure (25). The commercial cost of spraying the plate is estimated at $1.00 and is therefore ignored in the current study.

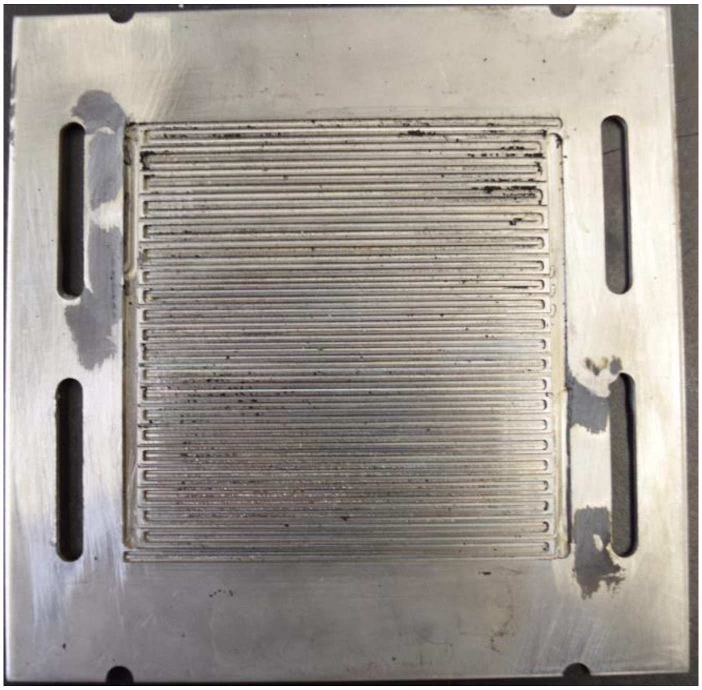


Figure (22) bipolar plates made of 304 stainless steel with 6x6 inches width, height, and 3.94 x 3.94 inches (10x10 cm) active area

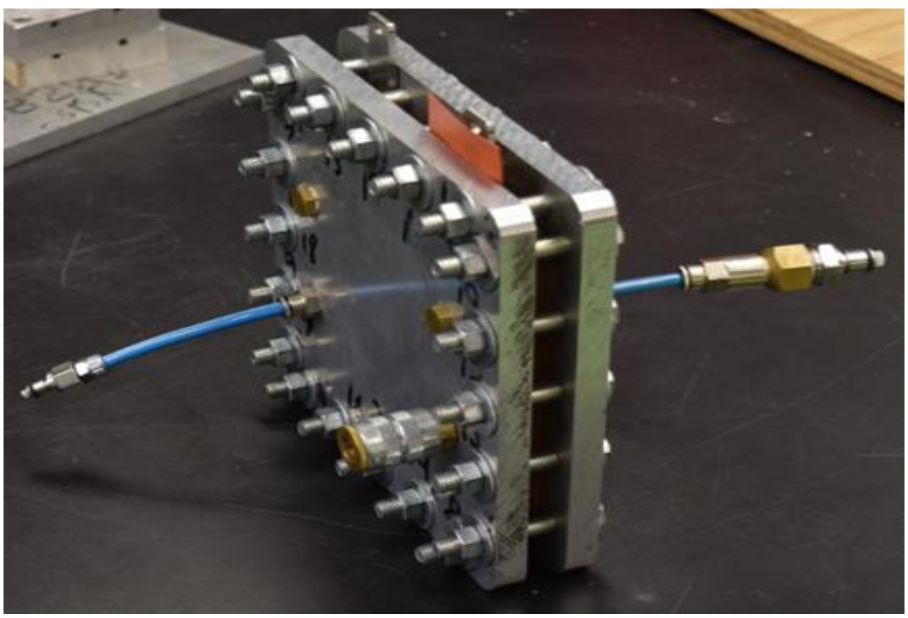


Figure (23) One cell short stack

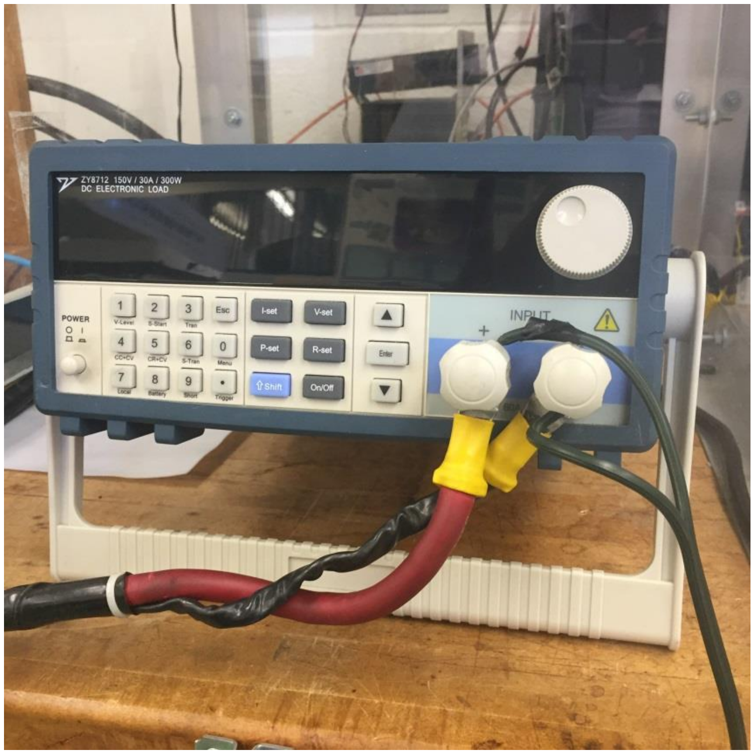


Figure (24) Electronic Load

Figure (25) High Velocity Oxygen Fuel (HVOF)

Ten repeated power output measurements for coated and uncoated stainless steel bipolar plates were averaged, analyzed and plotted as shown in Figure (26). The analysis clearly showed that the overall performance of the coated fuel cell demonstrated obvious improvement in performance as compared to the uncoated. This is attributed to the better and improved Interface Contact Resistance (ICR) of the applied coating that has resulted in enhanced power output with accumulated savings of approximately $1.2M over 5 years of operation as Figure (27) depicts. In addition, the coating has indicated long lasting durability and savings amounts to $0.3 per cm2 of the plate active area based on $0.15 kW per hr.

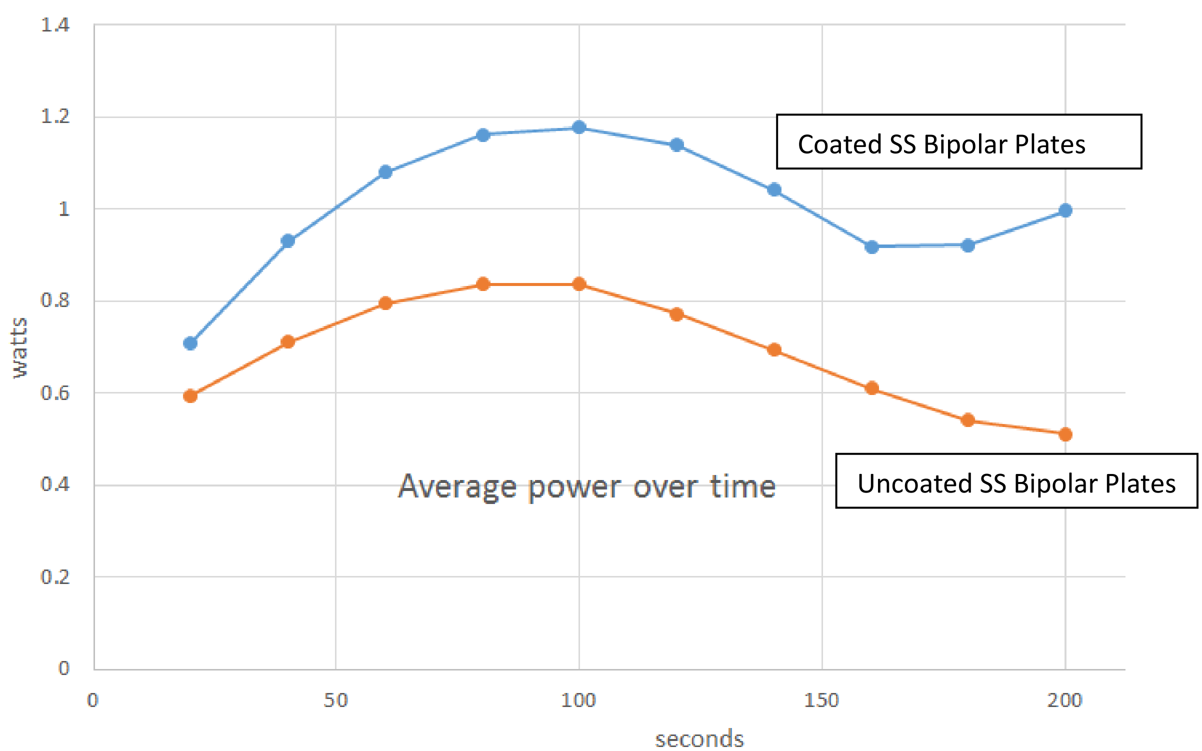


Figure (26) Improved power output and savings due to better conductive coating based on $0.15 kW.hr are valued at $0.3 per cm^2 of the bipolar plate active area

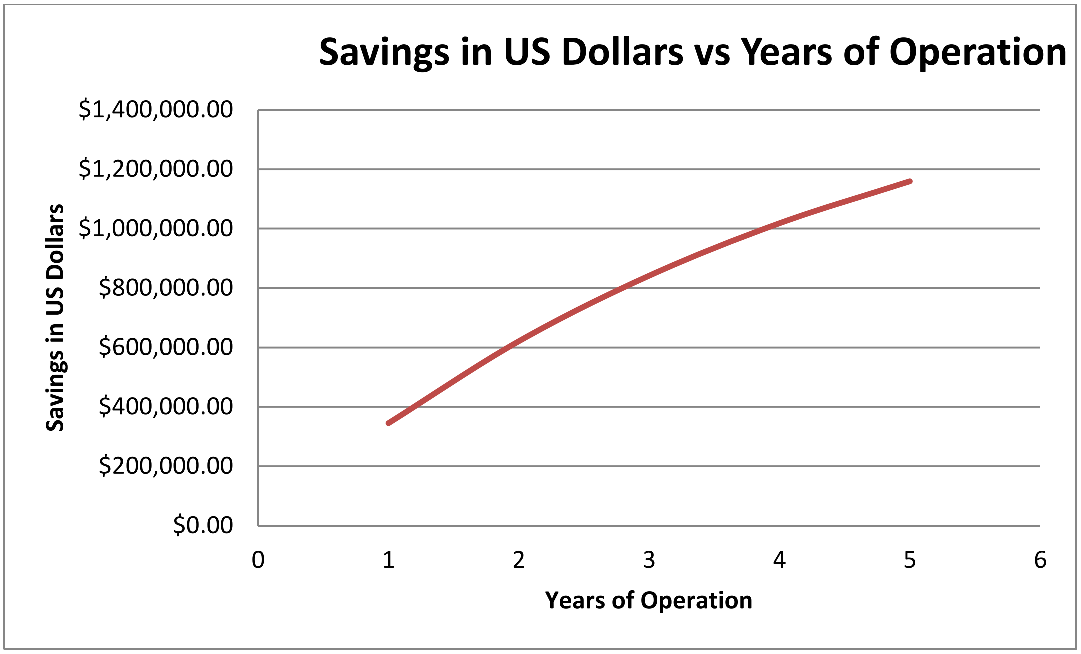


Figure (27) Improved power production and savings due to bipolar plate coating in comparison to uncoated valued in US dollars and based on $0.15 kW.hr

It should be noted that in this cost analysis study of coated bipolar plates the reference of comparison used was the uncoated bipolar plates. This is done to show the degree of improvement in performance due to our patented coating technology in comparison to the original plate as a reference. However, if the majority of applications will utilize different types of coatings for the reference plate the analysis will be different due to the reference plate coating price and performance. In this case, the analysis conclusion could be deemed unfavorable.

c) Effect of CO_2 on cell performance;

It is well known that CO has a considerable negative effect on the Pt catalyst performance; however, in this study CO_2 also showed some negative effect on the linearization curve and performance of the low temperature fuel cell as Figures (28&29) depict.

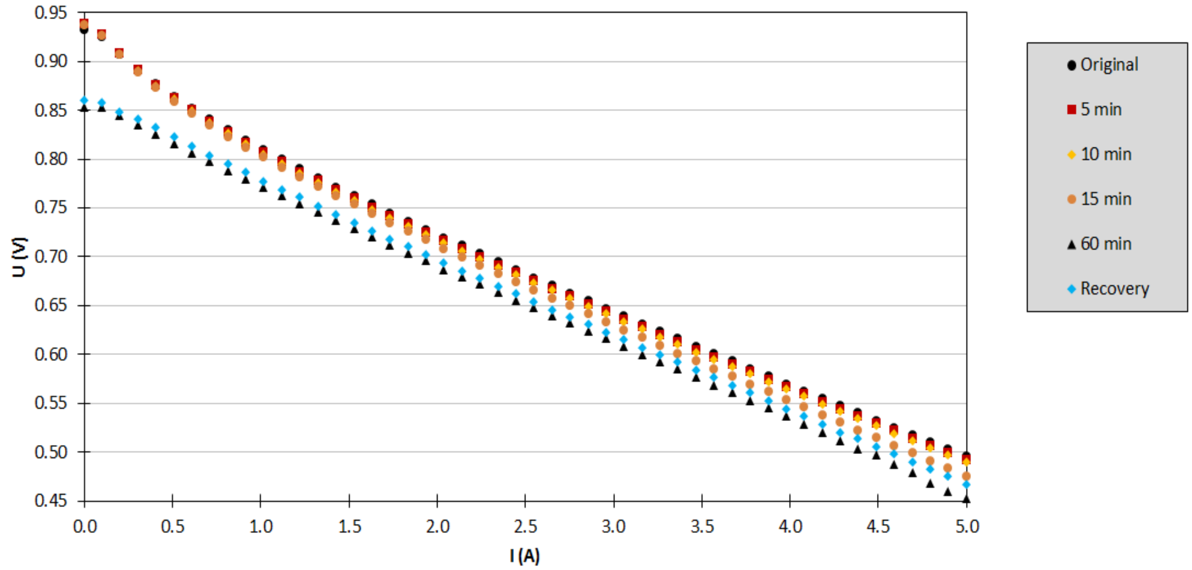


Figure (28) Shows the relatively small effect of 10% CO_2 on the low temperature fuel cell performance even with increased exposure time

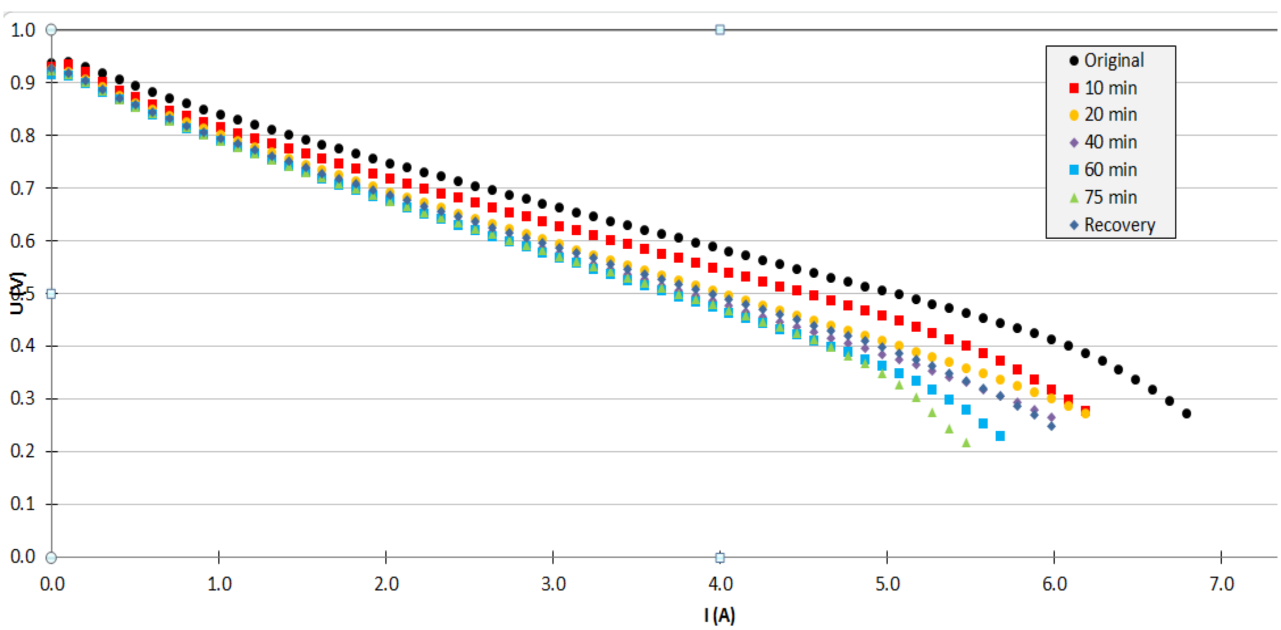


Figure (29) shows the effect of 30% CO_2 on the low temperature fuel cell performance as the exposure time increases

At high temperature PEM fuel cell, both effects of CO and CO_2 are expected to be reduced or eliminated, as the case of the CO_2 will show.

e) ICE Flex Fuel Vehicle performance – BMW 74i – using various flex fuels such as Gasoline, Natural gas, and Syngas:

As has been discussed earlier in this report – our biomass system displayed in Figure (20) is capable of producing Syngas with about 40% hydrogen and about 3% CO the rest is nitrogen, and carbon dioxide. Our initial test of this syngas produced with our gasifier shown in figure (20) on single cylinder two horsepower lawnmower internal combustion engine was very encouraging. Our lawnmower engine now runs on gasoline, propane and syngas. In a similar fashion after testing the donated BMW 74i with gasoline to establish a base line we are retrofitting it with a kit to get it amenable to use flex fuels such as propane, natural gas and Syngas. As shown in figures 30 and 31 we are testing and installing the natural gas and syngas kit.

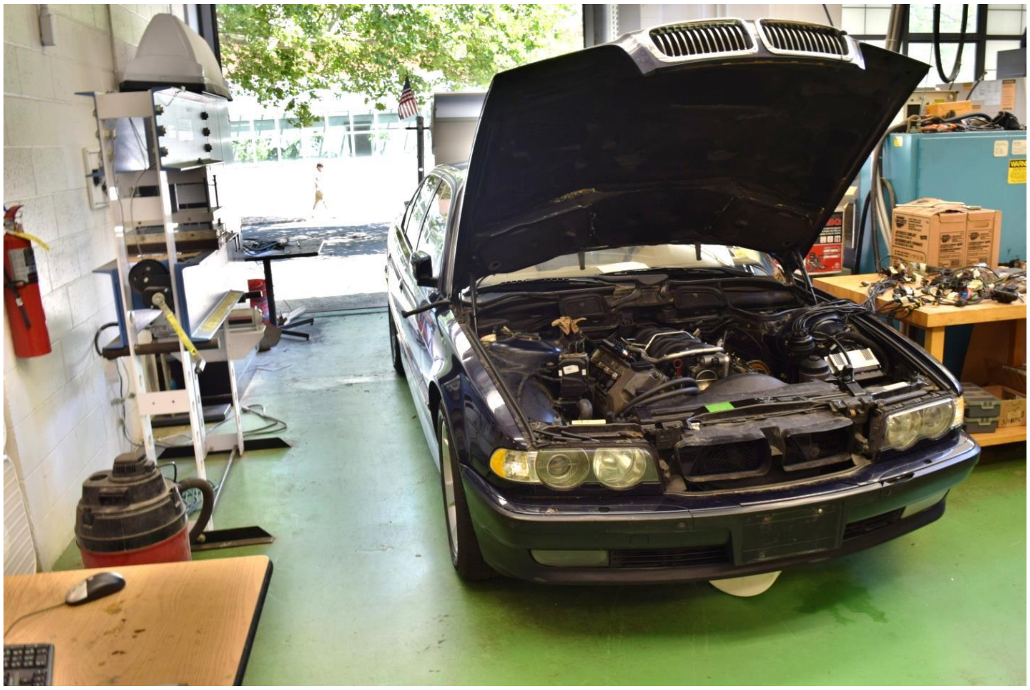


Figure (30) Testing the BMW 7 series using gasoline as fuel

Due to the abundance in forests and trees in the north east of the USA, the syngas will provide a very good cost effective solution to our gasoline constant fluctuating prices and instability in fuel cost.

Figure (31) Installing the natural gas and syngas kit

The vehicle showed excellent performance with gasoline and similar is expected with the recently installed natural gas and syngas kit

f) Hydrogen purification separator plates final design and testing

The hydrogen purifier separator plate design and the Stack Purifier testing station are all shown in figure (32) below – The separator flow field is designed to maximize the hydrogen purification and minimize hydrogen losses or waste.

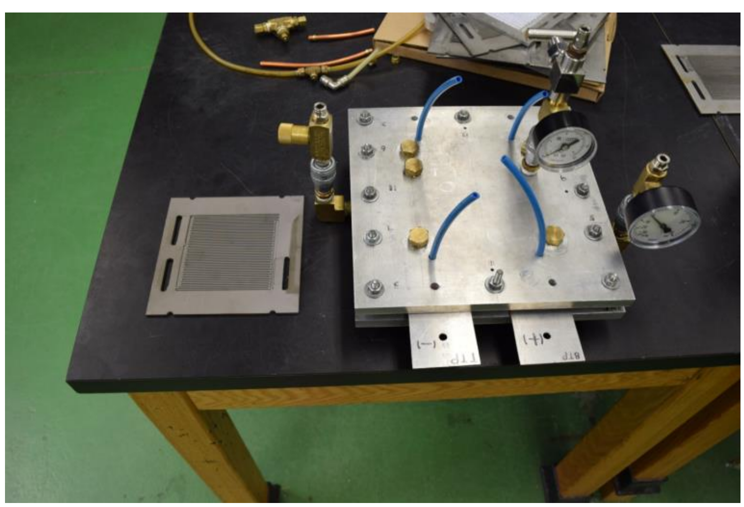


Figure (32) Separator plate and stack hydrogen purifier testing station

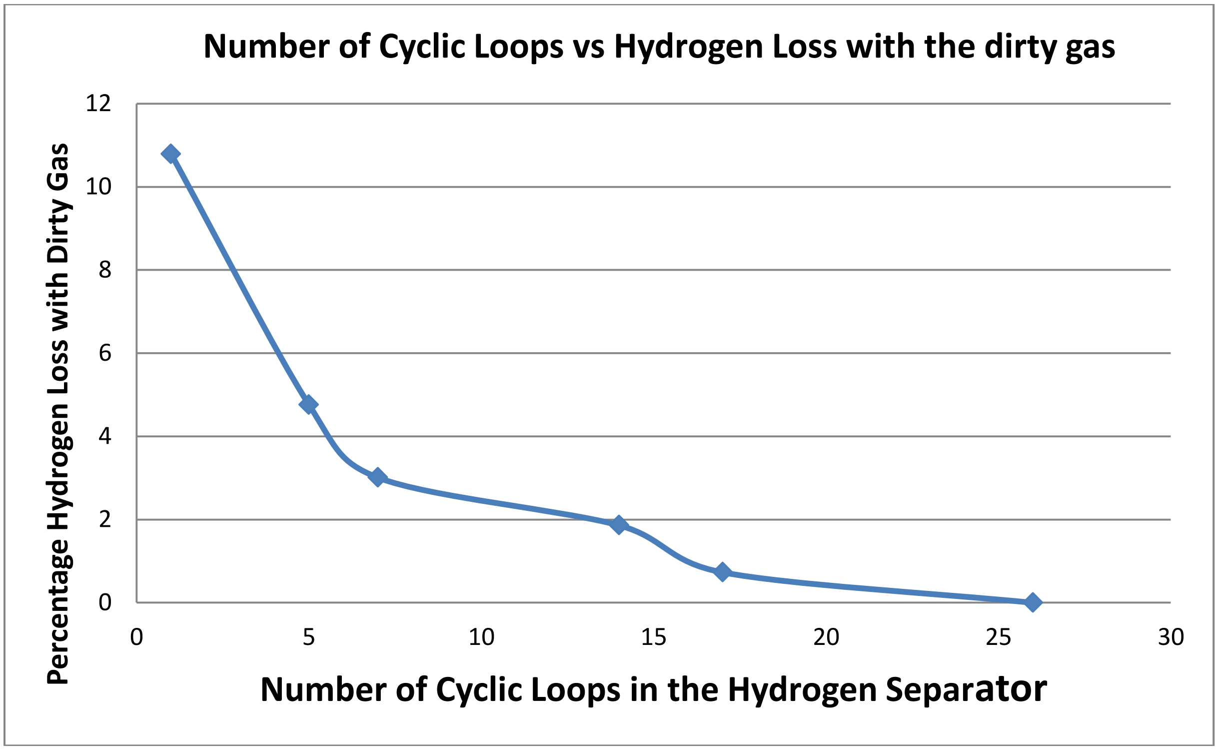
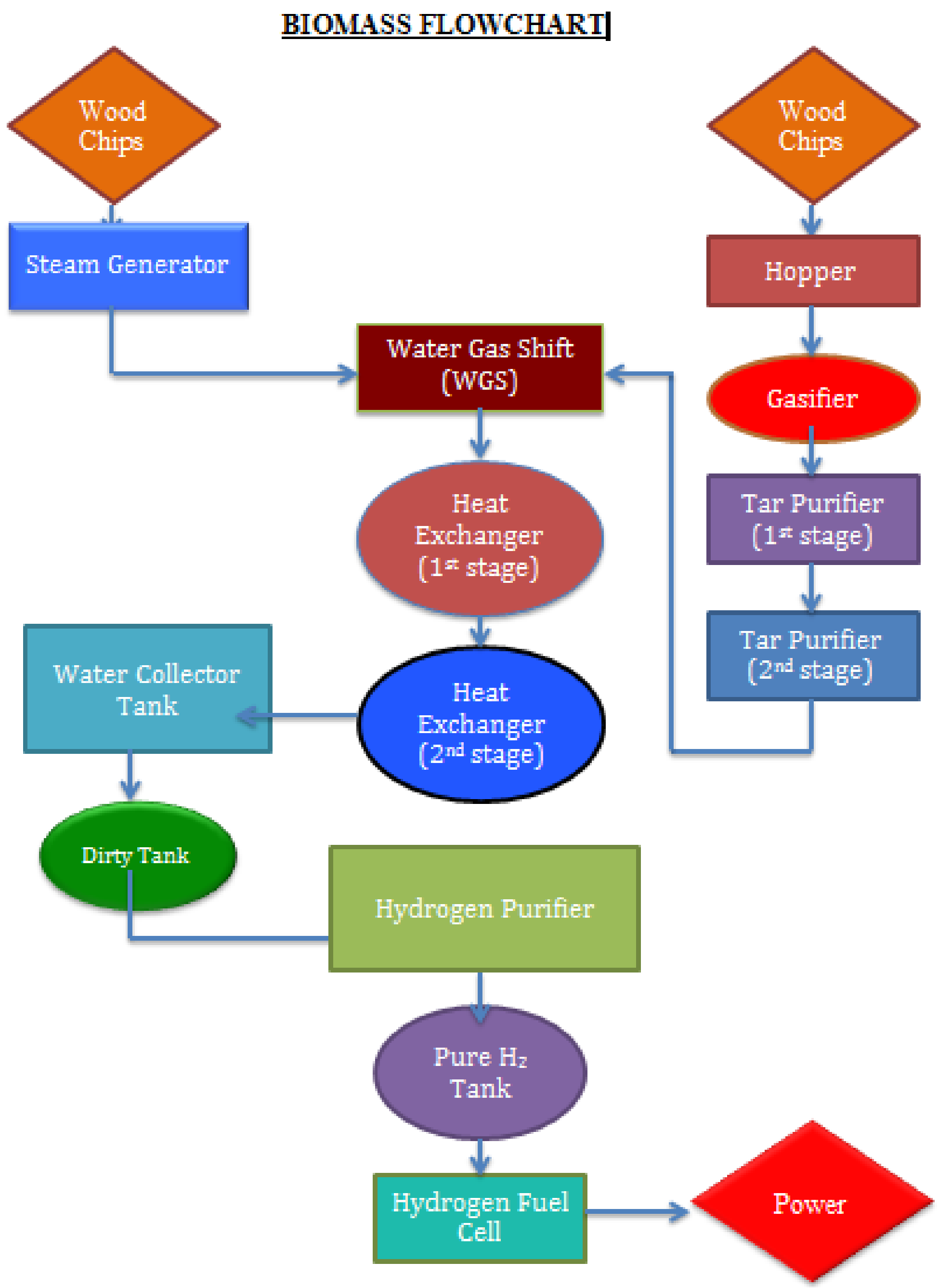


Figure (33) Shows the % loss of hydrogen with the dirty gas outlet from the purifier could be considered inversely proportional to the increasing number of loops in the flow field pattern in the hydrogen separator in the purifier stack

Therefore, he total number of the cyclic loops in the separator of the hydrogen purification system should be manufactured at 26 or higher.

Summary Flow Chart of the Biomass Project



Final Project Conclusions:

1) The project has achieved the Statement of Project Objectives (SOPO) that was approved by the DOE in the beginning of the project.

2) The project succeeded in the production of ultra-pure hydrogen with less than 10 ppm carbon monoxide using WGS as a clean-up process followed by two purification processes, namely Copper Chloride and Electrochemical separation process of hydrogen

3) Ultrapure hydrogen produced by this new technique can successfully and economically powers 5 kW Proton Exchange Membrane (PEM) fuel cells to generate combined heat and power (CHP) with 92% efficiency and about 7 cent per kW.hr since the wood chips, forest debris and farm waste such as corn husks used as fuel in this application are quite inexpensive.

4) Polyoxometalates were tested as an oxidizer during this project , but did not show repeatable performance.

5) Carbon dioxide has some negative effect on the low temperature PEM fuel cells but could be alleviated when the operating temperature is set at 80^{o}C

6) High temperature PEM fuel cells with operating temperatures up to 190^{o}C can tolerate up to 2% carbon monoxide and produce energy for about 6 cent per kW.hr

7) Internal combustion engine vehicles could be converted to alternative fuels such as Natural gas and Syngas and operates very economically compared to the fluctuating price of the gasoline, as this project demonstrates.

8) This project produced a number of innovative technologies that are proven economically viable as demonstrated earlier and are currently patented by the State University of New York Research Foundation. These technologies are ready to be transferred to industry for commercialization and creating high paying jobs to support the economic growth locally and nationally. In addition, these new technologies developed, in the current project, will directly contribute to solving our national energy problem.

Patents, Publications, Presentations

Patents:

Patent application was filed in the patent office by SUNY Research Foundation in collaboration with Farmingdale State College / The Institute for Research and Technology Transfer (IRTT).

Latest Presentations

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a IEC group, Depto. Ingeniería Química y Nuclear, Universitat Politécnica de Valencia (Spain)

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juagisan@etsii.upv.es; "Empirical modelling of the effect of CO2 poisoning on the polarization curve of a PEMFC)" Farmingdale State College International Energy and Sustainability Conference 2015, November 12 &13, 2015

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" Effect of CO_2 poisoning on the parameters of a PEMFC empirical model" Farmingdale State College International Energy and Sustainability Conference 2015, November 12 &13, 2015

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b Institute for Research and Technology Transfer (IRTT), Farmingdale State University (USA)

, "Experimental study of the effect of CO_2 poisoning on the polarization curve of a PEMFC", Farmingdale State College International Energy and Sustainability Conference 2015, November 12 & 13, 2015

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