University of Strathclyde Engineering

Department of Mechanical Engineering

Hydrogen Fuel Cell Power System

Performance of Plug Power GenCore 5B48 Unit

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Signed: Andres Gabriel Christou Date: 10/09/2010

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Abstract

In this Thesis are presented the results of an experimental analysis of the dynamic response of a low pressure proton exchange membrane (PEM) fuel cell stack to step changes in load, which are characteristic of both hydrogen stationary power systems and automotive applications.

The analysis and experiment are based on a low pressure 5 kW proton exchange membrane fuel cell (PEMFC) stack and the model tested was a GenCore® 5B48 Fuel Cell System.

This research main aim is to acquire a better understanding of the electrical and electrochemical processes when accounting for the characteristic cell voltage response during transients and establish the overall efficiencies.

The most important features of the GenCore 5B48 fuel cell system are illustrated in this thesis by analysing the obtained results from the experimentation, features such as electric characteristics, overall efficiency, fuel usage, and in general the operation performance of the fuel cell under load conditions.

This work is dedicated to family for giving me the opportunity to fulfil my dreams and support to achieve my ambitions.

And especially devoted to my fiancée, Ana who was always there for me, supporting and enduring me.

Whatever the dream, no matter how daring or grand,
Somebody will eventually achieve it.
It might as well you.
Bryce Courtenay

Acknowledgements

I would like to thank Professor Joe Clarke, my supervisor for giving me the opportunity to work on the "real" thing. Without your guidance this project would not be concluded.

Also I have to express my gratitude to Professor David Clelland from the naval department. Your cooperation and determination in establishing a safe and functioning fuel cell laboratory in a very short period of time was invaluable.

Extra thank to the personnel of the naval department and the mechanical engineering department for being always there and help me with my "bizarre" requests.

Special thanks to Mr. John Redgate the electrician from the mechanical engineering faculty for his willingness to provide assistance and run all the time to the building of the naval department to face the arising challenges. Your humour even on my darkest days was always appreciated.

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Nomenclature

Symbol	Explanation & Unit
A	Area cm^2
ASR	Area-specific resistance $\Omega \cdot cm^2$
E	Electron charge 1.6×10^{-19}
E	Thermodynamically ideal voltage V
F	Faraday constant 96.485 C/mol
G	Gibbs free energy J/mol
H	Enthalpy of reaction J
I	Current A
N	Avogadro‘s number 6.02×10^{-23} mol^{-1}
p	Pressure bar, atm, Pa
P	Power W
R_u	Ideal gas constant 8.314 J/mol·C
R	Resistance Ω
S	Entropy J/K
T	Temperature K
U	Internal energy J
V	Voltage V
V	Volume L, cm^3
W	Work J
α	Transfer coefficient Dimensionless
ε	Efficiency Dimensionless
η_{act}	Activation losses V
η_{conc}	Concentration losses V
η_{ohmic}	Ohmic losses V
Q_{fuel}	Fuel flow rate Slm
σ	Conductivity S/cm

1 Introduction

The demand for renewable energy power and renewable energy commercial applications is taking dominant place in the minds of people and guides the markets.

Large corporations and small developers of renewable applications are flooding the markets with plenty of products based on renewable energy technology.

The majority of these applications either for portable or stationary applications are based on the sector of the fuel cells. There are different types for different uses with dominant place on the market and not only the proton exchange membranes fuel cells (PEM FC) and the solid oxide fuel cells (SOFC).

Because of this variety of fuel cells and the claimed performances of them from the different manufacturers rises the need of evaluating and confirming their claims.

In the following sections is presented the PEM fuel cell technology and explained briefly its operation. Then it is performed an analysis of the performance for a specific PEM fuel cell product, the GenCore 5B48 PEM fuel cell system.

In addition on the appendixes is included a brief history of the fuel cells, the different fuel cell types and the applications suitable for, plus a comparison table illustrating their features.

2 Principles of fuel cells

2.1 General concept

A fuel cell (FC) is a device that produces electricity by electrochemical reaction of a fuel and an oxidant. In the most Hydrogen – Oxygen fuel cell, the oxidant is Oxygen and the fuel is Hydrogen.

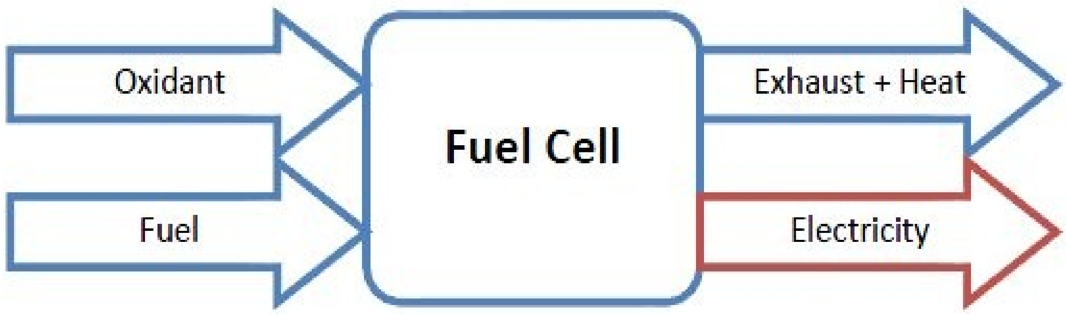

Figure 2.1 General concept of fuel cell

The H_2, O_2 fuel cell releases pure water (H_2O), electricity and heat which is treated as a waste in most cases but there is always a possibility of "harvesting" this heat in result too increase the efficiency of the FC system. The general idea of the operation of a FC as is presented in figure 2.1 above.

2.2 Advantages and disadvantages

The claimed operational advantages from the PEM FC manufacturers are plenty and significant. All of these claims need to be investigated further in order to be verified because none of the PEM F.C. types that exist on the market are yet cheap and/or reliable enough to widely replace traditional ways of generating power, such as internal combustion. For this reason this research is focussed in investigating the efficiency of a PEM F.C.

The main fuel cell advantages are:

a) Production of electricity as long as they are supplied with fuel;
b) Production of electricity directly from chemical energy;
c) Potential for very high efficiency;
d) High energy density and ability for quick recharging by refuelling;
e) Simple, no moving parts, silent;
f) Potential for high reliability and long-lasting systems;

g) Environmentally friendly - undesirable products such as NOx, SOx, and particulate
h) Emissions are virtually zero;
i) Flexible – allow easy independent scaling between power and capacity.

Even though the fuel cell technology is thriving and numerous studies have been conducted and this technology is under investigation and development; it has some significant disadvantages. The main disadvantages are:

a) High cost – the main barrier to fuel cell implementation;
b) Limitations in power density;
c) Fuel availability and storage – hydrogen fuel has a low volumetric energy density and is difficult to store, alternative fuels are difficult to use directly and usually
d) Require reforming;
e) Temperature compatibility;
f) Susceptibility to environmental poisons – some materials used, especially in low temperature fuel cells, are quite vulnerable to reactant contaminations;
g) Durability issues;

3 PEM Fuel Cell

3.1 PEM FC Structure and operation

The modern PEM fuel cells consist of three main parts: anode, electrolyte and cathode. They are manufactured in the form of three different layers connected to each other. Each of them has high influence on the cell's performance. The scheme of a Proton Exchange Membrane Fuel Cell (PEMFC) is shown in Figure 2.3.1 below.

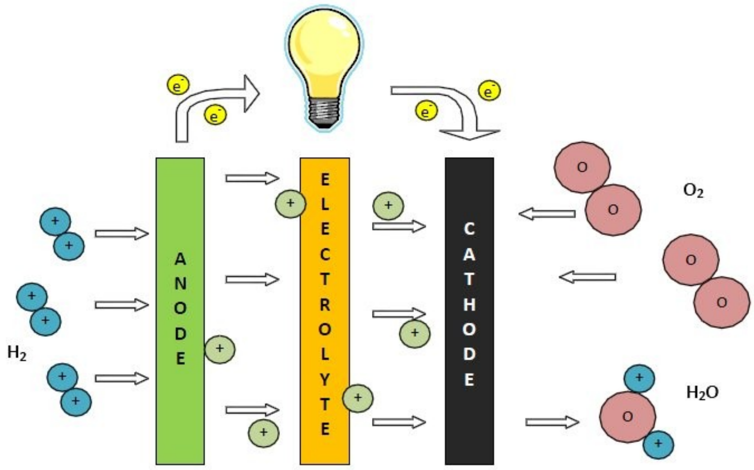

Figure 3.1 Theoretical concept of a proton exchange fuel cell

Hydrogen (H2) molecules are supplied to the anode. The Anode catalyzes the hydrogen molecule decomposition into protons and the electrons are released. It is possible because the next part of a FC is the electrolyte, which does not conduct electrons but allows protons to get through to the cathode side. The cathode catalyzes oxygen decomposition to let it react with the protons incoming through the electrolyte to form water. The electrons do the work (the light bulb lights) because of the electronic potential difference between cathode and anode, which actually pulls electrons through the light bulb. Besides water and electric power the by-product of a FC is heat, which comes mainly from losses in activation, transport of protons and electrons (Ohmic losses) and transport of the reactants.

The chemical reactions which occur in the process of generating electrical power are derived to be:

Anode: $2H_2 \rightarrow 4H^+ + 4e^-$

Cathode: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

Net reaction: $$2H_2 + O_2 \rightarrow 2H_2O$$

3.2 Commercial Applications for PEM FC

Beside the society demand to turn to environmental friendly technology and renewable sources, the need of adapting other energy sources for economic reasons have made the PEM fuel cell technology as one of the most attractive power source influencing a number of areas like stationary power supply and small-scale portable applications and transportation.

Figure 3.2 **Ovonic H2 Prius Showcases Solid Hydrogen Storage Technology & Hydrogen Powered Municipal Vehicle**

Besides the limitations of the PEM fuel cell technology especially when compared with other type of fuel cells, their advantages superposes them and makes them as the most suitable alternative power supply for use in transportation, power back up applications and small portable appliances lie cell phones and laptop computers

More specific the PEM fuel cell technology stands a the most adamant of all fuel cell technologies as it provides higher power densities (0.5W/cm^2 [13] or higher) which means reasonable analogy between power and volume which in result set them more attractive for plenty commercial purposes.

4 Fuel Cell characterisation

Fuel cell characterisation is a process that permits the comparison of fuel cell of the same type. There are different techniques for comparing same type fuel cells which focuses on specific properties of the fuel cells. The most important features of these techniques are:

a) Current interrupt
b) AC impedance
c) Pressure drop
d) Polarization curve hysteresis
e) Comparative polarization curves
f) Current density mapping
g) Temperature mapping
h) Flow visualization
i) Neutron imaging
j) Post-mortem analyses PR
k) Internal process structure
l) Lifetime and reliability

All of the above provides different information on the performance of the fuel cell and can assist in understanding the fuel cell's function.

4.1 Fuel Cell Characterisation methodologies

In order to proceed with the characterization of the PEM fuel cell it is essential to define the properties which would be used in order to carry out this investigation related to the electrical performance of the fuel cell and the heat processes that occur within the device and select an appropriate methodology to analyse them. Therefore four methods were acknowledged which could be used to distinguish the overall electrical performance of the fuel cell:

1. Polarization curves
2. Current-Voltage Measurement (I-V)
3. Current Interrupt Measurement
4. Electrochemical Impedance Spectroscopy

4.2 Fuel cell voltage

The calculation of the reversible fuel cell voltage for the oxidation reaction of hydrogen in the presence of oxygen is given by the Nernst equation:

$$E_{\text{Nernst}} = E_{\text{o,cell}} + \frac{RT}{2F}\ln[p^*_{\text{H}_2}(p^*_{\text{O}_2})^{0.5}]$$

This electrochemical reaction equation describes the voltage sources in the equivalent electrical circuit model which is a function of the temperature as well as the partial pressures of hydrogen and oxygen. This represents the cell voltage for a reversible energy conversion for a zero internal resistance. This approximates an open circuit operation with no current. Normal operating conditions have activation, Ohmic-resistance, and concentration losses which reduce the cell voltage:

$$V_{\text{cell}} = E_{\text{cell}} - V_{\text{act,cell}} - V_{\text{ohm,cell}} - V_{\text{conc,cell}}$$

The following section describes the voltage drop due to these resistances.

4.3.1 Polarization curves

One of the simplest but more effective methods for characterisation of a fuel cell is the use of polarization curves (I-V). With the I-V curves a researcher can derive the profile of the steady state variation of current against voltage and by obtaining this profile; derivations regarding the cell average performance can be obtained.

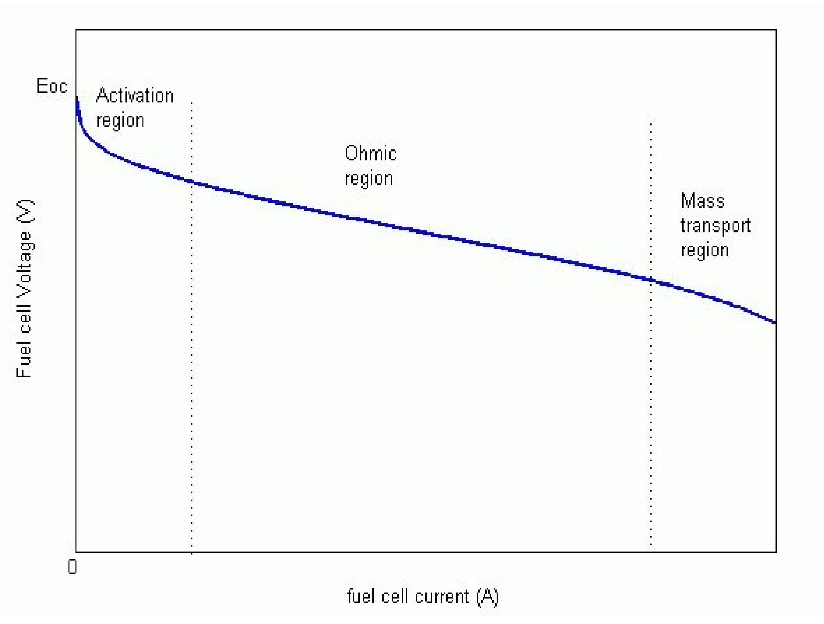

Figure 4.3.1 FC ideal polarization curve

A typical polarization curve is illustrated on the above figure 5. The horizontal regions of the curve indicate the internal losses of the fuel cell and where each is most influential. The combined contributions of these sources of overvoltage cause the cell voltage output to decrease with increasing current density thus the curve of the electrical profile slopes downwards as a result of the losses and increase of the current density.

There are four losses affecting the I-V profile curve, which are:

1. **Activation Losses**: Activation losses arise predominantly due to the kinetics at the electrodes. The effects of these losses are most pronounced at low current densities (~1 to 100 mA/cm2). Examples include sluggish oxygen reduction kinetics at the cathodes of polymer electrolyte and phosphoric acid fuel cells and sluggish methanol oxidation kinetics at the anode of a direct methanol fuel cell. In general they are observed at low current during the activation of the fuel cell and the loss is due to the work performed to drive the chemical reaction in a specific direction and the resultant over potential. The activation voltage drop can be described by the Tafel equation:

$$V_{\text{act}} = \frac{RT}{\alpha zF} \ln\left(\frac{I}{I_0}\right) = T[a + b\ln(I)] = V_{\text{act1}} + V_{\text{act2}}$$

   The activation potential can be separated into two parts, the first as a function of the temperature and the second as a function of the current:

$$V_{\text{act1}} = [k + a(T - 298)]$$

$$V_{\text{act2}} = Tb\ln(I)$$

2. **Ohmic Losses**: This type of losses arises due to the resistive losses in the electrolyte and in the electrodes. The effects of these losses are perhaps most pronounced at intermediate current densities (~100 to 500 mA/cm2). Ohmic losses are the result of the resistance to electron transfer in the graphite collector plates and graphite electrodes and also accounts for the resistance of the membrane to proton transfer. Thus, the Ohmic resistance in the cell consists of the polymer membrane resistance, the conduction resistance between the membrane and the electrodes, and the resistances of the electrodes themselves:

$$V_{\text{ohm}} = V_{\text{ohm,anode}} + V_{\text{ohm,membrane}} + V_{\text{ohm,cathode}} = iR_{\text{ohm}}$$

   The main effect of the Ohmic losses is that of heat loss and power loss in fuel cells.

3. **Concentration voltage drop due to Mass Transport Losses**: The mass transport losses occur due to non-reacting diffusion in the gas-diffusion layer and to reacting diffusion in the electrode layers. The effects of these losses are most pronounced at high current densities (>500 mA/cm2).In other words they are the result of over loading of the fuel cell. This occurs when at high loads; the reactants cannot move rapidly enough to complete the chemical process with the increase power requirements. Also these losses are take place due to the limited surface area of the electrodes that is limited in contrast with the loads that increases. The concentration over potential occurs when a voltage drop occurs due to concentration gradients at the cell surface due to limited mass transfer rates. Especially at high current densities, the slow reactant transport to and from the reaction sites in the gas diffusion layer limits the performance of the PEM fuel cells. The concentration over potential is defined as:

$$V_{conc} = -\frac{RT}{2F}\ln\left(\frac{C_s}{C_b}\right)$$

Where Cs is the surface concentration and Cb is the bulk concentration [1].

4.3.2 Current-Voltage (I-V) Measurement

The current density-voltage (I-V) measurement is a commonly used technique in fuel cell characterization investigations and its result is the primary value that is used for comparing same type fuel cells.

This method allows the researchers to a quantitative assessment of the fuel cell performance, and the data obtained from running the PEM fuel cell are used to build the power density curve of the device. The power density curve describes the power per area output of the system relative to the current supplied.

4.3.3 Current Interrupt Measurement

In order to obtain more accurate results the Current Interrupt Measurement is the more suitable. With this methodology it is achieved the separation of the voltage losses into Ohmic and non-Ohmic losses. Hence the Ohmic losses of the fuel cell can be quantified, as well as producing a current-dependant value for the summation of concentration and activation losses. Another main feature of this methodology is that results can be obtained very quickly and testing can be undertaken at the same time as the I-V measurements.

4.3.4 Electrochemical Impedance Spectroscopy (EIS)

Fuel cells, in common with other electrochemical cells, exhibit complex impedance characteristics that result in a non-linear voltage/current relationship. In order to measure electrochemical impedance an AC current is applied to the cell and the resulting voltage is measured. The response is an AC voltage signal that is out of phase with the applied current. To ensure that the cell’s response is pseudo-linear a small input signal is used that constrains the output range to the linear portion of the curve. The analysis of the response requires frequency and phase components to be extracted. This is commonly undertaken using Fast Fourier Transforms or a Lock-in Amplifier and is displayed with Nyquist Plots. EIS measurements require specialized test equipment that is of high cost and limited in channel count.

Figure 4.3.4 FCT-50S and FCT-150S Fuel Cell Test Station for PEMFC

Hence was decided that undertaking the EIS method would not be straightforward within the limitations of the fuel cell laboratory of the NA.ME at time being. Never the less it is recommended, that Electrochemical Impedance Spectroscopy will be carried out in the future with a more adequate and safe fuel cell laboratory.

5 Fuel cell laboratory

5.1 Laboratory set up and monitoring equipment

The fuel cell laboratory is located in the building Henry Dyer of the NA.ME department and it is recently being build. The equipment needed for this research included: a GenCore® 5B48 Fuel Cell System, a computer with the operating/monitoring software for this PEM fuel cell system, a hydrogen pipeline infrastructure, the required for safety reasons air extractor and a load bank panel for implementation of electrical loads.

Figure 5.1.a the GenCore® 5B48 Fuel Cell System

The GenCore® 5B48 Fuel Cell System description is given below including some of the specifications for the fuel cell power system which among others includes a 68 cell stack with a humidification, temperature management, reaction product management and electrical control. The main features of the GenCore® 5B48 Fuel Cell System are demonstrated on the following table.

Performance	Rated Net Output	0 to 5,000 W
	Adjustable Voltage	46 to 56 Vdc
	Operating Voltage Range	42 to 60 Vdc
	Operating Current Range (net)	0 to 109 Amps
Fuel	Gaseous Hydrogen	99.95% Dry
	Supply Pressure	5.5 +/- 1.1 bar
	Fuel Consumption	40 slm at 3,000W
		75 slm at 5,000W
Operation	Ambient Temperature	-40°C to 46°C
	Relative Humidity	0% to 95% Non condensing
	Altitude	-60 m to 1829m
Physical	Dimensions	112cm x 66cm x 61cm
	Weight	227 kg
Safety	Certifications	CE
		FCC Class A
		UL ANSI listed to 221.83
Emissions	Water	Maximum 1.75 liters per hour
	CO, CO2, NOx, SO2	<1ppm
	Audible Noise	60 dBA @ 1m

Table 1 Main features of GenCore 5B48

The GenCore® 5B48 Fuel Cell System was controlled and monitored by a remote computer with installed the GenCore® software. The computer and the fuel cell are connected through an RS-232C Serial cable connection.

Figure 5.1.b the computer with the monitoring software

The monitoring and operation software is to a certain extent user friendly and the operation of it quite straight forward. A tutorial of this software is included in the appendixes.

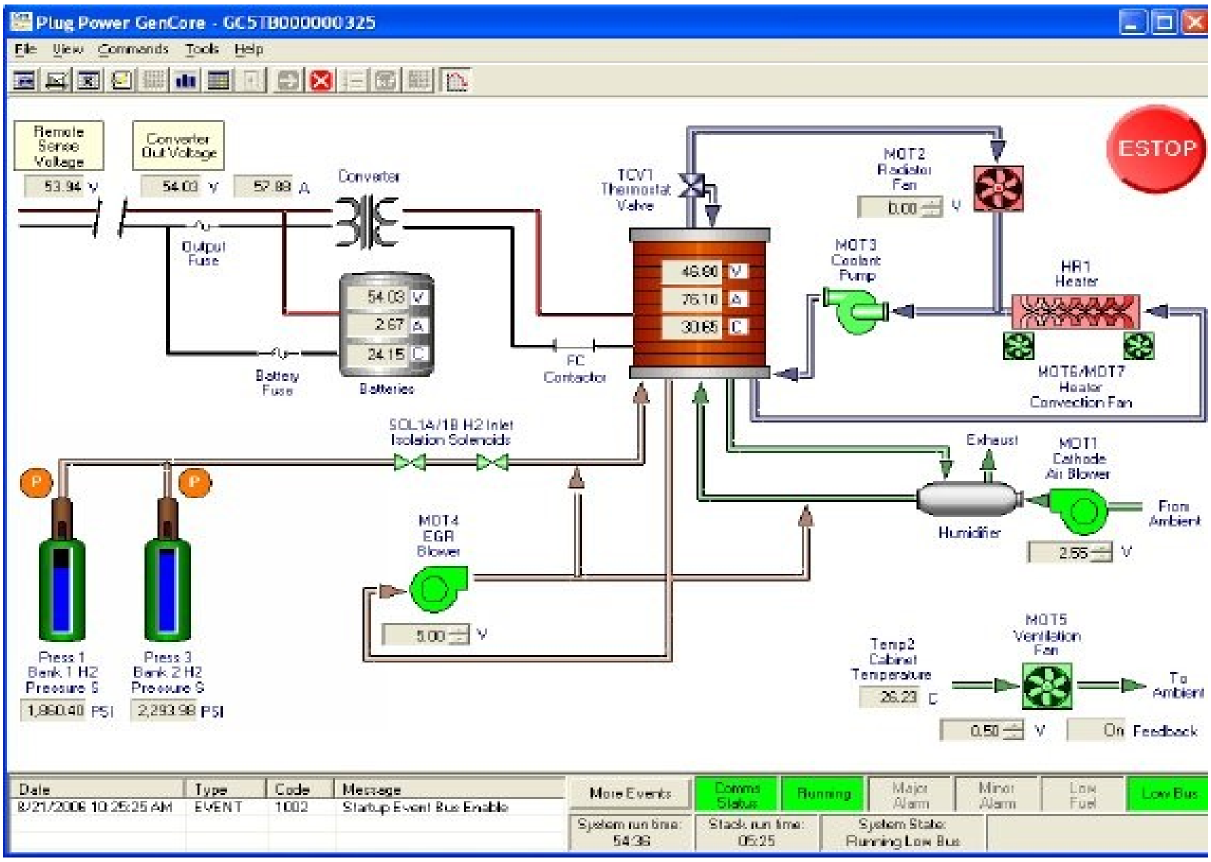

Figure 5.1.c Software interface

Event logging and data storing is performed by the program and stored as Excel files on a predefined directory of the monitoring computer. On this Excel file can be found the required parameters to understand the performance of each component and the performance of the whole system such as the converter out voltage & load, the stack temperature, voltage, current & power, the cabinet temperature, the system efficiency, etc.

	D	F	Q	U	W	X	AA	AB	AC	AD	AE	AF	AG	AK	AL	AM	AN	AO
1	Temp1 Stack Coolant Inlet Temperature	Temp2 Cabinet Temperature	Cell Summation	Actual DCL	System Efficiency	H2 Usage	Converter In/Ultracap Voltage	Converter In Current	Stack Current	Converter Out Voltage	Converter Out Current	Converter Current Load	Temp3 EESM Temperature	Stack Voltage	Time (sec)	STack ON	Electical power from converter	Electrical power from stack
2	20,321	19,659	4,2	5	0	0	0	0	0	0	0	0	0	4,2	2		0	0
3	20,323	19,659	4,2	5	0	0	49,9	0,35	0,42	48,82	0,38	1,55	17,62	4,2	4		18,5516	1,764
4	20,326	19,659	4,2	5	0	0	49,9	0,35	0,42	48,82	0,37	1,55	17,62	4,2	6		18,0634	1,764
5	20,323	19,659	4,2	5	0	0	49,9	0,35	0,42	48,82	0,37	1,55	17,62	4,2	8		18,0634	1,764
6	20,323	19,659	4,2	5	0	0	49,9	0,35	0,43	48,82	0,37	1,55	17,62	4,2	10		18,0634	1,806
7	20,314	19,744	4,2	5	0	0	49,9	0,35	0,42	48,82	0,37	1,55	17,62	4,2	12		18,0634	1,764
8	20,316	19,744	4,2	5	0	0	49,9	0,35	0,43	48,82	0,37	1,55	17,62	4,2	14		18,0634	1,806
9	20,325	19,83	4,2	5	0	0	49,9	0,35	0,42	48,82	0,37	1,55	17,62	4,2	16		18,0634	1,764
10	20,33	19,83	4,2	5	0	0	49,9	0,34	0,41	48,82	0,37	1,55	17,62	4,2	18		18,0634	1,722
11	20,328	19,744	4,2	5	0	0	49,9	0,35	0,42	48,82	0,37	1,54	17,62	4,2	20		18,0634	1,764
12	20,314	19,83	4,2	5	0	0	49,9	0,35	0,42	48,82	0,38	1,56	17,62	4,2	22		18,5516	1,764
13	20,308	19,744	4,2	5	0	0	49,64	-2,81	0,6	48,69	-2,89	-3,74	17,62	4,2	24		-140,7141	2,52
14	20,304	19,83	4,2	5	0	0	48,98	-10,76	1,2	47,8	-11,23	-17,89	17,62	4,2	26		-536,794	5,04
15	20,293	19,83	4,2	5	0	0	48,98	-10,76	1,25	47,65	-11,26	-18,01	17,62	4,2	28		-536,539	5,25
16	20,406	19,83	4,2	5	0	0	48,97	-11,01	1,66	47,44	-11,56	-18,87	17,62	4,2	30		-548,4064	6,972
17	20,6	19,915	4,2	5	0	0	48,97	-10,97	1,67	47,4	-11,54	-18,86	17,62	4,2	32		-546,996	7,014
18	20,901	19,915	4,2	5	0	0	48,97	-11,04	1,6	47,33	-11,62	-18,97	17,62	4,2	34		-549,9746	6,72
19	21,627	19,915	4,2	5	0	0	48,97	-11,09	1,58	47,32	-11,68	-19,01	17,62	4,2	36		-552,6976	6,636

Figure 5.1.d The Excel log file for the data of the experimentation

In order to test the GenCore® 5B48 Fuel Cell System in load conditions, a bank load panel developed by the Mechanical engineering department is being applied. It is connected to the fuel cell by two electric cables and the electrical loads are operated manually (on-off switches). Each resistive load has value of 10 Ohm and they are connected in series as also in parallel.

Figure 5.1.e The load bank panel

In the future is going to be introduced a more sophisticated equipment like a TDI Electronic Load Bank which will allow more advance control and testing like: Dynamic load-high quality, Low Voltage Measurements, accuracy± .25% FS for med/high ranges, ± .50% FS for low range, Accuracy: ± 3% FS for all ranges and better Resolution: .25% of full scale.

6 SYSTEM TESTS

6.1 General concept

In this section is presented the adopted testing methodology and the evaluation of the overall performance of the GenCore 5B48 unit. The tests included steady-state measurements of primary system properties, fuel consumption, efficiency analysis, cold start-up behaviour and transient analysis. Here has to be mentioned that the tested system is a few years old and this can have some negative influence on its overall performance.

6.2 Target and objectives

The main target of these tests was to establish the overall system performance, such as the electrical efficiency, the fuel consumption and fuel utilization efficiency. Investigate the system response during start-up, normal mode and shut down. Thus explore the suitability of the fuel cell system for use on mobile and stationary applications. And finally examine the GenCore® 5B48 Fuel Cell System reliability.

6.3 Measurements methodology

The measurements methodology included two parts:

I. Steady-state system response during load switching from 0% to 100% of available load. With these tests was sufficient to analyze the performance of the whole system as well as the fuel cell stack, including such parameters as general characteristics, efficiency, and fuel consumption.

II. System transition analysis. It consisted of the response time testing during switching from the standby operation into full operation, and vice versa. All data was captured by the software provided by the manufacturer.

6.4 Results and discussion

The data gathered from the actual testing session in comparison with previously findings allowed for a number of results to be produced regarding the operation and performance of the GenCore 5B48 fuel cell. The characteristic polarization curve was created, which enable us to characterize the overall performance of the PEM fuel cell unit.

6.4.1 Performance Curves

With the data outcome of the tests, modelling the performance curves was at hand. It can be seen in the following diagram that the voltage decreases and the power increases with current, which is normal operation for the fuel cell stack.

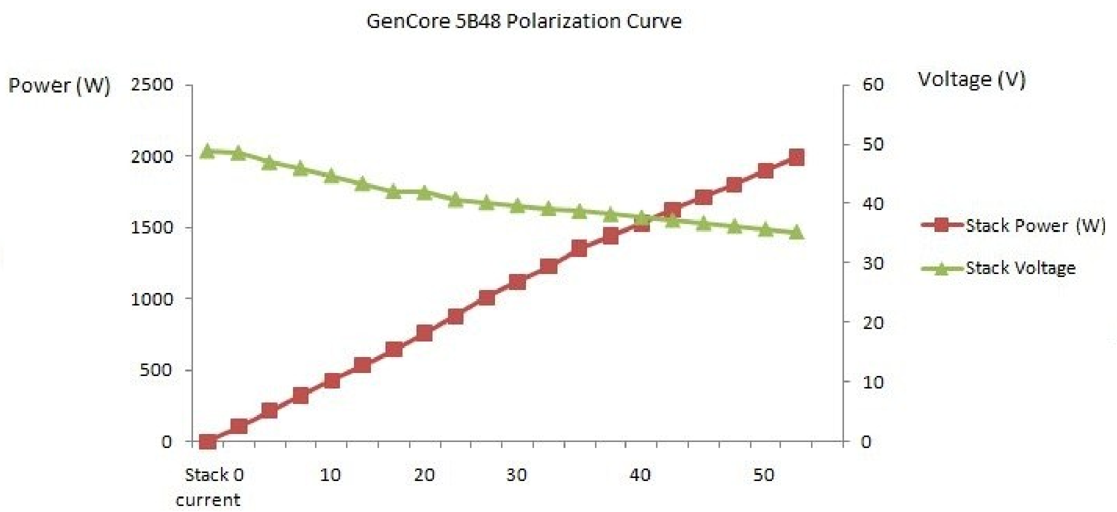

Figure 6.4.1 GenCore 5B48 Polarization curves

The reversible voltage of the stack under these conditions was established at 48.7V. The obtained voltage-current curve is almost all linear. The recognition of which parts are responsible for activation voltage losses it is not possible at this stage, especially without the required EIS equipment. In order to have solid results this measurement will be conducted a few times in order to ensure that the same will occur.

The activation losses are very small. The ohmic losses are clearly visible and increase with current. Unfortunately it was not possible to record if considerable concentration losses will occur due to the equipment limitation.

6.4.2 Stack Current & Voltage

The current is not often steady in the stack in starting mode but as soon the stack attains operational temperature the current becomes fairly steady with value depending on the connected load. The small variation of the current occurs due to internal operations of the fuel cell, especially when the cooling system starts in order to maintain the optimum stack temperature.

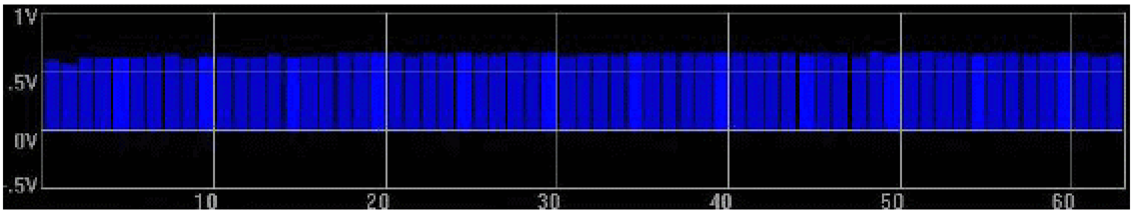

Figure 2.4.2.a Voltages of particular cells under 0,20kW of stack power

The voltage of the stack showed an unsteady state at the beginning of the experiment but the voltage remains stable as long as the connected load does not alter.

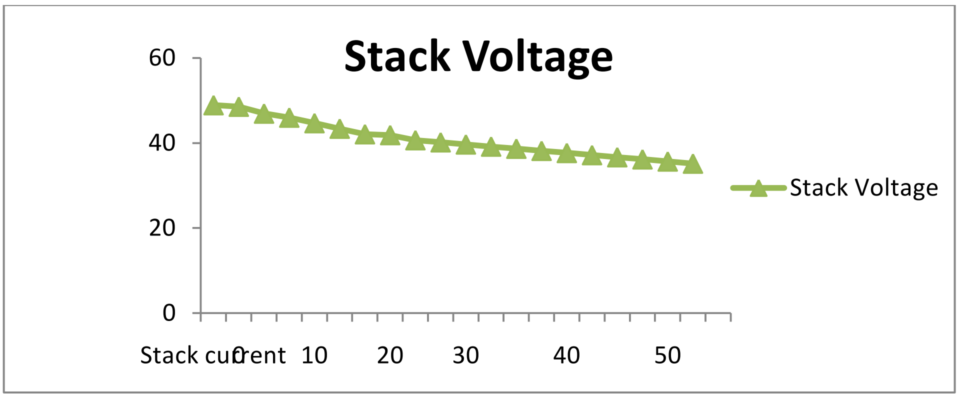

Figure 6.4.2.b Stack Voltage

6.4.3 Stack Temperature

The operational temperature of the GenCore 5B48 fuel cell is around 52^{o}C. At operational mode the stack requires about 16 minutes to reach this working temperature for any load, as shown in Figure 6.4.3. Of course, the required time to reach its working temperature depends on the weather conditions and ambient temperature.

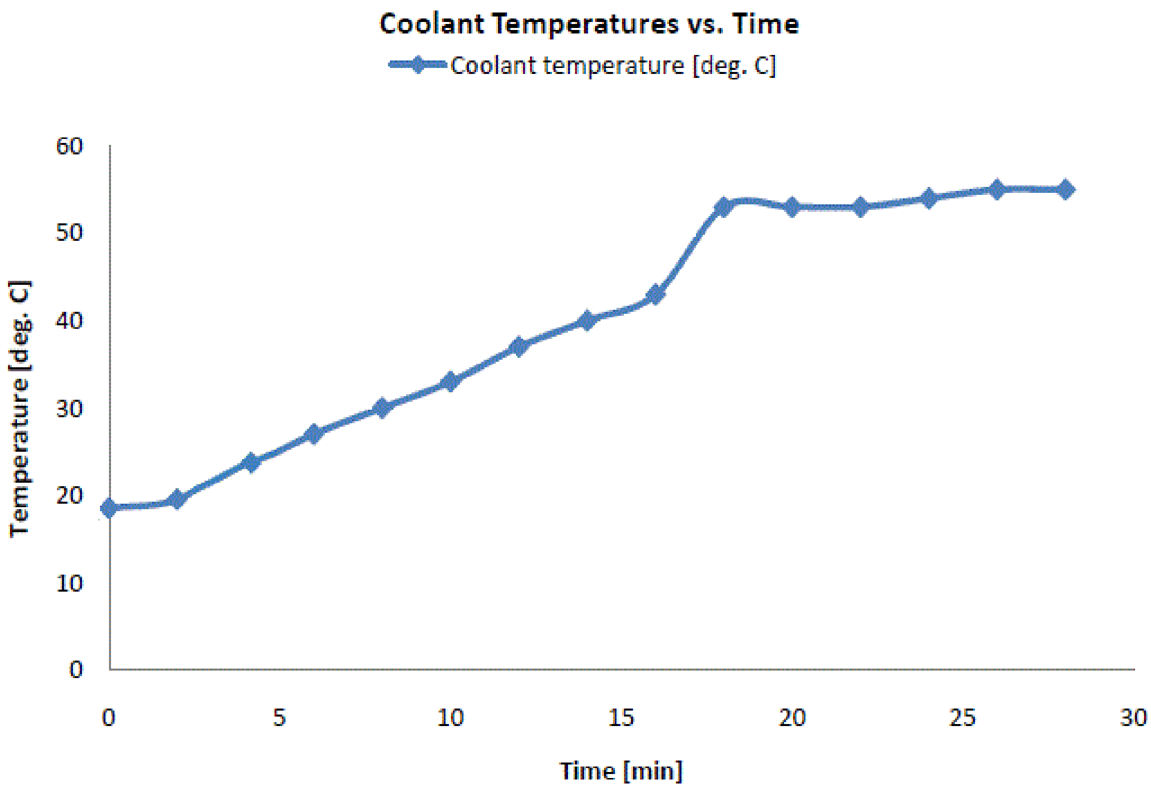

Figure 6.4.3 Stack temperature variation during testing

With one hydrogen cylinder of 50 litres, under compression up to 200 bars, the GenCore 5B48 fuel cell can operate continuously for nine hours at constant load of 1kW and on the maximum capacity of the system it can last about two hours, always according the manufacturer.

Because not all of the fuel provided to the GenCore 5B48 contributes in the electrochemical reaction it is required to introduce the fuel utilization efficiency and this is shown in the figure 6.4.4b.

6.4.4 Fuel consumption and fuel utilization efficiency

In order to determine the stack efficiency and in general the overall efficiency of the GenCore 5B48 fuel cell system the fuel consumption and the fuel utilization efficiency are the key components in order to do so.

The manufacturer company of the PEM fuel cell, Plug Power, provides data of fuel consumption for specific power outputs; at 3kW the fuel consumption of the GenCore 5B48 fuel cell system according the manufacturer consumes 70slm and about 40slm at full capacity of 5kW.

In this experiment the measured fuel consumption was at of 13slm at 1kW and of 1.8slm of hydrogen at 1.5kW and this is illustrated in the following figure 6.4.4.a.

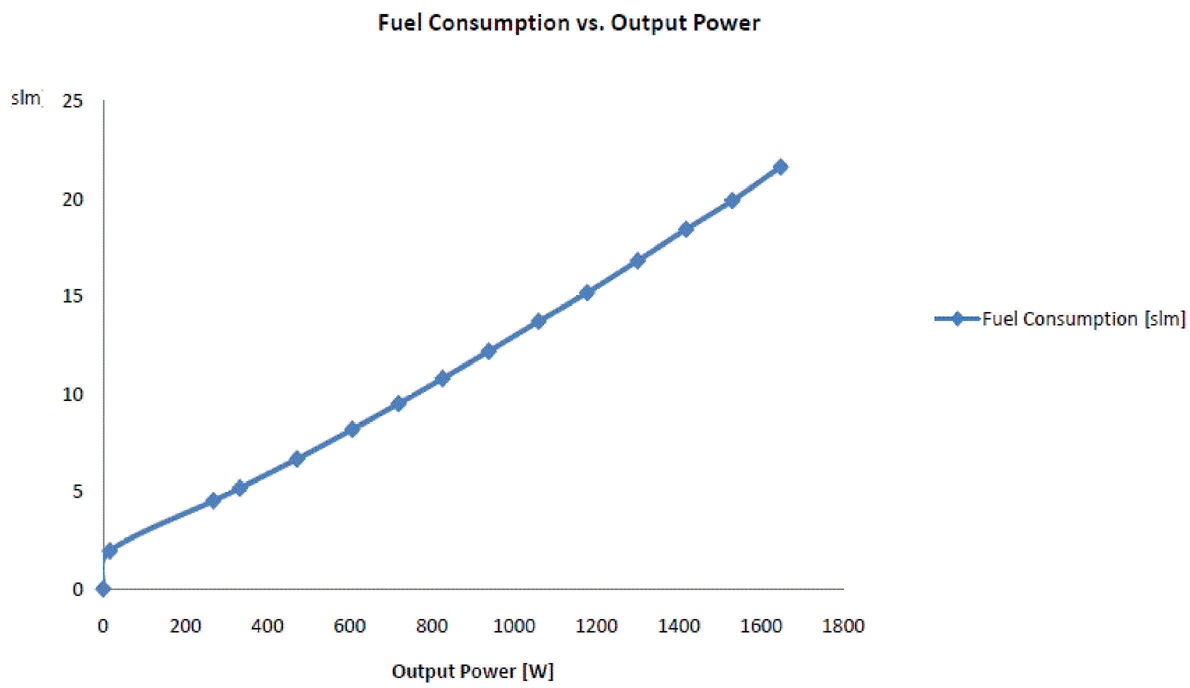

Figure 6.4.4.a Fuel Consumption

The electrochemical reaction taking place on the fuel cells can be quantified by the fuel utilization efficiency taking into account that the majority of the fuel cells will contribute with the conversion of energy. This was taken under consideration and on figure 6.4.4.b reveals the fuel consumption and efficiency as a function of the fuel cell stack current.

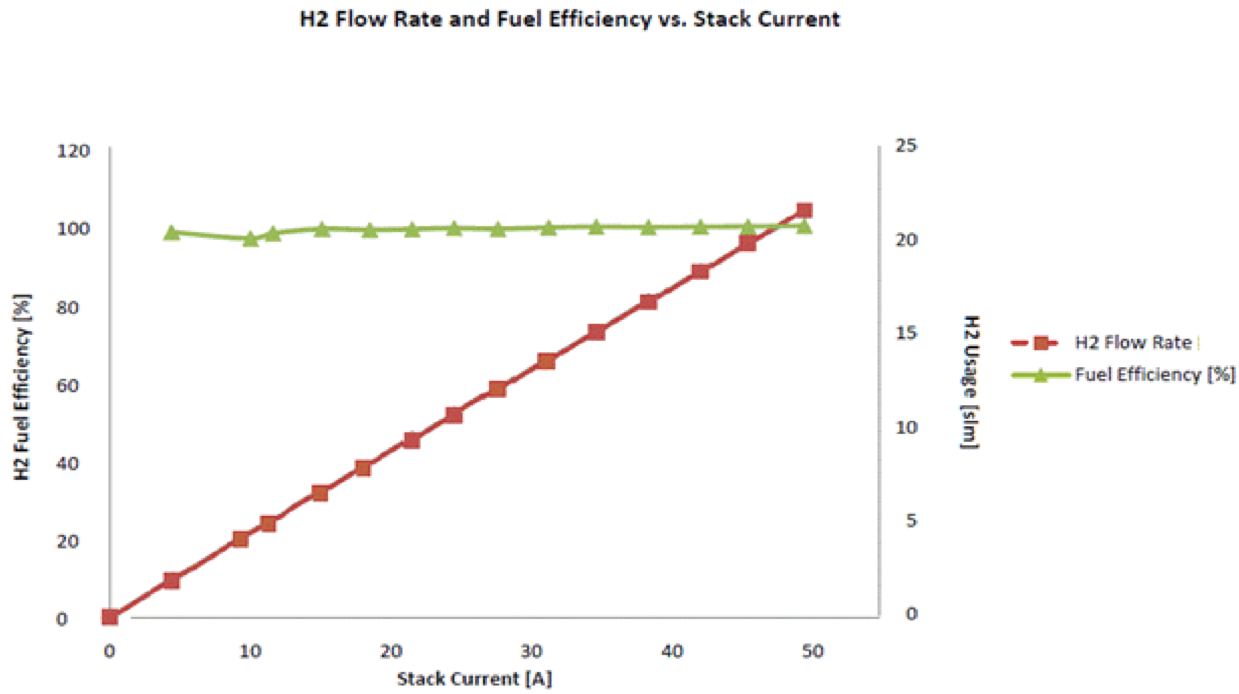

Figure 6.4.4.b Hydrogen flow rate and fuel efficiency vs. stack current

On the above figure we can observe that the hydrogen consumption is directly related to the power which can be yielded from the stack, and that this relationship is linear. Also the measured fuel efficiency measured indicates that it is very high and on average achieves about 99%. In other words shows that the PEM uses the full energy potential of the fuel. The fuel provided to the GenCore 5B48 fuel cell system is constant, where the flow rate is expressed in standard litres per minute (slm).

The amount of fuel used by the stack to generate electric current is calculated with the equation:

$$V_{fuel.flow} = \frac{I}{n \cdot F} \cdot N$$

Where : I the electric current

n the number of moles of electrons transferred

F Faraday's constant $96485 \cdot \frac{C}{mol}$

N the number of cell's

Here has to be mentioned that the unit of the above equation is mol/sec, hence in order to calculate the fuel utilization efficiency, the acquired data need to be converted from slm to mol/sec. Thus the ideal gas law was adopted in order to transform approximately the results to common units:

$$\frac{V}{n} = \frac{R_u \cdot T}{P}$$

Where : V volume
n the number of moles
R_u the ideal gas constant $8.314 \cdot \frac{J}{K \cdot mol}$
T the temperature
P the pressure

$$n_{fuel} = \frac{V_{fuel.flow}}{V_{fuel.supplied}}$$

The results of this transformation were almost identical with the values calculated using the fuel flow rate equation.

Thus the approximation of the fuel efficiency of the fuel cell stack was calculated as the ratio of the fuel used by the stack to generate electric current versus the total fuel provided to the fuel cell stack as follows:

$$n_{fuel} = \frac{V_{fuel.flow}}{V_{fuel.supplied}}$$

6.4.5 Overall fuel cell stack efficiency

The overall fuel cell stack efficiency is defined as the ratio of the electrical energy produced by a stack, consuming a certain amount of hydrogen to the theoretical energy content of the same amount of hydrogen and it is expressed as follows:

$$n_{PEM} = \frac{I \cdot V}{\Delta H_{HHV} \cdot Q_{fuel}} \cdot 100$$

Where : V the stack voltage
Q_{fuel} the fuel flow rate
H the enthalpy for liquid water $285.83 \cdot \frac{kJ}{mol}$

As it is observed on the figure 6.4.5, the stack efficiency decreases while the current increases. Also on the same figure we can see that for 1kW and 1.5kW of stack output power, the efficiencies are about 45.7% and 43.8% in that order and that at low stack power, the stack efficiency exceed more than 50%.

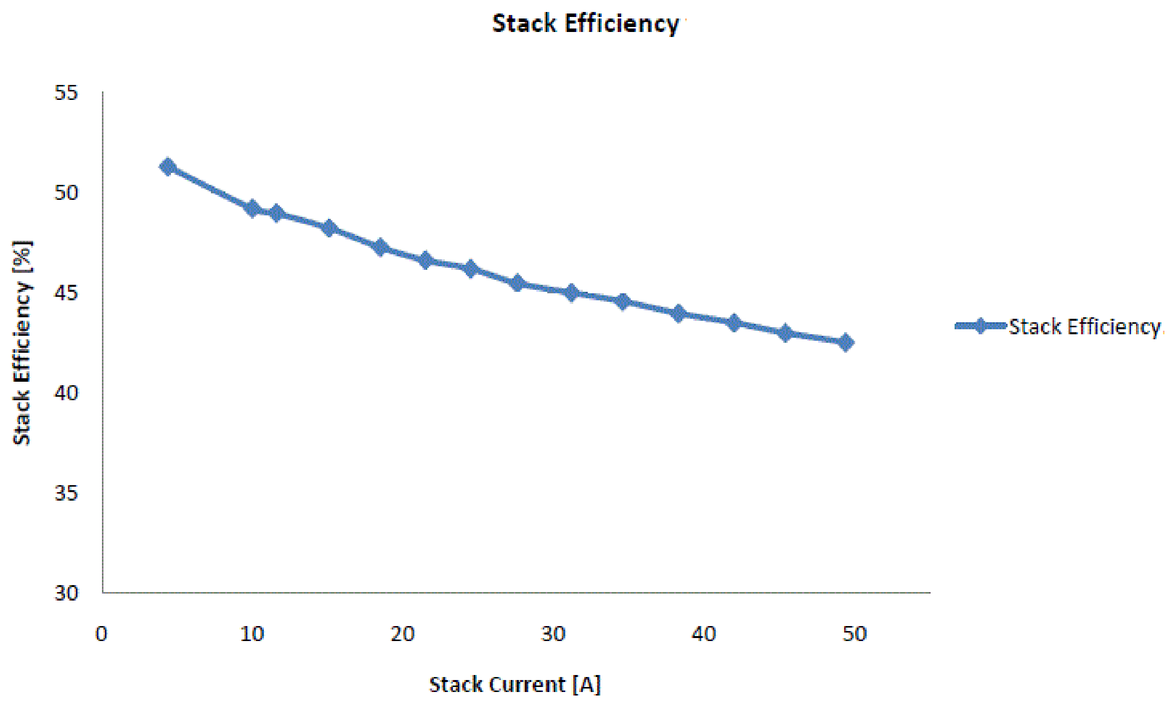

Figure 6.4.5 Stack efficiency vs. stack current

6.4.6 GenCore 5B48 overall electrical efficiency

The GenCore 5B48 overall electrical efficiency is defined as the ratio of the electrical power produced by the converter and the available energy for electrochemical conversion and it is expressed as follows:

$$n_{GenCore.5B48} = \frac{P_{converter}}{E_{energy.avail.for.electochemical.conversion}} \cdot 100$$

At low power the overall system efficiency increases and after exceeding roughly 1kW it starts to decay as expected. The corresponding efficiency for each power output is demonstrated on the figure 6.4.6.a with more significant the overall efficiency of 27.1% for 0.25kW, of 35.8% for 1kW and for 1.5kW correspond efficiency of 34.9%.

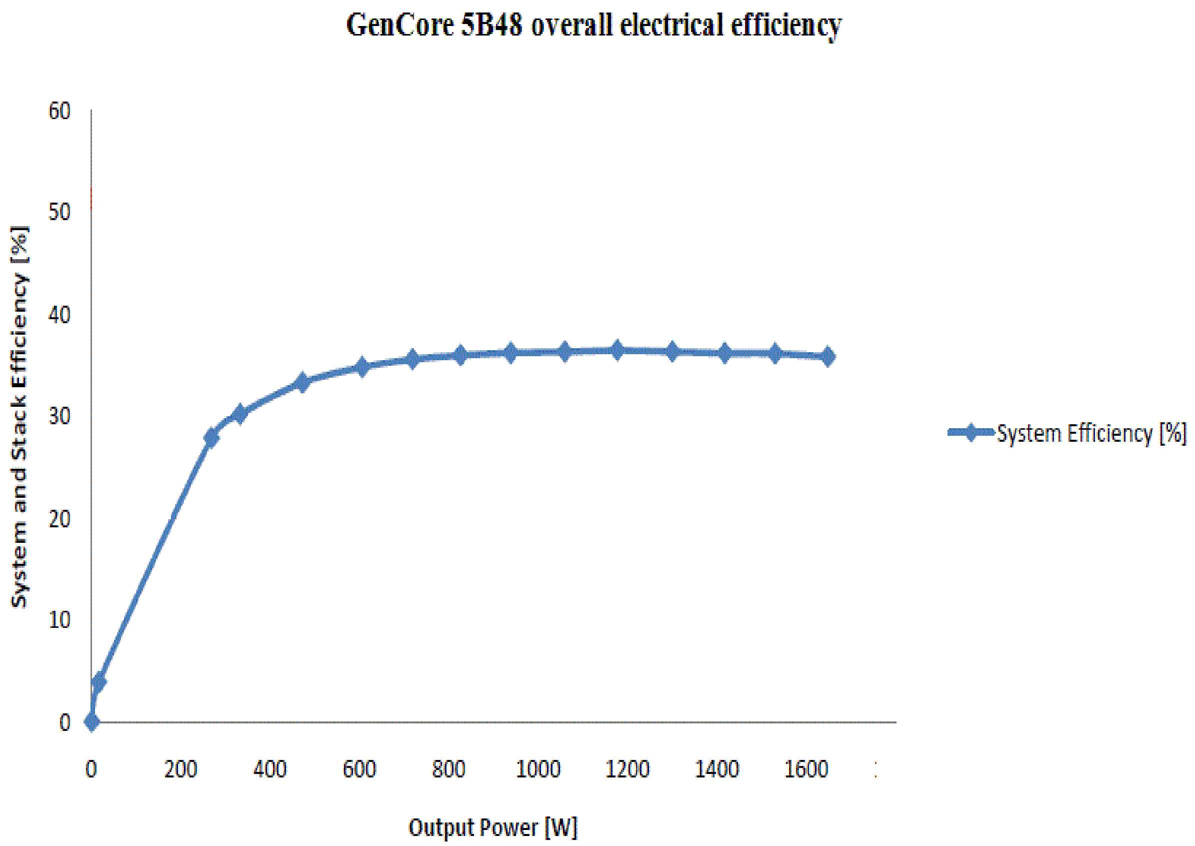

Figure 6.4.6.a GenCore 5B48 overall electrical efficiency

On the figure 6.4.6.b it is shown that for small power output the system is inefficient and this is due to the rest of the equipment power losses.

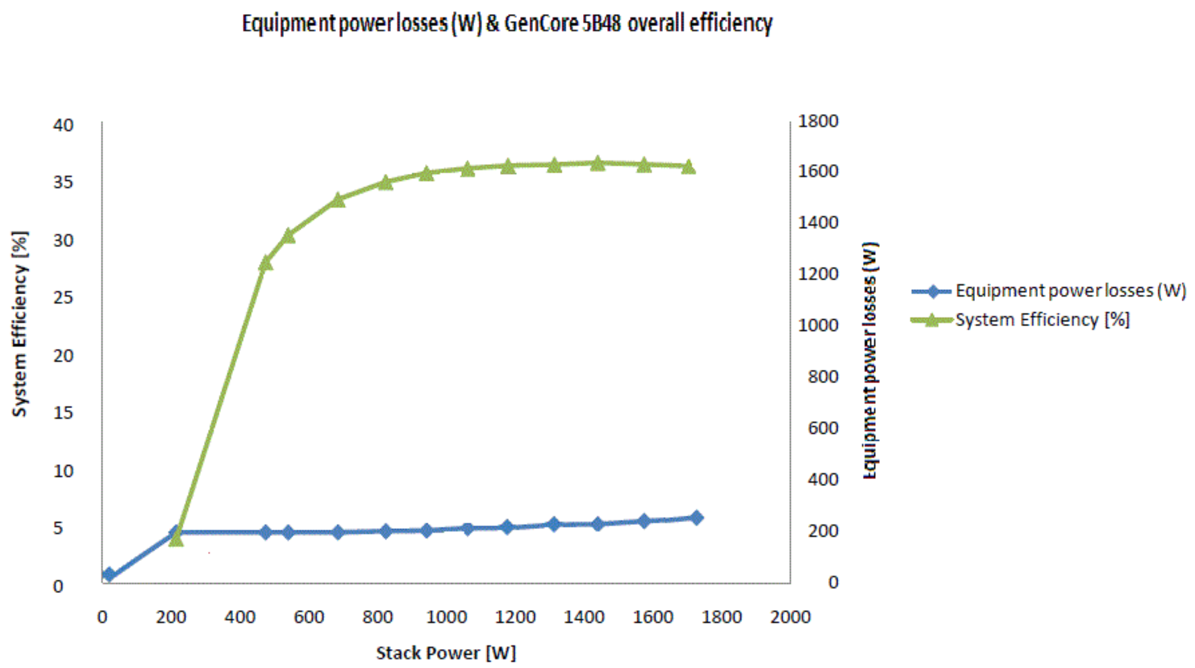

Figure 6.4.6.b Equipment power losses and overall system efficiency

6.4.7 Transition analysis

This test aims to evaluate the performance of the fuel cell stack and the whole GenCore 5B48 fuel cell system during operation mode, for predefined operational loads.

The loads were applied as step loads. This was accomplished by turning off the power to the DC Bus and at the same time applying the loads. The system at each step needed around ten seconds of operation on the batteries, then the fuel cell stack begin to operate and take over the load. The required time for the system to stabilise was near a minute. Within that required time for stabilization it was witnessed an increase in power demand which was due to the fact that other auxiliary components started their operation such as the cooling pump and the heater fun. The system was turned off manually after operating under load for approximately two minutes for each load.

There were applied four loads, of 200W, 250W, 1kW and 1.5kW to the fuel cell stack and the resulting diagram of these loads and the data obtain can be seen on figure 6.4.7.a.

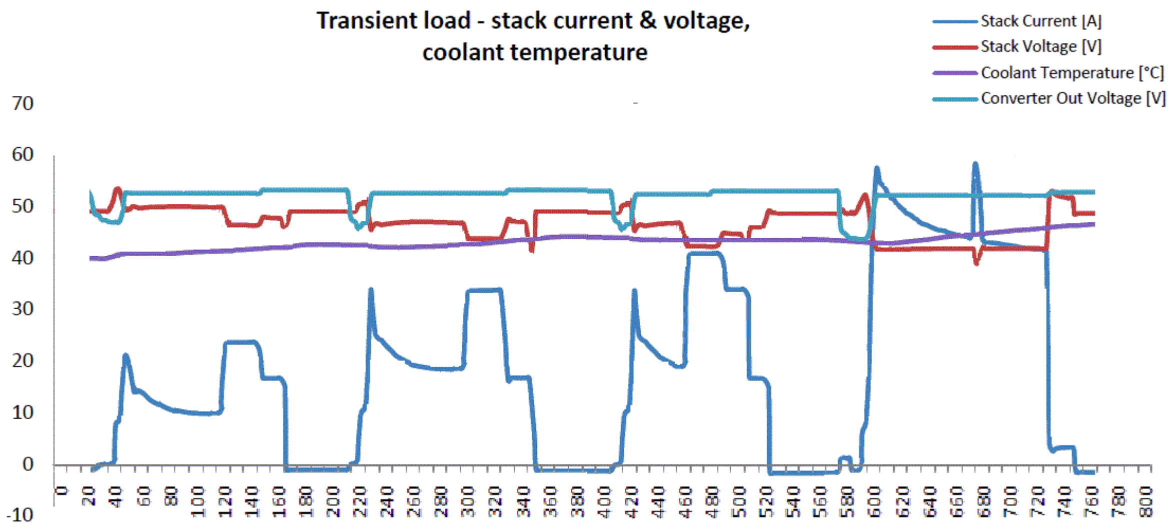

Figure 6.4.7.a Stack parameters over time during the test

Also on figure 6.4.7.a it is witnessed a sudden increase on the stack current which is result of the beginning of operation of the fuel cell stack. Then it is almost immediately followed by sudden drop of current due to the introduction of each load and after a minute of operation; followed by an increase of power due to the initiation of operation of the auxiliary components which draws the same instant current from the stack. In addition on each step the power demand is covered for few seconds from the batteries and then the fuel cell stack is set to take over and this also contributes in creating the peaks on the stack current while applying each load.

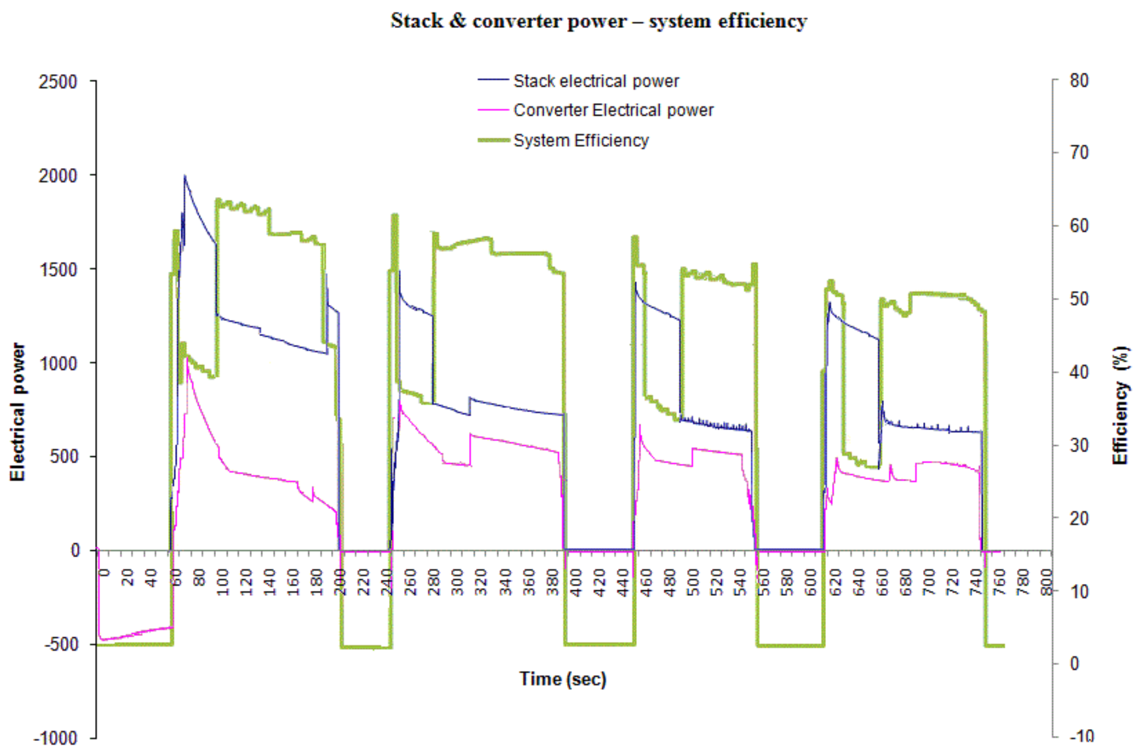

Figure 6.4.7.b Stack &converter power and system efficiency

The resultant power generated from the fuel cell stack and internal converter, are shown in Figure 6.4.7.b above. The variations of the power values are the outcome of the stack supplying power to the GenCore Control Card (GCC), through the auxiliary converter. Subsequently, the power values demonstrated in the graph are not representative of the applied resistive loads as supplementary energy is formed to power the system's internal processes.

Also in the same figure are illustrated the measured system efficiencies by the GenCore monitoring software for each load; and they are higher than the calculated overall system efficiencies. As can be noticed on figure 6.4.7.b the averages of the measured efficiencies for each corresponding load (250W, 250W, 1.0kW & 1.5kW) are: 60.2%, 58.1%, 55.6% and 50.4%. While the overall system efficiencies were: 27.1% for 0.25kW, of 35.8% for 1kW and for 1.5kW correspond efficiency of 34.9%.

7 Conclusions

The most important features of the GenCore 5B48 fuel cell system are illustrated in this thesis by analysing the obtained results from the experimentation, features such as electric characteristics, overall efficiency, fuel usage, and in general the operation performance of the fuel cell under load conditions.

Nevertheless, in turn to completely characterize the GenCore 5B48 system, more tests are required in order to establish the operational limits and investigate problems that occur during the operation, plus a reliability study of the system. Such research could include larger loads that the system can support, work under overpressure, cold start up with varying load demand, etc.

The results obtained from the experimentation on this fuel cell system in general can be used for characterization of PEM fuel cells, but only as roughly characteristics and not taken as axiom for all of these type fuel cells.

The testing results and their interpretation indicates firm response to different loads, good average efficiencies and all of that including the alluring rations of their efficiency with the volume/weight plus that the PEM technology improves continuously reducing their costs set them as the most attractive towards the other fuel cell types for merchandized applications.

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Appendixes

Appendix A GenCore 5B48 System Specification

plug power FUEL CELL SYSTEMS

Rugged, reliable design.

Flexible

Proton Exchange Membrane (PEM) Fuel Cell Stack – Proprietary fuel cell design delivers efficient, clean, quiet DC power. Integrated cell voltage monitoring provides continuous feedback for optimal fuel cell performance.

DC Power Conditioning – GenCore systems are offered in 48Vdc, 120Vdc power conditioning configurations.

Reliable

Electrical Energy Storage – Maintenance-free system provides immediate response to power interruptions.

Fuel Storage System – Available in a variety of forms, hydrogen fuel storage is scalable to meet site and provider specific needs.

Robust

Thermal Management System – Freeze-tolerant design allows for operation from -40°C to 46°C.

Insulated Cabinet – Rugged design is finished with high-quality paint process that protects the exterior finish.

GenCore.

PRODUCT CHARACTERISTICS		5B48	5U120
Performance	Rated Net Output[1]	0 to 5,000 W	0 to 5,000 W
	Adjustable Voltage	46 to 56 Vdc (48)	125.9 to +136.2 Vdc (120)
	Operating Voltage Range	42 to 60 Vdc	125.9 to +139.8 Vdc
	Operating Current Range (net)	0 to 109 Amps	0 to 39.9 Amps
Fuel	Gaseous Hydrogen	99.95% Dry	99.95% Dry
	Supply Pressure	80 +/- 16 psig (5.5 +/- 1.1 bar)	80 +/- 16 psig (5.5 +/- 1.1 bar)
	Fuel Consumption	40 standard liters per minute at 3,000W	40 standard liters per minute at 3,000W
		75 standard liters per minute at 5,000W	75 standard liters per minute at 5,000W
Operation	Ambient Temperature	-40°C to 46°C	-40°C to 46°C
	Relative Humidity	0% to 95% Non condensing	0% to 95 % Non condensing
	Altitude	-197 ft to 6,000 ft (-60 m to 1,829 m)	-197 ft to 6000 ft (-60 m to 1,829 m)
Physical[2]	Dimensions	44"H x 26" W x 24" D (112cm x 66cm x 61cm)	44"H x 26" W x 24" D (112cm x 66cm x 61cm)
	Weight	500 Lbs (227 kg)	500 Lbs (227 kg)
Safety	Certification	FCC Class A	FCC Class A
Emissions	Water	Maximum 1.75 Liters per hour	Maximum 1.75 Liters per hour
	CO, CO2, NOx, SO2	<1ppm	<1 ppm
	Audible Noise	60 dBA @ 1m	60 dBA @ 1m
Sensors[3]	Gas Hazard Detection	Included	Included
Control	Microprocessor	Included	Included
	2 LED Panel	Included	Included
	Low Fuel Alarm	Included	Included
	Communications[4]	RS-232C	RS-232C
		Digital Form C Contacts	Digital Form C Contacts

[1] Output rated from -40°C to 42°C. From 42°C to 46°C, output decreases 2.5% per degree Celsius. Above 1000 feet (305 meters), an additional de-rating of 1.5% per 305 meters applies.
[2] Excludes fuel storage.
[3] Optional sensors are available to detect: Pad shear, water intrusion and tampering.
[4] Optional communications include MODEM.

Specifications subject to change without notice.

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HEADQUARTERS
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www.plugpower.com

Appendix B Discovery of the fuel Cell

William Robert Grove was one of the first to understand the mechanism of electrolysis and how it could be used in both ways, how to use this phenomenon to produce hydrogen and oxygen and vice versa to produce electricity with the products of the electrolysis. Thus in the year 1839 he manufactured the first Fuel Cell. The apparatus he assembled could electrolyze water without any electricity source.

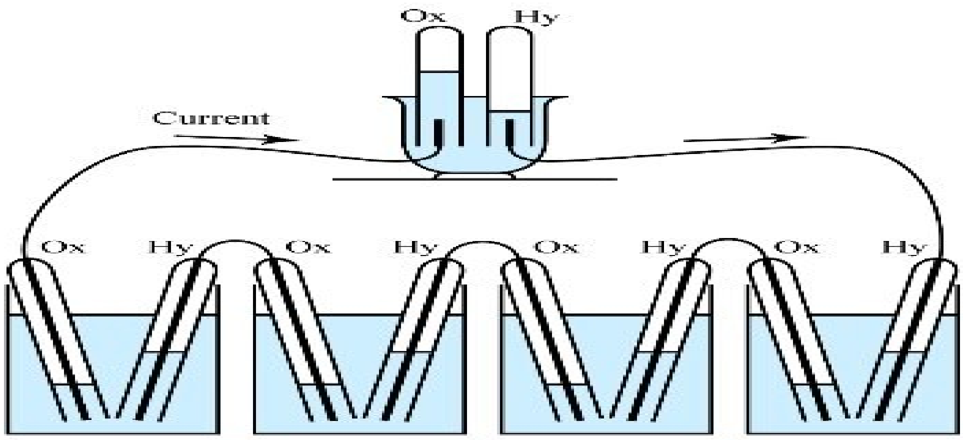


Figure 2.2 first Fuel Cell build by William Robert Grove

His device (see Figure 2 above) worked in such a way that hydrogen (Hy) and oxygen (Ox) gases were in the test-tubes above the four lower beakers. These gases reacted in a sulphuric acid solution and formed H2O. During this electrochemical reaction the electrons were released and they electrolyzed water in the upper reservoir to O2 and H2 using a catalyst metal as the electrodes.

Appendix C Fuel Cell Types & Features

There are several kinds of hydrogen fuel cell technology available or in development, and each operates slightly differently. In general terms, hydrogen atoms enter a fuel cell at the anode where a chemical reaction strips them of their electrons. The hydrogen atoms are ionised and therefore carry a positive electrical charge. The negatively charged electrons provide the current that pass through wires to do work. Hydrogen fuel cell types can be grouped as follow: a) Proton Exchange Membrane (PEM); b) Solid Oxide Fuel Cell (SOFC); c) Phosphoric Acid Fuel Cell (PAFC); d) Molten Carbonate Fuel Cell (MCFC); e) Alkaline Fuel Cell (AFC).

In some fuel cell types Oxygen (or air) enters the fuel cell at the cathode where it combines with electrons returning from the electrical circuit and hydrogen ions that have travelled through the electrolyte from the anode.

In other cell types the oxygen picks up electrons and then travels through the electrolyte to the anode, where it combines with hydrogen ions.

The electrolyte used in each fuel cell technology type performs a very important role as it must permit only the appropriate ions to pass between the anode and cathode. If free electrons or other substances could travel through the electrolyte, they would disrupt the chemical reaction, and in the worst case cause an explosion or fire.

Appendix D Comparison of main fuel cell types & features

The main futures of each type of Fuel Cell as fuel type, efficiencies, operation, power range, temperatures, technology statues and the application suitable for are presented in the following table:

	PEM	SOFC	PAFC	MCFC	AFC
Electrolyte	Polymer Ion	Ceramic	Phosphoric Acid	Molten Carbonate Salt	Potassium Hydroxide
Temperature (°C)	Ambient -80°C	600-1000	170-200	600-700	150-200
Fuels	H2 / Reformate	H2/CO2/CH4 Reformate	H2 / Reformate	H2/CO/ Reformate	H2 Reformate
Oxidant	O2/Air	O2/Air	O2/Air	CO2/O2/Air	O2/Air
Conductive Ion	H+	O-	H+	CO3-	OH
Electrical efficiency (HHV)	40-50%	45-55%	40-50%	50-60%	40-50%
Power range (kW)	1-250	1-900	50-200	1-2MW	0.6-12
Development stage	Commercialised (Production Prototypes)	Commercialised (Production Prototypes)	Commercialised (Mature Tech)	Commercialised (Production Prototypes)	Commercialised (Mature Tech)
Average Life (h)	1500-3000	3000-6000	65000	N/A	1500-3000
Advantages	Quick start up High power density Solid electrolyte	Solid electrolyte High efficiency	High tolerance to impurities High efficiency	High efficiency Fuel flexibility	High performance
Disadvantages	Expensive catalyst Sensitivity to impurities	Breakdown of cells Slow start up	Large size Heavy Expensive	Breakdown of cells Slow start up	Sensitive to CO2 Corrosive material
Suitable Applications	Small Stationary, Automotive, Portable	Stationary, Automotive	Large Stationary	Large Stationary	Space, Automotive

Table 2 Features of main fuel types

Appendix E General Issues regarding the GenCore 5B49 & the F.C. laboratory

Now regarding the specific PEM fuel cell system that was used for this investigation there are some problems that arise during operation that requires immediate concern and action to be taken.

One major issue that that affect directly the proper operation of the GenCore 5B48 fuel system is the fact that the system is quite old thus needs appropriate maintenance by a specialized technician.

The necessity of maintenance was more than obvious when the PEM fuel cell was on operation mode. The batteries when running on load (i.e. with hydrogen) should get recharged by the same system and that was not taking place. Also problem occurred during operation without load (i.e. without use of hydrogen) with symptom the fast loss of voltage with result to get small time span in order to proceed with the experimentation. A solution but not permanent on this is to be applied a D.C. charge of 50 Volts for direct use on the GenCore 5B48 fuel cell system in order to operate without load and/or to charge the batteries at the end of every session. A permanent and strongly recommended solution is the batteries to be replaced by new ones.

Other issues that occurred during the test runs of the PEM fuel cell were the loss of communication between the software and the GenCore system which indicates that the RS485 connection between GCC and converter may be bad; the MAIN LED was green and the SYS LED was slowly blinking red which implies bad operation of the converter; and finally after a period of time the batteries could not support the stack. Some of the faults as they appeared during the tests are illustrated on the following figure 7.0 as it shows when the system was operating properly.

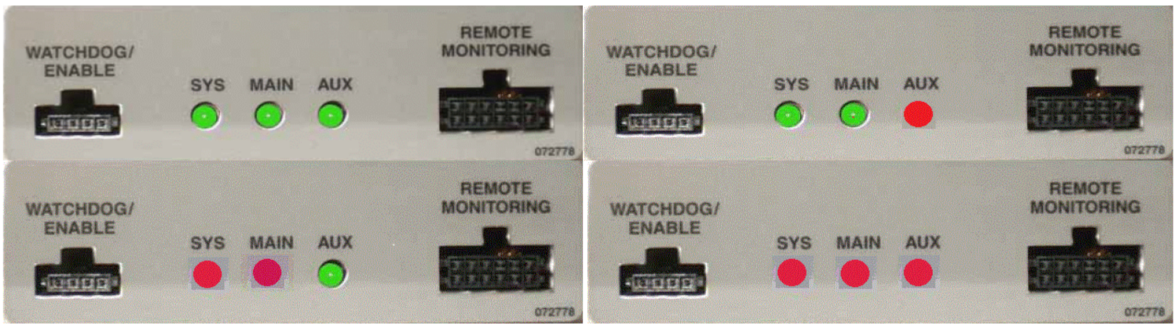


Figure E Operation and fault indication LED panel

According with the GenCore operation manual the PEM needs to be maintained by a specialized technician, preferably a company's technician and also actions to replace some worn parts.

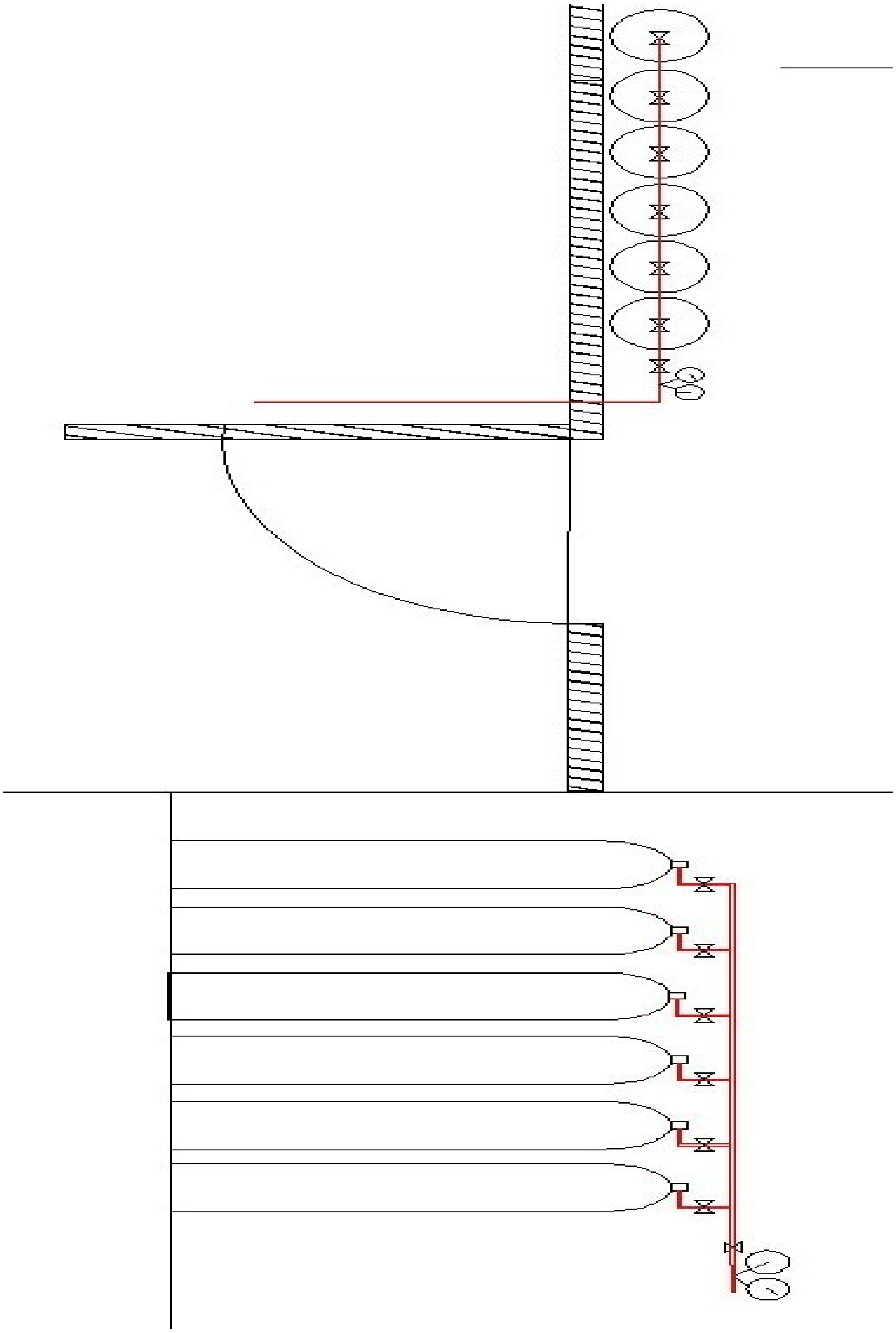
Regarding the fuel cell laboratory, the needs are demanding. As mentioned in previous chapters some equipment will be bought in the future like computerized load bank equipment for better control and/or load management, EIS equipment for enhanced monitoring of the PEM system and better understanding of the GenCore function and the internal operations that take place during its operation.

Finally the laboratory should get a better hydrogen supply system (distribution manifold has been suggested and can be seen a draft of it on the appendix 2), plus a secure storage system cause at the moment only one pressurized hydrogen cylinder can be connected and stored, but it is exposed on the weather elements.

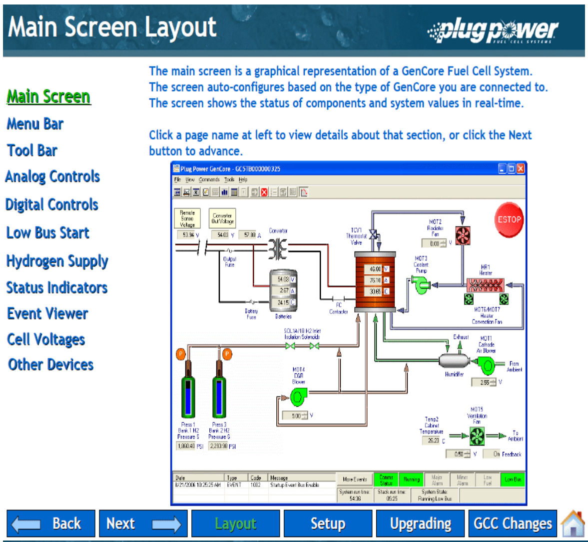
Never the less this project besides mishaps and delays the research was completed on time and shows that this type of fuel cell is suitable for applications mobile and/or stationary with power demands varying from 0 to 5kW giving good overall system efficiencies, depending always the applied loads.

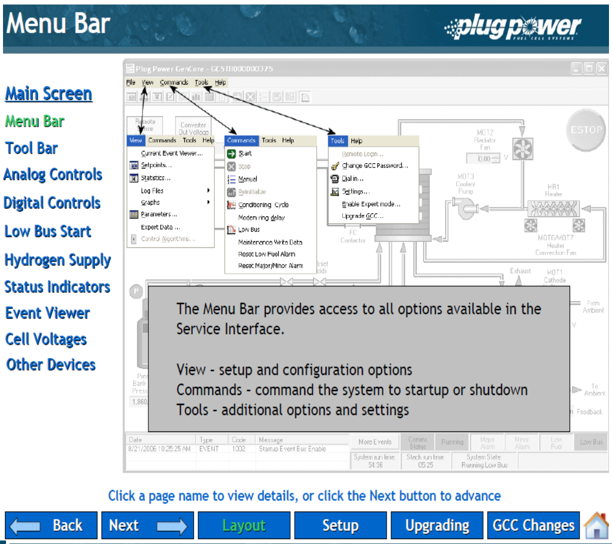
Appendix F Hydrogen distribution manifold

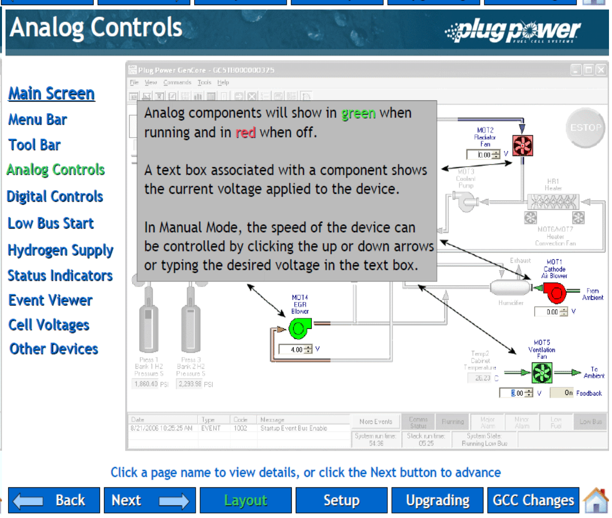
Hydrogen:- to install a 1x6 wall mounted manual manifold BOC part No 19309379, with cylinder connecting arms, single stage 0-10 bar adjustable pressure regulator conforming to BS EN 7291, with safety relief valve, Flash Back arrestor, purge and isolation valve, this would be connected to existing pipework system.

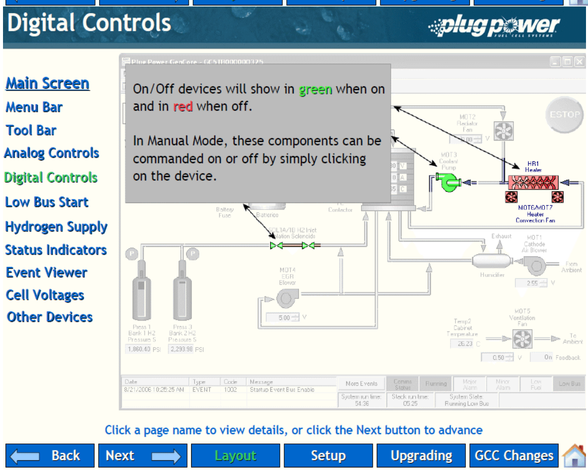


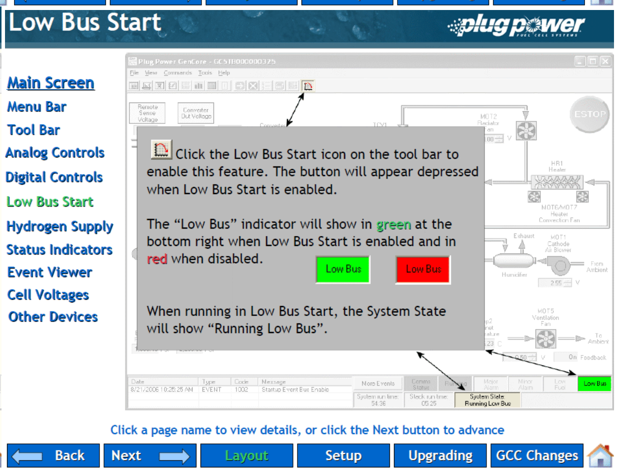
Appendix G Tutorial of GenCore software

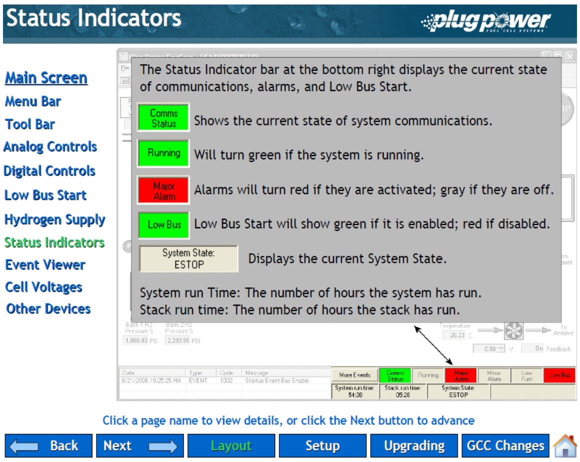


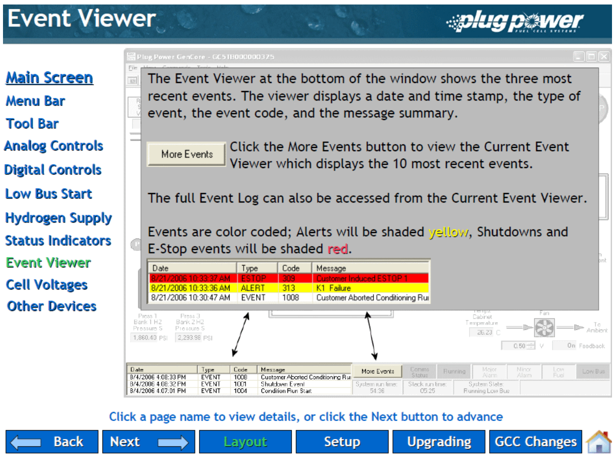









Status Indicators
plug power
Main Screen
Menu Bar
Tool Bar
Analog Controls
Digital Controls
Low Bus Start
Hydrogen Supply
Status Indicators
Event Viewer
Cell Voltages
Other Devices
The Status Indicator bar at the bottom right displays the current state of communications, alarms, and Low Bus Start.
Comms Status
Shows the current state of system communications.
Running
Will turn green if the system is running.
Major Alarm
Alarms will turn red if they are activated; gray if they are off.
Low Bus
Low Bus Start will show green if it is enabled; red if disabled.
System State: ESTOP
Displays the current System State.
System run Time: The number of hours the system has run.
Stack run time: The number of hours the stack has run.
Click a page name to view details, or click the Next button to advance
Back
Next
Layout
Setup
Upgrading
GCC Changes


Event Viewer
plug power
Main Screen
Menu Bar
Tool Bar
Analog Controls
Digital Controls
Low Bus Start
Hydrogen Supply
Status Indicators
Event Viewer
Cell Voltages
Other Devices
The Event Viewer at the bottom of the window shows the three most recent events. The viewer displays a date and time stamp, the type of event, the event code, and the message summary.
More Events
Click the More Events button to view the Current Event Viewer which displays the 10 most recent events.
The full Event Log can also be accessed from the Current Event Viewer.
Events are color coded; Alerts will be shaded yellow, Shutdowns and E-Stop events will be shaded red.
Date
Type
Code
Message
8/21/2006 10:33:36 AM
ALERT
313
K1 Failure
8/21/2006 10:30:47 AM
EVENT
1008
Customer Aborted Conditioning Ru
Click a page name to view details, or click the Next button to advance
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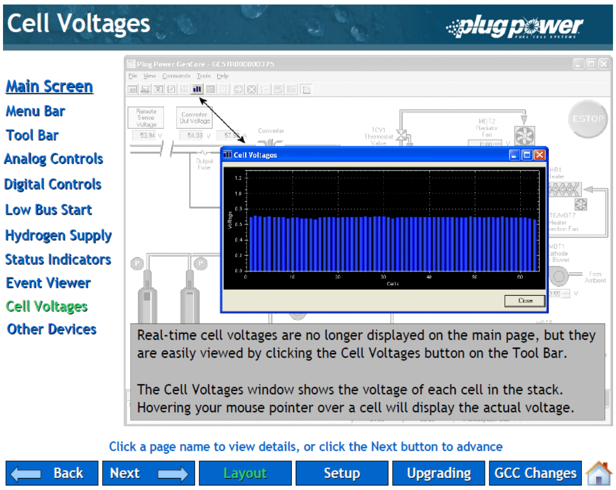
Cell Voltages
plug power
Main Screen
Menu Bar
Tool Bar
Analog Controls
Digital Controls
Low Bus Start
Hydrogen Supply
Status Indicators
Event Viewer
Cell Voltages
Other Devices
Cell Voltages
Close
Real-time cell voltages are no longer displayed on the main page, but they are easily viewed by clicking the Cell Voltages button on the Tool Bar.
The Cell Voltages window shows the voltage of each cell in the stack. Hovering your mouse pointer over a cell will display the actual voltage.
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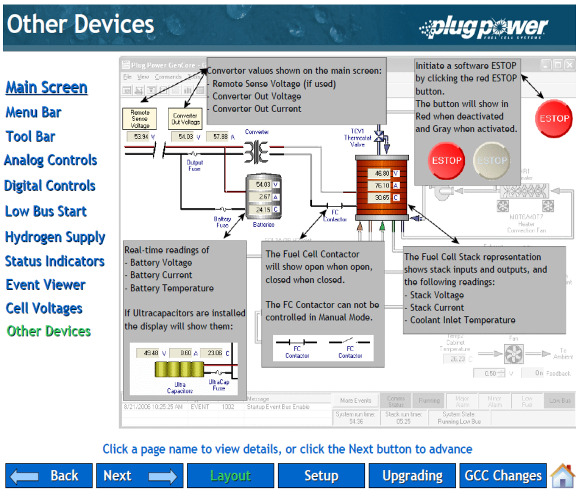
Other Devices
plug power
Main Screen
Menu Bar
Tool Bar
Analog Controls
Digital Controls
Low Bus Start
Hydrogen Supply
Status Indicators
Event Viewer
Cell Voltages
Other Devices
Convertor values shown on the main screen:
- Remote Sense Voltage (if used)
- Convertor Out Voltage
- Convertor Out Current
Initiate a software ESTOP by clicking the red ESTOP button.
The button will show in Red when deactivated and Gray when activated.
ESTOP
Real-time readings of
- Battery Voltage
- Battery Current
- Battery Temperature
If Ultracapacitors are installed the display will show them:
The Fuel Cell Contactor will show open when open, closed when closed.
The FC Contactor can not be controlled in Manual Mode.
FC Contactor
The Fuel Cell Stack representation shows stack inputs and outputs, and the following readings:
- Stack Voltage
- Stack Current
- Coolant Inlet Temperature
Click a page name to view details, or click the Next button to advance
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