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# ASSESSMENT REPORT

Report C066-20110721-1

**PREPARED FOR:**

**ROSS SPIROS – HYDROTECH EGEL**

## PERFORMANCE EVALUATION OF HYDROTECH EGEL'S HYDROXY GENERATOR

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## **1 – OBJECTIVES**

- To assess the performance, in terms of hydroxy gas generation rate per kWh of DC power applied to the Hydrotech EGEL's hydroxy generator (HEHG).
- To assess the reliability, in terms of stability of the HEHG over the trial period of 34 days.
- To determine the mass of material lost from the HEHG's electrolytic cells at the conclusion of the trial period.
- To determine the composition of the HEHG's hydroxy gas output at the completion of the 34 day trial in terms of vol % hydrogen, oxygen, water, carbon dioxide, nitrogen, nitric oxides and aerosolised sodium hydroxide.
- To determine the amount of iron, chromium and carbon introduced into the HEHG's electrolyte at the conclusion of the 34 day trial.

## **2 – SCOPE**

The data and conclusions presented in this report apply only to the HEHG as supplied by Ross Spiros of Hydrotech EGEL on the 10<sup>th</sup> February, 2011 and operated over a period of 34 days. No representation is made by Access Macquarie Ltd, Macquarie University or the author that the results presented in this report apply to any other HEHG systems or for the operation of the supplied HEHG for periods of greater than 34 days.

## **3 – EFFICIENCY AND RELIABILITY**

### **METHODOLOGY**

The reliability and efficiency of the HEHG was evaluated over a continuous period of 34 days (a total of 787 hours over the period 10<sup>th</sup> Feb 2011 to the 15<sup>th</sup> March 2011). DC power for the HEHG was supplied from a Lincoln Electric Invertec® V160-S inverter arc welder which operated as a constant current source. The Inverter was arbitrarily set to provide a nominal current of 35 amps. Actual current to the cell was measured using a Datel 100A/100mV precision current shunt (Datel Part No. 3020-01108-0) and a HP 3465A precision multimeter (calibrated 16 Jun, 2010). Cell voltage was measured using an additional HP 3465A precision multimeter (calibrated 21 May, 2010). Both voltage and current data were logged at 5 minute intervals to a computer via the multimeter's HP/IL interfaces. Energy into the HEHG, measured as kW·h, was determined by the direct multiplication of the instantaneous current and voltage at 1 second intervals and integrating the product over the 5 minute sampling interval.

As the HEHG needs to operate under pressure, hydroxy gas production rate was measured as the flow of hydroxy gas from the unit required to maintain a constant operating pressure of  $310 \pm 1$  kPa within the HEHG. An Alicat Scientific M Series Precision Gas Mass Flow controller was used to both measure and regulate gas flow from the HEHG. The flow controller was initially calibrated using a 2:1 mol/mol hydrogen/oxygen gas mix saturated with water vapour at  $15^\circ\text{C}$ , i.e.  $65.5 \pm 0.7$  vol% hydrogen,  $32.7 \pm 0.4$  vol% oxygen,  $1.7 \pm 0.1$  vol% water vapour. Flow data (mass flow, volumetric flow), pressure and gas temperature were logged to a computer at 5 minute intervals via the Mass Flow controller's RS-232 interface.

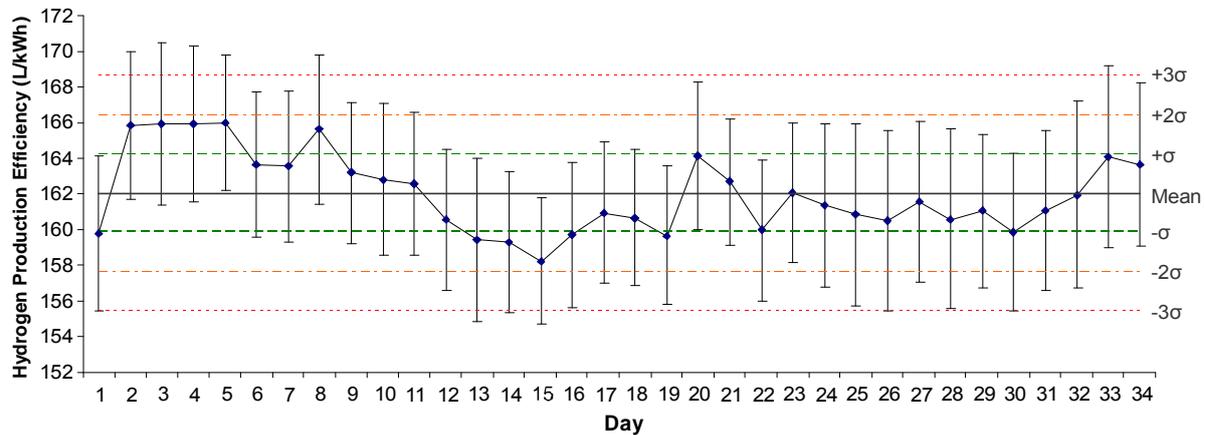
The HEHG operates on an hourly polarity swapping cycle. That is, the polarity of the electrolytic cell is swapped every 60 minutes. After the polarity has been swapped, there is a stabilisation period of 8-10 minutes where the cell voltage, gas flow and cell pressure vary considerably before settling down to more constant values. As a result of this variability, any data collected for a period of 10 minutes after polarity switching has occurred was excluded from the data set used for the calculations of hydroxy gas production efficiency.

## HYDROGEN PRODUCTION EFFICIENCY

The average daily (i.e. 24 hours, except Day 1 and 34 which are over 4 hours and 15 hours respectively) hydrogen production efficiency in terms of litres of hydrogen (at 101.3 kPa and  $25^\circ\text{C}$ ) per kW·h of energy input is given in Figure 1. Over the 787 hours of the trial, the HEHG averaged a hydrogen production efficiency of  $162 \pm 4 \text{ L/kW}\cdot\text{h}$  ( $13.4 \pm 0.3 \text{ g/kW}\cdot\text{h}$ ,  $6.62 \pm 0.16 \text{ mol/kW}\cdot\text{h}$ ). Power to the HEHG was provided by a constant current source which averaged a constant current of  $34.2 \pm 0.4 \text{ A}$  at  $18.0 \pm 0.6 \text{ V}$  for the period of the trial. At this current the HEHG produced hydrogen at an average rate of  $100 \pm 2 \text{ L/h}$  ( $8.24 \pm 0.16 \text{ g/h}$ ,  $4.09 \pm 0.08 \text{ mol/h}$ ). The average daily hydrogen production rates are shown in Figure 2.

## EFFECT OF TEMPERATURE ON EFFICIENCY

During the trial period the HEHG was housed in a non-temperature controlled environment where the ambient temperature varied from  $21$  to  $30^\circ\text{C}$ . Both the ambient temperature and the operating temperature of the HEHG's electrolytic cell were recorded for the period of the trial. The average daily temperature of the HEHG cell and the ambient temperature are shown in **Figure 3**. Over the 787 hours of the trial, the HEHG's cell temperature remained within  $5.8 \pm 1.6^\circ\text{C}$  of the ambient temperature. As shown in **Figure 4**, there is no correlation between cell temperature and hydrogen production efficiency. Thus within a cell operating temperature range of  $33 \pm 3^\circ\text{C}$  the HEHG's hydrogen production efficiency is unaffected by operating temperature.

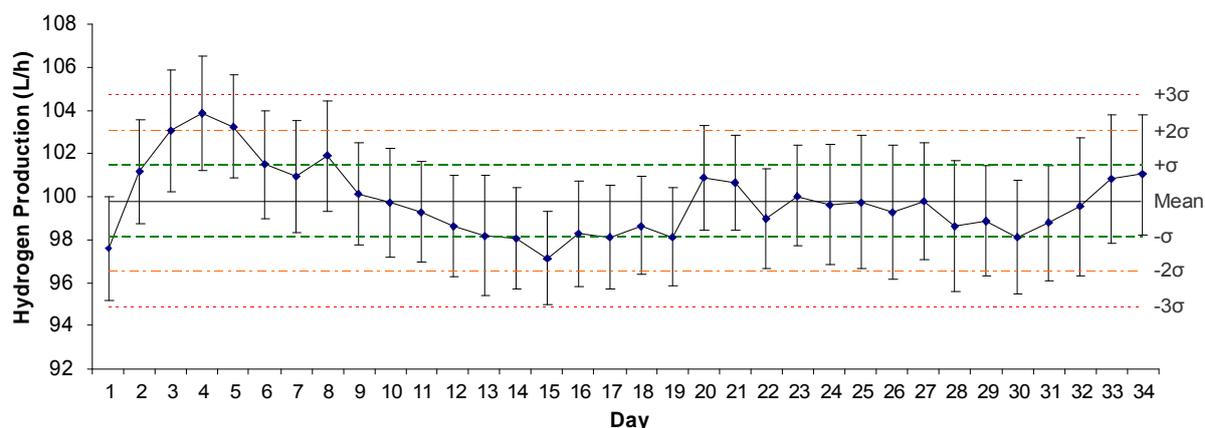


**Figure 1** – Average daily hydrogen production efficiency of the HEHG expressed as litres of hydrogen (at 101.3 kPa and 25 °C) produced per kW·h of energy input into the HEHG. Error bars represent 2 times the daily sample standard deviation of the efficiency. The mean efficiency together with control limits at 1, 2 and 3 times the standard deviation of efficiency over the trial period are presented as indicated in the right margin of the plot.

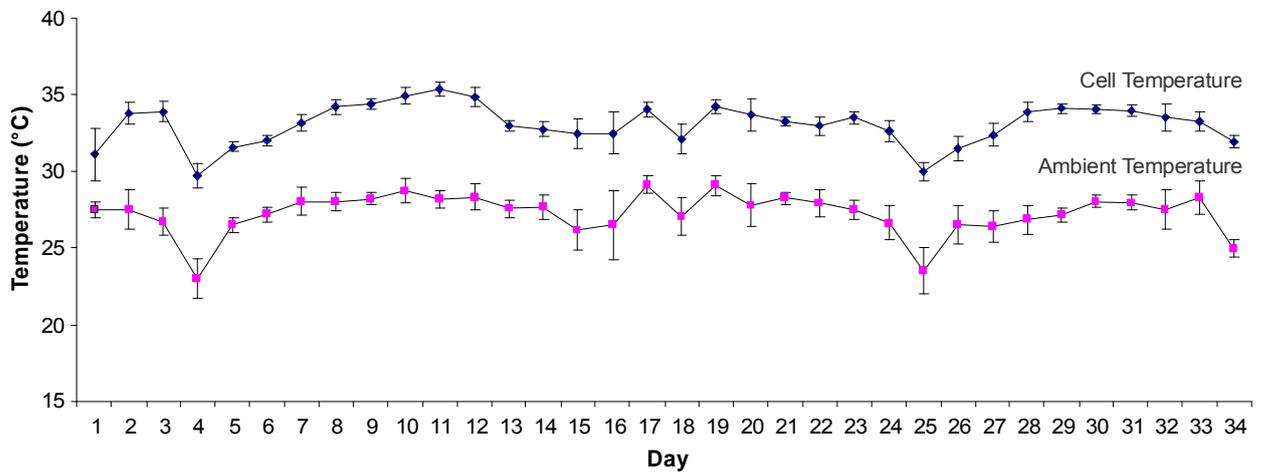
## RELIABILITY

Conclusions about the absolute reliability of the HEHG are not possible for a trial of only 34 days. However, for the period of the trial, the unit was able to produce hydrogen (as hydroxy gas) at a continuous rate of  $162 \pm 4$  L/kW·h staying within the  $\pm 2$  standard deviation control limits. The hydrogen production efficiency of the unit appeared to be unaffected by changes in the ambient temperature (within the temperature range of  $26 \pm 4$  °C) or operating cell temperature (within the temperature range of  $33 \pm 3$  °C).

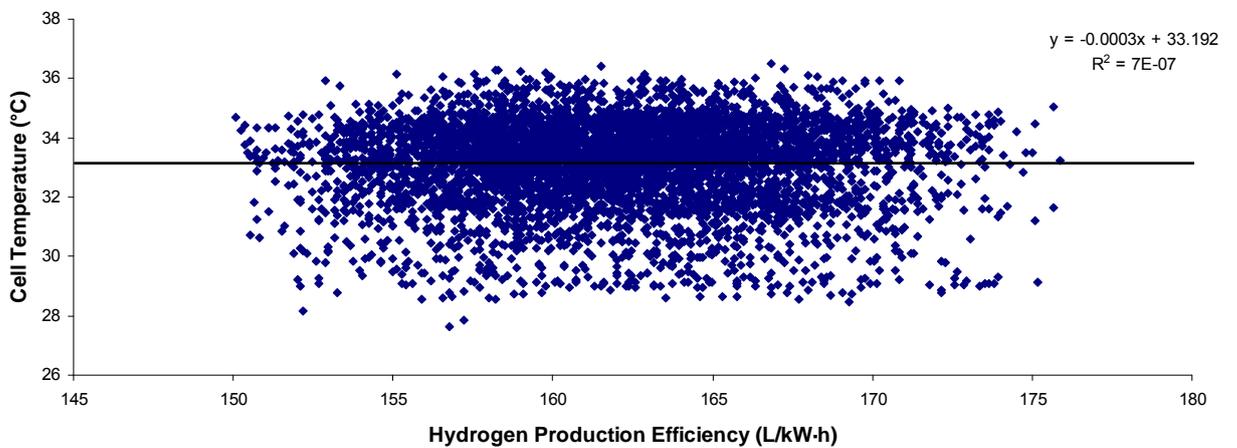
There was, however, a slight but noticeable drop-off in efficiency at around days 9-10. The exact reason for this drop-off was not determined; however an anomaly with one the HEHG's sub-cells (see Section 4 ) could explain this drop-off. Alternately, as the HEHG's electrolytic cells



**Figure 2** – Average daily hydrogen production rate of the HEHG at  $34.2 \pm 0.4$  A expressed as litres of hydrogen (at 101.3 kPa and 25 °C) produced per hour. Error bars represent 2 times the daily sample standard deviation of the production rate. The mean production rate together with control limits at 1, 2 and 3 times the standard deviation of production rate over the trial period are presented as indicated in the right margin of the plot.



**Figure 3** – Average daily HEHG operating cell temperature and ambient temperature. Error bars represent 2 times the daily sample standard deviation of the temperature.



**Figure 4** – Plot of HEHG operating cell temperature versus hydrogen production efficiency showing no correlation ( $p > 0.05$ ) between cell operating temperature and hydrogen production efficiency.

were brand new at the start of the trial, the drop-off may simply be the result of the system reaching an equilibrium operating condition.

#### 4 – CELL DEGRADATION

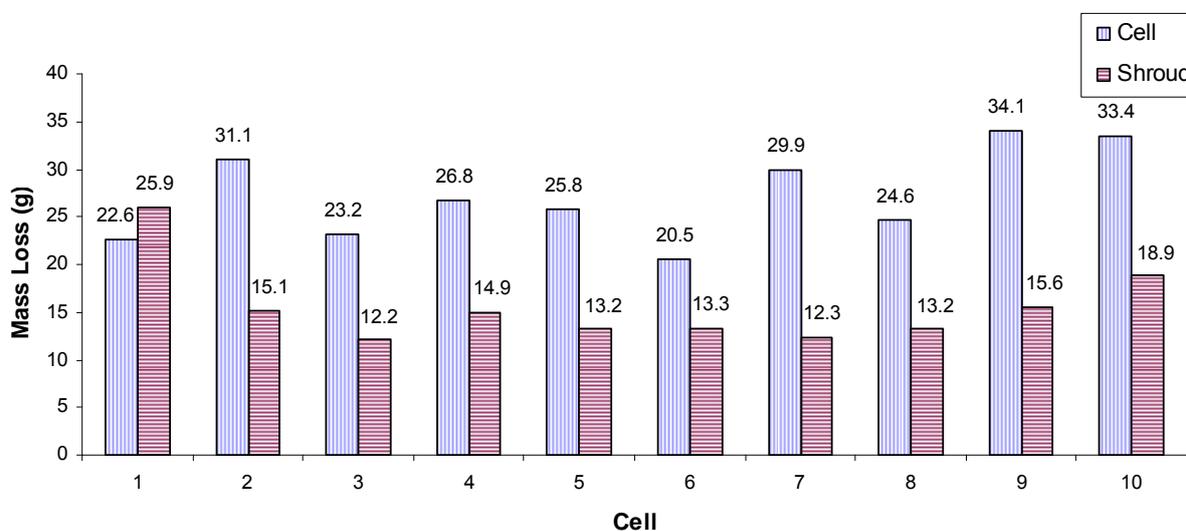
The HEHG’s electrolytic cell comprises 10 sub-cells linked together. Each sub-cell is made up of a cell stack and a shroud. During normal operation material from these cells is lost due to the electrolytic process. To estimate the rate at which material is lost from these cells under the conditions of the trial, the cell stack and shroud from each of the sub-cells were weighed at the beginning of the trial and again at the completion of the trial, a period of 787 hours run time. The mass of material lost from each of the sub-cells is given in **Table 1** and displayed graphically in **Figure 5**. Cells are presented in the table and figure in order of their relative position within the HEHG’s electrolytic cell.

**Table 1** – Mass lost from HEHG's electrolytic cells over the trial period of 787 hours

Sub-Cell	Initial Mass – Cell /g	Mass Loss /g	Initial Mass – Shroud /g	Mass Loss /g
1	3332.9	22.6	1187.8	25.9
2	3125.4	31.1	1118.8	15.1
3	2901.0	23.3	1061.0	12.2
4	2675.6	26.8	984.6	14.9
5	2449.1	25.8	911.5	13.2
6	2357.6	20.5	874.6	13.3
7	2578.7	29.9	949.5	12.3
8	2790.0	24.6	1009.7	13.2
9	3024.6	34.1	1089.5	15.6
10	3253.7	33.4	1145.1	18.9
<b>Totals</b>	<b>28488.6</b>	<b>272.0</b>	<b>10332.1</b>	<b>154.6</b>

Based on this data, it can be concluded that relatively more material is lost ( $p < 0.01$ ) from the shrouds ( $1.5 \pm 0.6$  % wt) than from the cell stacks ( $1.0 \pm 0.3$  % wt). Considering the total mass lost from the sub-cells and shrouds over the period of the trial, the HEHG's electrolytic cell loses on average  $8 \pm 3$  g/day from the cell-stacks and on average  $5 \pm 2$  g/day from the shrouds. As such the shrouds could be predicted to be consumed in  $6 \pm 2$  years and the cell stacks consumed in  $10 \pm 3$  years under the operating conditions of the trial.

Of particular note is the data for sub-cell 1. A statistically larger amount of material has been lost from the shroud of sub-cell 1 compared with the remaining sub-cells (Grubbs test at a 5% significance level). Although statistically, the mass of material lost from the cell stack of sub-cell



**Figure 5** – Mass of material lost from the HEHG's sub-cells and sub-cell shrouds. Original data is present in **Table 1**

1 is consistent with the other cell-stacks, referring to **Figure 5** it does appear to have lost comparably less material than its positionally related cell stacks 2, 9 and 10. This would indicate that sub-cell 1 may have developed a fault of some form and was not performing in the same manner as the remaining 9 sub-cells. As this fault was only detectable at the completion of the trial, it is not ascertainable as to when in the trial the fault occurred. Conceivably it may have occurred around days 9 -10 of the trial where a noticeable drop-off in hydrogen production efficiency was noted (see Section 3).

## 5 – HYDROXY GAS ANALYSIS

### METHODOLOGY

At the completion of the trial, the output of the HEHG was sampled after the mass flow controller using 1000 mL glass stopcocked gas sampling bulbs (Supelco). A total of 50 litres of gas (as determined by the mass flow controller) was allowed to pass through the gas sampling bulb before the bulb was sealed. A total of 3 gas samples were taken in the aforementioned manner.

Gas analyses of the bulb's contents were performed on a Balzer Instruments Thermostar GSD 300T gas analyser. The analyser was calibrated prior to use with gas standards of hydrogen, oxygen, nitrogen and carbon dioxide in argon. The analyser was calibrated for water vapour using a carrier gas of N<sub>2</sub> saturated with water vapour at 15 °C. It was assumed that the concentration of water vapour in the N<sub>2</sub> was equal to the vapour pressure of water at 15°C

### RESULTS

**Table 2** – Hydroxy Gas analysis results. All results are the mean result of triplicate analyses. The quoted uncertainty is the 95% confidence limit, based on 2 degrees of freedom and  $t_{2,0.05}=4.303$ . Concentrations of ozone and nitric oxides are approximations. See text for more detail

Gas	Concentration (% v/v)
Hydrogen	66.3 ± 0.9
Oxygen	31.5 ± 0.5
Nitrogen	0.09 ± 0.01
Water Vapour	1.59 ± 0.07
Carbon Dioxide	0.07 ± 0.01
Ozone	(~0.08 ± 0.02) <sup>see text</sup>
Nitric Oxides (NO + NO <sub>2</sub> )	(~0.005 ± 0.002) <sup>see test</sup>

The results of the analysis of the gaseous output of the HEHG are presented in **Table 2**. Of note is the presence of ozone and nitric oxides in the gas stream. Whilst it was possible to detect the presence of these gases, they were not able to be accurately quantified due to the lack of calibration gases standards for these components. As such, the concentrations given in **Table 2** for ozone and nitric oxides are approximations based on relative sensitivity values (relative to nitrogen) for these components estimated from literature values (RS=1.15 for NO) or estimated from similar compounds (RS=0.9 for ozone, 1.2 for NO<sub>2</sub>).

## 6 – ELECTROLYTE ANALYSIS

### METHODOLOGY

Samples (250 mL) of the electrolyte were taken at the start and completion of the trial. Iron and Chromium content was determined by flame atomic absorption spectroscopy (FAAS) using a GBC 908AA. Chromium was determined by standard addition at 357.9 nm (7 mA lamp current, 0.2 nm slit width) using a lean acetylene/nitrous oxide flame and deuterium background correction. Iron was also determined by standard addition at 248.3 nm (8 mA lamp current, 0.2 nm slit width) using a lean acetylene/air flame and deuterium background correction. Prior to analysis, 25 mL aliquots of the electrolyte were first neutralised using 15 mL concentrated nitric acid. Appropriate chromium or iron standards (to achieve 0.5, 1, 2 and 5 mg/L added analyte) were then added to the neutralised aliquots before making up to 50 mL with milli-Q water in volumetric flasks.

Total organic carbon content of the electrolyte was determined using a Shimadzu TOC-5000. Prior to analysis, 25 mL aliquots of the electrolyte were first neutralised to pH 3.5 using concentrated hydrochloric acid. The neutralised aliquots were then purged with nitrogen for 5 minutes to remove dissolved carbon dioxide before being made up to 50 mL with milli-Q water in volumetric flasks.

### RESULTS

**Table 3** – HEHG electrolyte analysis. All results are the mean result of triplicate analyses. The quoted uncertainty is the 95% confidence limit, based on 2 degrees of freedom and  $t_{2,0.05}=4.303$

	<b>Concentration at trial start (mg/L)</b>	<b>Concentration at trial end (mg/L)</b>
Iron	< 0.05	1.73 ± 0.03
Chromium	< 0.05	< 0.05
Total Organic Carbon	727.6 ± 0.2	1370.4 ± 0.2

## 7 – SUMMARY

In summary, the Hydrotech EGEL's hydroxy generator (HEHG) was operated for a period of 787 hours using a constant current power source delivering  $34.2 \pm 0.4$  A. During this period the HEHG averaged a hydrogen production efficiency of  $162 \pm 4$  L/kW·h. It was found that hydrogen production efficiency of the HEHG was not affected by ambient temperature changes of  $26 \pm 4$  °C or HEHG cell operating temperature changes of  $33 \pm 3$  °C. The gaseous output of the HEHG was found to contain primarily hydrogen ( $66.3 \pm 0.9$  %v/v), oxygen ( $31.5 \pm 0.5$  %v/v) and water vapour ( $1.59 \pm 0.07$  %v/v) with traces of nitrogen, carbon dioxide, ozone and nitric oxides.

## 8 – CODE OF CONDUCT STATEMENT

This report has been prepared in accordance with the District Court of NSW Expert Witness Code of Conduct. The author of this report has read the Code of Conduct and has undertaken to comply with it.

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