6. PRELIMINARY TESTING

6.1 Overview

The first stages of the experimental process involved the commencement of a number of small experiments, which were performed sequentially so as to develop the concept of hydrogen generation in a logical and methodical manner.

This comprised the verification of hydrogen generation followed by initial attempts to capture and measure the liberated gas. Thereafter, preliminary engine tests and equipment redesign were undertaken as necessitated by the initial results obtained. These experiments are detailed below.

6.2 Test 1: Concept Demonstrator

Since the generation of hydrogen from an onboard generating device was a novel concept and owing to the scarcity of reliable literature on the subject, it was decided that a small experiment would be undertaken to verify the concept of generating hydrogen from a set of electrodes supplied with a square wave pulse [25].

6.2.1 Objective

The objective of the experiment was to generate hydrogen through electrolysis and positively test for its presence.

6.2.2 Apparatus

The equipment used in the experimentation was as follows:

- ***Electrode Bank***

A single set of stainless steel electrodes was manufactured for use in the experiment. The electrode bank comprised two 1.5 millimetre flat plates of approximately 200 x 80 mm dimensions separated by a 2 mm strip of polyvinylchloride on either side. These were fixed together using contact adhesive and a 3 mm stainless steel rod was welded onto each plate to serve as the electrical connections.

- ***Electronic Circuit***

The square wave generating circuit was built according to the specifications detailed in Section 4.3 above. This was powered by a Lodestar power supply which converted 220 volt AC voltage to the desired DC voltage required to drive circuit.

- ***Other Equipment***

Other equipment used in the experiment were a 15 litre plastic bucket, a 50 ml glass vial and two electrical leads with crocodile clips on both ends.

6.2.3 Set-up and Test Procedure

The electrode set was placed in the 15 litre bucket and the bucket was filled with water until the electrodes were completely submersed. The crocodile clips were then used to connect the positive and negative electrode connecting rods to their respective circuit outputs. The power supply was connected to the circuit via the input jack and to the wall socket by means of a standard three-pin plug.

The testing procedure was then undertaken as follows:

1. The power supply plug was plugged into the wall socket and the switch turned on.

2. The voltage and current dials on the power supply were set to zero and the power supply was switched on.
3. The circuit was switched on.
4. The voltage dial was adjusted to 12 volts and the current was increased until the *"current"* LED turned off.
5. A glass vial was held inverted over the electrodes so as to capture some of the gas being formed.
6. A match was struck and held slightly above the water surface.
7. The full vial was lifted out of the water and immediately brought into contact with the burning match.
8. The match was then extinguished and the vial placed aside.
9. The voltage and current were returned to zero and the power supply and circuit were switched off.

6.2.4 Results and Discussion

Once the circuit was turned on and the current and voltage were set to the desired levels, fine bubbles were seen to be forming around the electrode bank. This was accompanied by a slight hissing sound emanating from the electrode plates.

The bubbles were also seen to rise to the surface of the water and "pop". This was determined as the cause of the hissing sound. Also, there seemed to be a greater propagation of bubbles from the area between the two plates rather than the outer surfaces of the electrodes. This confirmed the literature which stated that the proximity of the two electrodes to each other had a direct effect on the amount of hydrogen produced.

When the vial containing the gas captured from the electrode bank was brought into contact with a burning match, a loud popping sound was heard. From basic chemistry, this was a positive test for the presence of hydrogen. Also, a smell similar to that of a pool or spa was detected and it was determined to be caused by the formation of chlorine gas as a byproduct of the electrolysis process. This was confirmed by an orange discolouration evident in the water after prolonged operation of the circuit.

Also, it was found that the amplifier chip on the electronic circuit became extremely hot within approximately 30 seconds of operation. This necessitated the addition of a heat sink, which aided heat dispersion but was inefficient in keeping the circuit cool. Therefore, a separate fan was used to blow air over the heat sink.

The initial circuit was also found to be inefficient in that its output frequency was three orders of magnitude smaller than that originally designed for. This was thought to be the reason for the exceptionally small yield of hydrogen. Also, the current drawn by the electrode bank was seen to be 1 ampere at 12 VDC as compared to the 300 ma claimed in the literature [25].

6.2.5 Conclusions and Future Work

- The experiment showed that, by pulsing a set of electrodes with a square wave signal, it was possible to produce hydrogen from water by electrolysis.

- The rate of hydrogen generation was proportional to the current being drawn by the electrodes.

Since the production of hydrogen had been ascertained, it was decided that the logical next step would be to collect the hydrogen and channel it through an instrument capable of indicating the quantity of hydrogen being generated.

6.3 Test 2: Hydrogen Collection

6.3.1 Objective

To capture the hydrogen/oxygen mixture and measure the rate at which it was being produced.

6.3.2 Apparatus

The apparatus used in the experimentation was identical to that used in the previous experiment with the exception of the glass vial and 15 litre bucket.

- **Generating Chamber**

A 2 litre rectangular plastic “ice-cream” container, complete with a lid, was used as the generating chamber. The lid was fitted with a flexible rubber tube of 12 mm outer diameter and 500 mm in length.

This was done by drilling a hole of 10 mm diameter through the centre of the lid. The tube was then pushed through hole until it extended by approximately 5 millimetres from the underside of the lid. Silicon sealant was then used to glue the tube in place and prevent any gas leaks.

- **Oxygen Analyser**

A Servomex Oxygen Analyser was used to determine the percentage of oxygen present in the hydrogen/oxygen mixture liberated from the electrodes. The specifications of the analyser are indicated in Table 6.1 below.

Table 6.1: Oxygen Analyser Specifications

Manufacturer:	Servomex
Model:	OA 250
Serial Number:	250 / 940

6.3.3 Set-up and Test Procedure

The electrodes were placed in the 2 litre container and submersed in water as before. PTFE Threadseal tape was used to wrap around the lid seal and the lid was secured in place. The electrical connections were attached as before and, similarly, the electronic circuit was connected to the power supply as previously done.

The testing procedure was then carried out as follows:

1. Steps 1 to 4 of the previous experiment were repeated.
2. The hydrogen generator was left to run for five minutes in order for the reaction to stabilize.
3. While this was being done the oxygen analyzer was plugged into the wall socket and switched on.
4. The rubber tube from the generator was attached to the analyzer inlet and the reading recorded.
5. The tube was then removed after five minutes and, again the reading from the oxygen analyzer was recorded.
6. Steps 4 and 5 were repeated five times.
7. The voltage and current were returned to zero and the power supply and circuit were switched off.

6.3.4 Results and Discussion

Once the circuit had been turned on and the generation of hydrogen could be heard as before, it was expected that the oxygen analyzer would show an increase in the percentage of oxygen that was passing through it.

This was determined from the fact that when the analyzer was not connected to any gas stream, it would be measuring the amount of atmospheric oxygen present and thus, should indicate a value of approximately 21%. This was observed to be true.

From the chemical reaction for electrolysis as given by equation 3.4 above, the generation of hydrogen and oxygen should occur at a ratio of 2:1. This would mean that 33% of the liberated gases from the electrodes would be oxygen. Therefore, it was expected that the oxygen analyzer would show an increase in oxygen to around 33%. This was not the case.

In all five of the test iterations, the change in oxygen concentration, if any, was minimal. The largest change was recorded as an increase of 2% to 35% oxygen concentration. Also, it was observed that since the oxygen readings were indicated as a percentage, the amount of oxygen present from the electrolysis process would be 33 % regardless of the rate of generation.

The absence of any change in oxygen levels was thought to be due to the fact that the actual quantities of hydrogen and oxygen were too small to be sensed by the analyser. Also, it was thought that the pressure of the generated gases was insufficient to allow for these gases to pass through the analyser.

Another reason for the unchanging readings could be the possibility that the hydrogen/oxygen mixture was escaping through the container-lid interface.

6.3.5 Conclusions and Future Work

- The rate of hydrogen generation could not be determined due to insufficient hydrogen/oxygen concentrations.

- The oxygen analyser was unsuitable for determining the rate at which hydrogen was being generated.

The operational problems highlighted by performing of the experiment were addressed as follows:

- It was decided that a larger set of electrodes would be constructed. The rationale behind this was the fact that a larger electrode surface area would result in a more current being drawn and hence, greater hydrogen production.

- Another method for determining the rate at which hydrogen was being produced was developed and implemented.

6.4 Test 3: Temperature Effects

6.4.1 Objective

The objective of the test was to determine the effect of the water temperature on the rate of hydrogen production from the electrode bank.

6.4.2 Apparatus

While the square wave generating circuit and all the other electrical components remained the same, a new electrode bank was manufactured and used. Also, the introduction of a different measuring procedure entailed the use of other equipment as detailed below.

- ***Electrode Bank***

The electrode bank comprised six sets of electrodes, twelve plates, of dimensions 200 x 130 mm manufactured from 1.5 millimetre stainless steel plate. Each plate was electrically insulated from the next by a 20 x 130 mm strip of polyvinylchloride at either end of the electrode bank. The entire plate configuration was held together by an M8 plastic bolt at each corner of the plates.

The locations of the holes for these bolts were staggered so that every alternating plate would protrude at one end of the electrode bank while the remaining plates would do the same at the other end. These protruding ends were then bent and bolted together through a single stainless steel bolt, which served as the electrical connection to each plate. This resulted in the creation of alternate anode and cathode plates.

Attached to either bolt was a strip of stainless steel that extended above the surface of the water that facilitated the connection of the crocodile clips as mentioned before.

- ***Generating Chamber***

Since the new electrode bank could no longer be accommodated in the 2 litre container, a transparent 5 litre "*Valprẽ*" container was used to house the electrodes. The conical section of the container was removed and a flexible rubber tube was attached to the cap in the same manner as was done in the preceding test.

- ***Electronic Scale***

It was decided that an electronic scale would be used to measure the mass of water that was used up during electrolysis over a set time period. From the balanced equation for electrolysis, this could be equated to the molecular mass of hydrogen produced and, hence, the volumetric rate of hydrogen production.

- ***Thermocouple***

A Fluke thermocouple was used to measure the temperature of the water prior to the commencement of each test.

6.4.3 Set-up and Test Procedure

The bank of electrodes was placed in the 5 litre container and submersed in water as before. This container was then placed on the scale and the crocodile clips were connected to the anode and cathode respectively. The electronic circuit and power supply were connected as explained previously.

The test procedure was undertaken as follows:

1. Steps 1 to 4 were followed as per Section 6.2.4.
2. The temperature of the water was measured and recorded.
3. The electronic scale was switched on.
4. After the reaction had stabilized, the scale was zeroed and, simultaneously, the stopwatch was started.
5. The reaction was left run for fifteen minutes, after which the scale reading was recorded.
6. The voltage and current were returned to zero and the power supply and circuit were switched off.
7. The crocodile clips were disconnected and the water drained from the container.

The entire process was then repeated for water at varying temperatures as obtained from the laboratory geyser or a conventional kettle.

6.4.4 Results and Discussion

Table 6.2 below, contains the abridged results for the effects of temperature on hydrogen production. A complete set of results may be found Appendix C1.

Table 6.2: Experimental Results for Temperature Tests

Time	Mass of Water Loss	Temp	Rate of Water Loss	Mass of H_2 Produced	Volume of H_2 Produced
[s]	[g]	[deg C]	[g/s]	[g/s]	[m^3/s]
55	0.2	22.00	0.003636	0.000407	0.00453
900	5.1	36.40	0.005667	0.000634	0.00705
900	5.2	37.90	0.005778	0.000647	0.00719
900	9.9	48.80	0.011000	0.001231	0.01369
900	14	55.00	0.015556	0.001741	0.01936

A sample calculation at a temperature of 55º may be found in Appendix C1.

The relationship between hydrogen generation and water temperature is illustrated in Figure 6.1 below. It can be seen that the rate of hydrogen production is exponentially proportional to the temperature of the water, as shown by the uncorrected rate of hydrogen production.

However, at a temperature of 55°C, the liberation of a white gaseous substance was observed rising off the water surface. This was thought to be water vapour. It was then realized that the evaporation of the water would result in a loss of water mass and, therefore, the results obtained would indicate a false rate of hydrogen generation at elevated temperatures.

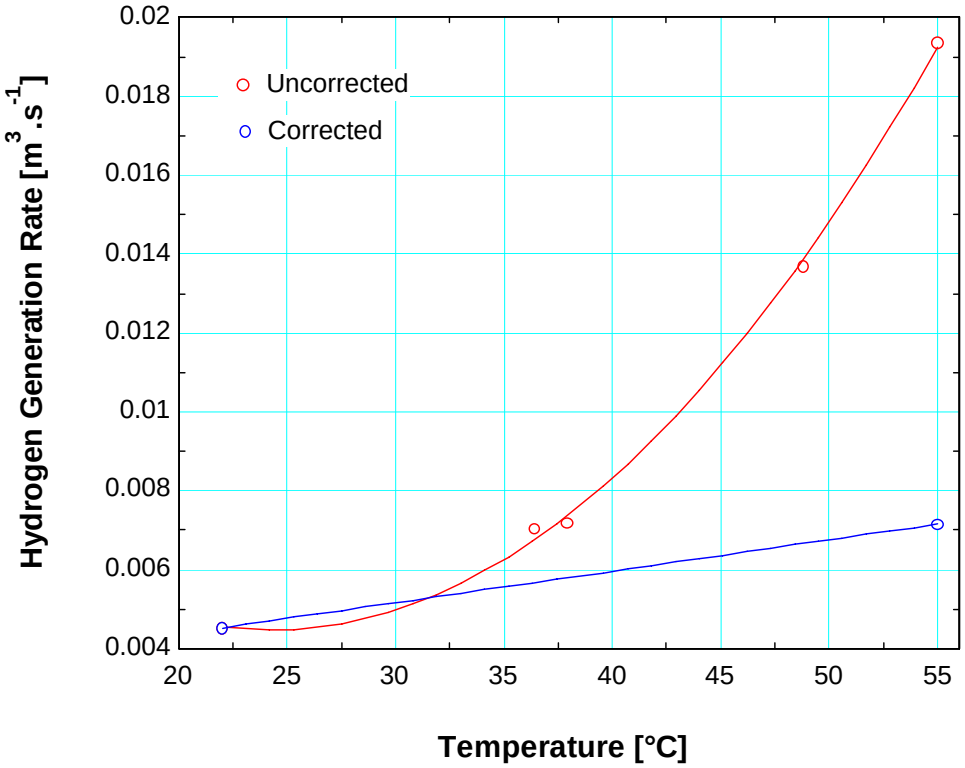

Figure 6.1: Graph of Hydrogen Generation vs. Water Temperature

It was then decided to conduct a test in which the mass of water lost through evaporation could be determined. This was performed by applying the procedure as laid out in Section 6.4.3. However, the electronic circuitry, even though connected, was not switched on. The change in mass, as indicated by the scale, was then the mass of the water lost due to evaporation.

For water at 55°C, this was found to be 0.01674 m^3/s. The corrected rate of hydrogen generation was then determined by subtracting this figure from the uncorrected rate.

This resulted in the corrected relationship between the rate at which hydrogen was being generated and the temperature of the water. This was found to be linear. It was noted that a 150% rise in the temperature of the water resulted in a 58% rise in the hydrogen production rate.

6.4.5 Conclusions and Future Work

- The rate of hydrogen generation was proportional to the temperature of the water being electrolysed.

- The increase in hydrogen generation as a result of increased water temperature was not substantial enough to justify the addition of a water heater to the generator design.

- The mass balance method of determining hydrogen generation rate was successful and yielded reasonable results.

Since the generation of hydrogen with use of water at room temperature was determined as being 4.53 litres per second, it was decided that the logical next step in the experimental process would be to test the generated hydrogen on an actual engine.

6.5 Test 4: Preliminary Engine Test

6.5.1 Objective

The objective of the test was to determine the effect of hydrogen fuelling on the operation of an internal combustion engine.

6.5.2 Apparatus

The equipment required for the commencement of the experimentation comprised the square wave circuit, electrode bank and generator housing as used in the previous experiment. Also, the power supply and electrical connections were used and connected in the same manner as before.

- ***Engine and Dynamometer***

A single cylinder, four stroke Briggs and Stratton spark ignition engine was used to test the engine's response to hydrogen fuelling. The specifications of the engine may be found in Table 6.3 below.

Table 6.3 Engine Specifications

Manufacturer:	Briggs & Stratton
Model:	196432
Capacity:	318.5 cm^3
No. of cylinders:	1
Bore:	76.2 mm
Stroke:	69.85 mm
Max. Recommended Power:	5.3 kW @ 3000 rpm
Max. Power @ Max. rpm	6.0 kW @ 3600rpm

The engine was coupled to a dynamometer in order to measure its torque output. A detailed description together with the dynamometer specifications may be found in Section 5.2 above.

- ***Voltmeter***

A digital voltmeter was used to indicate the voltage readings transmitted by the strain gauges in the loadcell. This was then converted to the corresponding torque values by applying the calibration equation.

- ***Fuel System***

The original fuel tank of the engine, which was mounted above the cylinder head, was removed and secured at a height of approximately one metre above the fuel intake. This was done so as to increase the gravitational feed to the engine. The fuel was supplied to a float feed carburettor complete with manual choke.

The air supply system comprised a gas carburettor conversion kit, which was bolted onto the carburettor by means of a specially designed attachment. This attachment also allowed for the connection of a flexible air hose. The air hose supplied air to the engine from a damping drum as discussed in Section 5.3.2 above.

- ***Gas Analyser***

The gas analyser as detailed in Section 5.5 above was used to determine any changes to the exhaust emissions once the hydrogen had been introduced to the engine.

6.5.3 Set-up and Test Procedure

The electronic circuitry was connected as described in the preceding tests. The bank of electrodes was submersed in water as before. However, the top of the 5 litre container, which was previously removed, was replaced and secured in place with insulation tape. The modified cap, as discussed in Section 6.4.2 above, was then screwed onto the container.

1. The electronic circuitry was switched on in the manner as described by steps 1 to 4 in Section 6.2.3 above.
2. The water inlet valve was opened to allow cooling water to the dynamometer. The water level was held constant by adjusting this valve accordingly.
3. The butterfly valve beneath the petrol tank was opened approximately one turn.
4. The ventilation fans in the test room were switched on.
5. The engine throttle control lever was set at approximately half its range and the air intake was choked by means of the engine choke.
6. The engine was fired by pulling on the starter cord and the choke was immediately released.
7. The engine was brought to idle and allowed to stabilize.
8. The throttle was increased to a predetermined setting and left there.
9. The rubber hose was then brought up to the air intake from the damping unit and secured there.
10. After approximately five minutes, the hose was removed.
11. Steps 9 and 10 were repeated several times.
12. The rubber hose from the hydrogen generator was then replaced by a hose from a bottle of hydrogen gas.
13. Steps 10 and 11 were repeated using hydrogen from the gas bottle.
14. The hose was removed permanently from the intake and the hydrogen bottle closed.
15. The electronic circuitry was switched off as in step 12 in the preceding section.
16. The engine was brought back to idle and allowed to settle for five minutes before being switched off.
17. The water supply valve was then turned off.

6.5.4 Results and Discussion

It was thought that by introducing hydrogen to the air intake stream, the engine would respond in some way to the additional fuel that was being supplied. An increase in, either, engine torque or engine speed was expected.

However, when the rubber tubing from the generator was secured to the inlet, no difference in either of the abovementioned engine performance parameters was observed. By repeatedly removing and re-attaching the hydrogen supply hose it was thought that the changes in engine torque would be noticeable by the varying voltmeter readings. This, however, was not the case.

It was then decided that a bottled source of hydrogen would be used to determine whether the engine was not responding to the hydrogen at all, or if the generator was problematic.

At first, the introduction of hydrogen fuel from the pressurized bottle had no observable effect on the engine performance. Due to the fluctuating nature of the voltmeter, the change in voltmeter readings could not be accurately attributed to the addition of the hydrogen.

Also, since the carburettor contained a small fuel reservoir beneath its float valve, the idea of decreasing the petrol supply to the engine and maintaining its load was not feasible. It was thought that had the engine sustained its load at a lesser fuel rate, this would indicate that the engine was indeed responding to, and operating with, hydrogen fuelling.

It was then decided to shut off the petrol supply completely and run the engine until it began to starve for fuel. This would indicate that the petrol reservoir beneath the carburettor was empty. At this point, the hydrogen would be introduced to the airstream as before and the effects on the engine would be noticed.

Upon introducing hydrogen to the starved engine, it was observed that the engine speed immediately increased and stabilized and the torque readings settled to their previous fluctuation levels. This showed that the engine was being operated on hydrogen successfully.

The fact that the engine did not respond to hydrogen fuelling from the generator but responded positively to fuelling from the bottled source of hydrogen indicated that the problems experienced during the testing occurred as a result of the generator. A number of factors were thought to have contributed to this.

Again, it was thought that the actual amount of hydrogen produced was insufficient to result in a noticeable change in the running of the engine. However, the flow rate of the bottled hydrogen that was supplied to the engine was so small that it could barely be felt against the skin. Therefore, the lack of results from the generator could not be conclusively attributed to an insufficient flow rate of generated hydrogen since the bottled hydrogen flow rate was not measured.

The greatest difference between the generated and bottled hydrogen was the fact that the bottled hydrogen was supplied under a pressure of 15000 kPa. This was thought to be the largest contributory factor to the non-performance of the generator. Since the generated hydrogen was supplied to the engine under ambient pressure conditions, it was thought that hydrogen was not drawn into the engine and thus it was not sensed by the engine. Initially, it was thought that the hydrogen would be sucked into the engine along with the air mixture.

However, the cylinder pressure variations of the engine as it progressed through each of its four strokes were clearly observed by the pulsations that it caused on the water surface of the generator. This reaffirmed the notion that the hydrogen was not being drawn into the engine.

Another contributory factor was that the generating chamber was insufficiently sealed, thus resulting in a leak of hydrogen to the atmosphere.

6.5.5 Conclusions and Future Work

- The engine did not respond to hydrogen fuelling from the generator.

- The engine did respond positively when supplied with fuel from the pressurized bottle of hydrogen and ran on the hydrogen supply.

- The largest contributory factor to the generator problems was the lack of pressure of the generated hydrogen.

- The engine, by nature of its operation, was inadequate in supporting a blend of petrol and hydrogen, as it was not sufficiently stable and hunted alot.

Since the experiment proved that an internal combustion engine could be operated on hydrogen, it was decided that a working prototype of the hydrogen generator, capable of supplying pressurized hydrogen, would be designed and built.

The operational concerns highlighted by the results of the experiment were addressed as follows:

- It was decided that a new, modified square wave circuit, capable of delivering a signal at the required frequency of between 10 to 250 kHz, would be built by an electronics specialist.

- The engine would be replaced by a new, later model, single cylinder engine which would be easier to control and monitor.

- A complete test rig, incorporating the hydrogen generator, test engine and gas analyzer would be built and commissioned.

6.6 Test 5: Circuit Optimisation

6.6.1 Objective

The objective of the experiment was to optimise the performance of the newly built square wave circuit so that the maximum volume of hydrogen would be generated. This was done by determining the frequency at which the most hydrogen was generated.

6.6.2 Apparatus

The apparatus used comprised the 2 litre plastic container together with the single set of electrodes and the power supply and electrical connections as used in the previous experiments. The scale and fans were also used in the same manner as before.

- ***Electronic Circuit***

The new square wave generating circuit, as shown in Figure 4.2 above, was used to provide the square wave pulse form to the electrodes. This circuit was built by *"Instruments for Engineering Measurement"* according to the design criteria contained in Section 4.3.2 above.

- ***Oscilloscope***

A digital oscilloscope was used to display the output waveform from the circuit and to determine the frequency and markspace ratio of the particular signal.

6.6.3 Set-up and Test Procedure

The circuitry and electrical connections were set up in the same manner as before. The 2 litre container, with the single set of electrodes, was placed on the scale. A test probe was connected to the input port of the oscilloscope and connected to the test point named TP3 in Figure 4.2 above.

The test procedure was then undertaken as follows:

1. Steps 1 to 4 were followed as per Section 6.2.4.
2. The volts/division and time/division dials on the oscilloscope were adjusted so that the markspace ratio could be set to approximately 1:10 as measured at TP3.
3. The time period was then recorded from the oscilloscope.
4. The scale was zeroed and at the same time the timer was activated.
5. The circuit was left to run at the particular frequency setting for thirty minutes after which the loss of water mass was recorded as shown by the scale.
6. The frequency of the circuit was then varied using the bank of dipswitches and steps 2 to 5 were repeated at the new frequency.
7. Step 6 was repeated at five different frequency values.
8. The voltage and current were returned to zero and the power supply, scale, oscilloscope and circuit were switched off.

6.6.4 Results and Discussion

Table 6. 4 below, contains the abridged results for the frequency tests. A complete set of results may be found in Appendix C3.

Table 6.4: Experimental Results for Frequency Tests

Time	Mass of Water Loss	Frequency	Rate of Water Loss	Mass of H_2 Produced	Volume of H_2 Produced
[s]	[g]	[kHz]	[g/s]	[g/s]	[m^3/s]
1800	2.3	16.67	0.001278	0.000143	0.00159
1800	3.4	20.00	0.001889	0.000211	0.00235
1800	2.8	20.00	0.001556	0.000174	0.00194
1800	3.3	20.83	0.001833	0.000205	0.00228
1800	2.9	22.73	0.001611	0.000180	0.00201
1800	2.7	25.00	0.001500	0.000168	0.00187
1800	3.7	50.00	0.002056	0.000230	0.00256
1800	3.6	62.50	0.002000	0.000224	0.00249
1800	3.3	66.67	0.001833	0.000205	0.00228
1800	3.6	100.00	0.002000	0.000224	0.00249

Figure 6.2 below, illustrates the relationship between the square wave frequency and the rate of hydrogen generation. It can be seen that the maximum rate of hydrogen generation occurs at frequencies of between 80 and 100 kHz. This confirms the results obtained from the Hydrogen Generator Manual [25].

Also, it should be noted that the maximum rate of hydrogen generation was calculated as being approximately 0.0025 m^3 per second. This was liberated from the single set of electrode plates whose surface area was approximately seventeen times smaller than that of the bank of electrodes, which generated 0.00453 m^3/s of hydrogen.

Thus, it could be said that the hydrogen yield had increased by approximately eight times as a result of the higher frequencies that were now obtainable.

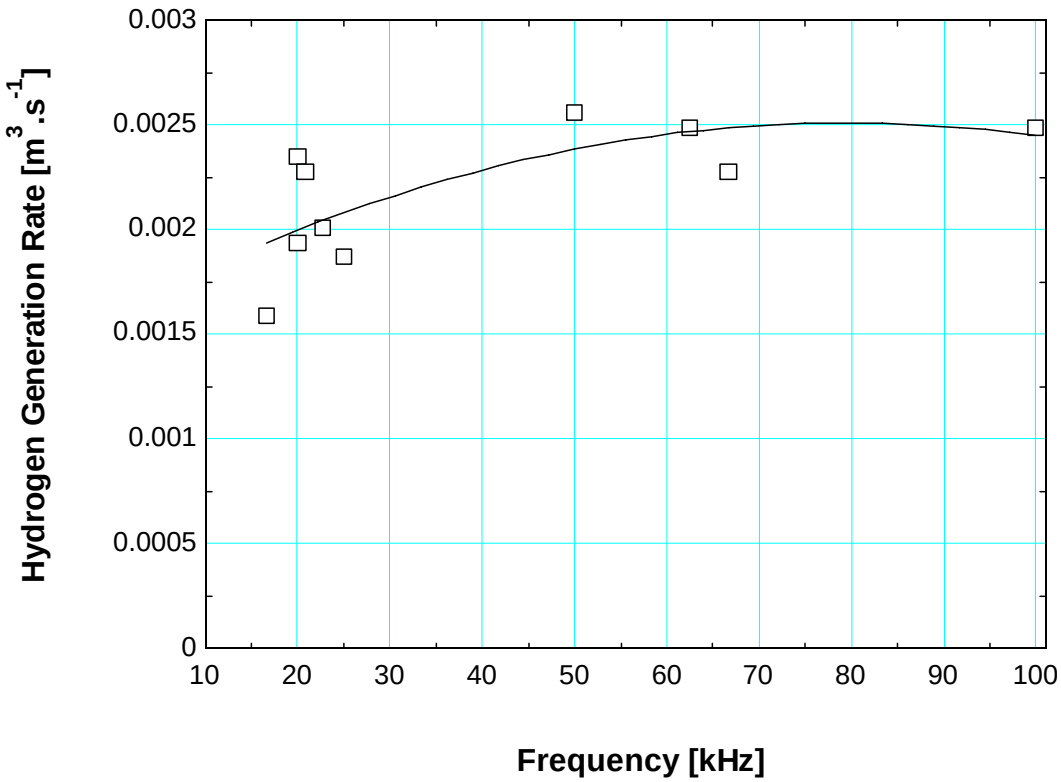

Figure 6.2: Graph of Hydrogen Generation vs. Frequency

Figure 6.2 also shows the inconsistencies in the rate at which hydrogen was being produced. This was especially pronounced at the lower end of the frequency spectrum. Also, the fact that the hydrogen rates were particularly high at 50 and 62 kHz seem to indicate that hydrogen production was favoured from frequencies as low as 50 kHz.

6.6.5 Conclusions

- The optimal frequency at which hydrogen was generated was between 80 to 100 kHz.

- The increased frequency resulted in the equivalent of an eight times greater hydrogen production rate as compared to the self-built circuit.