4. HYDROGEN GENERATOR DEVELOPMENT

4.1 Overview

A hydrogen-generating unit was developed in order to supply the engine with an "on-demand" source of hydrogen. The development of the unit entailed the design and fabrication of the mechanical and electronic components of the generator as discussed in detail in the sections that follow.

It was decided that electrolysis would be explored as the method of hydrogen production as steam reformation required the consumption of fossil fuels as well as equipment that was deemed more cumbersome to obtain or manufacture.

It should be noted that the generator design described below was based on the final design option. The development of all previous models and concept demonstrators would be discussed briefly in the sections pertaining to preliminary experimentation in Section 6.

4.2 Product Requirement Specification

4.2.1 Requirements

- The hydrogen generator must produce sufficient hydrogen to supplement 10% of the petroleum fuel consumption.

- The unit must be capable of operating continuously for an extended period of time.

4.2.2 Constraints

- The generator must be constructed from commercially available materials.
- The electrical power of the unit is limited by the availability of power supplies.
- The components must be manufactured using the existing workshop facilities.
- The geometry of the generating device must be such that it can be easily installed in road-going vehicle.

4.2.3 Wishes

- The cost of the generator should be as low as possible.
- The generator should require minimal maintenance.
- The unit should be portable and robust.
- The device should require minimal monitoring and supervision.

4.3 Design Development

4.3.1 Generating Chamber Design

The generator chamber design comprised the outer casing, top and bottom end caps, electrodes, electrode locators and mounting brackets.

- ***Generator Housing***

Since the governing principle involved in the operation of the generator was that of electrolysis, all components, with the exception of the electrodes, were required to be constructed from non-metallic materials. Metals were deemed inappropriate in the fabrication of the housing owing to the possibility of an oxidation or reduction reaction between them and the electrodes during the electrolysis process.

Thus, it was evident that the housing would have to be made from one of the engineering plastics. Polyvinylchloride (PVC) was chosen as the material for the construction of the casing, locators, end caps and mounting brackets, as it was easily obtainable and relatively inexpensive and it satisfied the abovementioned criteria. Also, prefabricated cross-sections of PVC pipe and sheet were readily available.

Table 4.1 below summarizes the relevant properties of the PVC used. A comprehensive list of specifications may be found in Table A1 of Appendix A.

Table 4.1: Generator Casing Properties [24]

Material:	SABS Class 16 uPVC
Max. Operating Pressure:	1.6 MPa
Surface Resisivity	10^{13} Ω.mm^{-2}
Max. Service Temperature:	65ºC

A cylindrical geometry was decided upon for the layout of the hydrogen-generating device as this minimised the size of the generator. This facilitated onboard installation of the device into a vehicle as the unit would occupy minimal space. Also, a cylindrical design was the most efficient manner of obtaining the maximum surface area of the electrodes without the need to create a bank of flat plates.

From a detailed specification for the manufacture of hydrogen generators [25], it was decided that the hydrogen generator would be designed to operate at a pressure of 520 kPa as this was sufficient pressure to supply the engine with hydrogen without the use of an in-line fuel pump.

An analysis of various commercially available prefabricated PVC pipes was undertaken so as to determine their suitability for use in the design of the casing. It was decided that a PVC pipe with an outer diameter and wall thickness of 110 millimetres and 7.1 mm respectively would be used.

The hoop stress that would be experienced by the housing was then calculated as [26]:

$$\sigma_{hoop} = \frac{pr_i}{t} \tag{4.1}$$

$$= \frac{(520000)(0.0958)}{(0.0071)}$$

$$= 7.016 MPa$$

Given the working pressure of uPVC from Table 4.1 above, the maximum hoop stress that the material can withstand was:

$$\sigma_{hoop,\max} = \frac{pr_i}{t} \tag{4.2}$$

$$= \frac{(1600000)(0.0958)}{(0.0071)}$$

$$= 21.59 MPa$$

This resulted in a safety factor of:

$$f.o.s = \frac{\sigma_{hoop,\max}}{\sigma_{hoop}} \tag{4.3}$$

$$= \frac{21.59}{7.016}$$

$$= 3.08$$

The length of the generator casing was taken as being 407 mm. As the casing fitted into a threaded pipe nipple of 43 mm in length, this would result in a total housing length of 450 mm. This was 120 mm longer than the electrode length, in order to ensure that there would be sufficient room for the mounting of the water level sensors above the electrodes [25].

The threaded nipple comprised a 110 mm male thread on one end and a smooth 110 mm female coupling on the other end. This was necessary as the bottom end cap contained a female 110 millimetre thread.

A quarter inch fitting would be installed into the side of the housing for connection to the water inlet line. The design requirements will be discussed in detail in the section titled *“Bottom End Cap”* below

- ***Electrodes***

The hydrogen generator comprised two electrodes, one being the anode and the other, the cathode. It was decided that both electrodes would be manufactured from 305L stainless steel, as it possessed the required rust-inhibiting properties necessary for continued operation under water.

Electrode length was determined as 330 millimetres, as this was the longest length possible whilst maintaining structural rigidity [25]. It was decided that the maximum surface area of the electrodes would be utilized as this resulted in the greatest amount of hydrogen being produced.

For optimal hydrogen generation, a gap of between 1 and 1.5 mm was to be maintained between the adjacent surfaces of the two electrodes [25]. Therefore, the outer electrode was designed with an outer diameter of 88.9 millimetres and a wall thickness of 1.6 mm. These dimensions were chosen because stainless steel pipes were readily available in these sizes. The outer diameter of the inner electrode was chosen as 83.3 mm and the wall thickness was given as 2.69 millimetres. This brought about a gap of 1.2 mm between the two electrodes.

The bottom end of each electrode contained eight 6 mm diameter holes to allow the flow of water into the areas between the electrodes and into the centre of the generator. These were located at 10 mm from the bottom edge. Also, twenty-four 3 mm diameter holes were drilled into the same ends so as to glue the electrodes to their locator rings. These were situated 3 mm above the bottom edge.

Each electrode also comprised a 3 mm connection rod, which would penetrate through the generator casing. This would allow for the electrical connections to the electrodes from the control circuit. These rods were attached to the inner surface of the inner electrode and the outer surface of the outer electrode respectively.

- ***Electrode Locators***

The inner and outer locators were designed to meet two basic requirements, namely; to provide a base on which the electrodes would be mounted and, to ensure that the electrodes were concentric when assembled.

Therefore, the inner locator was designed to fit tightly into the bottom end cap and all dimensions were selected so as to create a perfect fit between the locator base and the contours of the end cap.

The diameter of the locating ring was chosen as being 77.9 millimetres as this allowed for a 0.02 mm tolerance between the locator and the inner electrode. The locating ring was notched at half its 6 mm height to a depth of 3 mm. This was to create a cavity into which the adhesive could permeate once the electrodes were glued in place.

The inner locator also contained two 6 millimetre holes through its base to allow for the penetration of the electrode connection rods. These holes were located at diameters corresponding to their positions on the electrodes.

The outer electrode locator was designed such that it would centre the electrode once the male threaded nipple was tightened. Therefore, the inner diameter of the locating ring was determined as 88.9 mm as this corresponded to the outer diameter of the electrode. The outer diameter of the locator was chosen as 97.2 millimetres as this would ensure a tight fit between the ring and the male nipple.

As was the case with the inner locator, a 2 mm notch was cut into the locating ring at half its height in order to form the glueing cavity as discussed earlier.

The outer locator also comprised a 6 mm hole with its centre on the inner diameter so as to facilitate the electrode connection rod.

- ***Bottom End Cap***

A prefabricated threaded end cap was specified for the bottom end of the generator housing. This was to fit the 110 mm O.D. male pipe nipple.

The end cap was capable of withstanding the same pressure as the SABS Class 16 uPVC pipe and was, therefore adequate for the working pressure of 520 kPa.

Also, the bottom end cap would be equipped with a half inch drain valve, which would be threaded into the base of the end cap. This would require threads to be tapped into the end cap body. The wall thickness of the end cap was, therefore, analyzed for its suitability to tapping.

From Table A2, the major diameter (d_{major}) of a half inch fitting was taken as 12.7 millimetres. The wall thickness of the end cap was then substituted into equation 4.4 below, [27] to obtain the maximum force that the thread could withstand before shearing off would occur.

$$
\begin{aligned}
F_{thread} &= \pi d_{major}(0.75t)(0.58S_{y,PVC}) \qquad (4.4) \\
&= (3.14159)(0.0127)(0.75x0.01)(0.58x49100000) \\
&= 8521N
\end{aligned}
$$

This was compared to the maximum force that would be exerted on the end cap by the 520 kPa of internal pressure. It was assumed that all the pressure acted on the inner surface of the end cap. Therefore, the force exerted on the end cap was determined as:

$$F_{endcap} = p_{\text{int}} A_{cap} \tag{4.5}$$
$$= (520000)\left(\pi/4\right)\left(d^2\right)$$
$$= (520000)\left(3.14159/4\right)(0.110)^2$$
$$= 4942N$$

Therefore, the factor of safety for the design of the thread was determined as being:

$$f.o.s = \frac{F_{thread}}{F_{endcap}} \tag{4.6}$$
$$= \frac{8521}{4942}$$
$$= 1.72$$

From Juvinall & Marshek [27], a good standard in the selection of the female thread depth is for the ratio of thread depth to diameter to be in the region of 0.8. Equation 4.7 below determines the ratio for the current design as being:

$$Ratio_{Thread} = \frac{D_{thread}}{D_{major}} \tag{4.7}$$
$$= \frac{10}{12.7}$$
$$= 0.78$$

- ***Top End Cap***

As was the case with the bottom end cap, the top end cap was specified according to the same criteria for half inch fittings. The wall thickness of 10 millimetres resulted in the same loading of the thread and, therefore, an identical factor of safety.

Unlike the bottom end cap, the top cap would be unthreaded and would incorporate two half inch fittings. One would serve as the connection to a pressure relief valve set to 580 kPa and the other would connect to the hydrogen fuel supply line to the engine.

Also, the unthreaded end cap would contain a 5 mm hole through which the water level sensor leads would protrude. These would connect to the sensor mounted onto the inside of the end cap.

- ***Top Locator and Sensor***

A top locating plate was designed so as to incorporate the water level sensor. The outer diameter of the flange was chosen as 105 millimetres so as to ensure a close fit between the top end cap and the locator.

A cylindrical protrusion with a diameter of 45 mm was then selected for the sensor mounting tube. This comprised a 27 mm hole with a 8 mm depth to house the sensor attachment nut. This nut was then glued to the locator using PVC cement.

The overall height of 50 millimetres was determined by the water level height that would be required to completely immerse the electrodes and ensure that they remained under water throughout the water level control range.

The sensor was selected according to the appropriate range over which the water level could vary. From the geometry of the generator housing, it was found that the optimal control range of the sensor was 75 mm. Thus a simple level switch with a probe of 75 mm was sourced.

The sensor consisted of a float, which would move from the bottom base to the top as the water level rose and vice versa. As the water level dropped, and the probe reached the bottom base, it would close the electrical switch and allow for the flow of current to the pump. Once the switch was opened by the rise in water level, the circuit would be open and hence no current would be transmitted.

Since the switch would open as soon as the water level raised it above the base, and not after the 75 mm range had been traversed, a circuit was designed which would allow for the current to flow until the top base was reached. This will be discussed in detail in Section 6.3.2 below.

- ***Mounting Brackets***

It was decided that two mounting brackets would be designed to allow for the installation of the hydrogen generating device onto a test rig and, at a later stage, into a vehicle.

These brackets would be manufactured from prefabricated 110 mm pipe couplings, as they were readily available. The couplings would then be glued to rectangular plates of uPVC, which would comprise holes for mounting the generator.

It was assumed, based on the densities and volumes of water and stainless steel, as well as the mass of the PVC components and brass fittings, that the overall mass of the generating device would be 15 kg.

Therefore, the weight that the brackets would need to support was determined as:

$$W_{generator} = mg \qquad (4.8)$$
$$= (15)(9.81)$$
$$= 147.15N$$

It was decided that each bracket would be designed to support 150 N as this would incorporate the design factor of 2 when designing for impact loading.

The distance between the mounting hole centres was chosen as 200 millimetres as this was sufficient to provide adequate room for the tightening of fasteners while still remaining as compact as possible. The width of the rectangular mounting plate was taken as 40 mm and the thickness as 8 mm [25].

Using these dimensions, the bending stress of the plate was calculated. Firstly, the second moment of inertia was determined from equation 4.9 below:

$$I = \frac{1}{12}bh^3 \qquad (4.9)$$
$$= \frac{1}{12}(0.008)(0.040)^3$$
$$= 4.26667x10^{-8}m^4$$

The bending stress was then given by:

$$\sigma_{bending} = \frac{My}{I} \tag{4.10}$$

$$= \frac{(75 x 0.01)(0.02)}{4.26667\ x 10^{-8}}$$

$$= 3.52 MPa$$

The loading on each of the mounting holes was also considered in order to specify the size of the hole and bolt. The shear stress on the upper surface of each hole was computed for a hole size of 8 mm.

From Table 4.1, the yield strength of uPVC was taken as 49.1 MPa. The shear stress experienced by the upper hole surface was then calculated as being:

$$S_{y,PVC} = \frac{F}{A_{hole}} \tag{4.11}$$

$$= \frac{75}{\frac{\pi}{2} dh}$$

$$= \frac{75}{3.14159/2\,(0.008)(0.008)}$$

$$= 0.746 MPa$$

This was well below the yield strength and was thus adequate.

4.3.2 Electronic Circuit Design

The hydrogen-generating device required the development of two electronic circuits. The first circuit would generate a square wave pulse, which would be supplied to each of the electrodes, while the second would contain the logic required to control the generator water level.

- ***Electrode Circuit***

From the literature, it was found that a square wave pulse form with a markspace ratio of approximately 10:1 resulted in the most efficient production of hydrogen. Figure 4.1 below, illustrates the mark and space portions of a square wave.

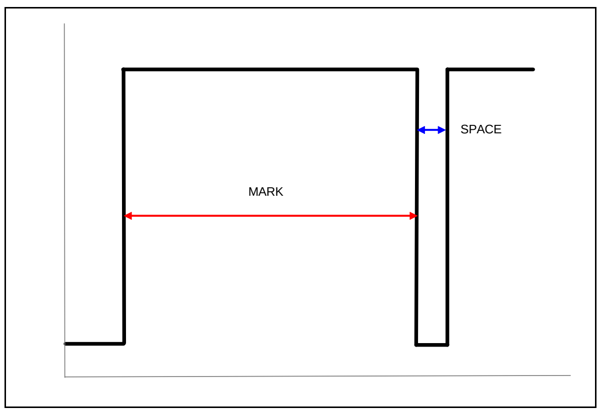

Figure 4.1: Square wave pulse form terminology

Also, the optimal frequency at which hydrogen could be generated was found to lie between 10 and 250 kHz. Therefore, a circuit was designed to allow for variable frequency, pulsewidth and markspace ratio while maintaining a square wave pulse as an output signal.

The circuit was based on a current square wave generating circuit [25], but was modified slightly owing to some difficulties encountered in the operation of the circuit. Figure 4.2 below shows a detailed schematic of the circuit.

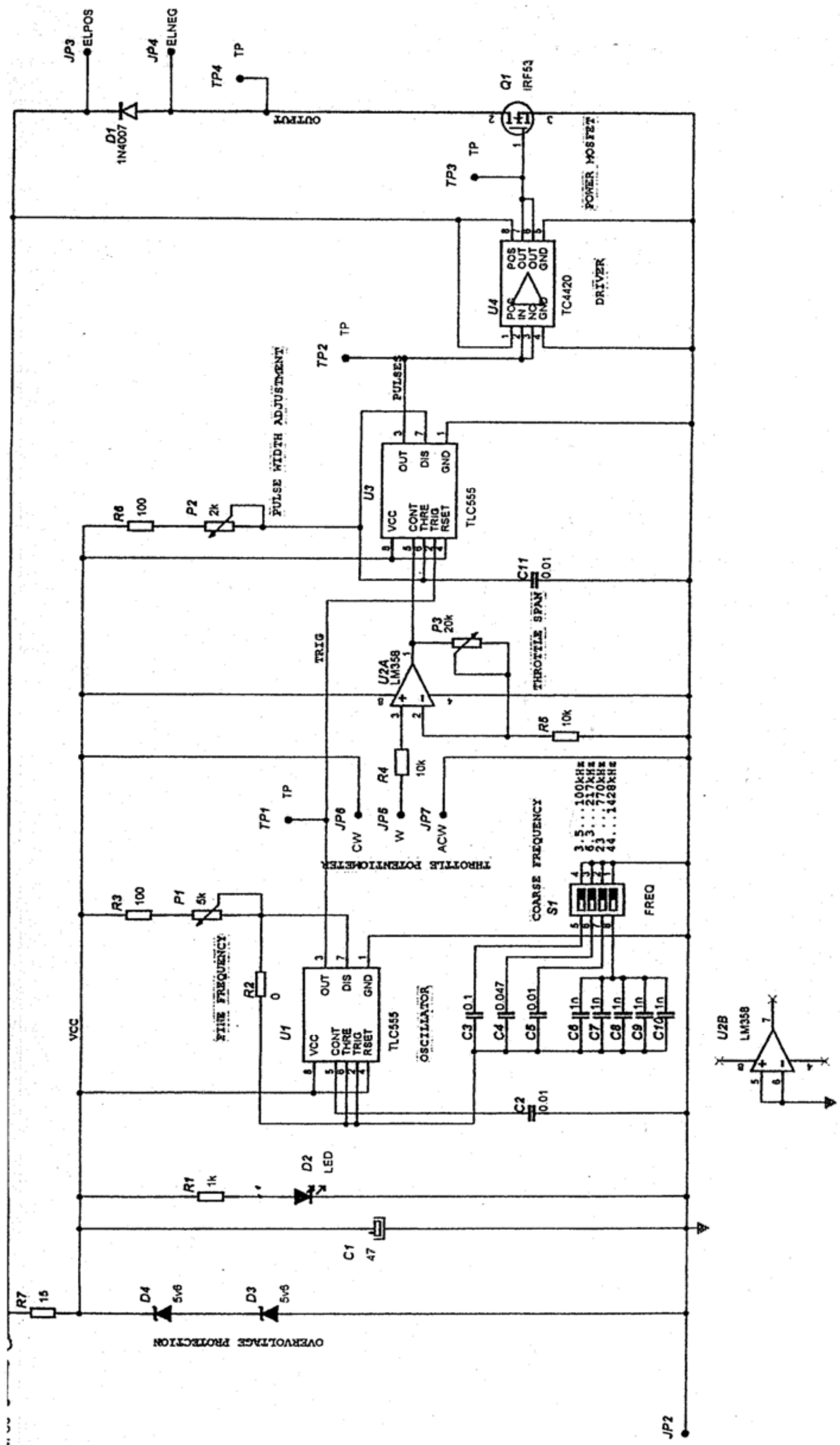

Figure 4.2: Electrode circuit schematic [28]

Essentially, the circuit comprised four integrated circuit chips (IC's), each with a specific function. These chips were supported by various electronic components, which manipulated the electrical signal into the desired format.

The first segment of the circuit controlled the input current, which was a function of throttle position. This chip was also responsible for the operation of the *"Power On"* LED and preliminary conversion of the direct current (DC) input signal.

The output from this circuit segment was then passed through a frequency and pulsewidth control chip which formed the basis of the succeeding part of the circuit. This section of the circuit comprised a NE555 timer configured to its astable setting as shown in Figure 4.3 below.

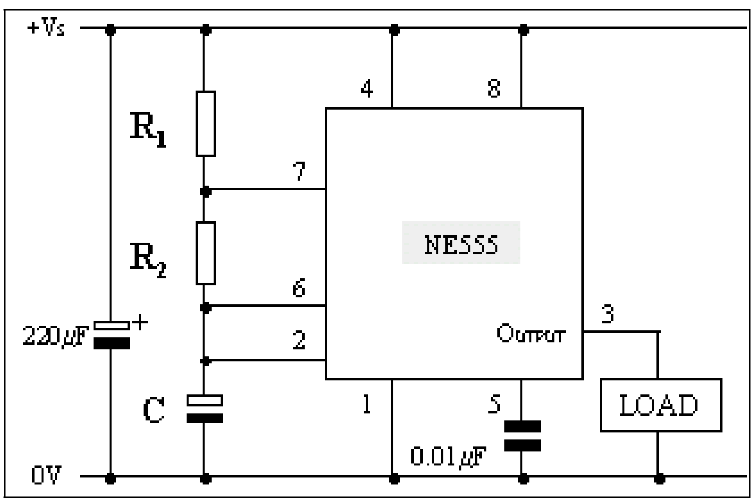

Figure 4.3: Schematic of the Astable NE555 chip [29]

The numerical values on the diagram indicate the respective pins to which each leg of the circuit must be connected. Values of capacitance (C) and resistance (R_1, R_2) were determined according to the desired frequency and markspace ratios.

For a chosen frequency of 100 kHz, the relationship governing the mark period (T_{on}) and the space period (T_{off}) was given by:

$$f = \frac{1}{T_{on} + T_{off}} \tag{4.12}$$

For a markspace ratio of 10:1, T_{on} must be equal to 10 times T_{off}. Thus, equation 4.12 becomes:

$$f = \frac{1}{11T_{off}}$$

Rearranging the above equation, the value of the space period could be determined for the chosen frequency:

$$\begin{aligned} T_{off} &= \frac{1}{11f} \\ &= \frac{1}{(11)(100000)} \\ &= 90.91us \end{aligned}$$

The mark period would then be:

$$\begin{aligned} T_{on} &= 10T_{off} \\ &= (10)(90.91x10^{-6}) \\ &= 909.19us \end{aligned}$$

The resistance required to obtain the calculated value of T_{off} could then be determined from equation 4.13 below [29]. However, since both resistance and capacitance are unknown, an initial value for the capacitor would need to be chosen and the resistance calculated. Therefore, the capacitor was assumed to be 1 nanofarad (*n*F)

$$R_2 = \frac{T_{off}}{0.7C} \tag{4.13}$$

$$= \frac{\left(90.91x10^{-6}\right)}{\left(1x10^{-9}\right)}$$

$$= 90.9k\Omega$$

Once the value of R_2 was known, the resistance governing the mark period could then be determined as [29]:

$$R_1 = \frac{T_{on}}{0.7C} - R_2 \tag{4.14}$$

$$= \frac{909.1x10^{-6}}{(0.7)\left(1x10^{-9}\right)} - 90.9x10^{3}$$

$$= 1207k\Omega$$

In the design of the actual circuit, the resistor, R_1, was replaced by a variable resistor so that the mark period could be varied. This allowed for a variation of markspace ratio, which was useful in illustrating its effect on hydrogen generation. Also, the single capacitance was replaced by a bank of capacitors and a dipswitch. By selecting combinations of capacitors, the resultant capacitance could be varied which would result in a frequency change.

The output signal from the astable NE555, which possessed the desired frequency and markspace characteristics, was then fed into the square wave oscillator circuit which was constructed from another NE555 timer in its monostable configuration. Figure 4.4 highlights the monostable setup of a NE555 IC.

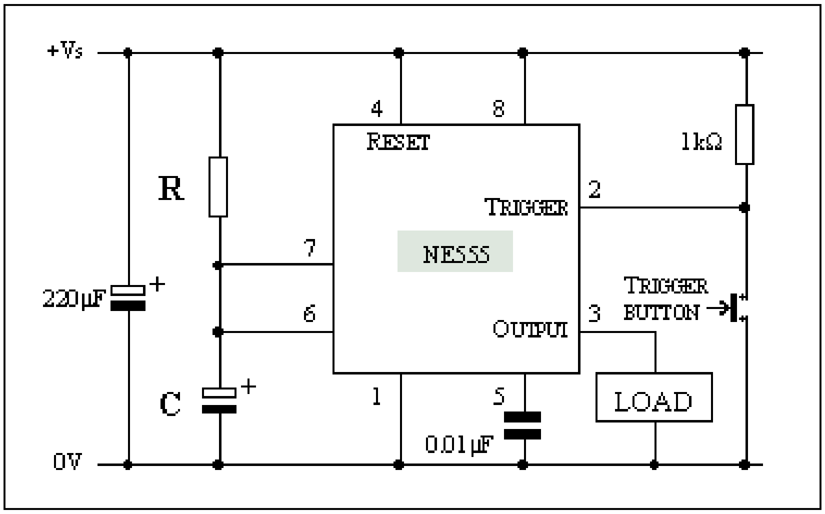

Figure 4.4: Schematic of the Monostable NE555 chip [29]

As was the case with the astable NE555, the frequency of the monostable was used in the calculation of the resistance and capacitance for the square wave generator. The same frequency of 100 kHz was used in the design calculations.

Equation 4.15 [29], below shows the relationship between frequency, resistance and capacitance:

$$f = \frac{1}{1.1RC} \tag{4.15}$$

Again, a value for capacitance needed to be specified. This was taken as being 1 nanofarad (nF). The resistance was then determined as:

$$R = \frac{1}{1.1Cf}$$

$$= \frac{1}{(1.1)(1x10^{-9})(100000)}$$

$$= 9.09k\Omega$$

The resistor was then replaced with a variable resistor, which allowed the frequency to be synchronised with that of the astable NE555 timer.

The output square wave was finally passed through two amplifiers, which strengthened the signal before supplying it to the electrodes.

Also, incorporated into the design of the circuit were various safety mechanisms such as an in-line fuse along the positive rail and, more importantly, a one way diode, which prevented a backflow of current from the electrodes to the rest of the circuit, in the event of short circuit between the electrodes.

While the initial circuits were constructed by the author on commercially available circuit board, the final circuit was built and modified by *"Instruments for Engineering Measurement"* [28] and comprised an etched layout board complete with optimised track positioning which resulted in a more compact circuit board.

- ***Sensor Circuit***

The electronic circuit that controlled the water level of the generator was designed with the aid of an electrical engineering postgraduate student and was built by the author. A detailed circuit diagram is illustrated in Figure 4.5 below.

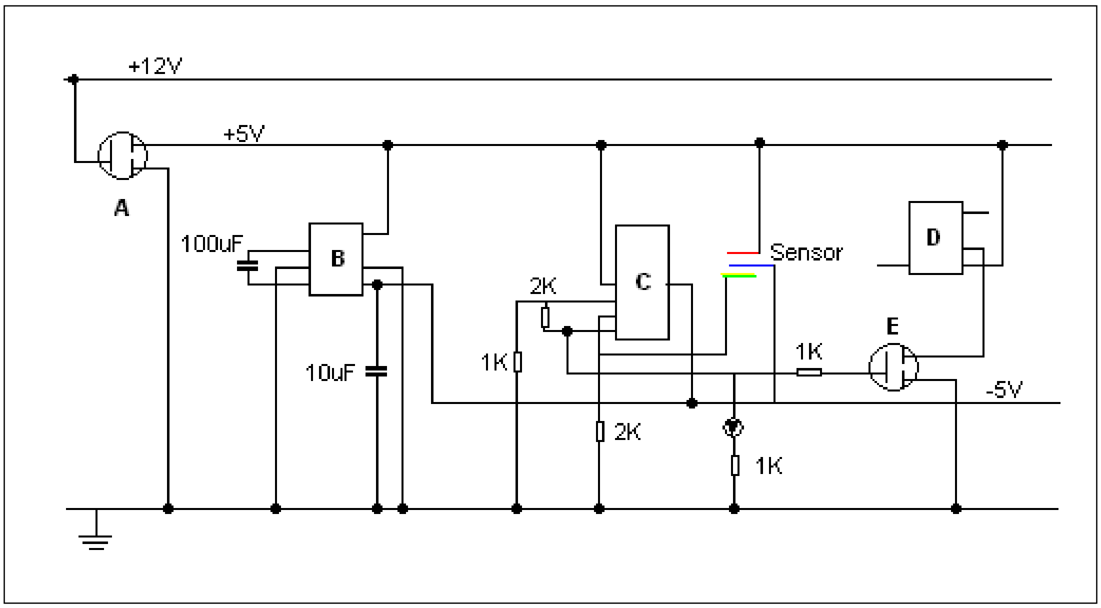

Figure 4.5: Water Level Sensor Control Circuit

The water level circuit comprised four integrated circuits each with the corresponding electronic components necessary to create the desired output.

The first chip, labelled as A in the diagram above, was a LM7805 transistor, which received a 12 V input from the positive rail to its base. The collector was connected to the ground rail and the emitter generated a filtered +5 V rail. Therefore, the purpose of the LM7805 was to filter the incoming voltage signal and produce a steady voltage supply.

A MAX660 chip, labelled B, was then used to generate a –5 V output from an input of +5 V as generated by the previous IC. The values of the two capacitors were determined from the MAX660 data sheet.

The next portion of the circuit comprised a LM324N operating amplifier configured as a Schmitt trigger, as illustrated by chip C. The purpose of this chip was to hold the voltage state of the triggered signal until the second trigger state was reached. The chip would then hold this voltage state until the original state was re-attained. Therefore, in the context of the water level sensor, once the sensor had reached the bottom base a –5 V state would be reached. The chip would hold this state, even though the switch was opened as the water level rose, until the float reached the top base. The chip would then change its voltage to the +5 V and hold this state as the float dropped. Once the float reached the bottom base, the process would repeat itself.

The output signal from the op-amp was then passed through an LED, which would indicate whether the pump was operational, to the base of a E3055 transistor, chip E. The collector of this transistor, was connected to a relay and the emitter to ground. The transistor acted as a switch, which would open at a –5V voltage and close at a +5V voltage. Therefore, when the float was at the bottom base the transistor would recognise the +5 voltage and close the relay. This would then activate the pump. Similarly, when the top base was reached, the transistor would read a –5 V voltage and open the relay, thus turning off the pump.

The purpose of the relay, was to switch an AC signal on and off from a DC trigger. This was necessary as the pump was powered by a 220V AC voltage.

4.4 Design Specification

4.4.1 Generator Design

Table 4.2: Generator Specification

Generator Housing	
Material:	SABS Class 16 uPVC
Height:	450 mm
Outer Diameter:	124.3 mm
Inner Diameter:	110 mm
Fittings:	1 x quarter-inch NPT brass hose connector
Bottom End Cap	
Outer Diameter:	145 mm
Inner Diameter:	125 mm
Wall Thickness:	10 mm
Fittings:	1 x half-to quarter-inch NPT brass male/male reducer
	1 x quarter-inch NPT brass ball valve
Top End Cap	
Outer Diameter:	145 mm
Inner Diameter:	125 mm
Fittings:	1 x quarter-inch NPT brass hose connector
	1 x quarter-inch NPT male/male nipple
Mounting Brackets	
Length:	240 mm
Width:	40 mm
Thickness:	8 mm
Hole Diameter:	8 mm

Outer Electrode	
Material:	305L Stainless Steel
Outer Diameter:	88.9 mm
Inner Diameter:	85.7 mm
Height:	330 mm
Mounting Hole Diameter:	3 mm
Water Hole Diameter:	6 mm
Inner Electrode	
Material:	305L Stainless Steel
Outer Diameter:	83.3 mm
Inner Diameter:	77.92 mm
Height:	330 mm
Mounting Hole Diameter:	3 mm
Water Hole Diameter:	6 mm

4.4.2 Electronic Circuit Design

Table 4.3: Electronic Circuit Specification

Electrode Circuit	
Input Voltage:	12 V DC
Output Signal:	Square wave pulse
Output Frequency:	10-1000 kHz
Water Level Circuit	
Input Voltage:	12 V DC
Output Signal:	220 V AC on/off state
Output Frequency:	50 Hz

4.4.3 Engineering Drawings

Table 4.4 indicates a list of CAD drawings produced with their respective drawing numbers. The drawings may be found in Appendix B.

Table 4.4: List of Engineering Drawings

Drawing Number	Description
001	Detail Drawing – Outer Electrode
002	Detail Drawing – Inner Electrode
003	Detail Drawing – Inner Locator
004	Detail Drawing – Outer Locator
005	Detail Drawing – Housing
006	Detail Drawing – Top Locator

4.4.4 Design Drawings

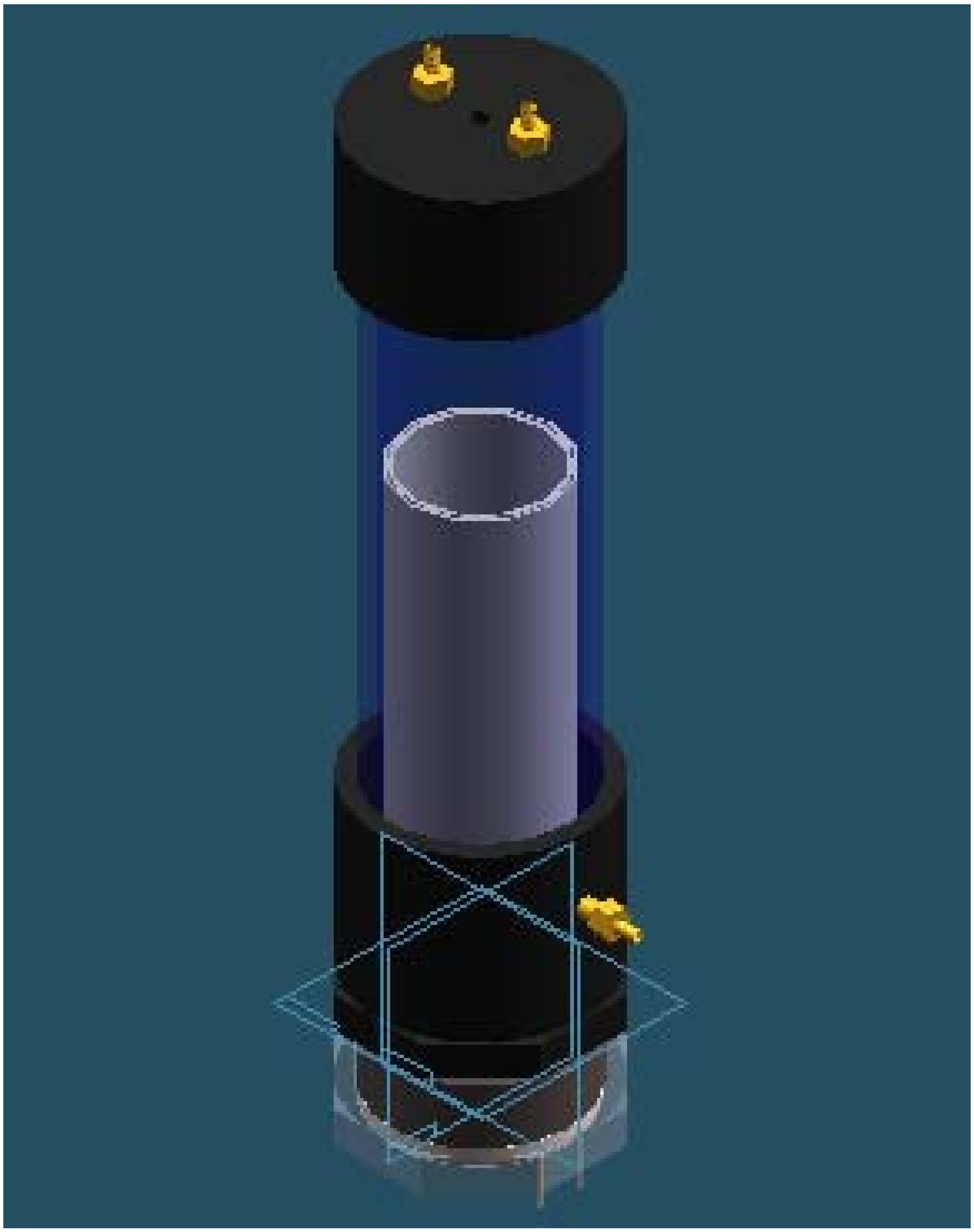

Figure 4.6: Isometric View of Hydrogen Generator

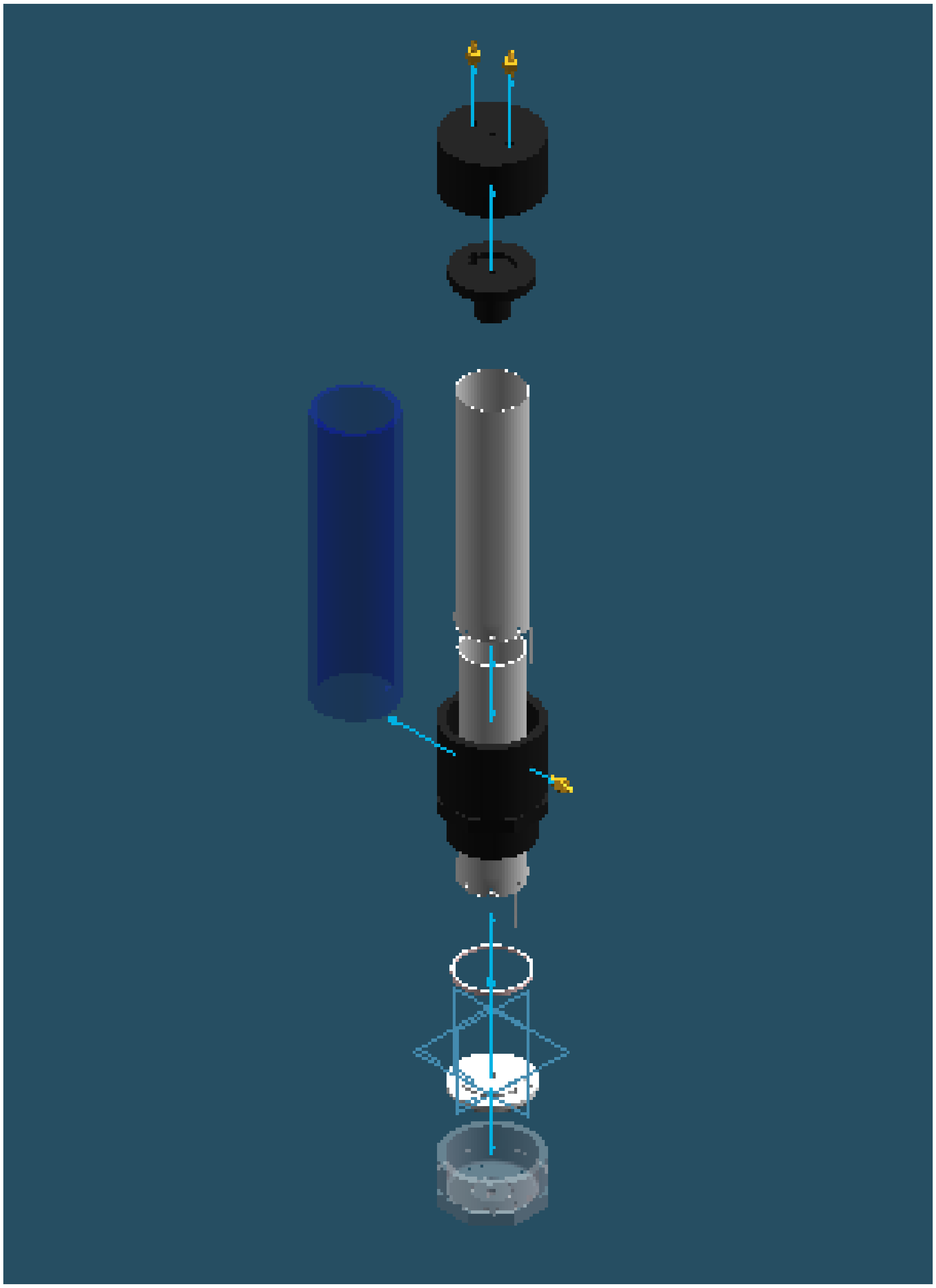

Figure 4.7: Exploded View of Hydrogen Generator