Open Science Hardware Setup for investigating the Stability of Organic Solar Cells - Interim Report

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Chapter 1

Introduction

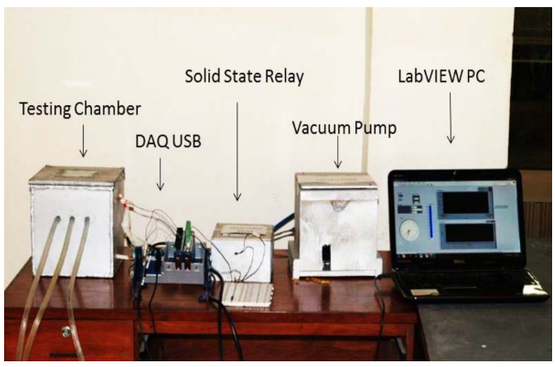
1.1 Literature Review

In order to provide a device to add to the field a thorough literature review was conducted and modified throughout the project. The main objective of this project was to provide the AFMD research group with a device that created different conditions to degrade organic photovoltaic cells.

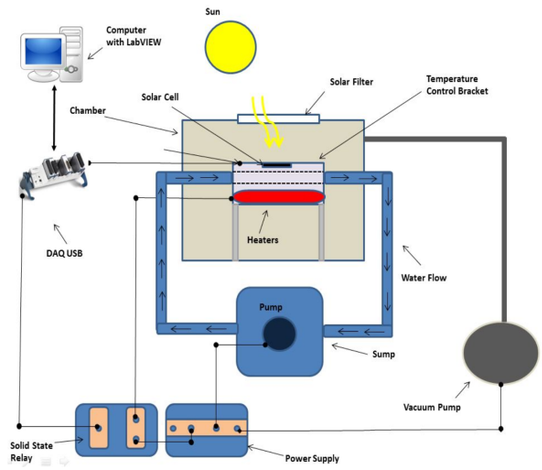
Currently the market leader in solar cells are Crystalline Silicon photovoltaics which hold a dominant 95 % market share in the solar energy sector [1, p. 1] . Organic solar cells have the opportunity to disrupt this market by providing versatile light-weight devices which have little material consumption and low temperature processing. However, the current problems with organic solar cells boil down to long term stability, alongside higher power outputs [1, p. 7] . This project looks at creating a method to help solve the issue of long-term stability by providing the AFMD group (and the world) a device which is able to simulate a lifetime (10-20 years) of outdoor degradation in a matter of months.

To ensure that the conditions were analogous to a lifetime of degradation in depth research was conducted looking at failure mechanisms of organic solar cells, alongside failure times, current devices which may be similar as well as industry standards for both organic and silicon PVs. There are multiple degradation mechanisms which cause the short lifetimes of organic solar cells[2, p. 141][HT 8, ai]. The ones that the container will try and emulate are: diffusion of water into the cell, diffusion of Oxygen into the cell operation under high temperatures. Other degradation mechanisms will also play a part such as photochemical degradation by UV light and oxygen [3, p. 106][HT 7, bii].

An important factor for the entire set up is to ensure that these degradations are measurable, thereby requiring careful control of the ambient conditions. This meant a container that would not let in ambient air (due to the oxygen and water content) as well as have a controllable chemical and physical atmosphere. Degradation experiments are essential in the testing of solar cells; therefore it was expected that something would have been manufactured for the testing of any solar cell. In 2015 Jaffery et al. [4][Ht9] released a paper outlining a similar setup that was designed for the testing of PVs. This design incorporated



(a) The Test chamber and relevant accessories used in the research



(b) Schematic of the test chamber and relevant accessories used in the research

Figure 1.1: Showing the Test chamber used by Jaffery et al.

temperature control, varying lighting conditions. The set-up is shown in the Figure 1.1 [4, p. 3,4] below.

This set-up is a good start to build on to meet the goals of this project however, it lacks the simplicity of what is required. There are multiple large scale components which mean a complicated building and testing process. For the chamber this project specifies, it needs to be easily replicable worldwide, thereby allowing it to contribute to the development of OPV(Organic Photovoltaic) technology.

Another example is Lai and Potters paper [5] which referenced a large scale industrial chamber. This chamber also provided different conditions for testing a photovoltaic cell. This module was manufactured by Envirotriks (now Weiss Technik) who specialise in the manufacturing of environmental testing equipment. Their technology ranges from aerospace to biological environmental applications. On further investigation, their products were large scale expensive modules which would not be applicable to one of the key goals of this project, being easily replicable worldwide.

Adding to this, a further set-up was used in Pearson et al [6]experiments on the degradation of organic solar cells. This set up ensured that the cells were loaded into the container while in a glovebox, and held and an overpressure to ensure atmospheric gases (specifically water and Oxygen) did not leak into the container. Furthermore, the atmospheric make-up of the container was monitored by a gas analyser and the cells measured using a Keithley source meter [6, P. 227]. This chamber is the closest to what was specified in my project description; however, the gas make-up monitoring adds further complexity to the chamber which again reduces the replicability worldwide.

Despite these flaws, there were key components in all three set ups which I took inspiration from for my designs. From Figure 1.1 the small container is something which appealed to me, especially if it were tweaked to ensure ease of set up. Furthermore, from the commercial modules, the holistic nature of all the components was something that I desired to emulate, as this would ensure that the container would be suitable for all manners of testing. From Pearson et al [6]I thought the idea of overpressure to prevent leakage was clever, as well as making the device small enough to load in a glovebox. These were all features which I incorporate into my device.

I also noted some of the drawbacks which I determined will not plague my design. ....

This all has influenced the functionality that will be designed into the container. However, one of the key features is to align closely with the standard for testing organic solar cells. Different papers reference different standards, therefore I decided to see where they overlapped and create a container that was able to meet as many as possible. Zhang et al [7, p. 1] talk about the IEC61646 standard developed by the International Electrochemical Committee. This testing standard includes: " 1000 h damp heat (DH) test at 85 ℃ and 85% humidity, 200 cycles of thermal cycling (TC) from 40 to +85 ℃, and a sequence test consisting of UV exposure, 50 cycles of TC, and 10 cycles of humidity freeze (HF) from 40 to +85 ℃ at 85% humidity. After finishing each test, modules are then characterised to determine device efficiency."

Further to the IEC61646 is the guidelines referenced in Reese et al. [8, p. 1254][HT 3 P1254]. These were developed at the International Summit on Organic and Hybrid Photovoltaic Stability in the years 2008. 2009 and 2010. These 3 guidelines (ISOS 1,2,3) show different methods for testing solar cell degradation, some of which can be seen in Figure 1.2 [8, p. 1255] below.

Table 1
Overview of different types of test protocols.

Three levels						
Basic (Level 1)	"Hand held" measurements using the simplest equipment and few conditions					
Intermediate (Level 2)	Fixed conditions and protocols suited for most labs					
Advanced (Level 3)	Standardized tests applied in certified labs. Extended range of parameters to monitor, etc.					
Test type	**Dark**			**Outdoor**		
Test ID	ISOS-D-1 Shelf	ISOS-D-2 High temp. storage	ISOS-D-3 Damp heat	ISOS-O-1 Outdoor	ISOS-O-2 Outdoor	ISOS-O-3 Outdoor
Light source	None	None	None	Sunlight	Sunlight	Sunlight
Temp.[a]	Ambient	65/85 °C	65/85 °C	Ambient	Ambient	Ambient
Relative humidity (R.H.)[a]	Ambient	Ambient (low)	85%	Ambient	Ambient	Ambient
Environment[a]	Ambient	Oven	Env. chamber	Outdoor	Outdoor	Outdoor
Characterization light source	Solar simulator or sunlight	Solar simulator	Solar simulator	Solar simulator	Sunlight	Sunlight and solar simulator
Load[b]	Open circuit	Open circuit	Open circuit	MPP or open circuit	MPP or open circuit	MPP
Test type	**Laboratory weathering testing**			**Thermal cycling**		
Test ID	ISOS-L-1 Laboratory weathering	ISOS-L-2 Laboratory weathering	ISOS-L-3 Laboratory weathering	ISOS-T-1 Thermal cycling	ISOS-T-2 Thermal cycling	ISOS- T-3 Thermal cycling
Light source	Simulator	Simulator	Simulator	None	None	None
Temp.[a]	Ambient	65/85 °C	65/85 °C	Between room temp. and 65/85 °C	Between room temp. and 65/85 °C	−40 to +85 °C
Relative humidity (R.H.)[a]	Ambient	Ambient	Near 50%	Ambient	Ambient	Near 55%
Environment/setup	Light only	Light & Temp.	Light, Temp. and R.H.	Hot plate/oven	Oven/env. chamb.	Env. chamb.
Characterization light source	Solar simulator	Solar simulator	Solar simulator	Solar simulator or sunlight	Solar simulator	Solar simulator
Load[b]	MPP or open circuit	MPP or open circuit	MPP	Open circuit	Open circuit	Open circuit
Test type	**Solar-thermal-humidity Cycling**					
Test ID	ISOS-LT-1 solar-thermal cycling		ISOS-LT-2 solar-thermal-humidity cycling		ISOS-LT-3 solar-thermal-humidity-freeze cycling	
Light source	Simulator		Simulator		Simulator	
Temp.	Linear or step ramping between room temp. and 65 °C		Linear ramping between 5 and 65 °C		Linear ramping between −25 and 65 °C	
Relative humidity (R.H.)	Monitored, uncontrolled		Monitored, controlled at 50% beyond 40 °C		Monitored, controlled at 50% beyond 40 °C	
Environment/setup	Weathering chamber		Env. chamb. with sun simulation		Env. chamb. with sun simulation and freezing	
Characterization light source	Solar simulator		Solar simulator		Solar simulator	
Load[b]	MPP or open circuit		MPP or open circuit		MPP or open circuit	

[a] The ambient conditions are defined as 23 °C/50%RH in general, and 27 °C/65%RH accepted in tropical countries according to ISO 291(2008): Plastics—Standard atmospheres for conditioning and testing.
[b] Open circuit refers to a simply disconnected device or device connected to a sourcemeter set to 0 current.

Figure 1.2: Showing some of the testing procedures in Reese et al.

Figure 1.2 has been taken from Reece et al. [8] and outlines some different testing conditions for organic solar cells. As can be seen the guidelines are similar to those referenced in the IEC61646 standard, however, there is more detail on the exact light source, as well as the load the solar cell should be subject to.

From these two sets of guidelines, basic functionality for the container could be drawn up. This includes:

Temperature variation with a minimum maximum temperature of 85 degrees, ability to vary humidity, regular measurement of Voc and Jsc and light conditions which would vary from a solar simulator to outdoor sunlight to darkness. Both sets of guidelines reference temperatures below ambient room temperature; however, this would require some sort of refrigerant running through the device, connected to pumping systems and a heat exchanger. This would cause the box to be particularly cumbersome as it would require significantly more components, space and complexity meaning it would struggle to fit the requirement of easily replicable. Thereby, the decision was made to not have testing conditions below ambient room temperature.

Another integral consideration was sampling time. Ideally the during testing there would be regular short intervals between the measuring of the cells Voc and Jsc. However, this is not possible due to the observed characteristics of OPVs. Degradation can be broken down into three distinct phases, “an initial period of steep degradation that slows down with time, a period of relatively constant degradation that lasts for most of the solar cell’s usable lifetime, and rapid and complete degradation that results in device failure” [9, P. 1]. This non-linear nature of degradation can clearly be seen in Figure 1.3 [9, P. 3].

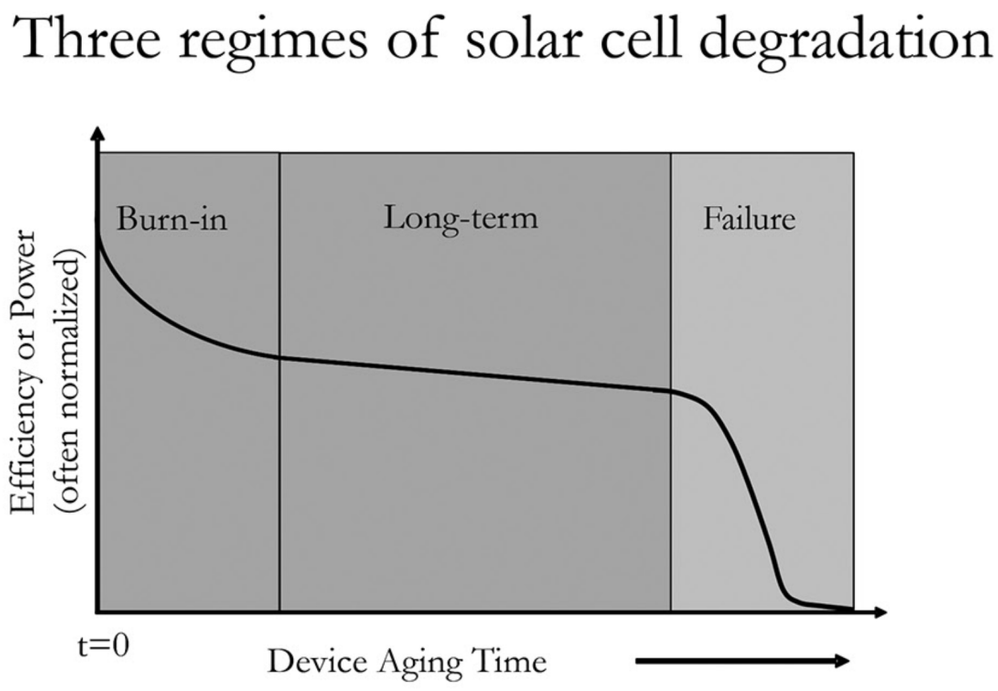


Figure 1.3: Illustrating the non linear nature of OPV degradation

From Figure 1.3 it is clear to see that the 2 regions that need short interval measurement times are Burn-in and Failure. These can be categorised as the time to reach 80 % and 50% of initial performance [9, P. 4]. Thereby the most accommodating testing regime, that won’t create unnecessary excess data-points would be a collecting data at small intervals during Burn-in and Failure, while having longer interval times during the long-term testing regime. This will be discussed further during the x chapter.

The above research guided the entire project, particularly the specification which will be discussed in the Design chapter.

Chapter 2

Chamber Design

2.1 Introduction

The design of the container and associated electronics was a process that encompassed several months. This chapter will go through the entire design process, outlining the key aims, decisions and analysis behind the container design.

During the mechanical design process, there were two different software's used: OpenSCAD and SOLIDWORKS. OpenSCAD is an open-source software which is compatible with all major computer operating systems. This enabled the start of the design process to occur before the beginning of the Michaelmas Term. Furthermore, as mentioned in the introduction, using opensource software is a key tenant of this project as it needs to be replicable for teams worldwide. SOLIDWORKS however, is not open source, but was still used. This is because there is some key functionality in SOLIDWORKS which helps reduces the time needed on a few of the important steps (such as rendering photos, heat simulations and producing engineering drawings). However, as I will lay out further in the chapter, the main designs were completed on OpenSCAD, and they do hold enough information for a group elsewhere to replicate without significant difficulty.

A key consideration was what processes would be needed for the manufacturing of the container. The engineering department has different facilities which could be useful including: a workshop with a CNC machine, multiple different 3D printers, a mechanical workshop which I would be able to use along with an electrical workshop. These all were considered when designing the container and each will be mentioned during this chapter.

During the electrical Design process there was more of a conundrum. Due to COVID-19 regulations the design lab was closed (at the time when I needed to conduct electrical designs), meaning that I was unable to access key software (SOLIDWORKS PCB and Electrical) – the favoured software by the electrical workshop. Therefore, an open-source solution needed to be found, the solution was KiCAD. KiCAD not only ran on my machine, but also had extensive documentation for me to use and learn from while creating these PCBs.

As I was relatively new to PCB design and manufacture, the process required many iterations, edits and extensive help from both the electrical workshop and Physics department researchers. This will be discussed further in the later section on electrical design.

2.2 Physical Specification

The first stage of the design process was to outline a specification for the testing container. These specifications were drawn from the project brief, the literature review and discussion with my supervisor Professor Moritz Riede. The specification of the design is outlined below:

1. The container must be able to accommodate a 30 mm x 30 mm substrate provided by AFMD research group.
2. The container must be leakproof to outside air.
3. The container must allow electrical connections from outside to connect to the substrate for measurements.
4. The container must enable the substrate to be heated to a given temperature[1].
5. The container must have a window allowing light to be shone into the box.
6. The container must contain a gas inlet.
7. The container should fit into the small glovebox inlet with diameter 150 mm.

This specification is a clear guide to what functionality there needs to be within the container, as well as any size limitations. As mentioned in both the introduction and literature review, is is essential for the container to be leakproof, to ensure that the solar cell does not degrade due to atmospheric O2 and water vapour. This would result in flawed results due to the cell having some unmeasured degradation before the experiments even begin. Another important point in the specification is the ability of the cell to be heated to a given temperature*. This functionality is important as its role is to attempt to emulate a lifetime (20 years) of temperature degradation in the space of 3 months.

The gas inlet is another feature to enhance the degradation. This will be used to create a ‘cocktail’ of different gases (guided by the literature) to try and emulate lifetime degradation of the solar cell. The last point on the specification is to ensure the ease of use with the AFMD research group. The gloveboxes they use have a small inlet with a diameter of 150 mm, using this would vastly reduce the time needed to insert the solar cell into the testing container.

Along with the specification, some further goals were drawn up to provide aims that would provide important functionality but were not essential for the solar cell. These are shown below:

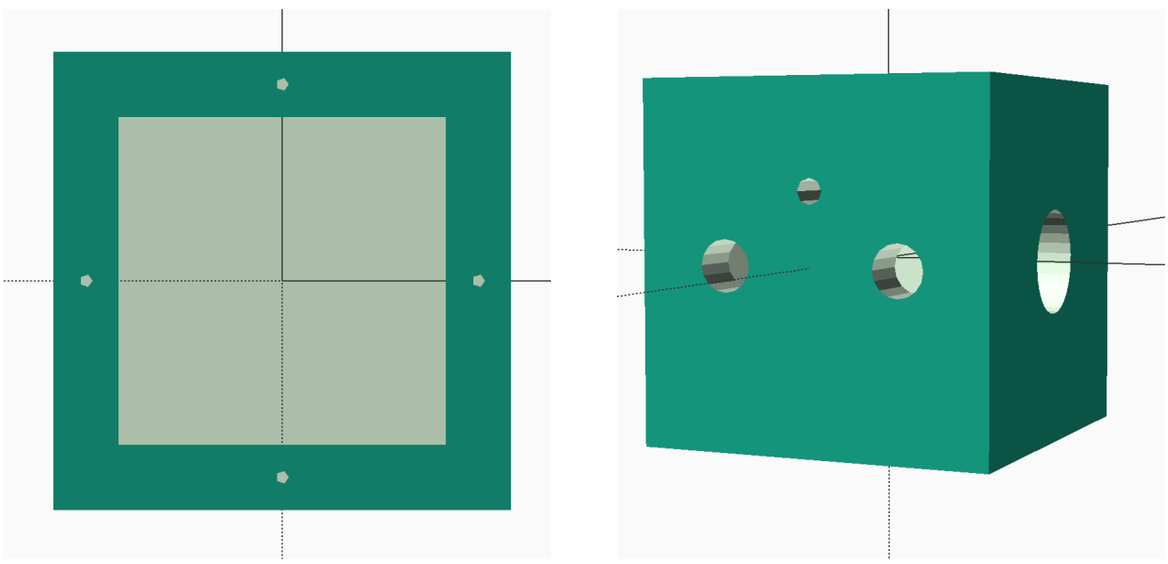
[1]The reason for a none specific temperature

- Build a Python based GUI (Graphical User Interface) to enable programmatic testing of the solar cell
- Enable a programmable atmosphere for the box which should be embedded into the GUI built.

These goals are important to ensure the ease of use of the box, as well as to reduce the amount of time needed for setting up and running the container. The programmatic testing of the cell, along with a programable atmosphere is useful as it enables the researchers to simply input time, temperature and what combination of gases, which then allows the system to run a test, all the time measuring the outputs and logging it for further analysis.

2.3 Initial Mechanical Designs

This specification provided the structure for the testing container. Using work done in the literature review, it was clear that this type of testing container is unusual for the market, thereby requiring innovative design. I was put in contact with Karl-Augustin Zaininger - a Physics researcher who had developed a simplified version of this device – to discuss viable methods for achieving the specifications. This conversation allowed me to create an extremely simple first iteration of the outer shell of the design shown in Figures 2.1 and 2.2.



(a) Plan View of Model (b) Perspective View of Model

Figure 2.1: Showing a Plan and Perspective view of the First Iteration of the Outer Shell

This model is supposed to coincide with a smaller module named the Substrate Holder, which is designed to sit within the outer shell, holding the substrate, temperature sensor and heater, shown in Figure 2.3. The substrate holder is designed to be a removable component which can be edited to match the substrate provided. During the design process, this module was designed to be 3D printed to ensure low costs and easy modification.

Both the substrate holder and Outer Shell were 3D printed to provide a physical representation of the

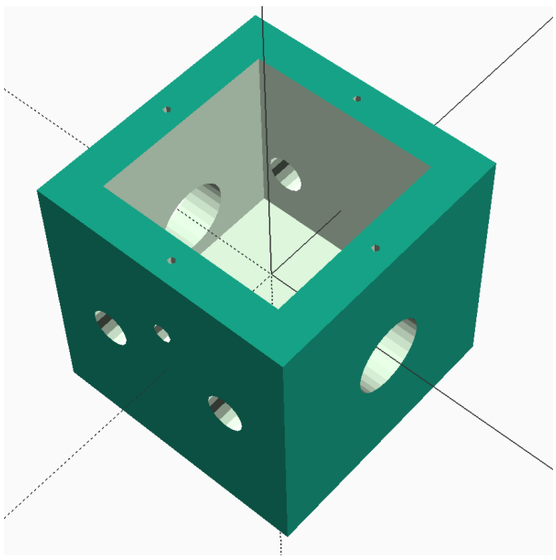


Figure 2.2: Showing Isometric View of the Outer Shell

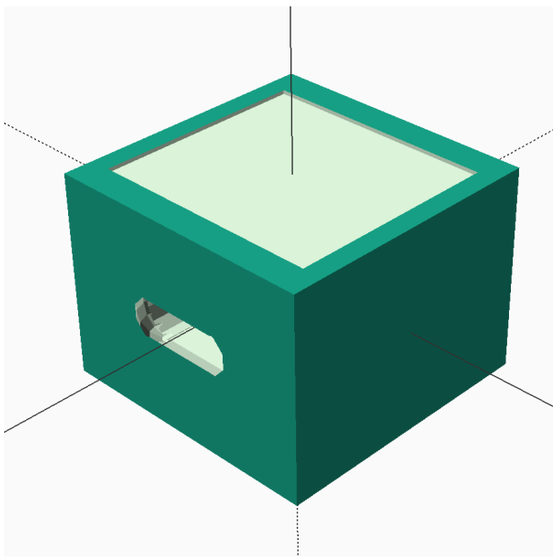


Figure 2.3: Showing the Isometric view of the first iteration of the Substrate Holder

model(with a photo shown in Figure 2.4), where it became possible to see some of the flaws that were hidden by the virtual design. The first thing was that this design was very small, making it difficult for use within the glovebox. This was a problem as all assembly needed to occur within a glovebox to ensure there would be no unwanted oxygen or water residue able to degrade the cell. Adding to this, it seemed that there wouldn't be enough room to wire the components in the container, this would cause significant problems as the modularity of the design would be compromised. This would go against one of the tenants of the project (modularity) which would be a problem when thinking of using this set up on different substrate layouts.

2.4 Final Container Models

These problems caused a redesign of the container, resulting in the model shown in figure (n). The Outer Shell is larger in this model with dimensions 100 mm* 110 mm* 77 mm, with a wall thickness 16 mm, resulting in more space within the container. Additionally, there was a rethink of the sealing method, to eliminate the need of directly screwing onto glass, risking a break, therefore a lid was constructed for the

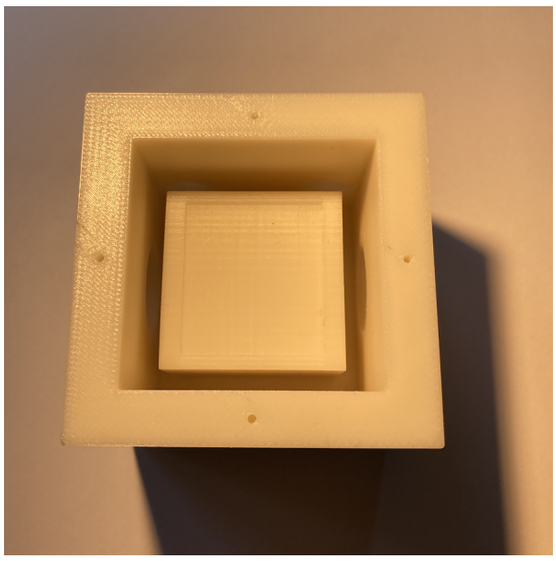


Figure 2.4: Showing the result of the first 3D print of the model

substrate holder, which would cause the glass window to be sandwiched between 2 O-rings creating an airtight seal. The changes to the outer shell can be seen in Figure 2.5.

Figure 2.5: The Final Outer Shell model.

The substrate holder was also modified with the intention of being unique to this particular substrate layout resulting in a more detailed design. The substrate layout was provided to me by Dr. Grey Christophoro, a researcher working in the Physics department, and can be seen in Figure 2.6.

As shown in Figure 2.6 the substrate has x contact points and y cells, meaning that the substrate holder needs to provide a method to cleanly contact the contact points, without hindering the flow of air around the cell, or blocking the light incident on the cell surface. The solution was to develop a small lid which would be screwed into the substrate holder, thereby providing downward pressure onto the substrate to ensure clean contacts with the pins. This lid was designed so that the outline did not block any light being incident on the cells. The lid can be seen on top of the substrate holder in Figure 2.7.

Another important consideration was the ability for the substrate holder to be easily attached to the outer shell within the glovebox. Therefore, the substrate holder needs to have electrical wiring within it, to easily connect up the solar cell with the monitoring device. This process required more time than

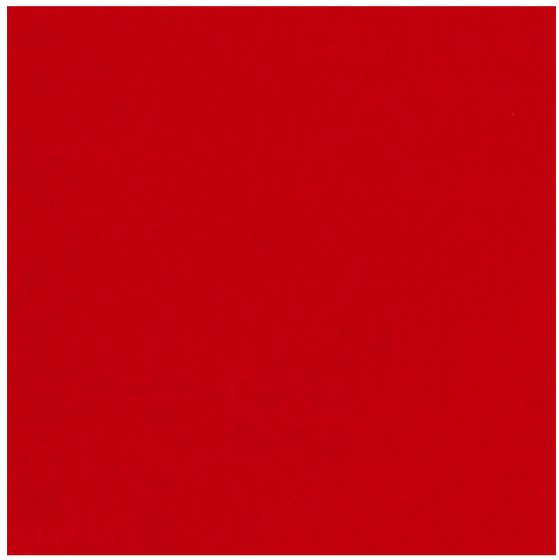


Figure 2.6: Showing the substrate layout provided by Dr. Christophoro.

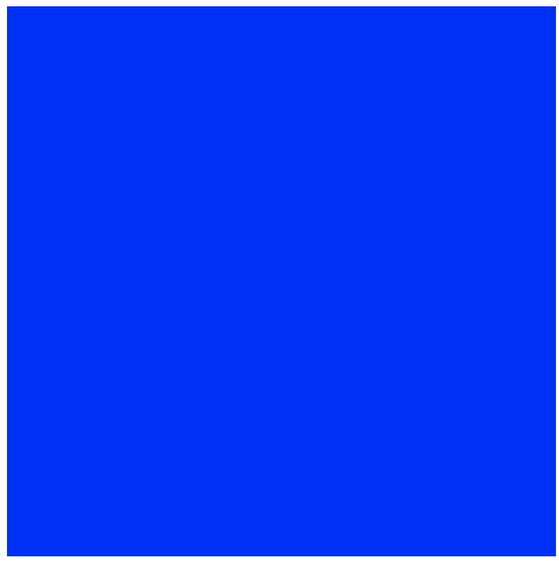


Figure 2.7: Showing the lid used to exert downward pressure on the substrate.

planned as it was surprisingly difficult to come up with a viable idea. However, conversations with the electrical workshop helped me come up with a simple idea of creating a ‘plug’ which would enable the substrate holder to be connected to wiring that in turn would be connected with the monitoring device. This will be spoken about in the later chapter on electrical design, however, required the altering of the substrate holder so that pins could be placed at the top with space for wires to then be soldered onto them.

Moreover, when speaking to Professor Riede, he pointed out that there needs to be air flow below the substrate for the mixture of gases to have any substantial effect on the degradation of the solar cell. This led to a slight change which can be seen in figure n of 2 holes below where the substrate is meant to sit, which lead to empty space where there can be a good range of mixing to encourage degradation. Another issue was where the heater and temperature sensor would sit. This lead be to place the two holes running through the substrate holder one on top of the other to place the sensor and the heater. These holes were positioned there tactically so that the sensor temperature could be correlated with the predicted substrate temperature by modelling and testing *Link to different chapter*. These changes are shown and labelled in Figure 2.8.

Figure 2.8: The Final Substrate Layout

2.5 Electrical Specification

This section will take a more in depth look at the electrical requirements of the chamber. From the substrate layout it is clear that there are 6 solar cells to contact, each with 2 pins, meaning a total of 12 wires will be connected to the cell itself. This means a PCB needs to be manufactured which is able to connect 12 wires to the cells. From there each cell needs to be measured and the value of the Voc and Jsc recorded with the time, temperature and gas composition the substrate is subjected to.

Adding to this, a measurement device needed to be chosen, along with a controller to run and record the data. After discussion with the AFMD group, Dr. Christophoro and my supervisors Professors Riede and Morris the following electrical specification was drawn up:

- The set-up requires a method of differentiating the cell voltages and currents (ideally through the use of a multiplexer
- The set-up requires a method of controlling the heat and gas composition within the chamber as well as the measurement intervals.
- The set-up requires a method to record the many* Voc and Jsc measurements.
- The set-up requires a method of measuring the Voc and Jsc.
- The set-up requires a method of measuring the temperature conditions within the container.

This specification is non-exhaustive but does provide a clear structure to what is needed for the successful manufacturing of the set-up

2.6 Electrical Design

For the control systems, there were two options: a Raspberry Pi or an Arduino. Both have extensive documentation and are relatively inexpensive given their power. To decide which would be more suitable a Multi-Criteria analysis was undertaken with the results shown below:

	Raspberry Pi	Arduino
Cost	4	10
Simplicity of use	10	5
Size	3	5
Adaptability	20	10
Total	37	30

The cost of a Raspberry Pi 4 from RS- components was £53.22 [10]while the cost of the Arduino Uno Rev3 which I planned on using is £20.40 [11]. Cost was a factor in my decision, it was not as important as adaptability, yet more important than size, therefore I rated the Arduino with a score of 10, and Raspberry Pi with a score of 4. The simplicity to use was something that I believe should have the same weighting as cost. From discussions with colleagues, it was clear that running different programs was more difficult on the Arduino due to the fact it stored one program at a time, meaning each time a procedure needed to be changed, the Arduino needed to be plugged in to a computer. The Raspberry-Pi, however, is simpler, it itself is more like a conventional computer, able to store multiple programs, run with a modified Linux operating system, thereby creating a simpler system for use by different people.

The size was a small factor to consider, thereby the reduced emphasis on scoring. Lastly, adaptability of the device was integral. The device needed to be able to store data, as well as run code which was easily modifiable for those using it. This created a clear divide between the two products as the Raspberry-Pi is by far considered a more ‘rounded’ device compared to an Arduino which is usually used for highly specific applications.

From the Multi-criteria analysis above it is clear that the Raspberry-Pi is the preferred device and thereby was the chosen product for this application. From here I consulted Dr. Christophoro again (after advice from Professor Riede) to see is he had any pre-made equipment that I could use/modify that would suit my needs. After discussions with Dr. Christophoro, I was pointed to some PCB designs in his GitHub repository which could be modified to suit my applications [12]. The two schematics of designs that I was directed to are shown in the appendix 1 and 2.

These designs were surplus to my needs and required significant modification to ensure that they were both manufacturable within the engineering workshop and suitable for the role they fulfilled in the set-up.

Firstly, the design named Base 8x, had significantly more sockets than was needed, I was only planning on testing 1 substrate, therefore did not need a base, which could ‘handle’ 8. Furthermore, the PCB was designed to interface with an Arduino, meaning a subsequent header needed to be implemented to ensure that the PCB was able to interface with the Raspberry Pi. Other small modifications include adding resistors and a header for a temperature sensor to be wired in, as well as creating the mounts for a secondary PCB to be mounted (which would hold the Solid-State Relay needed to control the mains powered cartridge heater).

Other changes included ensuring that the tracks were routed with large enough profiles to be printed on the departmental printers, as well as modifying the PCB so that it only had two working layers. These modifications in the schematic can be seen in appendix 3.

For the PCB named Solar Mux- appendix 2, there needed to be significantly fewer modifications, yet they were still significant. Firstly, the number of relays were reduced from n to 17 as only 6 solar cells were being measured rather than 10. Furthermore, there were significant modifications to the routing of the tracks as again this PCB was not designed to be printed in the engineering department thereby meaning the tracks needed to be made larger. These changes to the schematic can be seen in appendix 4.

2.7 Code Planning

Another integral component to the container is the control electronics which are created to run it. After the Raspberry Pi was chosen there was some general research through the documentation to understand the ways to use the General-Purpose Input Output header to control electronics (GPIO). From reading the documentation for the GPIO [**?**], it was clear there were 3 real options for programming language, C, C++ or Python. As someone who has experience in Python, alongside the *extensive* documentation for the GPIO pins in Python [**?**] it was a clear choice to use Python as the programming language.

Using the library Gpiozero, I was able to run some tests to ensure that the raspberry Pi purchased was working correctly, as well as checking some other features (such as the multiprocessing library) work with Gpiozero. To do this I ran multiple LEDs blinking in parallel with each other, using different time intervals for the blink. This proved that the Gpiozero library worked with the multiprocessing library and enabled the planning of the main script that was going to control the testing container.

The thought process behind the code architecture was to develop a Graphical User Interphase (GUI) to enable easy control of the testing container. The GUI would then display specific information while the test was running, enabling a convenient ‘check’ for the user to ensure the test is proceeding as planned. The resultant GUI can be seen as a screen-shot in Figure **??**. There were, however, some problems with this set-up. Once the GUI itself was constructed I attempted to integrate it with the Multiprocessing package. No matter how I tried, this did not work. Therefore, I had to make a decision, do I learn another package and attempt to make a GUI that works with a package that runs multi-processing, or do I put the GUI to one side, and create a script which is easily editable and thereby negates many of the advantages of the GUI, allowing me to save time and focus on other aspects which are more important to the successful development of the chamber?

Due to the iterative nature of this project, the decision was taken to prioritise constructing a working container that may not hit all the specification, rather than create a container that was 80% working yet not ready to test solar cells. For this reason, I decided to put the GUI to one side and develop the code

so that it was simple to change the parameters of the test from within.

To do this, I opted to use Object Oriented programming to keep track of all the different parameters, as well as to ensure simplicity for those using the code. An overall architecture was drawn up and is shown below in Figure **??**.

There were many difficulties and issues which arose when developing and testing this code, which will be discussed further in the manufacturing chapter.

Chapter 3

Manufacturing

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Appendices