University of Southern Queensland

Faculty of Health, Engineering and Sciences

An Investigation into harvesting electrical energy from plants through the Rhizo-deposition process in Australian environmental and climatic conditions

A dissertation submitted by

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in fulfillment of the requirements of

Courses ENG4111/ENG4112 Research Project

towards the degree of

Master of Engineering Sciences (Power Engineering)

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Limitations of Use

CERTIFICATION

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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ABSTRACT

An Investigation into harvesting electrical energy from plants through the Rhizo-deposition process in Australian environmental and climatic conditions

Sponsor –School of Mechanical and Electrical Engineering

Stuart Miles

Master of Engineering Sciences (Power Engineering)

Supervisors: Mr Andreas Helwig, (Electro-Mechanical Engineering) USQ

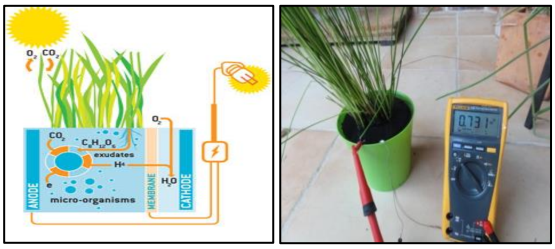

Figure 1 Model of a plan Microbial Cell. Courtesy of Strik D, et al 2008. Early experiment results of 0.731 V output from Australian native plant Juncus Usitatus

Keywords: Rhizo-deposition, Plant Microbial Fuel Cells (PMFCs), Bio-electrochemical System (BES).

Introduction

Renewable energy technologies are being increasingly integrated into social, commercial and governmental life. The development of solar, wind, hydro, geothermal, ocean and bio energies will cause major reductions in traditional power generation, providing a more sustainable future. This may prevent the further degradation of the planet, by reducing our “uneven footprint of human consumption and related environmental impacts.” Drigo et al (2009).

Background

A BES is considered to be a Microbial Fuel Cell (MFC) if electrical energy is harvested from it. Relatively small amounts of energy can be harvested through the Microbial processes as a result of Photosynthesis and Rhizo-deposition operation. Improving the efficiency of this electron harvesting process is the basis of the research project.

Methodology

By constructing battery cells it is proposed to produce electrical output at low levels. Each cell comprises of a tray, containing Titanium wire for anode and cathode, a growing medium, a plant species, a polymeric membrane filter and Carbon Felt inert electrode. The project was not aimed to out-perform renewable technologies, but to investigate outputs from <1 m^2 PFMCs and compare these results. This may determine if proportionally, PFMCs can deliver a cost effective addition to renewable technology.

Key Outcomes

There are four main factors affecting the operational efficiency of the cell; Plant health, solar radiation, Temperature and root density. By altering the characteristics of the cells, these factors have been as practicably optimised in order to achieve a hierarchy of goals; light a low power LED, light a number of LEDs, charge a LV battery, running a two-tier pond system

Further Work

To this point in time, the output current has limited the successful completion of the Project goals. Continuing steps are being taken in order to increase the current levels.

Conclusions

Interpreting the results and measurements of the PMFCs, only low levels of power are generated. From the six month recording period of power output, it can be deduced that if a larger scale with correct plant species and condition were implemented, PMFCs could be practically developed and further explored. There are apparent difficulties with the existing small scope of the project and some of the materials used are expensive in terms of supply logistics and availability.

Acknowledgements

Thank you to USQ and Mr Andreas Helwig, for allowing me to perform these studies. Thank you to my wife and son, for their support throughout the project.

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I would first and foremost, like to thank the University of Southern Queensland and Mr Andreas Helwig, for allowing me to perform these studies, that although frustrating to achieve any results at times, has been quite enjoyable and rewarding so far.

Further, I would like to show my appreciation to my wife and son, for their understanding in this time consuming process.

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CHAPTER 1: INTRODUCTION

Renewable energy technologies are being increasingly integrated into social, commercial and governmental life. The development of solar, wind, hydro, geothermal, ocean and bio energies will cause major reductions in traditional power generation, providing a more sustainable future. This will prevent the further degradation of the planet, by reducing our "uneven footprint of human consumption and related environmental impacts." [Drago, B, et al]. In the renewable energy area, the use of Bio-electrochemical Systems (BES) has seen success in generating "in situ green electricity or chemical compounds such as hydrogen, methane, ethanol and hydrogen peroxide." [Imhoff, Marc L. et al (2003), Hamelers, H.V.M. et al. (2010) Steinbusch, K.J.J. et al. (2010)].

A BES is considered to be a Microbial Fuel Cell (MFC) if electrical energy is harvested from it. Although relatively small amounts of energy can be harvested through the Microbial processes as a result of Photosynthesis and Rhizo-deposition operation [Rozendal, R.A. et al. (2006)] the possibility of improving this electron harvesting process and its efficiencies could provide for an interesting research project, applicable to local climates and environmental conditions.

From early discussions with Associate Professor Tony Ahfock and Mr Andreas Helwig (USQ School of Mechanical and Electrical Engineering) the idea of further researching the topic of MFCs and their potential has developed into investigations into other species of plants able to produce similar photosynthetic and Rhizo-deposition processes in Australian environmental conditions. The ultimate goal is to construct a two-tier pond system which produces enough power to drive a small pond pump, which in turn provides a water rotation cycle for the health of the system.

Further to this point, the effective storage of aforementioned harvested electricity will be a secondary part of the research proposal, which obviously would not be achievable until the initial concept is proven to operate as expected. As outlined in the phasing of the project in Chapter 3, Methodology, each progression of the project is dependent upon the successful completion of the previous task. Thus, the final goals of constructing of a two tier pond and effective storage of harvested power in a battery are only rudimentarily represented at this stage.

By keeping the above statements in mind the focus of the Project is upon to main objectives:

- What level of power density can be achieved by specific plant species in Australia
- Is the level of power density scalable and practical for realistic applications

Early investigations have shown small levels of voltage and current (0.005V-0.731V and 0.001A-0.2A).See Figure 2 below.

Some species have shown improvements upon these levels through different electrical and physical configurations.

Figure 2. Early results

CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

The existence of renewable technologies in Australia and across the world has advanced enormously in recent years. This project seeks to form the basis of an argument into continuing investigations into the operations of Plant Microbial Fuel Cells (PMFCs) as a renewable option worth undertaking. As some of the most recent published studies were completed from 2008 until 2016, many of the processes are still being improved upon [Moqsud, M.A. et al]. Within Australia's climatic zones, apart from desert areas, there lies an opportunity to develop studies into the applications of PMFCs. Notwithstanding the rural possibilities in and around water ways, retention systems and dams, PMFCs could be installed as supplementary to solar and wind projects within urban areas, if planning and design considerations were made. In reviewing existing studies the harvesting of electricity from a plant's root system has been explored, with published evidence of the operation of Plant Microbial Fuel Cells (PMFCs) [Moqsud, M.A. et al.].

There are two processes which occur to allow the PMFCs to produce electricity.

1. Photosynthesis occurs for the plant to produce its own energy, which is not completely utilised by the plant; and
2. The surplus sugar ($C_6H_{12}O_6$) is used by the bacteria to produce electrical energy.

With $288 billion spent on renewable energy worldwide last year (2015) [Imhoff. et al. (2009)], the improvements in availability, economic viability and functionality of a multitude of technologies has become apparent. This is the motivation behind performing the proposed research. The possibilities of scaling up the experiments have, at this stage, not been fully explored [Helder, M et al (2013)].

The pH and Temperature are important elements in the generation process [Strik, D. et al. (2013)]. The proposed project will monitor and stabilise the pH of the growing medium and pond water until expected outcomes are achieved, then moves to alter these parameters shall be made and reactions recorded and analysed.

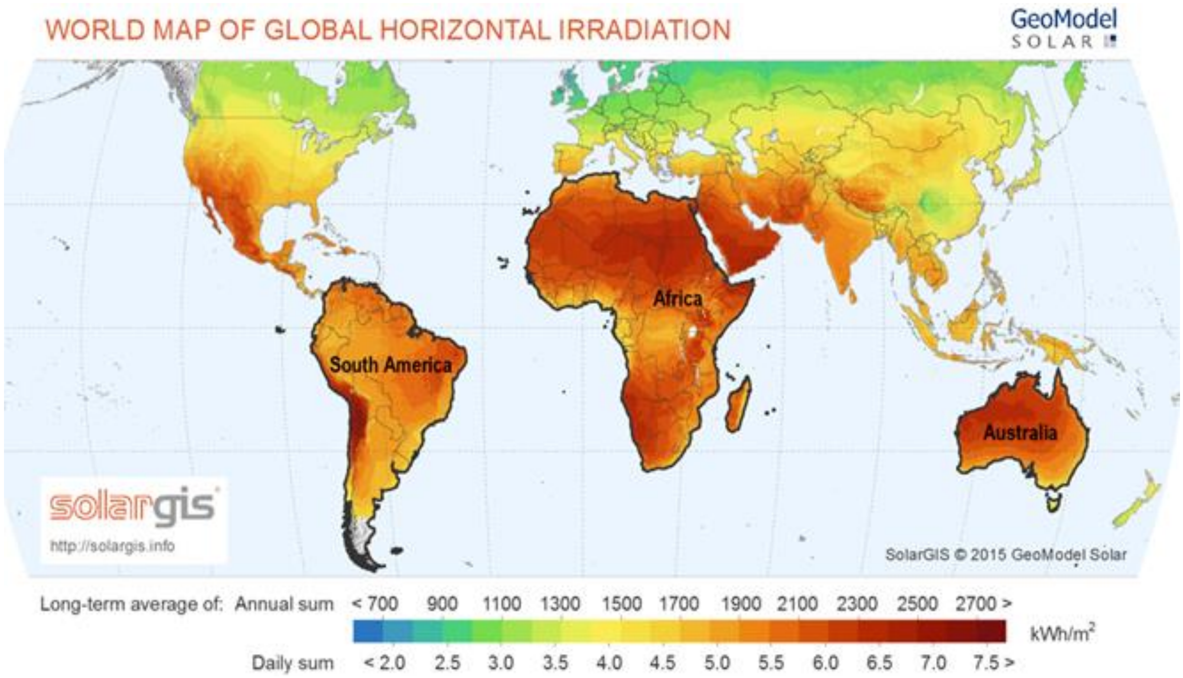

Figure 3. Solar Radiation. Courtesy of www.solaris.info

With the average solar radiation in Australia at around 5kwh/m^2/day [www.solaris.info], compared to 2.5kwh/ m^2/day [www.solaris.info], where some of these previous studies have occurred in Europe. The assumption is that an increased output may be achieved. The project will investigate this, as the process may or may not be limited by merely the efficiency of the photosynthesis operation.

CHAPTER 3: METHODOLOGY

An unavoidable comparison to other renewable technology will be exhibited in the output capabilities of PFMCs. The project will not aim to out-perform the previously stated technologies but to provide an alternative which will:

- Confirm the levels of electrical output in areas of <1m2 of PFMCs, to light a low power LED.
- Determine if proportionally PFMCs can deliver a cost effective addition to renewable technology
- Compare the output of different plant species

Due to Availability and cost the list of plant selections has been amended. The plants obtained were:

- Water Chestnut (Eleocharis Dulcis)
- Common Rush (Juncus Usitatus)
- Mat Rush (Lomandra Filiformis)
- Spiny head Mat Rush (Lomandra Longifolia)
- Rock Orchid (Dendrobium Speciosum)
- Native Violet (Viola Hederacea)

See Appendix D for plant information. The six species above were selected with the following criteria in mind:

- Water based Rhizomatous species
- Availability of species within Australia
- Suitable climatic and environmental conditions in Australia
- Food bearing capabilities (Water Chestnut)

- Utilisation of a native plant used in wetland regeneration (Common Rush, Mat Rushes)

Phases 1, 2 and up to 3b have now been completed. The timeline has been altered slightly due to practicality and analysing results. See Appendix C for Gantt chart and Timeline table. By the end of week 6 (03/04/17), the background and proof of concept had been researched to provide substantive evidence of an Engineering Research Project. Mimicking the purchased PMFCs kits proved to be more difficult than first thought, due to the logistical constraints of purchasing some materials internationally (namely the Carbon felt bulk order from China). Each cell requires a tray, containing the Titanium wire for anode and cathode, growing medium (soil of sorts) a plant species and the Carbon Felt used as an inert electrode. See Table 1 below for a bill of Materials.

PHASE	PRODUCT	SOURCE	COST TO DATE($AUD)
1	**Modular DIY Plant kit**	**Plant-e.com**	**$319.78 (inc. shipping)**
1	**Plants(2xLomandra)**	**Hardware /Garden Store**	**$60**
2	**Circuitry and electrical equipment and insulation**	**Electrical supplies Store**	**$20**
2	**Timber and materials for support framework**	**Owned**	**Nil**
2	**Plant Food, Soil, Fertiliser, Miscellaneous Pond Equipment**	**Hardware /Garden Store**	**$50**
2	**Carbon Felt For use as Inert Electrode**	**Manufacturer in China**	**$US 740**

2	**Polymeric membrane –Household Scouring Pads**	**Grocery Store**	**10*Pack of 5 - $15**

Table 1 Bill of Materials to Date.

Unfortunately, with the various shapes and sizes of plants, comparing results was difficult. Thus, set out below are the plant specifications.

Plant	Size(height in mm)	Specifications of Plant Medium
Water Chestnut	500	200mm (diameter) x 250mm (deep)
Common Rush	500	200mm (diameter) x 250mm (deep)
Mat Rush	400	100mm (diameter) x 150mm (deep)
Rock Orchid	100	100mm (diameter) x 150mm (deep)
Spiny head Mat Rush #1	250	100mm (diameter) x 150mm (deep)
Spiny head Mat Rush #2	550	200mm (diameter) x 250mm (deep)
Native Violet #1 – tube stock	50	40mm (diameter) x 40mm (deep)
Native Violet #2 – 16 x tube stock	50	40mm (diameter) x 40mm (deep) Arranged in 300mm x 300mm Plant Tray

Table 2 Plant Specifications

Through the phases of the project, 3 plants were identified as being the most efficient in their electrical operation:

- Common Rush
- Spiny Head Mat Rush
- Native Violet

Physically increasing the size of these three original cells has been made to attempt to improve the “battery” outputs. By far the most efficient plant when comparing size and specifications of the plants was Native Violet. Designing and constructing a larger cell of Violet provided for excellent results, which will allow a point of further investigation in the next phases of the project, particularly in battery charging and storage.

Below is the circuit whose output ranged between 330mV and 560mV. Considering each tube stock is approximately 10% of the size of some of the other plants selected, this is a significant result.

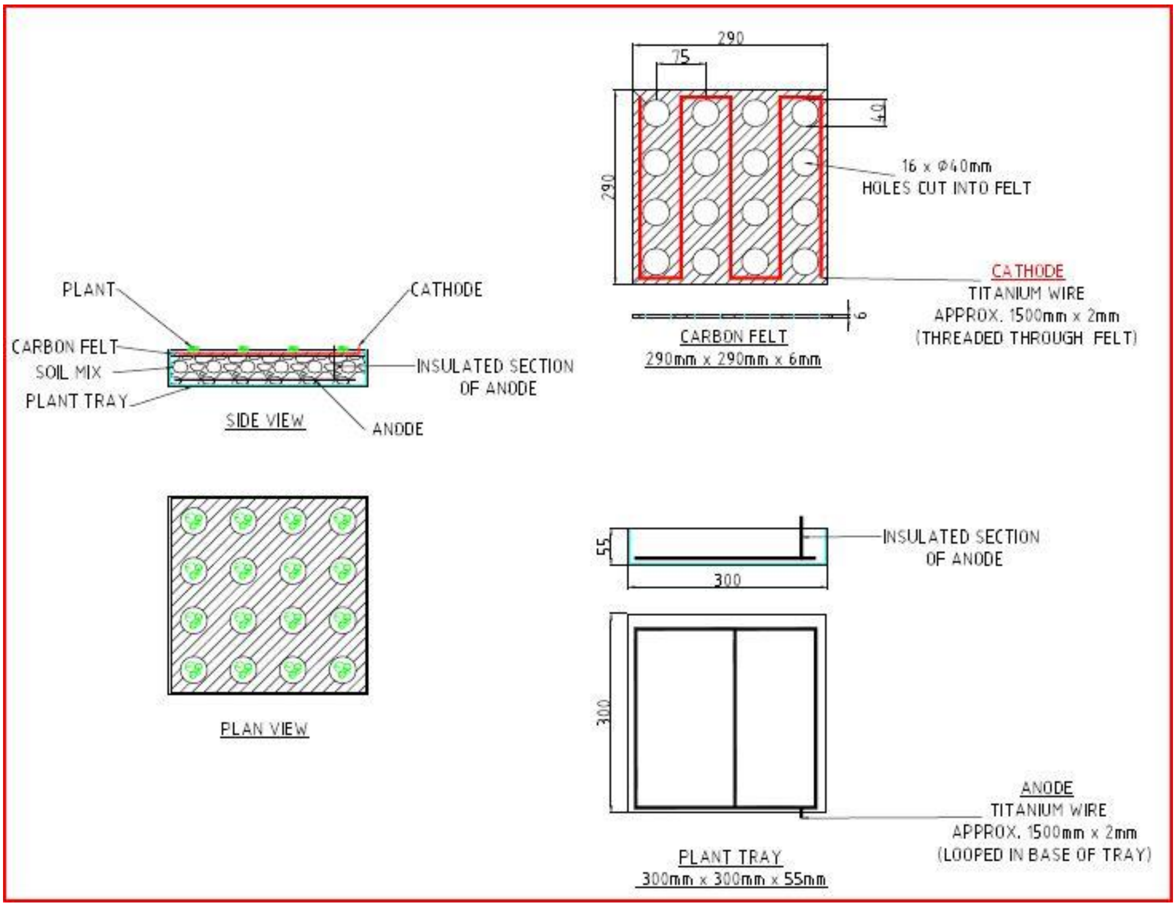

Figure 4 Native Violet x 16 Celle 4.

From this point onwards, most of the fiscal challenges have been met. Purchases will still be required, pending the results of the next phases. If enough voltage and current can be produced to light an LED and subsequently a series of LEDs, the project can move into its final experimentation and analysis stage.

Whether or not this is achieved will determine if the penultimate and ultimate phases of charging a battery, then running a two-tier pond system will be feasible. Theoretically, these phases are achievable.

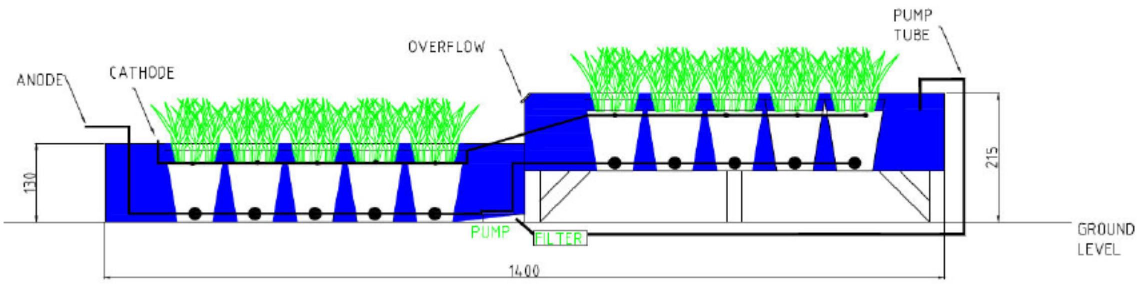

Figure 5. Two-Tier Pond System

At the mid-stage of the project the seasonal factors affecting the cells were discovered. The growth pattern of the Native Violet had substantially decreased. This fact, as well as low current output, required a different approach again. With the output of the Native Violet not seemingly going to achieve the required results to progress past the earlier phases of the project, the next best plant species was selected to attempt to focus upon optimising output and results.

On the basis of these findings, *Juncus Usitatus* was selected as the next best performing flora for the use in the plant cells. The next steps were to scale up the project; this process consisted of constructing as many cells as feasible (financially) to obtain any meaningful results. A total of twenty seven (27) cells were constructed as an ultimate experiment, with an aim of connecting the cells both in parallel and in series. See figures six to eight below. These cells provided for the most efficacious outcomes and are discussed further in the Results section.

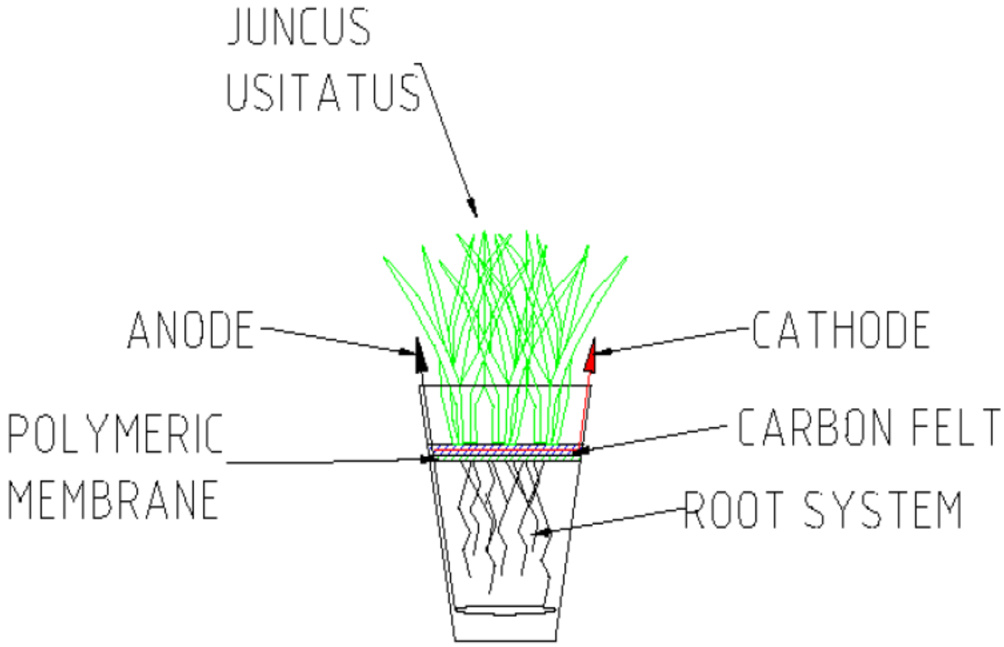

Figure 6 Model of the Ultimate cells

Figure 7 Output of the Ultimate Cells

Figure 8 Array of 27 Ultimate cells

The above cells, although producing the best results, highlighted the major problem with the Rhizo-deposition process, in that the size of the project limits power density available. The current producing ability of the cells is not adequate enough to light the Low Power LED selected.

For the reason stated above, the lack of current carrying capacity, the further experiments sought to improve these electrical characteristics. Stainless steel mesh and off-cuts of Carbon felt were added to the circuit. At the latter stages of the project, it was difficult to measure whether any greater electrical output was available due to the installation of said products, but this is discussed later in the Results section

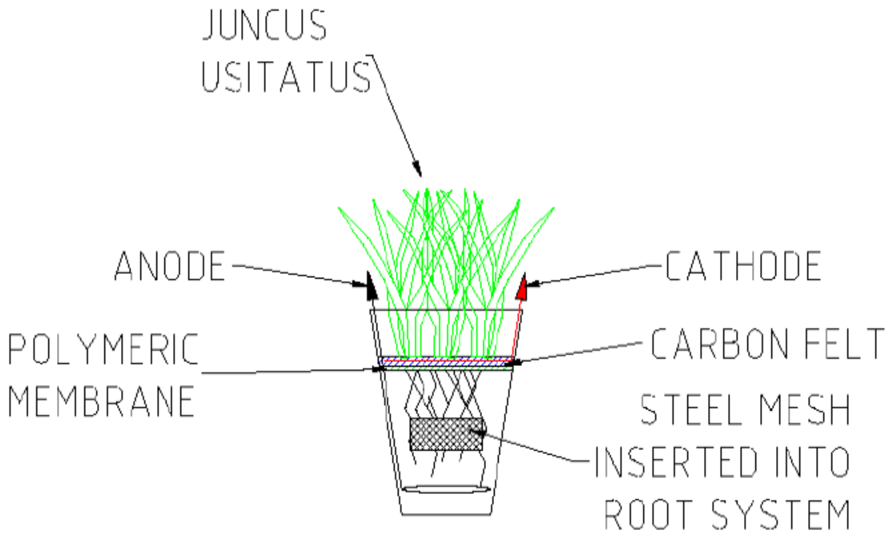

Figure 9 Ultimate Cell with Stainless Steel

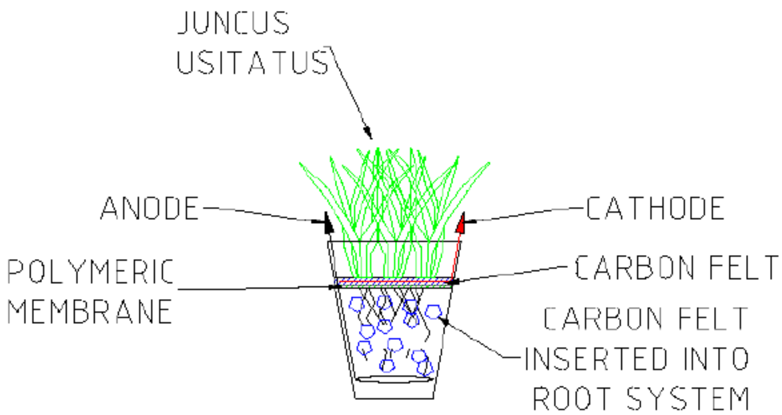

Figure 10 Ultimate Cell with Carbon Felt

RISK ASSESSMENT

Risk Matrix

	Consequence				
Likelihood		Minor	Moderate	Major	Extreme
	1. Rare	A1	B1	C1	D1
	2. Unlikely	A2	B2	C2	D2
	3. Likely	A3	B3	C3	D3
	4. Almost Certain	A4	B4	C4	D4

Project Risk

Phase	Risk	Score	Mitigation
Start-up (1)	• Modular kit is not delivered	D2	• Early works cannot proceed • Seek clarification or refund and select another topic
Start-up (1)	• Modular kit does not adequately perform	D2	• Early works cannot proceed • Select another topic
Start-up (1)	• Proposal not accepted	C2	• Seek early feedback • Further preparation • Apply feedback to proposal

Start-up (1)	• Unable to find suitable location	D1	• Experiments will not occur and select another topic
Start-up (1)	• Miss enrolment in appropriate subjects	D2	• Will only occur upon failure to enrol or complete pre-requisites
Experimentation and Analysis (2)	• Unable to construct, operate or perform any meaningful analysis on project	D1	• Considered to be particularly unlikely, once past the Initiation and Planning Stages, although would be catastrophic for the project.
Experimentation and Analysis (2-4)	• Unable to complete data analysis	D1	• Although catastrophic, as above, periodical checks throughout the phases should have prevented the project progressing this far.
Experimentation and Analysis (2-4)	• Unable to complete final stages of project due to limited or low output	B3	• At this stage of the project, the outputs required to run a two-tier pond seem difficult to achieve. • Although reasonable effort has been made to achieve required outputs, the feasibility of the ultimate goals seems unattainable for the scope and financial limitations of the project. • This is not a failure in terms of the analysis, but has consequences affecting the hypothesised aim and outcomes of the research.
Final (5)	• Unable to complete Dissertation	D1	• Although catastrophic, as above, only major events outside of research life would cause this.

Personal Risk

Phase	Risk	Score	Mitigation
Experimentation and Analysis (2-4)	• **Harm to myself or others via electric shock**	**D1**	• **Although Low Voltage, Electric Shock can have long lasting negative effects. Compliance with AS 3000 and appropriate safety rules to prevent any occurrence.**
Experimentation and Analysis (2-4)	• **Harm to myself or others via inadequate Structural design and construction**	**D1**	• **Perform calculations and seek Engineering advice, although the size of the experiment does not seem excessive.**
Final (5)	• **Unable to complete Dissertation**	**D1**	• **Although catastrophic, as above, only major events outside of research life would cause this.**

CHAPTER 4: RESULTS

Upon construction of each cell, initial readings were low. Once the plant battery had settled for a period of, sometimes a day, other times up to a period of seven days, a fairly consistent range of Voltage output was achieved. Plants which showed unsatisfactory results were abandoned when it was assumed that no better performance would be achieved.

Every attempt was made to take output readings at the same time of day. Employment and social constraints prevented continuous recordings. This may be perceived as inconsistency. The Project will therefore have obvious limitations in its findings, as budgetary and environmental constraints prevent any pure analysis, when compared to laboratory results. Anomalous readings were removed from the below table, but have been recorded. Refer Appendices A and B for Readings Tables and Graphs.

Plant Species	Initial Output (V)	Steady Range
Water Chestnut	0.005	0.005-0.009
Common Rush	0.378	0.423-0.776
Mat Rush	0.163	0-0.341
Rock Orchid	0.02	0.04-0.088
Lomandra #1	0.431	0.58-0.74
Lomandra #2	0.02	0.372-0.549
Native Violet #1	0.044	0.105-0.17
Native Violet #2	0.281	0.264-0.45

Table 3 Plant Voltage Ranges

From the above results, it is shown that Water Chestnut, Rock Orchid and Mat Rush showed unsatisfactory results. These cells were abandoned after a maximum period of fourteen days. However, Common Rush, the two Lomandra and the two Native Violet cells all displayed results which were worth persevering.

Surprisingly, Lomandra #1, was severely affected by water stress, but kept producing Voltages of a similar rate. A cold snap overnight and a period of inclement weather conditions saw the health of the plant deteriorate from the 14/04/17 for the following seven days.

pH levels were deemed to be of a minor importance, which were steady at slightly acidic of around 6, due mainly to the all-purpose potting mix used as a soil growing medium. This being said, there were four main factors which seemed to affect the operational efficiency of the cells:

1) **The health of the plant**. This seems quite obvious, but, in most cases the electrical yield increases/decreases depending upon the wellbeing of the plant species.
2) **Solar Radiation.** Interestingly, once a relatively steady or settled state of output is achieved, a variance in solar radiation between full sun versus overcast and cloudy conditions does not dramatically affect these levels of yield. Hence, the geographical position of Australia relative to the rest of the world and its climatic conditions do not necessarily influence cell output, as first thought. It is supposed that the plant species and its efficiency at surviving have greater impact upon any operational characteristics as a PMFC.
3) **Temperature.** The area selected for analysis is based upon necessity and not the ideal environment, such as laboratory conditions with provisions for synthetic UV

light. Every attempt was made at allowing for plants to receive adequate growth conditions, but unusual fluctuations in temperature, particularly cold snaps overnight, served to guide the outputs.

4) **Root Density.** The term Root Density has been selected for want of a more accurate term. From the plant species selected, those that have robust root growth characteristics provided for the best outcomes. Comparatively, those plants that are mainly water based, such as Water Chestnut and Water Lily, with little and sparse soil, growing medium and root system interaction were quickly abandoned in the study. These findings highlight there is a definite link between the root system, the soil and the moisture levels.

The Native Violet used in the innovated cell, regrettably faced adverse growing conditions during the particularly dry winter months in Sydney this year. The average rainfall for area in Sydney where the analyses occurred was a total of 59mm, 54.9 mm and 58.1mm for the months July, August and September, respectively. In the year of 2017, the monthly rainfall averages totalled at 4.8mm, 20.2mm and 0.4mm for July, August and September, respectively. With the findings of the direct link between moisture levels and electrical output, as well as an unusually dry end to winter, these issues had an obvious effect on the operation of the cells

From this point onwards, as discussed earlier, the Native Violet cells had to be abandoned, moving onto the As can be seen in the Tabulated readings Part D and Part E on pages 28 and 29 respectively, the moisture levels in the cells are certainly linked to the output of the cells. The charts which are correlated to these tables are displayed in pages 38-41.

After the usual period of settling, the cells reached an equilibrium or steady state range of voltage. Several plants, which were located in an area that received more sunlight, exhibited some interesting results as a consequence of dehydration. The charts show that cells affected by more sunlight actually drew power out of the system, with some negative voltages being recorded. This fact illustrates an interrelationship between the transferral of electrons through the Rhizo-deposition process and the moisture levels of the cell. Discovering this was meaningful, although unfortunate at a later stage of the project, as measurements and analysis of this phenomenon would have allowed for a relevant study of the apparent connection.

In order to increase the conductivity of the cells, certain inclusions were made in the cell's compositions. After fertilising with Ammonium Sulphate, a high source of Nitrogen and Sulphur, as well as 'Seasol' that contains plant nutrients, trace elements, alginic acid and other bioactive compounds which promotes healthy roots, encourages beneficial soil micro-organisms, there was no immediate effect upon the electrical output. A longer period of study would be required in order to investigate the full effects.

With Biological and chemical means attempted with little or no apparent effect, the alteration of the electrical configuration may provide for some benefit. As seen in Figures 9 and 10, some cells were installed with Stainless Steel Mesh and off-cuts of the Carbon Felt into the growing medium, in an attempt to increase the current carrying capacity of the Cells. Time constraints and scale prevented the full studies of these inclusions.

CHAPTER 5: CONCLUSIONS

Interpreting the results and measurements of the PMFCs in sizes less than $1m^2$ illustrate only low levels of power generated. After recording these levels over a six to eight month period, it is implied that a larger scale with correct plant species and conditions, PMFCs could be practically developed and further explored. The scope of the project, time constraints, financial limitations and logistical problems provided a definitive hindrance to the research.

The readings in Table 9, which are charted in Figures 23-25, show that the Technology is not a myth. This data emphasizes that there are definitely a chemical and electrical processes occurring which can be harnessed. Voltage of up to 3.7V out of nine cells in series show this and further or more focussed studies may improve these levels.

FURTHER WORK

Having a better understanding of the processes involved in the Rhizo-deposition process and the components involved, continued studies in this area may prove to be fruitful.

1. An improved monitoring system and analyses of the relationship between the moisture levels and the output of the cells could have been implemented. This was probably a drawback in the research conducted, as expected results didn’t rely upon a contingency. With the advent of small micro controllers such as the Arduino and the Raspberry Pi, similar experimentation could occur with these systems in place for interpretation.
2. The inclusions of circuitry components such as Stainless Steel, Carbon electrodes, and other current collectors may provide for some areas of elevated outputs. This may be a problem with conductivity or internal resistance of the cells.

3. The Technology is firmly based in the rural or non-built up areas, where space restrictions are not an issue. The impracticality of larger scale installations in urban areas is apparent. Possible large scale applications may include, water courses and catchments, rice paddies and large agricultural areas where water stores are present.

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APPENDIX A – PROJECT SPECIFICATION

Title: An investigation into harvesting electrical energy from plants through the Rhizo-deposition process in Australian environmental and climatic conditions.

Major: Electrical Engineering (Power)

Supervisor: Andreas Helwig

Enrolment: ENG4111 – EXT S1 2017
ENG4112 – EXT S2 2017

Project Aim: To investigate the levels of power density that can be achieved through the Rhizo-deposition process by specific plant species in Australia, whether improved efficiencies can be achieved in Australia and any realistic applications for the power output can be realised.

Programme: Issue V1, 15th March 2017

1. Research the background information relating to Rhizo-deposition, photosynthesis and solar radiation produced and utilised by plants in local environmental conditions.
2. Produce modular Plant Microbial Fuel Cells (PMFCs) with different plant species and investigate power density produced, with an aim of identifying the most efficient species for further development and investigation.
3. Analyse the collected data and investigate possible improvements systematically through:
    a. Biological means: differing pH levels, differing solar access and increasing nutrient availability.
    b. Electrical means: altering circuit configuration (series/parallel) and altering conductor sizes and arrangements.
    c. Physical means: combining multiple ‘cells’ into one.
4. Develop and apply the most efficient system to power low output LED.

5. Up-scale system to power numerous low output LEDs
   If time and resources permit in no particular order:
6. Up-scale system to power rechargeable batteries efficiently.
7. Design and implement "Two-tier pond system" as outlined in the Project Proposal.

APPENDIX B – READINGS TABLES

Water Chestnut							
Date		3/04/17	4/04/17	5/04/17	6/04/17	7/04/17	8/04/17
Time	Day of Reading	1	2	3	4	5	6
5:30	Output in Volts	0.005	0.009	0.005	0.005	0.005	0.005
16:30		0.005	0.005	0.005	0.005	0.009	0.005
17:00		0.005	0.005		0.005	0.005	0.005

Common Rush															
Date		3/04/17	4/04/17	5/04/17	6/04/17	7/04/17	8/04/17	9/04/17	10/04/17	11/04/17	12/04/17	13/04/17	14/04/17	15/04/17	16/04/17
Time	Day of Reading	1	2	3	4	5	6	7	8	9	10	11	12	13	14
5:30	Output in Volts	0.378	0.391	0.344	0.44	0.526			0.68	0.711	0.634	0.62	0.484	0.423	
7:00							0.661	0.73							0.501
12:00		0.32						0.776						0.499	0.544
16:30		0.35	0.38	0.401	0.51	0.54	0.696				0.678	0.663	0.481		
18:00		0.364	0.352	0.41	0.546	0.535	0.691	0.701							

Date		17/04/17	18/04/17	19/04/17	20/04/17	21/04/17	22/04/17	23/04/17	24/04/17
Time	Day of Reading	15		16	17	18	19	20	21
5:30	Output in Volts	0.534		0.62	0.633	0.576			0.581
7:00							0.651	0.677	
12:00									
16:30		0.569		0.143	0.668	0.687	0.701	0.679	0.711
18:00									

Mat Rush #1															
Date		3/04/17	4/04/17	5/04/17	6/04/17	7/04/17	8/04/17	9/04/17	10/04/17	11/04/17	12/04/17	13/04/17	14/04/17	15/04/17	16/04/17
Time	Day of Reading	1	2	3	4	5	6	7	8	9	10	11	12	13	14
5:00	Output in Volts	0.163	0.199	0.225	0.238	0.284	0.313	0.325	0.341	0.293	0.187	0.182	0.05	0.1	0.118
12:00		0.18					0.33						0.128	0.142	
17:00		0.19	0.185	0.246	0.278	0.282				0.325	0.19	0.186	0.13	0.093	0.102
18:30		0.176	0.201	0.27	0.266	0.291	0.318		0.318						

Table 4 Tabulated Readings part A

Rock Orchid															
Date		3/04/17	4/04/17	5/04/17	6/04/17	7/04/17	8/04/17	9/04/17	10/04/17	11/04/17	12/04/17	13/04/17	14/04/17	15/04/17	16/04/17
Time	Day of Reading	1	2	3	4	5	6	7	8	9	10	11	12	13	14
5:30	Output in Volts	0.02	0.025	0.025	0.034	0.062		0.074	0.04	0.055	0.05	0.06	0.045		
8:00							0.066	0.07						0.064	0.072
12:00		0.021					0.061	0.07						0.068	0.088
16:30		0.019	0.035	0.03	0.045	0.059	0.063	0.065	0.042	0.05	0.06	0.06	0.054	0.067	0.08
18:00		0.022	0.032		0.036	0.06	0.06	0.069	0.045	0.049	0.061	0.057	0.053	0.07	0.086

Lomandra #1															
Date		3/04/17	4/04/17	5/04/17	6/04/17	7/04/17	8/04/17	9/04/17	10/04/17	11/04/17	12/04/17	13/04/17	14/04/17	15/04/17	16/04/17
Time	Day of Reading	1	2	3	4	5	6	7	8	9	10	11	12	13	14
5:00	Output in Volts	0.431	0.42	0.388	0.457	0.511	0.127	0.679	0.6	0.599	0.715	0.691	0.58	0.67	0.638
12:00		0.321						0.677	0.656					0.658	0.711
17:00		0.378	0.475	0.395	0.501	0.696	0.69				0.707	0.689	0.688	0.643	0.705
18:30		0.369	0.472	0.39	0.514	0.678	0.676	0.725	0.674	0.683					

Date		17/04/17	18/04/17	19/04/17	20/04/17	21/04/17	22/04/17	23/04/17	24/04/17
Time	Day of Reading	15		16	17	18	19	20	21
5:00	Output in Volts	0.672		0.694	0.684	0.671	0.706	0.733	0.726
12:00									
17:00		0.714		0.694	0.7	0.692	0.74	0.775	0.718
18:30									

Lomandra #2															
Date		24/04/17	25/04/17	26/04/17	27/04/17	28/04/17	29/04/17	30/04/17	1/05/17	2/05/17	3/05/17	4/05/17	5/05/17	6/05/17	7/05/17
Time	Day of Reading	1	2	3	4	5	6	7	8	9	10	11	12	13	14
5:00	Output in Volts	0.02	0.128	0.185	0.26	0.399	0.412	0.429	0.45	0.459	0.44	0.372	0.426	0.407	0.48
12:00		0.05						0.445						0.406	0.5
17:00		0.25	0.17	0.189	0.417	0.41	0.455				0.442	0.418	0.431	0.422	0.549
18:30		0.12	0.201	0.22	0.419	0.412	0.43	0.483		0.449					

Table 5 Tabulated Readings Part B

Native Violet #1															
Date		3/04/17	4/04/17	5/04/17	6/04/17	7/04/17	8/04/17	9/04/17	10/04/17	11/04/17	12/04/17	13/04/17	14/04/17	15/04/17	16/04/17
Time	Day of Reading	1	2	3	4	5	6	7	8	9	10	11	12	13	14
5:00		0.044	0.048	0.04	0.056	0.128	0.127	0.111	0.12	0.14	0.105	0.108	0.116	0.118	0.1
12:00		0.055						0.115						0.128	0.122
17:00		0.04	0.04	0.047	0.06	0.119	0.12				0.107	0.108	0.113	0.13	0.131
18:30		0.038	0.04	0.044	0.063	0.105	0.17	0.168		0.121					

Date		17/04/17	18/04/17	19/04/17	20/04/17	21/04/17	22/04/17	23/04/17	24/04/17
Time	Day of Reading	15		16	17	18	19	20	21
5:00		0.124		0.119	0.109	0.1	0.1	0.11	0.124
12:00									
17:00		0.121		0.13	0.101	0.128	0.009	0.14	0.13
18:30									

Native Violet #2																
Date			24/04/17	25/04/17	26/04/17	27/04/17	28/04/17	29/04/17	30/04/17	1/05/17	2/05/17	3/05/17	4/05/17	5/05/17	6/05/17	7/05/17
Time	Day of Reading		1	2	3	4	5	6	7	8	9	10	11	12	13	14
5:00	Output in Volts	0.044	0.048	0.04	0.056	0.128	0.127	0.111	0.12	0.14	0.105	0.108	0.116	0.118	0.1	
12:00		0.055						0.115						0.128	0.122	
17:00		0.04	0.04	0.047	0.06	0.119	0.12				0.107	0.108	0.113	0.13	0.131	
18:30		0.038	0.04	0.044	0.063	0.105	0.17	0.168		0.121						

Table 6 Tabulated Readings Part C

Ultimate Cells #1												
Date		01/07/17	02/07/17	03/07/17	04/07/17	05/07/17	06/07/17	07/07/17	08/07/17	09/07/17	10/07/17	11/07/17
Time	Day of Reading	1	2	3	4	5	6	7	8	9	10	11
5:00:00	Output in Volts	0.220	0.100	0.100	0.170	0.460	0.560	0.380	0.150	-0.300	0.360	0.480
12:00:00		0.180	0.280	0.320	0.500	0.480	0.750	0.320	-0.130	-0.010	0.380	0.700
17:00:00		0.330	0.240	0.480	0.260	0.480	0.650	0.220	-0.050	0.100	0.500	0.610

Ultimate Cells #1					
Date		12/07/17	13/07/17	14/07/17	15/07/17
Time	Day of Reading	12	13	14	15
5:00:00	Output in Volts	0.200	0.355	0.610	0.250
12:00:00		0.500	0.455	0.530	0.450
17:00:00		0.500	0.600	0.600	0.640

Ultimate Cells #2												
Date		01/07/17	02/07/17	03/07/17	04/07/17	05/07/17	06/07/17	07/07/17	08/07/17	09/07/17	10/07/17	11/07/17
Time	Day of Reading	1	2	3	4	5	6	7	8	9	10	11
5:00:00	Output in Volts	0.150	0.050	0.130	0.260	0.340	0.455	0.570	0.325	0.110	0.050	-0.100
12:00:00		0.150	0.220	0.300	0.270	0.390	0.585	0.570	0.300	0.105	-0.050	0.100
17:00:00		0.120	0.110	0.300	0.260	0.405	0.665	0.565	0.325	0.115	-0.050	0.150

Ultimate Cells #2					
Date		12/07/17	13/07/17	14/07/17	15/07/17
Time	Day of Reading	12	13	14	15
5:00:00	Output in Volts	0.375	0.520	0.595	0.580
12:00:00		0.375	0.580	0.700	0.450
17:00:00		0.400	0.610	0.690	0.620

Table 7 Tabulated Readings Part D

Ultimate Cells #3												
Date		01/07/17	02/07/17	03/07/17	04/07/17	05/07/17	06/07/17	07/07/17	08/07/17	09/07/17	10/07/17	11/07/17
Time	Day of Reading	1	2	3	4	5	6	7	8	9	10	11
5:00:00	Output in Volts	0.050	0.100	0.200	0.350	0.370	0.280	0.340	0.150	-0.105	0.190	0.375
12:00:00		0.000	0.150	0.220	0.450	0.350	0.310	0.345	-0.200	-0.050	0.260	0.390
17:00:00		0.100	0.190	0.200	0.390	0.370	0.340	0.355	-0.200	0.050	0.380	0.400

Ultimate Cells #3					
Date		12/07/17	13/07/17	14/07/17	15/07/17
Time	Day of Reading	12	13	14	15
5:00:00	Output in Volts	0.400	0.550	0.550	0.555
12:00:00		0.425	0.515	0.545	0.650
17:00:00		0.400	0.540	0.525	0.655

Ultimate Cells #4												
Date		01/07/17	02/07/17	03/07/17	04/07/17	05/07/17	06/07/17	07/07/17	08/07/17	09/07/17	10/07/17	11/07/17
Time	Day of Reading	1	2	3	4	5	6	7	8	9	10	11
5:00:00	Output in Volts	0.150	0.420	0.375	0.365	0.500	0.655	0.455	0.215	0.155	0.335	0.465
12:00:00		0.350	0.550	0.375	0.600	0.635	0.655	0.485	0.255	0.150	0.300	0.470
17:00:00		0.450	0.480	0.375	0.595	0.685	0.645	0.445	0.245	0.125	0.300	0.470

Ultimate Cells #4					
Date		12/07/17	13/07/17	14/07/17	15/07/17
Time	Day of Reading	12	13	14	15
5:00:00	Output in Volts	0.485	0.600	0.610	0.650
12:00:00		0.500	0.715	0.595	0.650
17:00:00		0.515	0.695	0.680	0.640

Table 8 Tabulated Readings Part E

Combined Cells #1								
Date		01/08/17	02/08/17	03/08/17	04/08/17	05/08/17	06/08/17	07/08/17
Time	Day of Reading	1	2	3	4	5	6	7
5:00:00	Output in Volts	1.800	1.250	2.600	3.150	3.400	3.655	2.850
12:00:00		1.450	2.300	2.605	3.005	3.250	3.525	3.105
17:00:00		1.300	2.050	2.950	3.500	3.700	3.330	3.205
Combined Cells #2								
Date		01/08/17	02/08/17	03/08/17	04/08/17	05/08/17	06/08/17	07/08/17
Time	Day of Reading	1	2	3	4	5	6	7
5:00:00	Output in Volts	0.050	2.645	3.115	3.400	3.000	2.400	2.685
12:00:00		0.250	2.115	3.110	3.400	2.855	2.555	3.000
17:00:00		0.785	2.035	3.215	3.405	2.675	2.995	2.460
Combined Cells #3								
Date		01/08/17	02/08/17	03/08/17	04/08/17	05/08/17	06/08/17	07/08/17
Time	Day of Reading	1	2	3	4	5	6	7
5:00:00	Output in Volts	1.015	1.000	1.800	2.435	1.500	3.055	3.500
12:00:00		1.115	1.755	2.000	2.400	2.485	3.810	3.215
17:00:00		1.005	1.385	2.110	2.445	2.950	3.750	3.335

Table 9 Tabulated Readings Part F

APPENDIX C – READINGS CHARTS

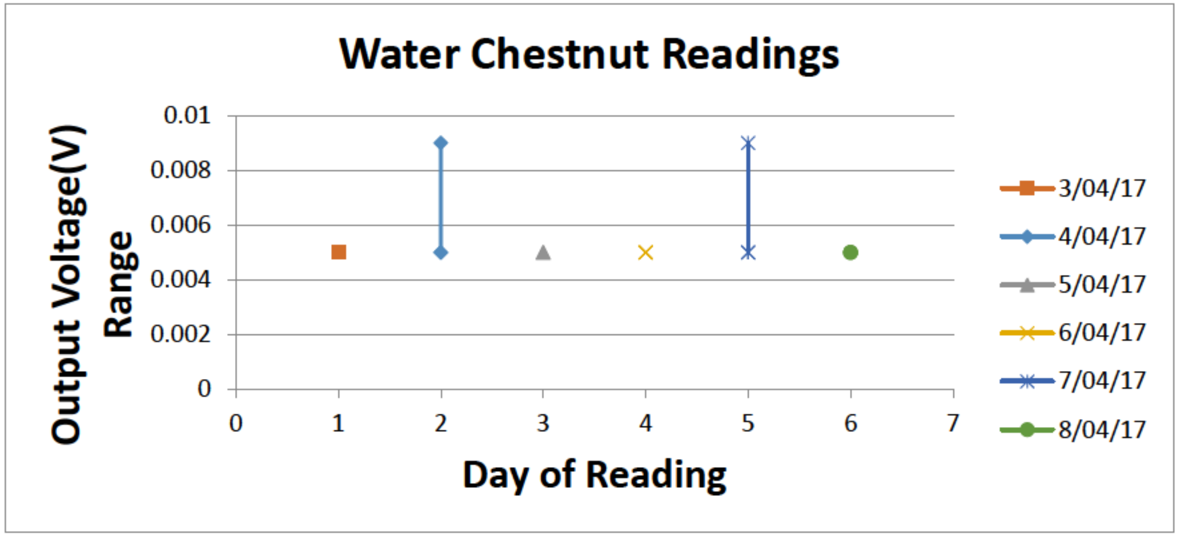

Figure 11 Water Chestnut Readings

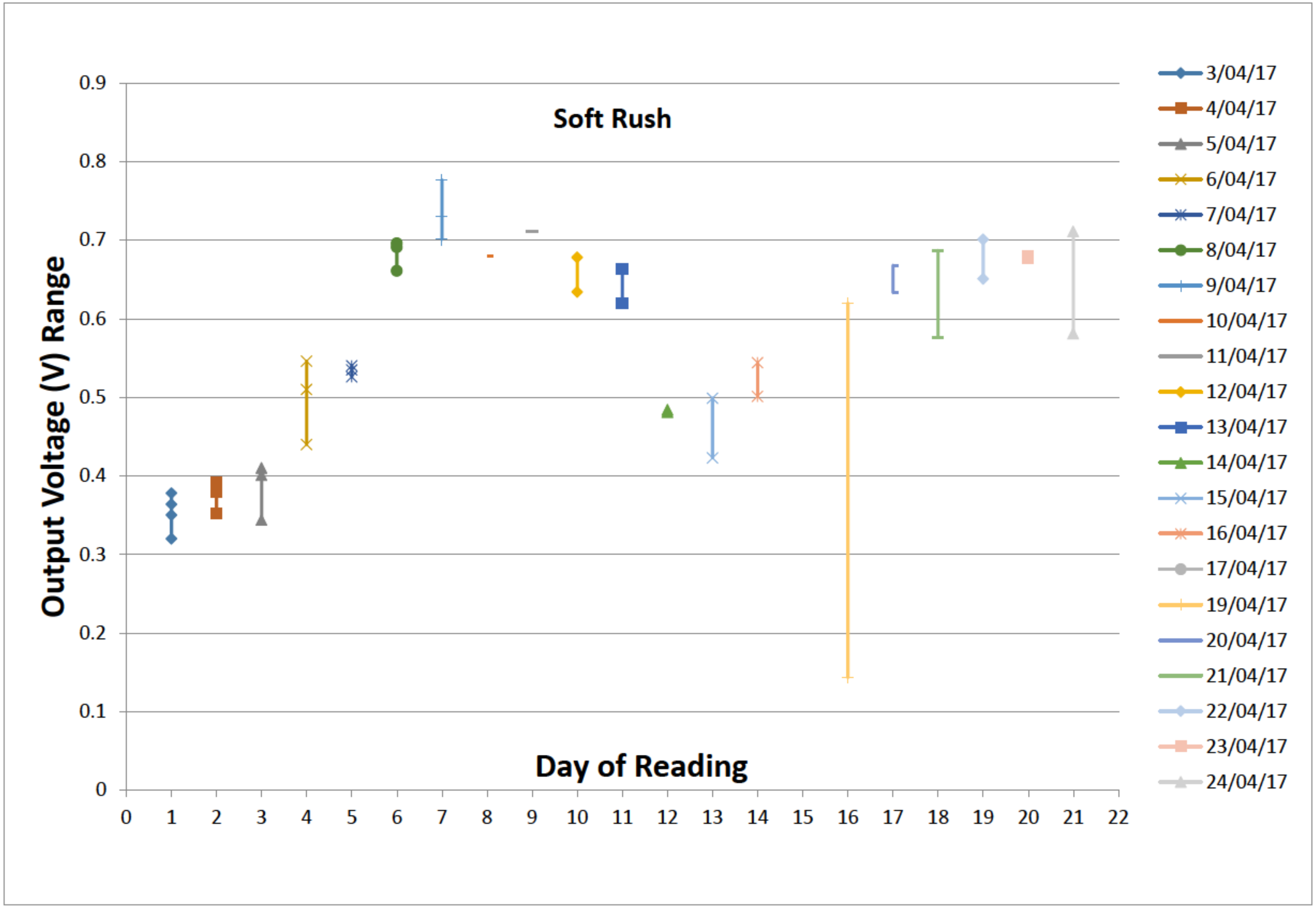

Figure 12 Common Rush Readings

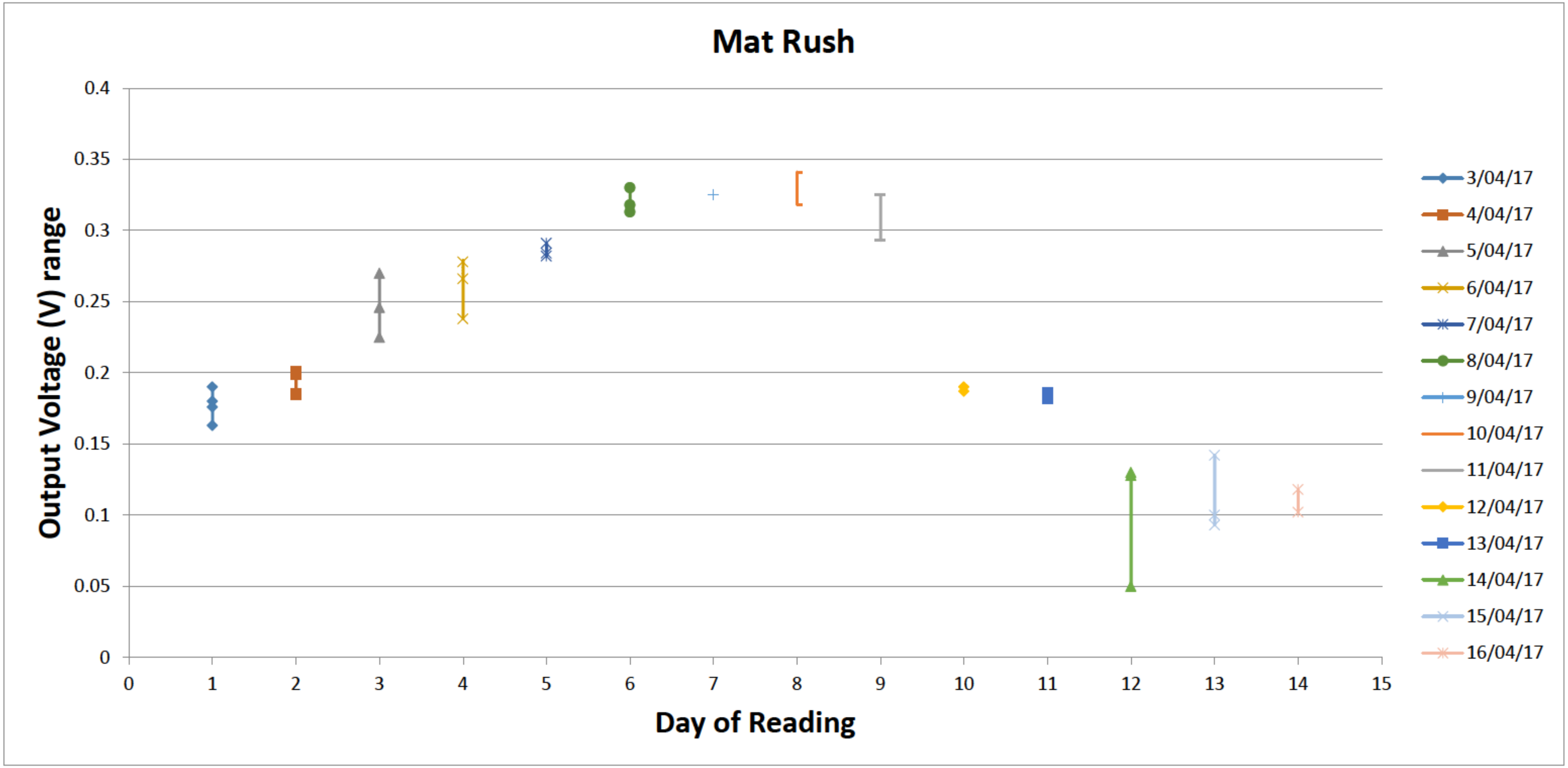

Figure 13 Mat Rush Readings

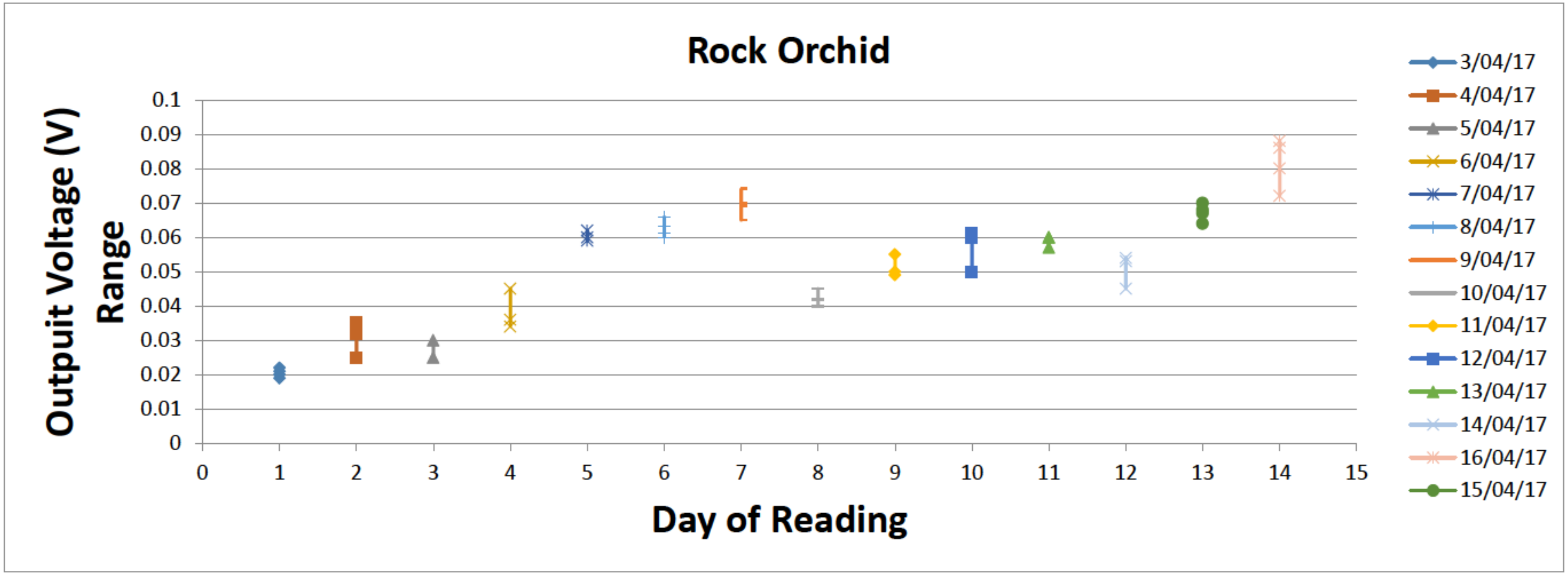

Figure 14 Rock Orchid Readings

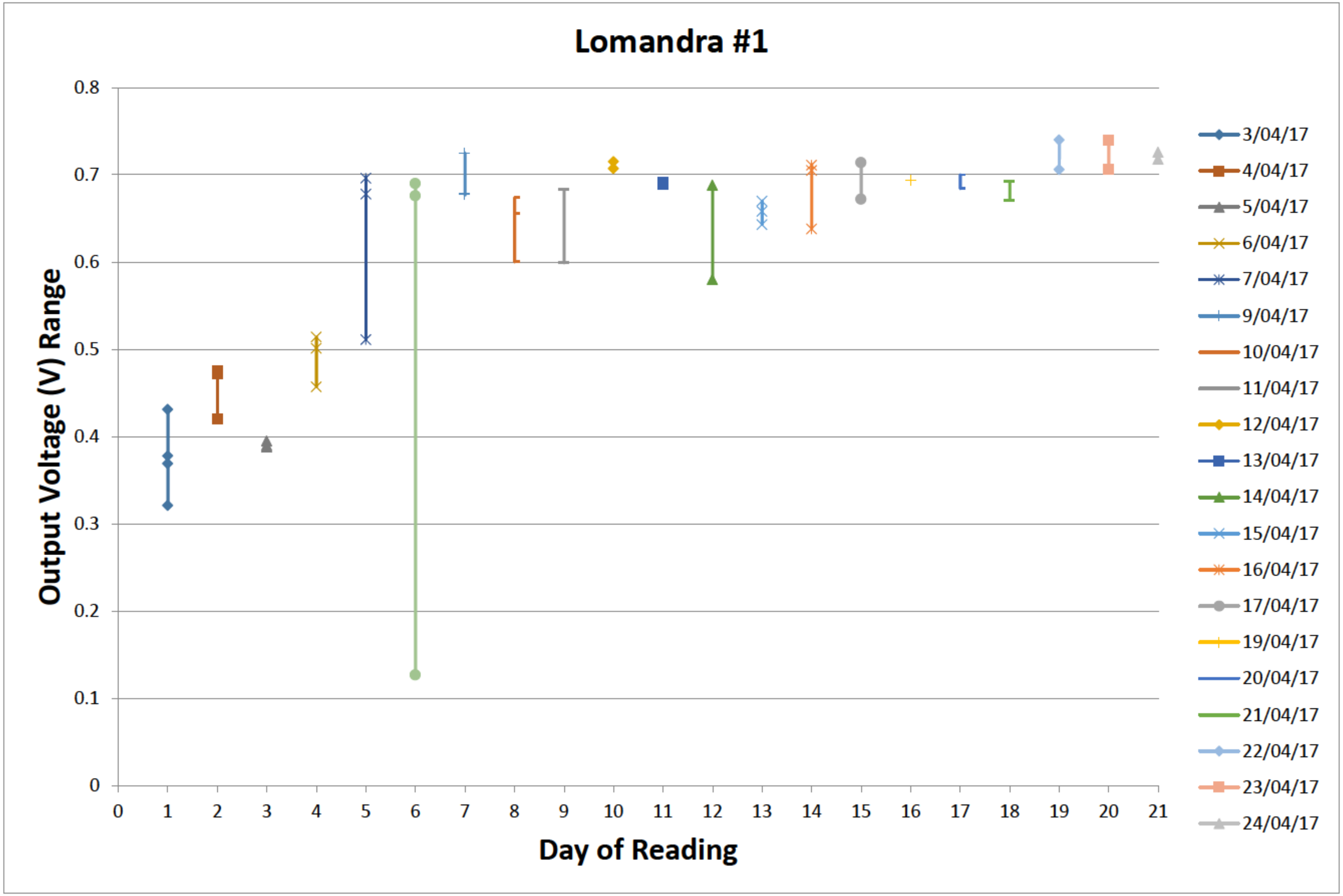
Lomandra #1
Output Voltage (V) Range
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Day of Reading
3/04/17
4/04/17
5/04/17
6/04/17
7/04/17
9/04/17
10/04/17
11/04/17
12/04/17
13/04/17
14/04/17
15/04/17
16/04/17
17/04/17
19/04/17
20/04/17
21/04/17
22/04/17
23/04/17
24/04/17

Figure 15 Lomandra #1 Readings

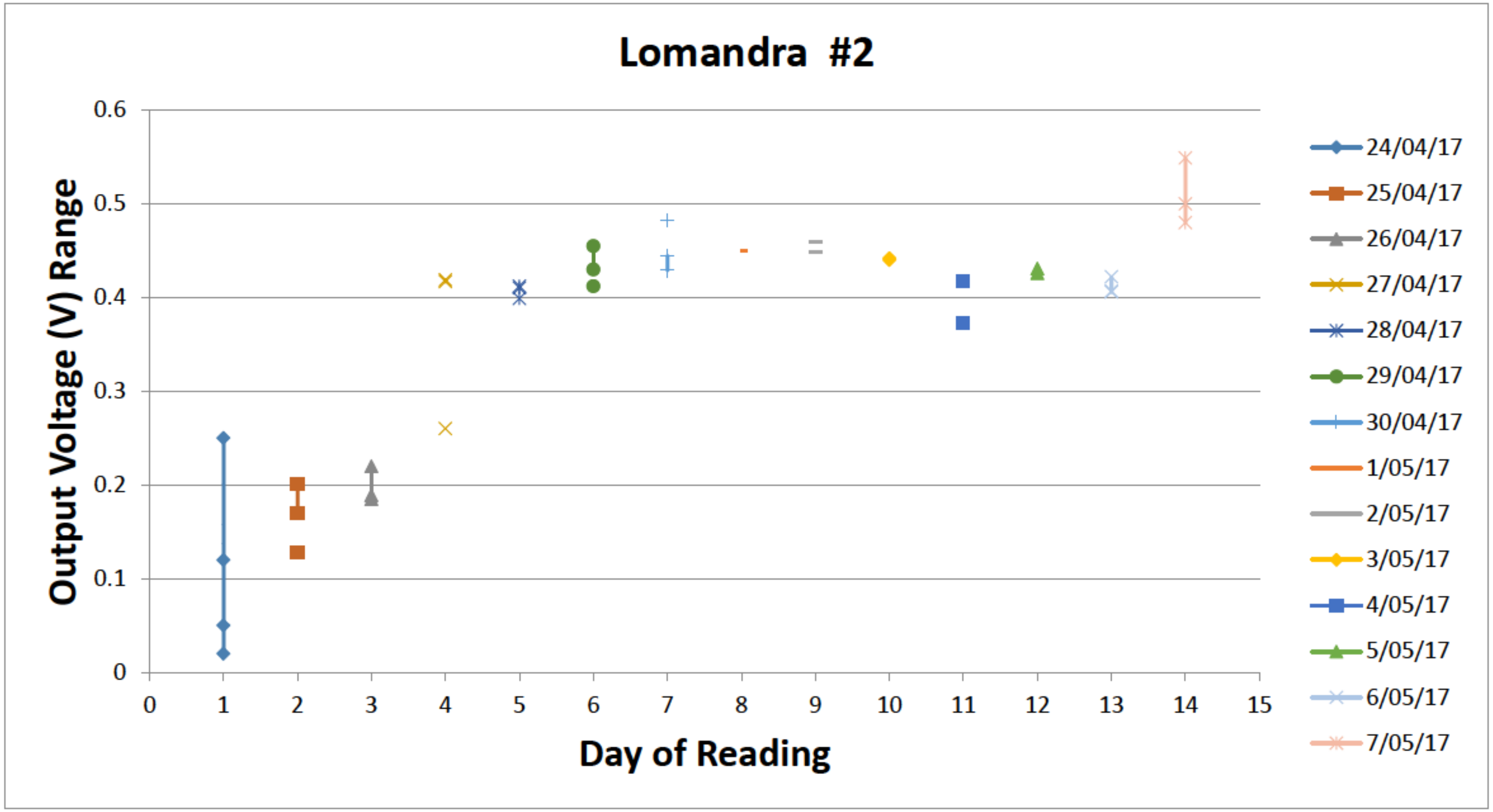

Figure 16 Lomandra #2 Readings

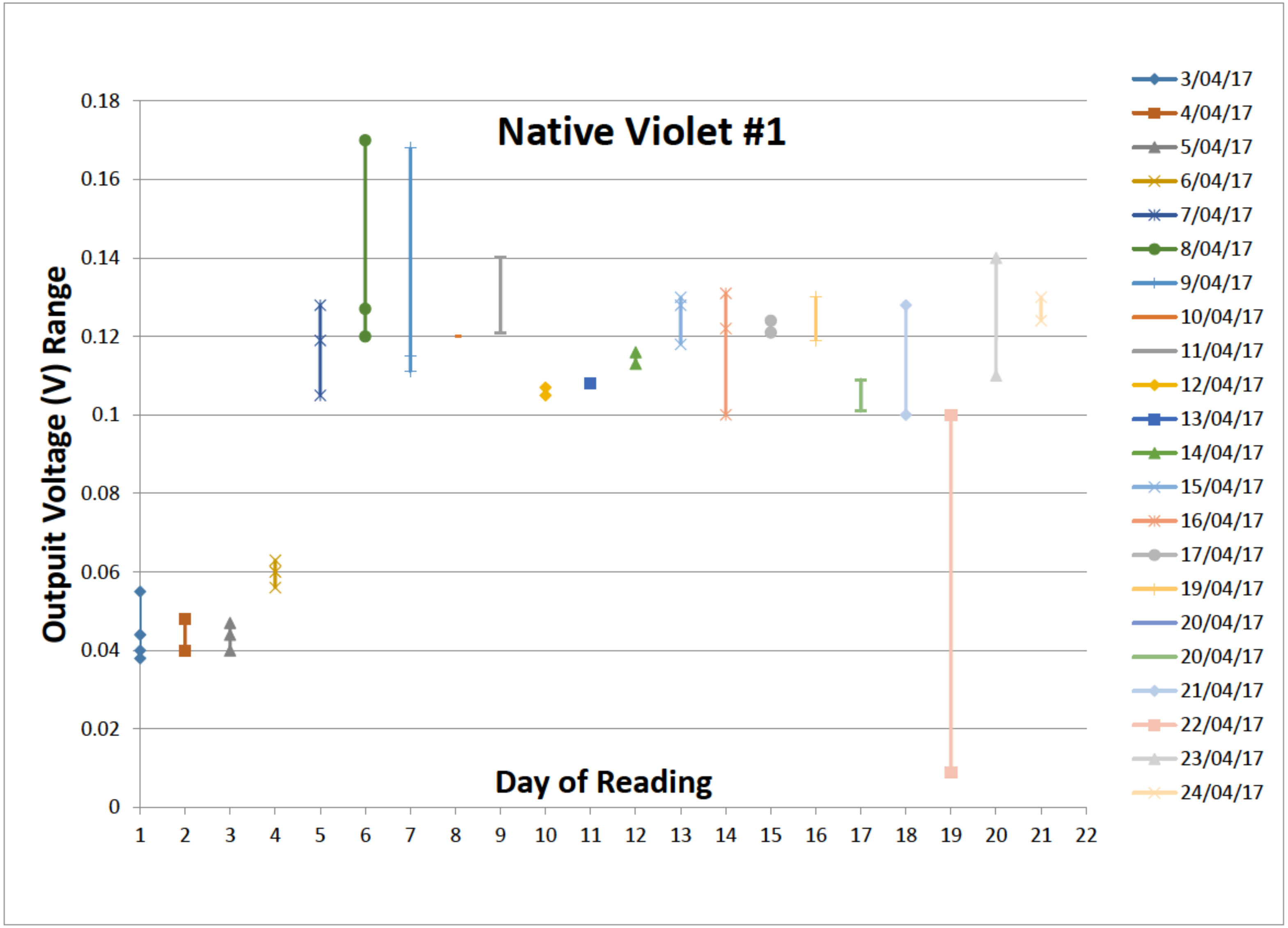

Figure 17 Native Violet #1 Readings

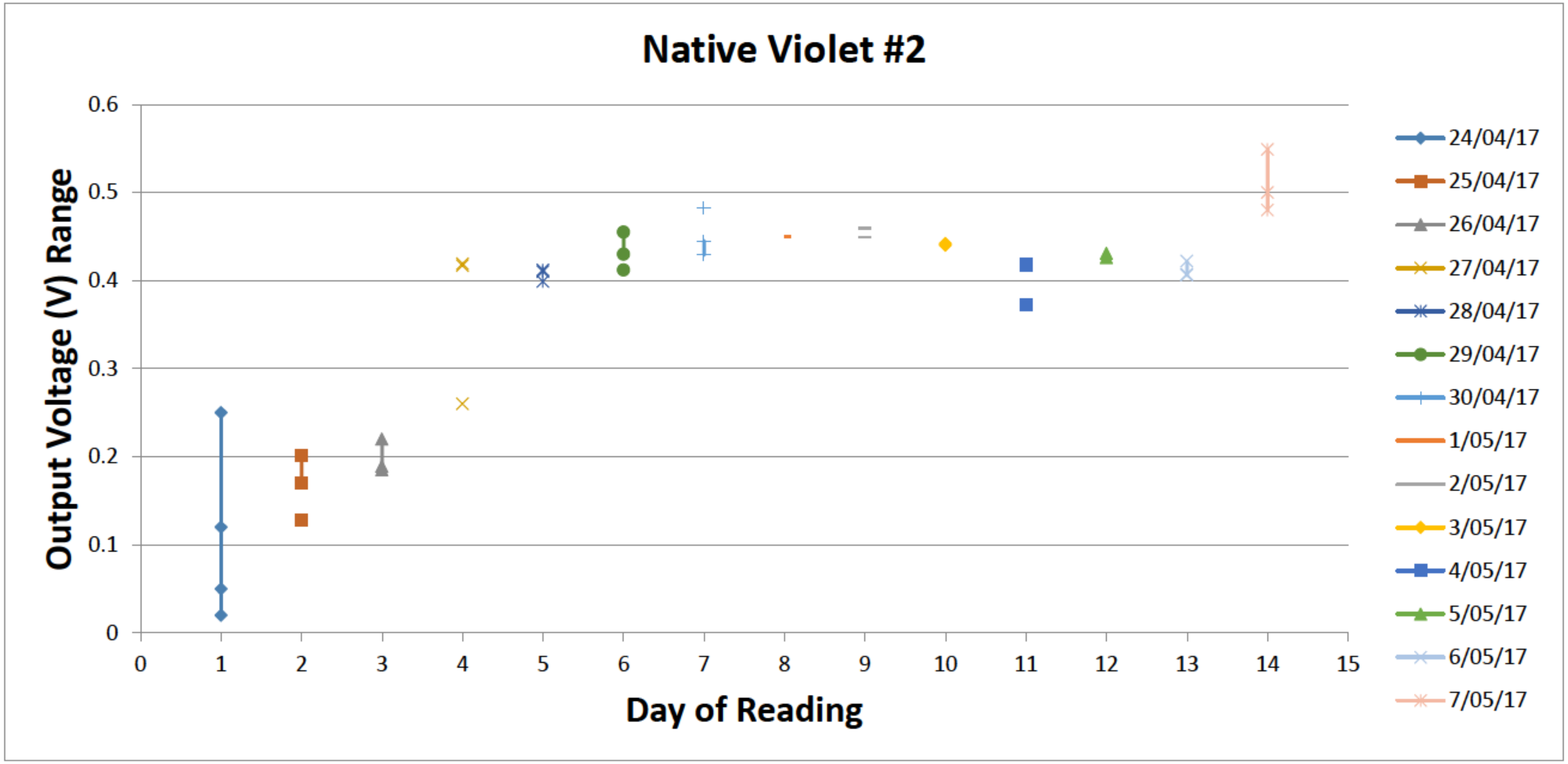

Figure 18 Native Violet #2 Readings

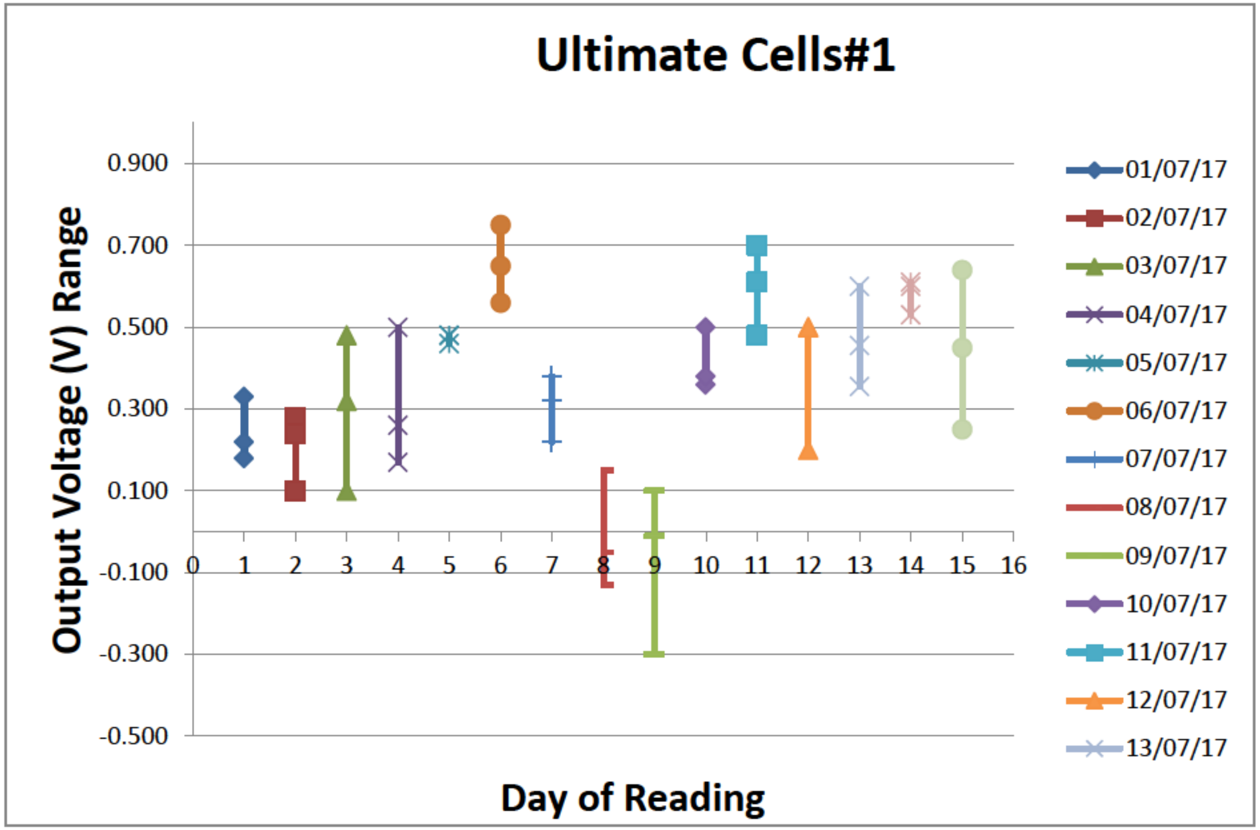

Figure 19 Ultimate Cells#1 Readings

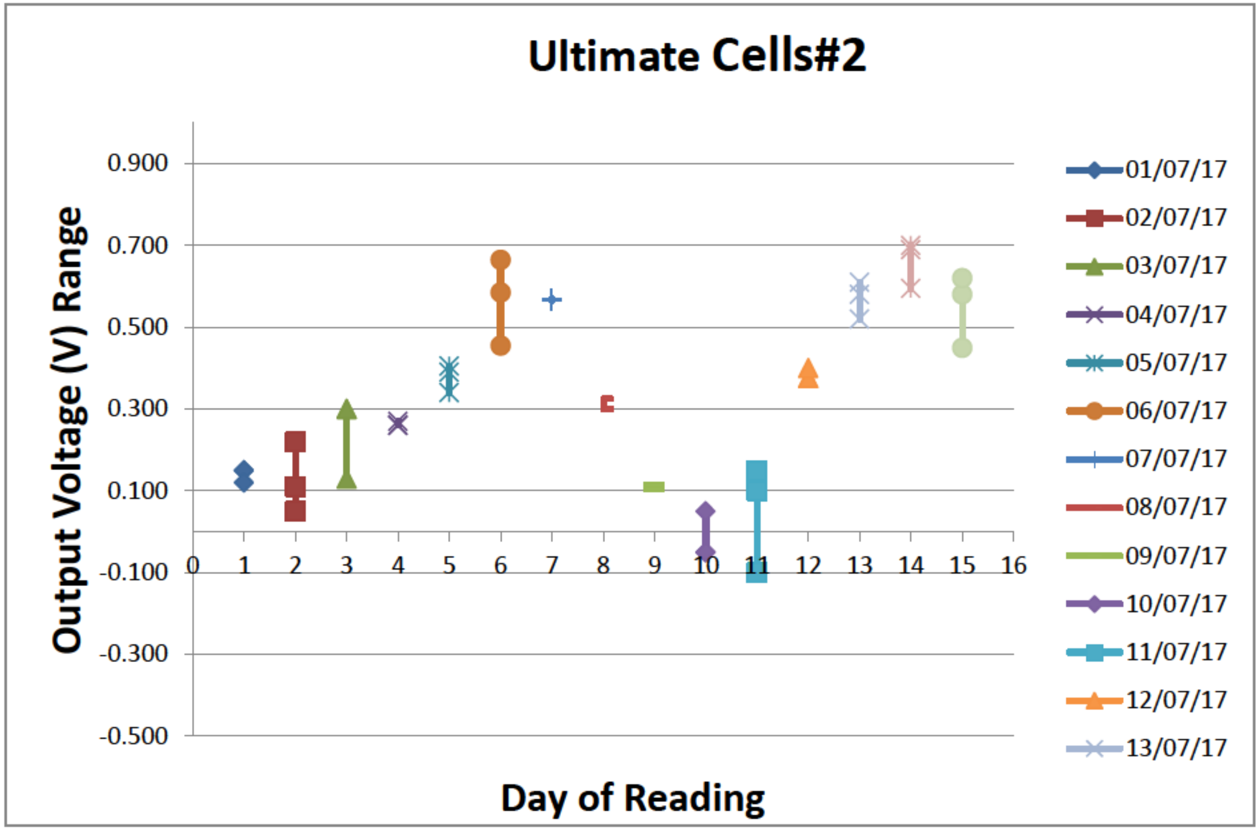

Figure 20 Ultimate Cells#2 Readings

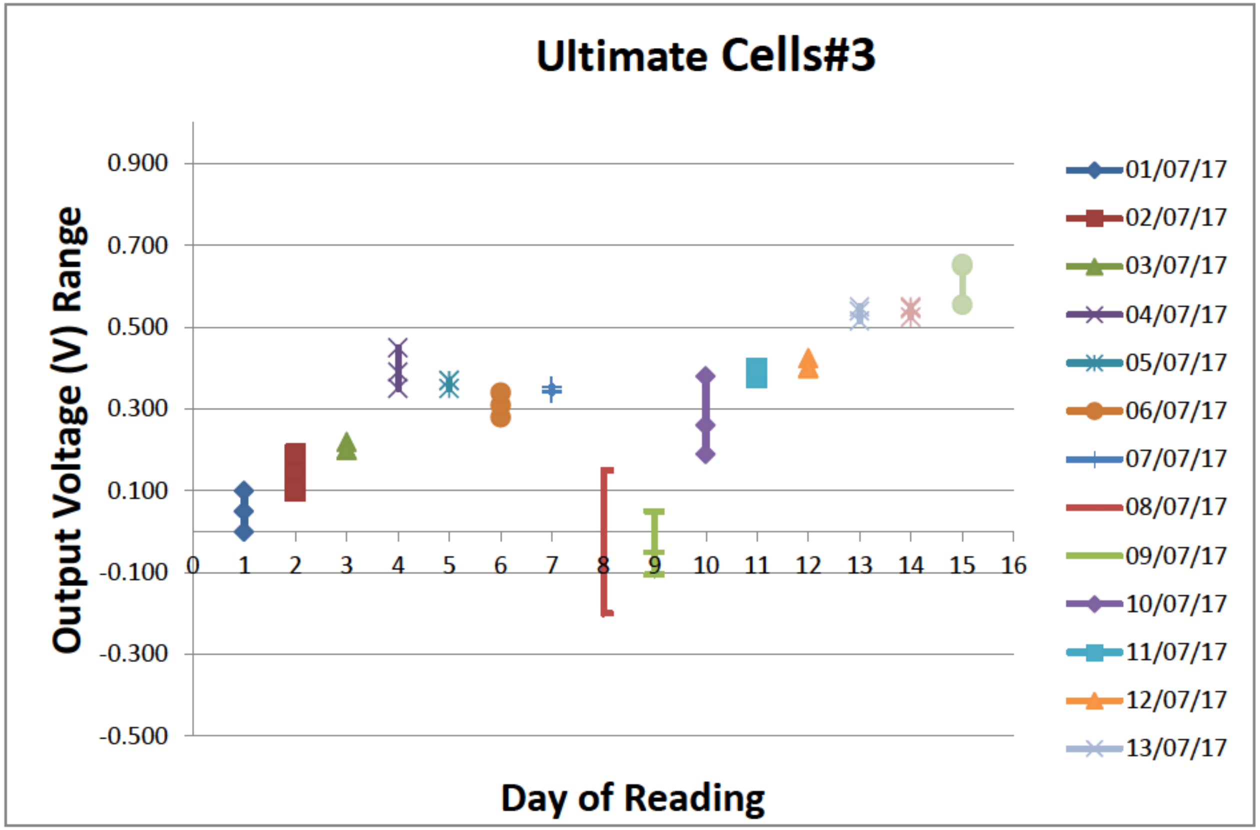

Figure 21 Ultimate Cells#3 Readings

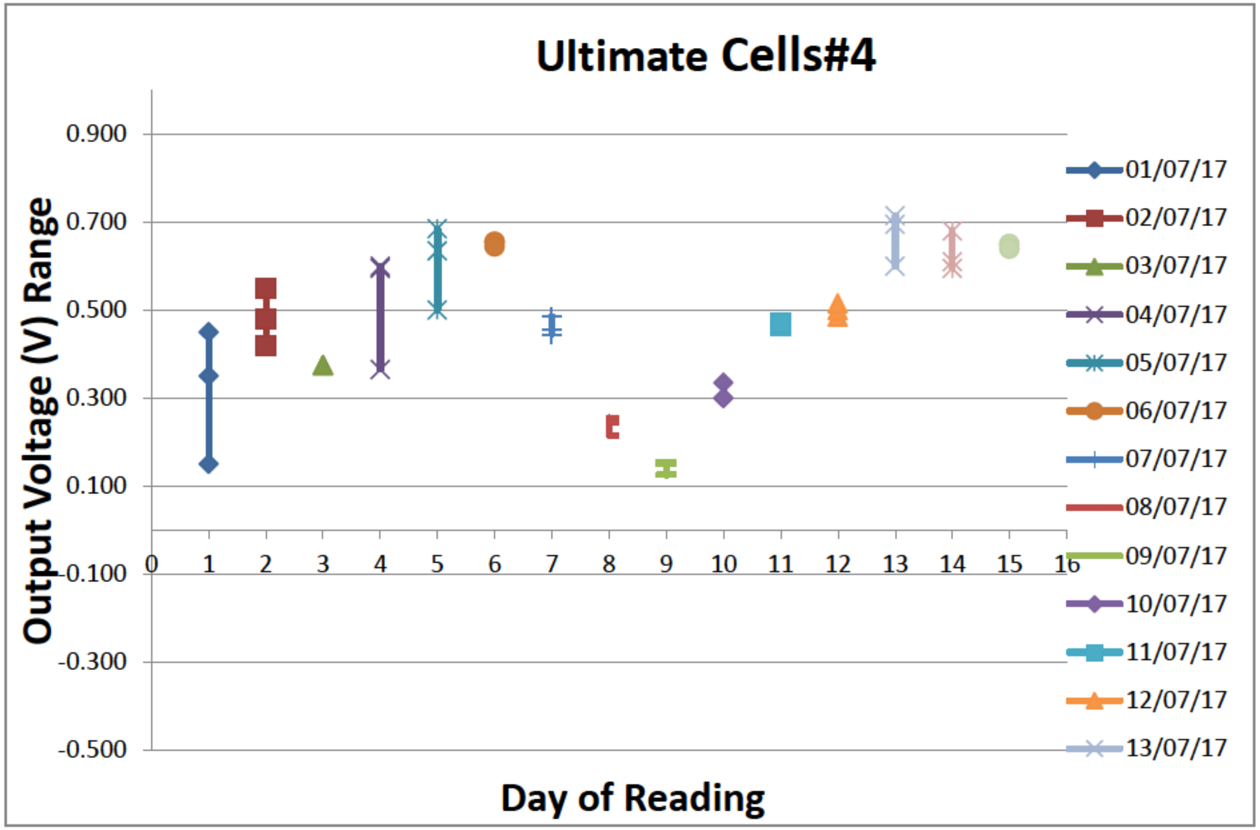

Figure 22 Ultimate Cells#4 Readings

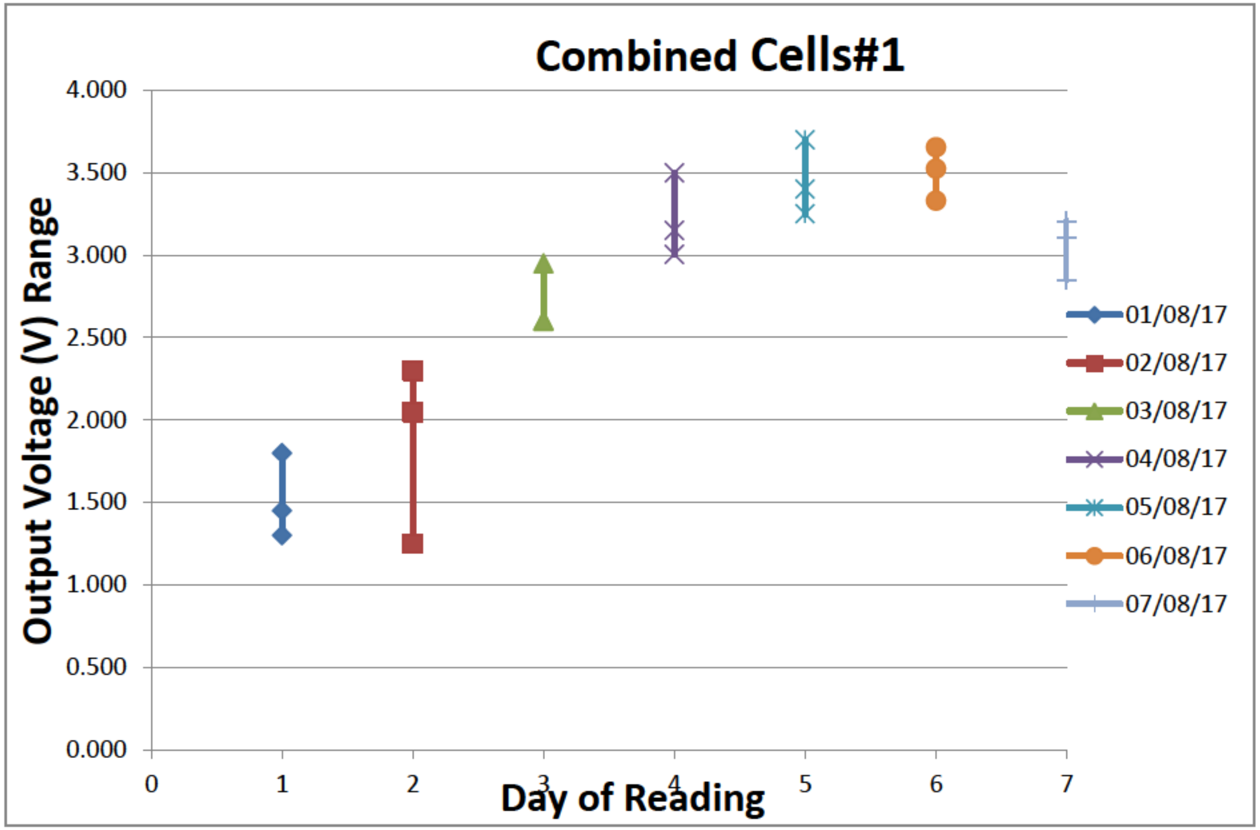

Figure 23 Combined Cells#1

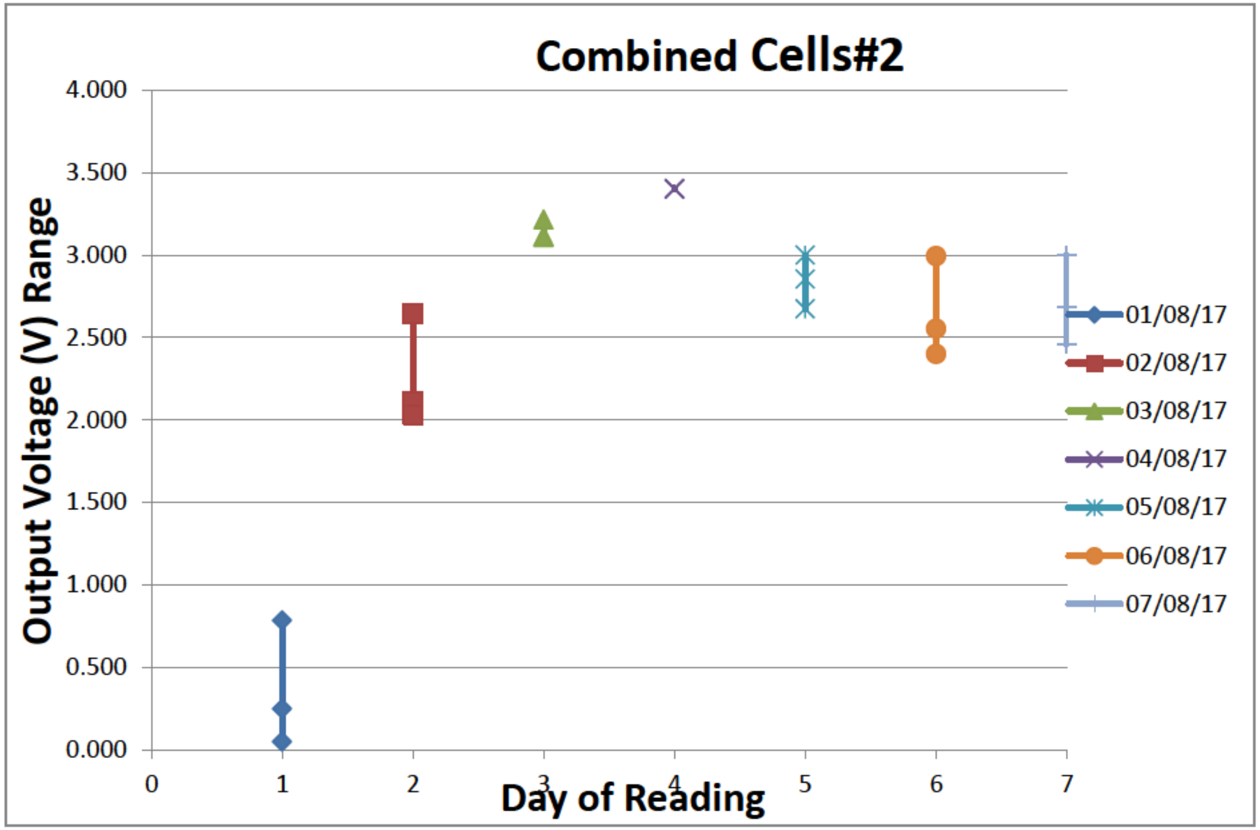

Figure 24 Combined Cells#2

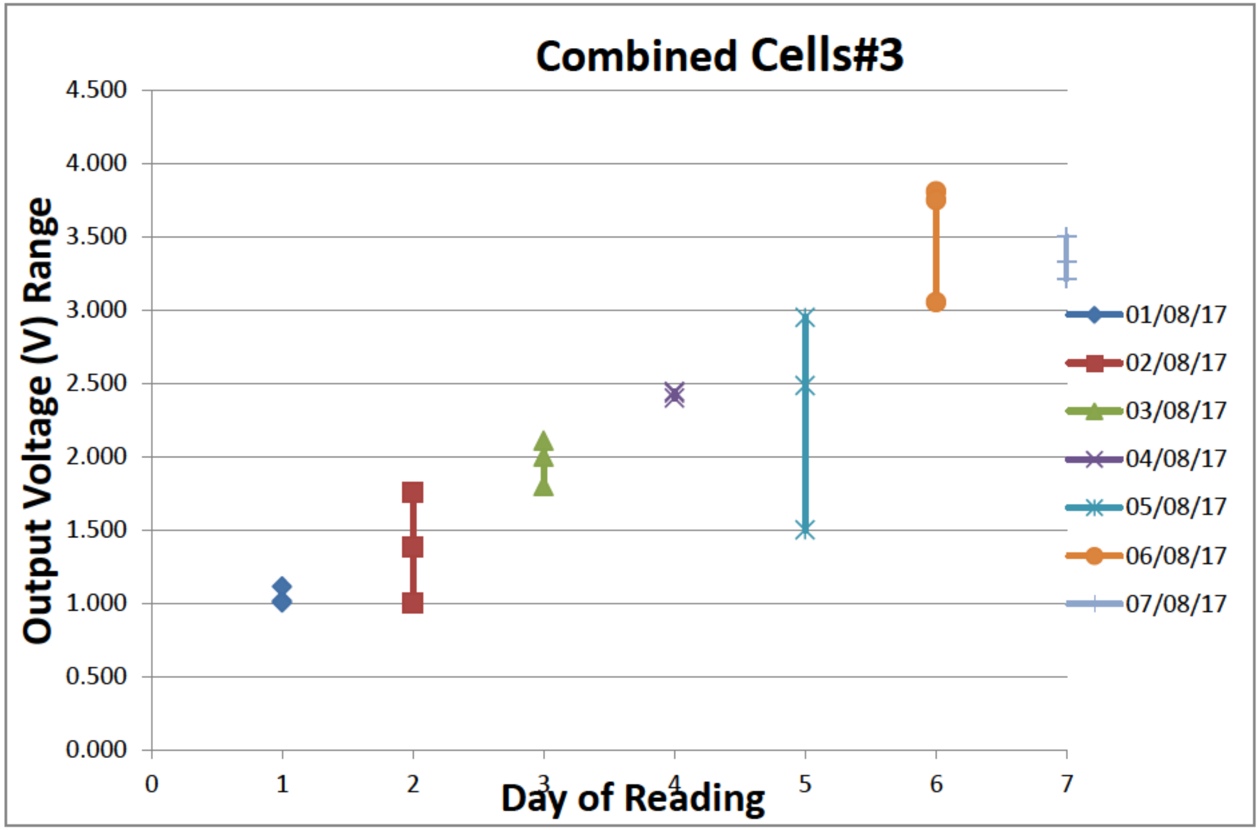

Figure 25 Combined Cells#3

APPENDIX D – TIMELINE

Table 10 Timeline

ACTIVITY	Start date(Week)	Duration(Weeks)	End Date(Week)
1. Start-up Phase 27/03/2017- 31/04/2017	1	5	5
1.A. Enrol. Obtain Approval	1	1	2
1.B. Research Background and Proof of Concept	1	1	2
1.C. Project Plan, Specification, Resources	2	1	3
1.D. Produce Modular PMFCs	2	4	6
2. Experimentation and Analysis Phase - Stage 1 31/04/2017- 24/05/2017	6	7	14
2.A. Confirm and Analyse Most Efficient PFMC	6	1	7
2.B. Biological Improvements	7	2	9
2.C. Electrical Improvements	9	2	11
2. D. Physical Improvements	11	2	13
2. E. Compile and Analyse Data	7	6	13
2.F. Progress Report 1	13	1	14
3. Experimentation and Analysis Phase - Stage 2 24/05/2017- 14/06/2017	14	3	17
3.A. Apply system to power LED	14	2	16
3.B. Apply system to power numerous LEDs	14	2	16
3.C. Compile and Analyse Data	14	2	16
3.D. Progress Report 2	16	1	17
4. Experimentation and Analysis Phase - Stage 3 14/06/2017- 04/08/2017	17	6	23
4.A. Up-Scale attempt at battery charge	17	6	23
4.B. Up-scale attempt at Pond System	17	6	23
4.C. Compile and Analyse Data	22	1	23
5. Final Phase 04/08/2017- 12/10/2017	23	11	34
5.A. Prepare Dissertation Draft 1	16	10	26
5.B. Prepare Dissertation Final Draft	26	2	28
5.C. Partial Dissertation	28	1	29
5.D. Prof Prac 2	29	1	30
5.E. Final submission	30	4	34

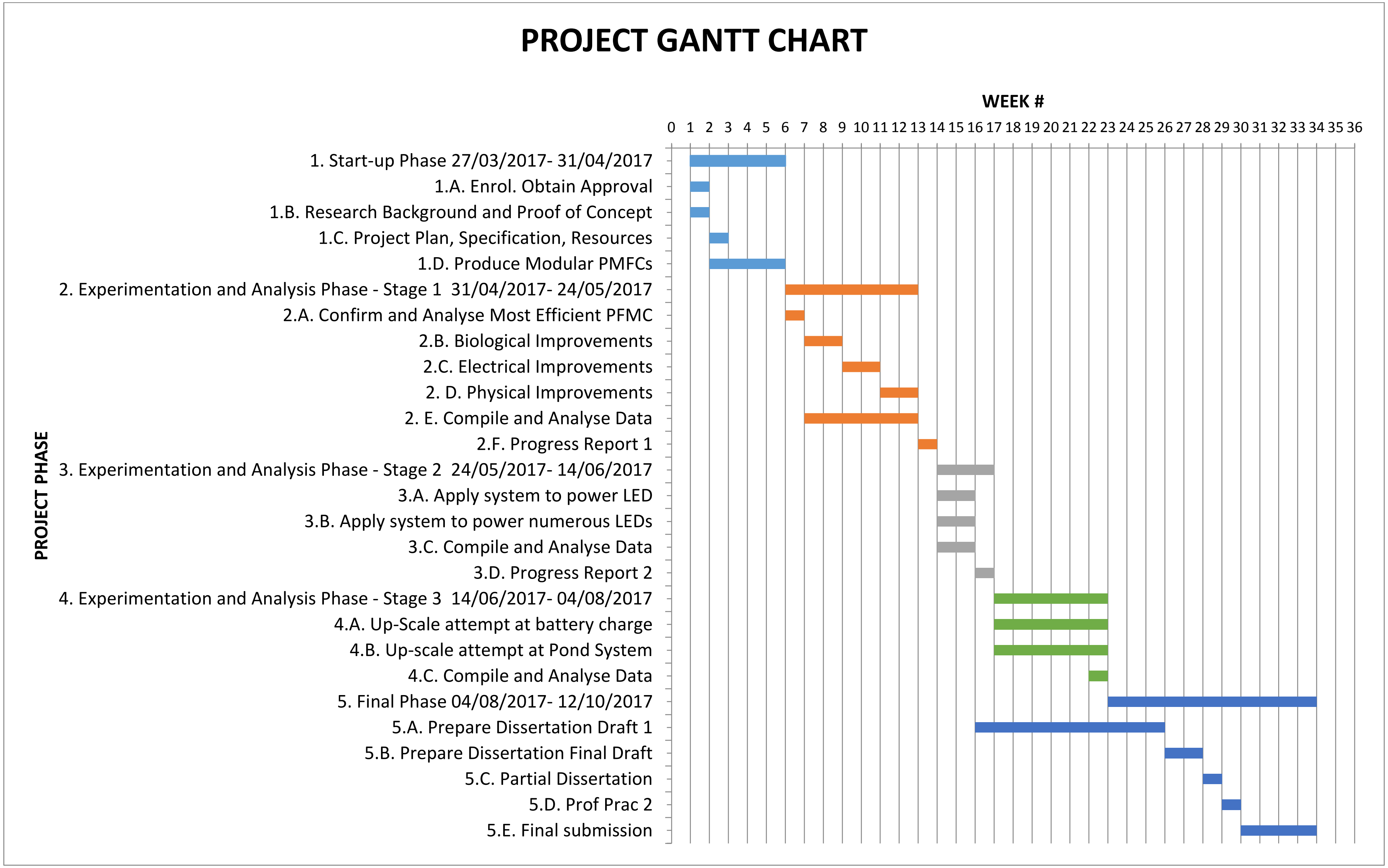

Table 11 Timeline Gantt chart

APPENDIX E – FLORA USED

- **Water Chestnut.** Latin name of Eleocharis dulcis. A rush like perennial plant to 1m tall. Native to swampy tropical areas of the southern hemisphere.

  Nutritious edible root bulb of the plant is used in cooking.

  Water chestnuts are swap or edge plants with rich sandy well limed loamy soil with a pH of 6.5-7.2

- **Common Rush.** Latin name of Juncus usitatus. Densely tufted Rhizomatous perennial to 1m tall. Native to parts of South Eastern Australia.

  A hardy plant which performs well in sandy, muddy and wet soils

- **Mat Rush.** Latin name of Lomandra filiformis. A compact Rhizomatous perennial growing up to 75cm tall native to eastern Australia.

  A hardy plant which tolerates drought conditions, in sandy soil

- **Rock Orchid**. Latin name of Dendrobium Speciosium. A soft epiphytic flowering perennial growing up to 50cm tall native to Australian eastern states.

  Shade loving plant requires well drained sandy soil.

- **Lomandra. Latin name Lomandra Longifolia. Sedge and grass-like** perennial growing up to 150 cm tall.

  Native to middle and Eastern parts of Australia, tolerating poor to muddy to clay soils and drought conditions. A robust and hardy rhizomatous perennial.

- **Native Violet.** Latin name Viola Hederacea. A native Australian annual/perennial ground covering flowering creeper that flowers eleven months of the year and spreads via rhizomatous expansion.

  Tolerates full sun to full shade, in poor to sandy to muddy soils and will thrive in wet conditions.