University of Southern Queensland

Faculty of Health, Engineering and Sciences

An investigation of small-scale wave energy converters for marine sensors

A dissertation submitted by

Peter Courtis

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Abstract

The existence of ocean renewable energy (ORE) is well documented, with Australia's wave energy resource being assessed as arguably the largest in the world (McInnes et al. 2018). Wave energy conversion devices (WECs) are recognised as an effective method for harvesting ORE, this dissertation examines the small-scale application of WEC principals, an area of the technology that has not been thoroughly researched.

This project builds on work carried out at the Commonwealth Scientific and Industrial Research Organisation (CSIRO), investigating and proposing a design for small-scale ORE devices in order to power marine sensors. It achieves this outcome thorough a review of WEC technologies and wave data, application of modelling methods for power analysis as well as the design, partial fabrication and testing of the proposed prototype.

The literature review serves to inform of the status of development related to WEC devices. It identifies the challenges particular to ORE devices, examining the adverse environments and conditions of their deployment, also providing details on the justification of WEC validity. The review found that the current technology focus is on large-scale, potentially grid-based devices, with the sub 1 Watt demands of marine sensors well below this scope.

The modelling carried out focusses on a WEC design featuring a fully enclosed vertical axis pendulum concept. Based on the pendulum mass and distance to its centre of gravity, a power matrix was generated for any given sea state combination of significant wave height and period. Selection of components was carried out to satisfy the many design criteria of the project including satisfying power requirements and consideration of dimensional restrictions, remaining maintenance free and robust, as well as incorporating provision for testing and data capture.

While many components of the design were able to be tested, issues arose in the final fabrication and testing of the prototype, limiting the scope of the data available for real world analysis. Where possible, finite element analysis (FEA) using computer aided design (CAD) has been carried out to supplement the modelling and testing to justify the design. These analysis as well as recommendations for more rigorous testing are included as important considerations for future development.

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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.

Peter Courtis

Student Number: [redacted]

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Chapter 1 – Introduction

1.1 Introduction

The existence of ocean renewable energy (ORE) is well researched and documented, with Australia's wave energy resource being assessed as arguably the largest in the world (McInnes et al. 2018). Just as in other physical energy harvesting applications, ORE devices typically seek to exploit one or more degrees of freedom of movement and convert it to a more desirable form. Additionally, specific to ocean environments, some methods can utilise characteristics such as thermal and salinity gradients.

In relation to the research and development into ORE, wave energy conversion devices (WECs) are recognised as quite effective, the first patented example being registered in France in 1799 (Behrens et al. 2015). The Commonwealth Scientific and Industrial Research Organisation (CSIRO) report titled: Ocean Renewable Energy: 2015-2050 confirms WEC validity stating that it is the single greatest potential source of ORE for Australia (CSIRO 2012). The report surmises that Australia's Southern Ocean is the primary location of this resource, utilizing global atlases of wave energy resources to verify this.

The general focus on large scale WEC has resulted in limited literature related to the development and efficiencies of small-scale applications. The need for small scale WEC devices for marine sensor applications continues to be recognised by various stakeholders including Australia's CSIRO; specifically, to address the particular challenges of observing coral reef environments. The organisation has identified that in the Australian context the challenges of persistence and scale are particularly acute given the large geographic distribution of reef environments and their remote locations.

The design of a WEC system for use in this scenario presents significant theoretical, design and environmental considerations that are addressed within this report. This project proposes to explore and develop a miniature WEC style system to be used to supply marine sensor demands which require power in the sub watt (<1W) range. Such a system would greatly extend deployment times for sensors and enable improved observing for Australia's reefs.

1.2 Project Brief

The project investigates and proposes a design for a small-scale WEC device in order to power marine sensors. The process to achieve this involved the investigation and selection of appropriate data and modelling methods and the design and application of physical prototyping following an iterative process focusing on rigorous data collection and analysis.

1.3 Research Objectives

The research objectives below detail the processes and milestones required to fulfill the project outcome, the project timeline to achieve these objectives is included in Appendix B.

1. Conduct a thorough literature review of ORE and WEC technologies
2. Identify relevant data for marine sensors and the various stakeholder requirements
3. Carry out an analysis of wave data and wave characteristics
4. Carry out computational modelling for methods based on wave data
5. Create conceptual prototypes for viable designs
6. Design and manufacture the most viable design
7. Carry out onshore dynamic testing and data collection to verify numerical modelling
8. Carry out offshore dynamic testing and data collection to compare against numerical modelling and onshore testing
9. Carry out data analysis and draw conclusions on efficiencies and design
10. Adjust Prototype and reiterate steps 10-12 as many times as practical, logging progress
11. Present a final analysis and viable design

1.4 Project Overview

The project was structured as follows to achieve the required outcomes, in line with the selected project methodology detailed in section 3.2 Methodology;

1.4.1 Research Phase

Chapter 2 – Literature Review examined the global and Australian status of ORE, the various challenges of ORE design and provides a focus on wave energy conversion design validity for small scale applications.

Chapter 3 – Methodology and Parameters for WEC modelling explains how the project followed the double diamond methodology as a structured approach in generating a solution to the requirement of a small scale WEC device. This model was engaged for the entirety of the project. This section also presents the initial selection of data from the Australian Renewable Energy Agency's Mapping infrastructure on-line tool as well as analysing the wave profiles at selected locations for future physical testing. It details the method for analysis of data for a given significant wave height and period as well as outlining the theory for mechanisms of energy harvesting.

Various mechanisms for harvesting of ORE were examined and evaluated at this stage. Once viable mechanisms were identified, further mathematical models were created and in order to evaluate the design best suited for physical prototyping.

1.4.2 Development

All matters related directly to the prototype were examined here, from initial design to final data analysis;

Chapter 4 – WEC Mathematical Modelling examines the theory of the gyroscopic WEC prototype. It begins by outlining the assumptions used for the calculations, then presents each variable and details how it was calculated.

Chapter 5 – WEC Physical design details of each of the device components, all the design decisions are also evaluated and justified. The design focuses on achieving power outputs, reproducibility and ease of maintenance and modification.

Chapter 6 – Design Testing details the testing of critical design components. It provides an overview of the testing methods, while the results and analysis of the data is carried out in chapter 7 - Results and Discussion.

1.4.3 Design

This section of the design methodology addresses the requirements of the course Engineering Research Project 2020 (ERP2020) and presents the final project outcomes;

Chapter 7 – Results and Discussion presents the results and analysis of test data and prototype physical characteristics. Chapter 8 – Conclusions contains the final conclusions and analysis of the project and design.

1.4.4 Deliver

The deliver stage is the submission of the dissertation, representing the completion of a major technical task. It has been written in a clear, logical, concise and accurate professional style using standard referencing and citation conventions and within the designated timeframe.

1.5 Project Risk Assessment

All activities inevitably carry some form of inherent risk which may present a hazard that requires addressing. As such, risk assessments were employed where applicable during all phases of this project. Particularly, risk must be addressed for activities during execution of the project and where there is risk that might exist beyond completion of the project. The risk assessment matrix utilised for the project is extracted from the online risk management platform Smartsheet, shown below in Figure 1.

RISK ASSESSMENT MATRIX TEMPLATE

RISK RATING KEY	LOW 0 – ACCEPTABLE OK TO PROCEED	MEDIUM 1 – ALARP (as low as reasonably practicable) TAKE MITIGATION EFFORTS	HIGH 2 – GENERALLY UNACCEPTABLE SEEK SUPPORT	EXTREME 3 – INTOLERABLE PLACE EVENT ON HOLD

	SEVERITY			
	ACCEPTABLE LITTLE TO NO EFFECT ON EVENT	TOLERABLE EFFECTS ARE FELT, BUT NOT CRITICAL TO OUTCOME	UNDESIRABLE SERIOUS IMPACT TO THE COURSE OF ACTION AND OUTCOME	INTOLERABLE COULD RESULT IN DISASTER
LIKELIHOOD				
IMPROBABLE RISK IS UNLIKELY TO OCCUR	LOW – 1 –	MEDIUM – 4 –	MEDIUM – 6 –	HIGH – 10 –
POSSIBLE RISK WILL LIKELY OCCUR	LOW – 2 –	MEDIUM – 5 –	HIGH – 8 –	EXTREME – 11 –
PROBABLE RISK WILL OCCUR	MEDIUM – 3 –	HIGH – 7 –	HIGH – 9 –	EXTREME – 12 –

Figure 1: Risk assessment matrix template (smartsheet 2019)

At each phase of the report, requirements for objective achievement carrid risks of different likelihood and severity. Where risks are identified they were documented and the process re-evaluated so far as reasonably practical to reduce the risk. The table Appendix C highlights the hazards associated with the overall project, for individual project phases and following its completion. It also rates the hazard risk and provides guidance for mitigation.

1.6 Project Ethical Considerations

The primary ethical consideration for the project is related to the environmental impact of the completed device in real world deployment. Throughout all stages of the project effort was made to ensure that the information gathered and presented is unbiased and fit for purpose. While there are no other immediate ethical issues were foreseen in the theory and design phases of the project, care was be taken in construction and testing to ensure both are carried out responsibly. Materials were obtained and disposed of correctly with testing carried out with minimal environmental impact.

As presented in The Wave Energy Deployments Physical Impact Guidelines, produced by the CSIRO, it is noted that ORE devices will inherently reduce surrounding hydrokinetic energy and have possible ecological repercussions (McInnes 2018). The document aims to provide the ‘best practice guidance on assessing the influence of arrays of Wave Energy Converters (WECs) on the hydrodynamic attributes of the surrounding ocean’. Whilst addressing ‘the limited evidence base and methodology for assessing impacts of wave energy extraction on the marine and coastal environment’.

The ORE 2015-2050 report (CSIRO 2012) assesses the potential locations available for ORE device deployment based on competing uses and evaluates factors required for consideration when addressing the environmental impact of any ORE deployment locations, these include;

- Native title and land rights
- Marine Protected Areas
- Fishing, aquaculture and fisheries
- Oil, gas and mineral resource development
- Shipping

- National security
- Tourism, recreation and visual amenity

It should be noted that although it is important to consider these factors within the design, the device will be deployed with other sensors currently in use which will share similar impacts. The stressors, receptors, duration, extent of effects and direct impacts of ORE devices are typically more prevalent the larger in scale the deployments are. The physical impact guideline states that ‘Single devices are unlikely to have adverse environmental impacts (Copping et al., 2016).’

The environmental impact of the small scale ORE device can justifiably be predicted to be quite minimal. Its profile and typically singular deployment, as well as the fact that the device will be utilized with other sensors and apparatus already intended for deployment further reduces its considered impact. When added to an assessment process or template already in use for sensor deployment as part of current operations, addition of the WEC device is expected to have minimal impact.

1.7 Dissertation Overview

The dissertation is organised as follows;

Chapter 1 provides an introduction to the project topic and its motivation. It also outlines the research objectives, provides and overview of the dissertation and a statement of its final outcome.

Chapter 2 consists of the literature review, provides an overview of WEC technology, details on its challenges and examines its validity. It also examines the knowledge gap that exists for small scale WEC applications.

Chapter 3 details the methodology and parameters of the project.

Chapter 4 focuses on the mathematical modelling of the device.

Chapter 5 details the physical design process and the specifications of each component.

Chapter 6 consists of the design testing information, both simulated and physical.

Chapter 7 provides the results and discussion for the modelling versus real world data.

Chapter 8 concludes the dissertation, providing a critical analysis of the work undertaken, looks at what could have been done differently and where future work could be undertaken.

Finally, the dissertation references and appendices are catalogued at the end of the document.

1.8 Conclusions

The key outcome of the project is to produce a fully modelled, easily replicated and readily integrated design as a solution to the CSIROs marine sensor powering requirements, the processes and details of this outcome are presented in the body of this dissertation.

Chapter 2 – Literature Review

2.1 Chapter Overview

This section consists of the literature review, it identifies the knowledge gap relating to small-scale WEC device development and provides and overview of WEC technology, details on its challenges and examines its validity.

2.2 Ocean Renewable Energy Introduction

It is established in the literature that there are vast amounts of energy able to be harvested from the oceans by a variety of means. CSIROs Wave Energy Deployments Physical Impact Guidelines report provides a detailed examination of ORE, stating that 'The ocean possesses a largely untapped renewable energy resource with the potential to provide clean electricity to coastal communities and cities', particularly in light of the fact that 'Australia's wave energy resource has been assessed as being arguably the largest in the world' (McInnes et al. 2018).

Recognition of this fact has led to research as carried out by the CSIRO Wealth from Oceans Flagship (WfO) to produce maps of wave, tidal and non-tidal ocean flow energy distributions around the Australian coastline, to more accurately quantify resource availability (CSIRO 2012).

There are three recognised categories of ORE, being the ocean wave, tidal and non-tidal ocean flow scenarios. Both the report 'A review of ocean energy converters, with an Australian focus' (Knight et al. 2014) as well as the 'CSIRO ORE 2015-2050 report' (2012) adopt these conventions for category classification. The project aim is to produce a device capable of generating power from the ocean's surface and so the ocean wave category is deemed appropriate.

Research performed previously as part of the ORE: 2015-2050 (CSIRO 2012) report briefly examines Ocean Thermal Energy Conversion (OTEC) and Salinity Gradient Energy Conversion (SGEC) but acknowledges that these options are limited both technologically and due to difficulties in effective geographic placement, furthermore the scale required for such mechanisms are beyond the practical scope of a small scale system.

A significant gap in the existing research is the fact that performing an accurate assessment as to how the size and performance of current ORE designs might sufficiently downscale is not possible, with much of the test data and specifications of functioning devices not readily available or easily comparable. Additionally, with over 200 devices being proposed for the extraction of ORE very few have actually been constructed or are near demonstration or commercial size for testing in actual operating conditions (CSIRO 2012).

2.3 Australian ORE Status

Research and development and commercial ORE activity in Australia is steadily increasing, (CSIRO 2012) partly in response to the 'government mandated target of 20 per cent of Australia's domestic energy (mainly electricity) to be produced from renewable sources by 2020.' Knight et al. 2014 carries out an evaluation of current R&D worldwide and evaluates these against Australian coastal conditions.

Localised energy distribution maps are an important tool to begin identifying optimal ORE positioning and quantify possible energy returns by ascertaining local variables applicable to the various ORE designs (Knight et al. 2014). It is explained that preliminary Australian energy distribution maps, produced from the best available existing information, provide evidence of substantial, but imprecisely quantified, potentially extractable energy.

Data such as this may then be used with available device performance data/curves to generate power output figures and a power output map, Figure 2 shows an example of this for the design of a particular WEC device. The process is described in more detail within the ORE 2015-2050 report (CSIRO 2012). With respect to the project criteria, this resource may be utilised to access reasonably accurate characteristic wave height, wavelength and ocean floor current data for prospective sensor locations.

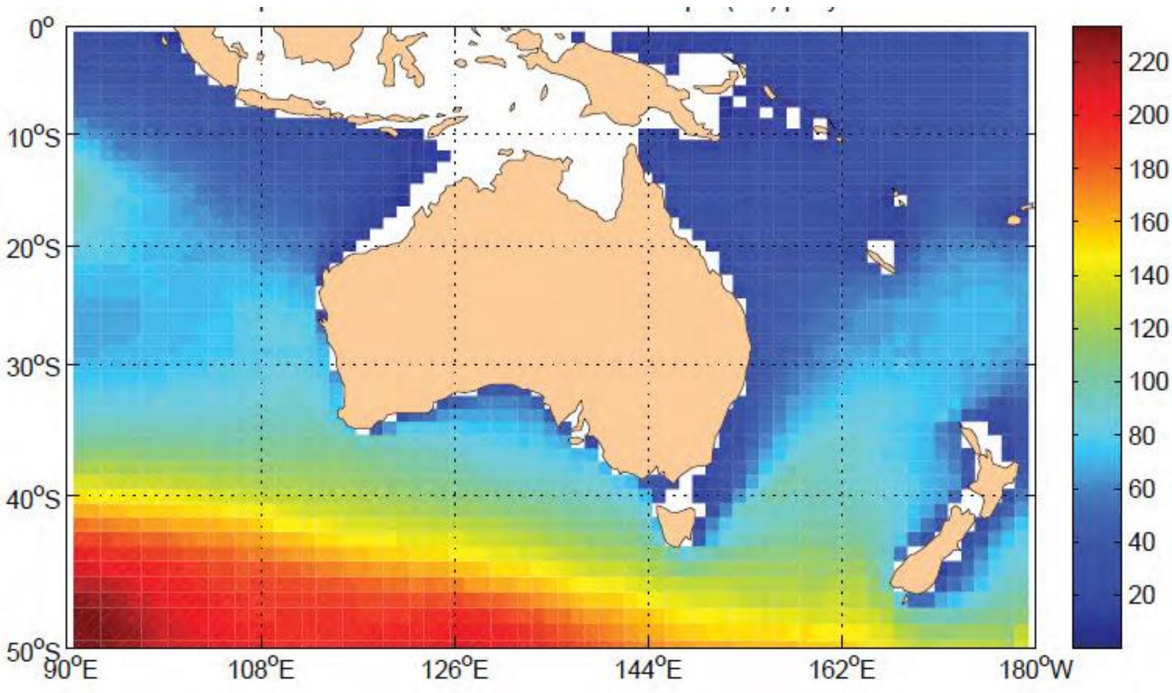

Figure 2: WEC device power output map — 50th percentile for power output (kW) per year (CSIRO 2012).

The ‘Ocean Renewable Energy: 2015-2050 report’ (CSIRO 2012) presents the following as a summary of Australia’s ocean energy resources;

Wave Energy

Australia has considerable wave energy resources in reasonable proximity to population and potential industry users. For example, the total wave energy crossing the 25 metre depth isobath between Geraldton and the southern tip of Tasmania is over 1300 TWh/yr, about five times the country’s total energy requirements. Wave energy in Australia is not resource limited. Other factors such as the economics of energy extraction, transmission, environment and social impacts will determine its future exploitation. We caution that the wave assessment in this study was preliminary, and needs to be augmented by further investigation.

Tidal Energy

Of the three main sources of ORE, tidal flows appear to be the Australian resource with the smallest upper limit (and the most isolated from end users). An 8TWh/yr estimate exists for a King Sound (Kimberley, Western Australia) barrage scheme and 0.13TWh/yr at most for a

Banks Strait (Tasmania) tidal stream project. Nonetheless, there are Australian developers currently active in the planning stages of large tidal projects and the resource should not be ignored. Some additional work needs to be done to better quantify the available extractable power from tidal flows.

Non-Tidal Ocean Current

This form of ORE is the furthest from being technically and economically viable. However, the potential is large enough (the order of 44TWh/yr) to attract commercial interest.

The small scale and individual nature of the project requirements means that these large scale evaluations are not entirely applicable, but do further identify the potential of the available resources.

2.4 Australian developments

McInnes et al (2018) provides a recent evaluation of WEC devices in testing around Australia, table A.2 from this report, included below as Table 1, summarises the devices considered or trialled around Australia together with their various attributes according to the different available classification systems. Figure 3 shows the locations of these marine-energy trials while Appendix D contains the remainder of the report's findings in relation to the wave energy resource and development in Australia.

Table 1: Summary of wave devices table as extracted from the CSIRO Oceans and Atmospheres report on Wave Energy Deployments Physical Impact Guidelines report (McInnes et al. 2018)

Table A.2 Summary of wave devices considered or trialled around Australia together with their various attributes according to the different available classification systems. Adapted from Manasseh et al (2016, 2017). MC: morphological classification; OC: operating principle classification; PALR: point-absorbing linear resonator; OWC: oscillating water column; WAB: wave activated body; WTLR: wavelength-tuned linear resonator; OTC: overtopping converter. Subscripts s, m and x denote short, medium and long devices, respectively. WTLR01); MC: OWC, floating.

	Location	Year	Company	Device type		Power rating	Operational depth
1	Gold Coast	2016	Wave Mill	OWC, floating	WTLR01	~ 3 kW	5-10 m
2	Port Kembla	2006	Oceanlinx	OWC, fixed	$PALR01_x$	Up to 2.5 MW	~11 m
3	Lorne		Aquagen	WAB, heave	$PALR02_m$	1.5 kW	~5 m
4	Port Fairy	2015	Biopower Systems	WAB rotation, fixed	$PALR01_m$	250 kW	~5 m
5	Portland	-	Victorian Wave Partners Ocean Power	WAB, (two-body array)		19 MW (45 buoys)	
6	Port McDonnell	2014	Oceanlinx	OWC, fixed	$PALR01_x$	1 MG	
7	Adelaide	2011	Waverider	WAB array	WTLR02	500 kW	
8	Bunbury		Protean	WAB, heave	$PALR02_m$		
9	Garden Island	2014	Carnegie	WAB, heave	PALR02m	Up to 250 kW	24 m
10	Fremantle		Bombora	Non-resonating bladder	Absorber		

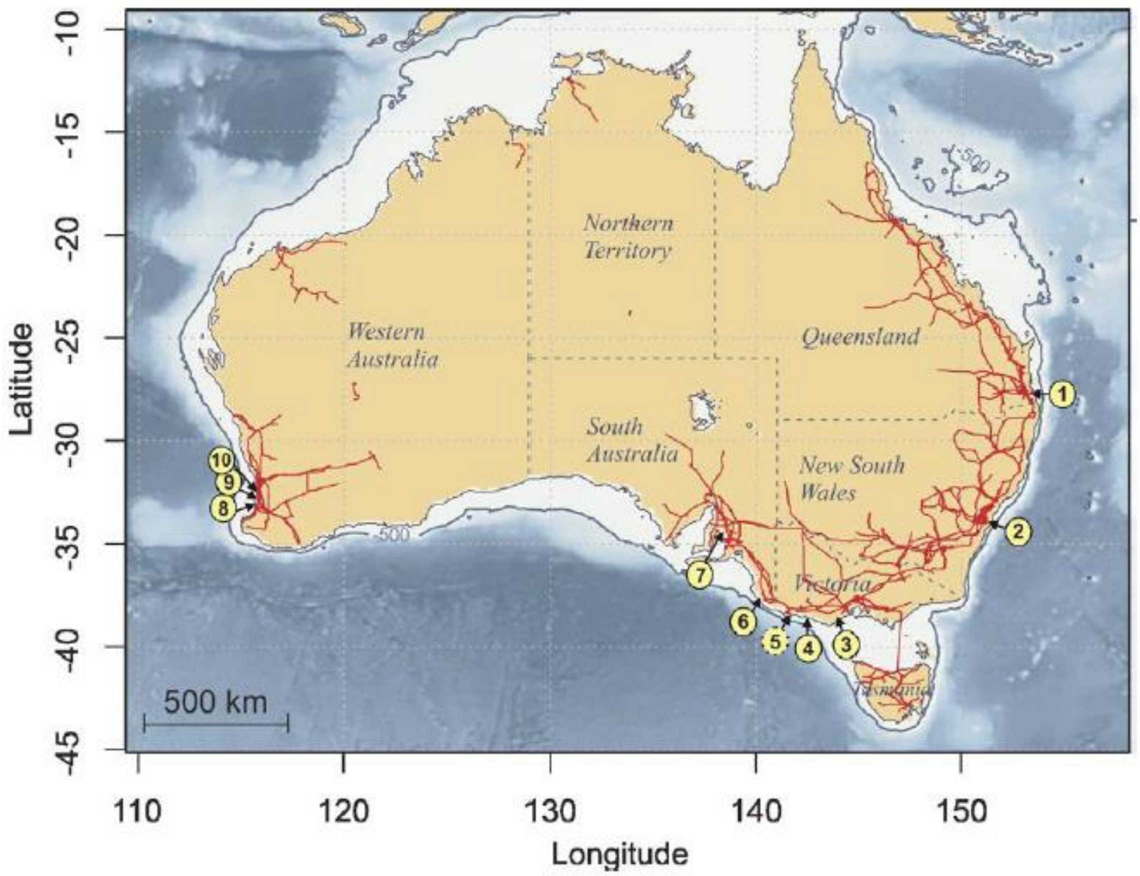

Figure A.1. Locations of marine-energy trials in Australia. Solid surrounded circles represent wave-energy trials, while symbols with dotted surrounds indicate locations where pre-trial feasibility assessments have been undertaken. Electricity transmission lines are shown in red. Further details are provided in Table 1. Adapted from Manasseh et al (2017).

Figure 3: Locations of marine energy trials. Extracted from Annex A of the CSIRO Oceans and Atmospheres report on Wave Energy Deployments Physical Impact Guidelines

The ORE 2015-2050 report (CSIRO 2012) has also ‘identified 16 Australian companies that are either actively developing ORE projects, have received significant government and/or private funding or have announced ORE plans’. At the time it identified 6 devices that show sufficient data to be assessed as promising for use in Australia, outside of the required scale of the project, but further justifying the design of a WEC device for the project application.

2.5 Current Australian ORE Regulations and Guidelines

The Wave Energy Deployments Physical Impact Guidelines report (McInnes et al. 2018) provides a recent summary of the planning and legislative considerations for ORE in Australia. This source addresses the requirements for 'approvals from authorities within different levels of government at different stages of the project cycle'. Guidance and information on the processes required for obtaining approvals to conduct wave energy projects across Australia is provided by the report and included here in Appendix E.

2.6 Global Trends in ORE

The literature notes the global trend of 'increasingly significant ORE activity worldwide' and that currently 'Device research is centred in Europe with Ireland, Portugal and the UK making large investments into the development of "wave hubs". These are sea-based test centres that serve the dual purpose of testing developer's devices and providing experience in integrating the outputs into local grids. There is also active work in the US and Canada. (CSIRO 2012).

Research presented by Falcao (2010) confirms this, finding that the majority of research over the last fifteen years or so has been based in Europe, 'largely due to the financial support and coordination provided by the European Commission, and to the positive attitude adopted by some European national governments', noting that interest has been growing rapidly in other parts of the world. The author additionally highlights the fact that the technology is still far from commercially developed, with 'a wide variety of wave energy systems, at several stages of development, competing against each other, without it being clear which types will be the final winners.'

Falcao (2010) goes on to report on a detailed timeline of ORE developments within the European region. The analysis indicates a large buy-in to the technology across many countries. It is found that 'The situation in Europe was dramatically changed by the decision made in 1991 by the European Commission of including wave energy in their R&D program on renewable energies. The first projects started in 1992. Since then, about thirty projects on wave energy were funded by the European Commission involving a large number of teams active in Europe.' The majority of these being WEC devices, however with a focus to large scale grid integration.

Regular regional conferences have also been established, with a series of *European Wave Energy Conferences* held in Edinburgh, UK (1993), Lisbon, Portugal (1995), Patras, Greece (1998), Aalborg, Denmark (2000), Cork, Ireland (2003), Glasgow, UK (2005), Porto, Portugal (2007), Uppsala and Sweden (2009). Global uptake for ORE is further evidenced as;

> In 2001, the International Energy Agency established an Implementing Agreement on Ocean Energy Systems (IEA-OES, presently with 17 countries as contracting parties) whose mission is to facilitate and co-ordinate ocean energy research, development and demonstration through international co-operation and information exchange.
>
> In the last few years, growing interest in wave energy is taking place in northern America (USA and Canada), involving the national and regional administrations, research institutions and companies, and giving rise to frequent meetings and conferences on ocean energy. (Falcao 2010).

2.7 Challenges of ORE

2.7.1 Environmental Impact

The Wave Energy Deployments Physical Impact Guidelines (McInnes et al. 2014) notes that ORE devices will inherently reduce the surrounding hydrokinetic energy and have possible ecological repercussions, the document aims to provide the 'best practice guidance on assessing the influence of arrays of Wave Energy Converters (WECs) on the hydrodynamic attributes of the surrounding ocean'. Whilst addressing 'the limited evidence base and methodology for assessing impacts of wave energy extraction on the marine and coastal environment'.

The Impact Guidelines (McInnes 2014) stress that 'an important component of the site selection process for wave energy developments is an assessment of the impact of an array of wave energy converters on the local wave climate'. Some considerations for the type and distribution of devices can be found in the framework shown in Figure 4. This framework may be used to 'review the environmental risks associated with wave, tidal, current, and ocean thermal sources of renewable energy and to highlight both the known impact and those potential impacts that remain unresearched.' (CSIRO 2012).

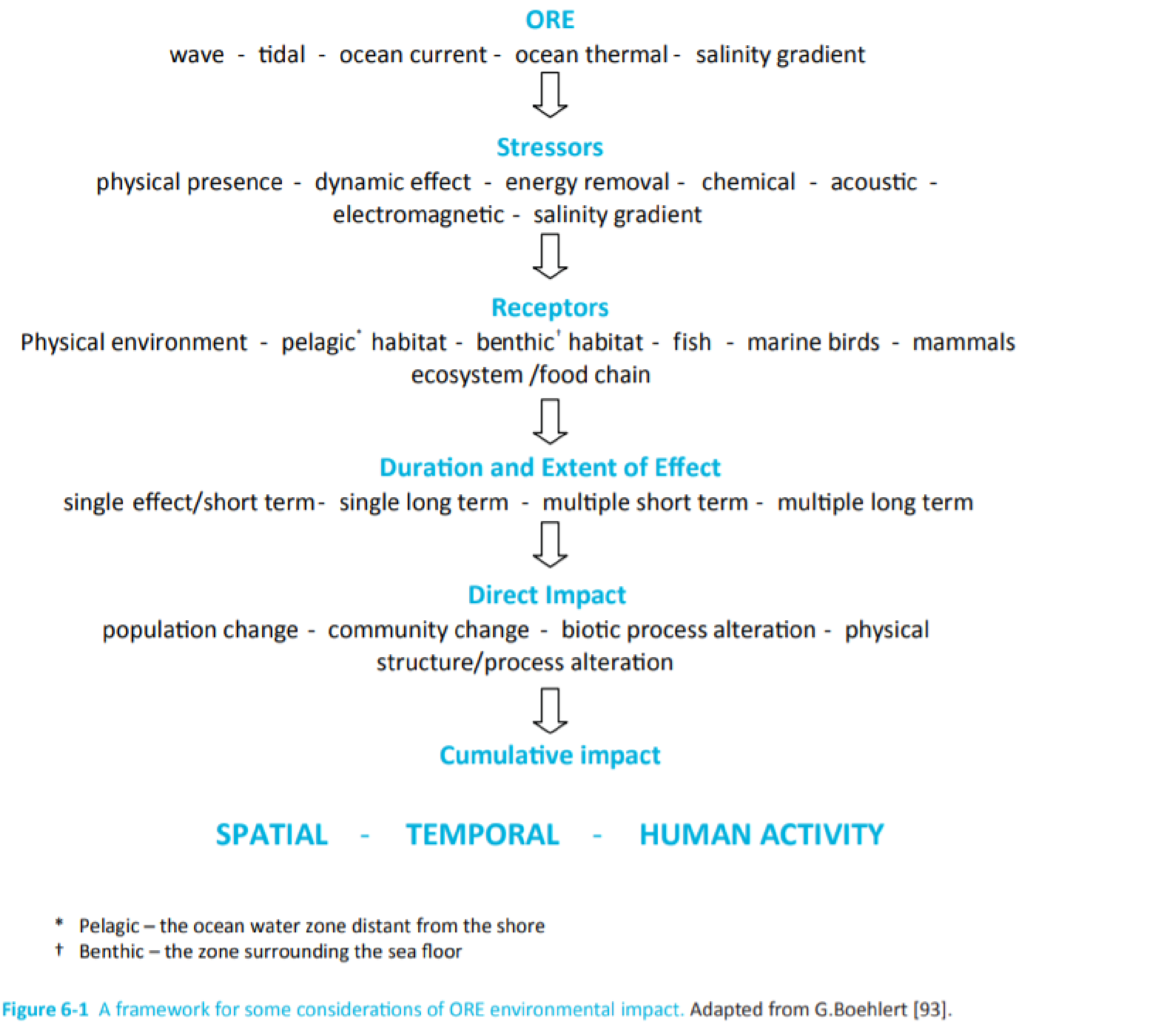

Figure 4: A framework for some considerations of ORE environmental impact. Adapted from G.Boehlert [93] (CSIRO 2014)

The stressors, receptors, the duration and extent of effects and direct impacts as identified in Figure 4 are typically more prevalent the larger in scale deployments of ORE devices are. The physical impact guideline stating that 'Single devices are unlikely to have adverse environmental impacts.

The environmental impact of the project therefore can be predicted to be quite minimal at this stage. Its 'small scale' nature and typically singular deployment, as well as the fact that the device will be utilized with other sensors and apparatus already intended for deployment further reduces its considered additional impact.

2.7.2 Geographic Location

The literature suggests that geographic location as one of the key ORE device design constraints, having a 'considerable impact on the cost effectiveness of a design approach' (CSIRO 2012). While WEC and other ORE devices may be designed for most ocean environments, the environments that marine sensors will be deployed in will dictate the design criteria for the project. The ocean environment is typically classified into four separate sub-regions; Deep ocean, Off-shore, Onshore and Nearshore. The design will be predominantly operate in the deep and offshore as characterised below;

Deep Ocean (greater than 500 metres depth)

While ocean waves at these depths have lost very little energy, the difficulties of anchorage, the limitations on design imposed by longer wavelengths and smaller wave heights, and logistical costs are all likely to preclude this option, except where there may be a local need for power such as for island communities or drilling rigs.

Off shore (greater than 50 to 70 metres depth)

As waves reach the continental shelf overall wave energy is lost. However the wave heights increase and the wave lengths decrease, expanding the range of WEC design and anchorage options. In addition, the relative proximity to land would reduce capital and operations and maintenance costs. (CSIRO 2012).

This information will assist in determining the potential operational envelope of the WEC design.

2.7.3 Failure Modes

Consideration of device failure modes is an important aspect of the design process. In relation to ORE device design when specifying parameters used for modelling in the 'CSIRO Economic modelling of wave energy in Australia' (2011) report, it is noted that the 'lifetime of the devices affects their economic viability, and there is great uncertainty surrounding lifetimes for ocean energy devices as they are located and generating power in a hostile environment. We have assumed that the lifetime is the same as other renewable technologies, since the devices are being built to withstand up to an extreme wave event' (Hayward 2011). It can be seen that consideration of the uncertainty of lifetimes and associated failure modes must be part of the project design process.

The CSIRO (2012) defines the following anticipated failure modes, all of which must be considered in the project design;

Corrosion — this is conventionally managed using:

- Cathodic protection, in which an electric current or a sacrificial anode made from magnesium or zinc, is used to counter corrosion current. Sacrificial anodes need to be monitored for replacement and have to be managed carefully to avoid the build-up of chalky deposits in regions of stagnant water.
- Use of specialised coatings and selection of material not susceptible to corrosion.
- Regular maintenance that is typically scheduled for between two to five-year intervals.

Marine growths — these can add weight or friction to moving surfaces or restrict the movement of mechanisms such as levers or pistons. Such "biofouling" is not restricted to static surfaces; there are many marine organisms that require substrate movement to grow. Biofouling and corrosion are both likely to be worse for components at the sea surface where movement and air encourage oxidation and the growth of marine organisms. Prevention and remediation involves:

- Survey of each site where a wave farm is to be constructed, to determine the composition of local flora and fauna.
- Use of specialised coatings that discourage growth and are self polishing; there is usually a trade-off between durability and the self polishing characteristic.
- Regular maintenance that is typically scheduled for between two to five year intervals concurrent with corrosion management.

Leakage — this can result in biofouling and corrosion as well as sinking of the device. It is generally thought to be a more severe problem for devices located on the sea floor due the increased water pressure. However, constant exposure to wave impact may create similar pressure stresses at the sea surface. This kind of damage has compromised several wave energy development projects.

Broken moorings — this kind of failure is most likely to occur in storm conditions when it has the potential to disrupt the whole wave farm as well as local shipping. Prevention would seem to be the only solution in this case, using appropriate design and quality control measures. It may also be possible to use backup buoys to facilitate retrieval.

Knight et al (2014) emphasises the need for designing for extreme ocean conditions to prevent failure modes such as leakage, broken moorings and other mechanical means. This is particularly important for surface or 'near-surface' devices, with tidal and current systems relatively protected from significant events. The identified strategies for coping with such an event include;

- Providing protection mechanisms such as automated lowering of expensive components to the sea floor when extreme conditions are forecast,
- The device and the farm could be made large enough or sufficiently seaworthy to cope with the extreme conditions,
- Shutting down the devices so that they are not operating, and simply "ride the waves", and if a device or components of that device were cheap enough for their energy and economic costs to be paid back between extreme wave events, then it could be an acceptable strategy to design them as potentially disposable or recyclable elements.

These strategies are applicable to the project design brief and serve to assist in evaluating options for failure prevention.

2.7.4 Theory

The theory relating to ocean dynamics and ORE devices is complex and very situational. Falcao (2009) provides an examination the difficult nature of the theory, providing the summary that wave energy absorption is;

> A hydrodynamic process of considerable theoretical difficulty, in which relatively complex diffraction and radiation wave phenomena take place. This explains why a large part of the work on wave energy published in the second half of the 1970s was on theoretical hydrodynamics, in which several distinguished applied mathematicians took leading roles.

> An additional difficulty is related to the conception of the power take-off mechanism (PTO) (air turbine, power hydraulics, electrical generator or other) which should allow the production of usable energy. The problem here lies in the variability of the energy flux absorbed from the waves, in several time-scales: wave-to-wave (a few seconds), sea states (hours or days) and seasonable variations. Naturally, the survivability in extreme conditions is another major issue.

While the most common method of evaluating ORE devices explored so far has been through utilising generalised ocean resource data in combination with rated outputs and capacity factors to generate an expected output. Actual output figures are much broader over more discrete intervals, this will require consideration of a larger variation of ocean scenarios for each design. Knight, Davidson and Behrens (2008) also present theoretical challenges of ORE that are particularly relevant to the project in their work on wireless sensor nodes.

2.7.5 Data Collection and Modelling Ocean Environment

'Wave predictions based on scatter diagram data. A review' (Capitao and Burrows 1995), cites that relevant wave data is available from 3 different sources, namely visual observations, instrumental observations and hindcast analysis. It stresses that 'Good wave data collection is the first important prerequisite to obtaining reliable wave predictions.' And that wave predictions 'depend not only upon the selected probability distribution to describe the extreme wave climate, but also upon the type, size and quality of the data samples, upon the method of fitting used and, with graphical procedures, the plotting position formula selected'. The 'ORE 2015-2050' report confirms that in situ observations are an important contributor in wave prediction and are necessary for verification of model estimates (CSIRO 2012).

Capitao and Burrows (1995) however do highlight the fact that 'the engineer should be aware of the problems and, consequently, of the errors that can occur when using different methods of wave measurement' as well as the methods by which the data is generated. They detail the types and methods of data collection as well as the fact that designing or modelling devices based on these different types of data, the user must remain cognisant of the data source and intent.

McInnes et al (2018) further examines the complexities of data collection in the ocean environment. Particularly noting the need to make assumptions and simplify the data due to simulation complexity making the statement that; ‘the number of potential permutations of array/device configurations and important local environmental (physical, geological, ecological) and human (societal, economic, infrastructure) attributes at potential installation sites could be nearly infinite’. It can be seen that some method for analysis simplification must be introduced.

Simplification of ORE analysis may be achieved through various approaches, with McInnes et al (2018) ‘restricting the total number of WEC device types, WEC array configurations and wave climates considered and performing the simulations at two different idealised nearshore morphologies’. Even so despite this the total number of simulations within the report was 68000. Theoretically, for the project design brief, modelling complexity should be considerably less as less variation in device type and no array configuration factors will apply. The wave climates and local morphologies will provide the greatest variation in designing the device, mitigated by wave climate data that is presumably accurate for sensors that are currently deployed and will be integrated with the device.

2.7.6 Energy Storage

Dependant on the type, number and environment in which the sensors are deployed, Knight, Davidson and Behrens (2008) find that it is difficult to identify a ‘one size fits all’ solution in terms of battery storage. With designers needing to ‘choose the right mix of energy storage and harvesting options for their particular application’. Typically, this issue is addressed through design by catering ‘for the largest demand leaving the power system massively oversized for large portions of the node's operating time’

Such a solution is not always desirable, with Knight, Davidson and Behrens (2008) positing that

> a battery that is large enough to last the life, say five years, of a sensor node would dominate the overall size of the node, and thus would not be very attractive or practical. Additionally, the battery chemistries often involve toxic heavy metals, and present disposal issues, regardless of rechargeable technology.

Saying this, whilst an ideal solution might appear to be energy harvesting from the local environment - potentially achieving greater run-times and lower cost and weight, the nature of the energy may be intermittent, too low or in the wrong form. Some method of storage will be required to address these issues.

Knight et al. (2014) explores the concept of "capacitance" as a method for short or potentially long term power smoothing. It proposes the use of flywheels, hydraulic accumulators, a head of water, batteries, mechanical or pneumatic springs, salinity gradient systems for example as viable options to offset the cyclic nature of wave energy. The viability of these methods for the small scale and particular power requirements of the project are evaluated as design matures.

2.8 WEC Validity

2.8.1 Theory

As the project is to focus on a small scale, surface located device for energy harvesting, WEC will be examined as the preferred source of ORE. The literature in fact shows that in the larger scale, WEC is the single greatest potential source of ORE for Australia (Knight et al. 2014). The 2015-2050 report (CSIRO 2012) again stating that Australia's Southern Ocean is the primary location of this resource and 'is recognised in global atlases of the wave energy resource'. This is because in this environment 'Waves are generated by the wind and can travel large distances in the deep ocean because the rate of energy loss is very small until the waves reach shallow water and start experiencing frictional drag on the sea floor' (CSIRO 2012).

The ORE report (CSIRO 2012) confirms the potential of WEC devices based on wave properties for power generation, detailing the considerable regional resources. It indicates that 'Swell periods range from about 8 to 14 seconds with wavelengths in the deep ocean of 100-300 metres. The maximum wave height measured in Australian waters, over an approximately 30-year record, was approximately 18 metres.' While the southern coastal regions wind waves 'typically range in height from a few centimetres to 2 or 3 metres with wave periods from about 2-8 seconds, while swell can typically range in height from a few centimetres to 7 metres or more'. And swell off the coast typically 2.5 to 3.5 metres, with a period of 11 seconds.

The CSIRO report (2012) states that accurate data of swell (wave height) and period are the two most important variables when determining WEC design. Twidell and Wier (2015) confirm this in the textbook Renewable Energy Resources, with the primary equations for wave power dependant on the density of water, the gravitational constant, wave height and period. Blanco et al states that "There is a strong connection between wave energy at a given location and the geometrical design of a WEC" and that this “implies that even for a WEC of the same type and power, the characteristics and its geometry will have different designs for different locations under optimized design and operation conditions”

In the Australian context, the Australian Renewable Energy Mapping Infrastructure (AREMI) tool provides an invaluable resource for high fidelity, reliable wave data. Thedatabase provides the following definitions for wave height and wave period data.

Regarding wave height data;

The 50th percentile of significant wave height is derived from the CAWCR global wave hindcast, using data from the archived hourly 4’ Australian grid, using data from 1st January 1980 to 31st December 2010. Significant wave height, Hs, represents the average height of the upper third of the waves in the wave-field, and roughly corresponds to the mean wave height as described by a trained observer. Hs is a spectrally derived time-series, calculated as $Hs = 4\sqrt{m0}$, where m0 is the zero-th moment of the wave spectrum. (AREMI, 2020)

And for wave period;

The 50th percentile of wave energy period is derived from the CAWCR global wave hindcast, using data from the archived hourly 4’ Australian grid, using data from 1st January 1980 to 31st December 2010. Wave energy period, Te is a measure of the length of a wave. The wave energy period is the mean period of the wave field with respect to the spectral distribution of energy in the wave field. (AREMI, 2020)

Falcão (2009) provides a comprehensive review and analysis of working principals of WEC technology and addresses the fact that WEC devices ‘achieve energy generation through a range of design classifications’, noting that ‘Drew, Plummer and Sahinkaya (2009) state that ‘Research in this area is driven by the need to meet renewable energy targets, but is relatively immature compared to other renewable energy technologies’. This makes it difficult to determine the characteristics of a ‘scaled down’ approach as required for the design. Current published research and development lends itself to large scale installations, whereas the literature on the development and efficiencies of small scale WEC is again very limited.

2.8.2 Previous WEC Work

Pender and Sarjan (2019) found in their research that 'The first ocean WEC was introduced by Girard and his son in Paris in 1799. Additionally, a preliminary WEC to feed a low consumption load was proposed by Yoshio Masuda in the 1950s. In 1970, due to the crisis of oil, ocean wave energy projects were highly paid attention.' Falcão (2009) also attributes the oil crisis of 1972 to the 'major change in the renewable energies scenario and raised the interest in large-scale energy production from the waves.' McInnes' (2018) modern day findings state that the 'growing interest in wave renewable energy over the past two decades has seen an increase in studies that assess the potential impact of wave energy devices'.

The OES Annual report 2017 appears to be the most up to date and authoritative source of information on WEC and other ORE devices found within the literature (Ocean Energy Systems, 2017). This document provides locations and details of all current ocean energy related projects and companies, data on global energy capacities, details government policies and national strategies, research and development and technology demonstrations for 23 different participating countries. The report indicates typically that "small scale" devices currently in development have outputs between 300-1000W, well outside the scope of the project.

WEC devices are separated into categories, being oscillating water column, oscillating body, pitching devices, attenuators and terminators. Work has been done on several of these using data and WEC device power matrices to evaluate performance in Australian applications, with McInnes (2018) examining the four devices shown in Figure 5 to perform an analysis. 'The WECs represent differing device types, which utilise different physical principals for wave energy extraction; the nominal capacities of individual devices range from 200 kW to 3 MW and have performance metrics available in the public domain' Historically, primary sources of WEC modelling are carried out in a similar way, observed again in the article Numerical benchmarking study of a selection of wave energy converters, taking wave statistics and multiplying by the power matrix of the device (Babarit et al. 2012).

Table 1 Description of WECs selected for assessment in this study.

WEC Name	Description	Nominal (Nameplate) Capacity (MW)
Bref-SHB	Bottom-referenced submerged heave buoy	0.209
F-OWC	Floating oscillating water column	2.880
B-OF	Bottom fixed oscillating flap	3.332
P-PA	Pitching point absorber	0.457

Figure 5: WEC devices examined within the Wave Energy Deployments Physical Impact Guidelines report (McInnes, 2018).

In addition to numerous Australian theoretical and modelling studies, there are a number of ORE devices operating in Australian waters, ranging from 'small scale testing to pilot demonstrations and the beginning of commercial developments' (CSIRO 2012).

2.8.3 Numerical modelling

The literature concerning the mathematical analysis of wave energy extraction has been well documented. Evans (1981) paper 'Power from water waves' detailing the derivation of the governing equations of wave motion, power and models for wave irregularity. Further to this Evans also examines two- and three-dimensional models to account for complications arising from additional degrees of freedom in WEC design.

The literature highlights that the most common method of performance evaluation is via wave data and device power matrices, primarily due to the fact that more consistently 'WEC manufacturers provide performance data on their products as a function of significant wave height and wave period (Dunnett and Wallace 2009). An approach that may be considered to evaluate the projects performance.

This wave data is available from a number of sources, with the 'Wave Energy Deployments Physical Impact Guidelines' (McInnes, 2018) extracting data from the CAWCR wave hindcast (Durrant et al. 2014). The National Oceanic and Atmospheric Administration (NOAA) WaveWatch III (NWW3) model detailed in the ‘Wave energy for Australia's National Electricity Market’ (Behrens et al. 2015) is another resource, with significant wave height, peak wave period and peak wave direction being archived at 3 hourly intervals since the model's commencement. The report ‘Electricity generation from wave power in Canada’ uses data obtained from the website of the Marine Environmental Data Service of Canada (MEDS) (Dunnett and Wallace 2009). And finally the AREMI online tool is reliable for Australian ocean data.

Dunnett and Wallace (2009) further explain numerical modelling relationships of wave heigh and period as introduced previously by the AREMI definitions;

> To measure the incident energy of a complex seastate, two characteristic values are used: significant wave eight, HS (m), and energy period, Te (s). Both of these values are independent of the direction of wave propagation. The significant wave height is the average height of the highest 1/3 of waves. This measurement closely corresponds to the wave height that an observer would estimate when describing ocean activity.

These are important wave characteristics that will be used in the project design.

The article provides performance tables with expected power output indexed by significant wave height and wave period (table 2). The performance table provides the expected power output indexed by significant wave height and wave period. A distinct pair of HS and T is referred to as an energy bin.

Table 2: An example of WEC performance data (Dunnett and Wallace 2009)

Table 5
Performance data for the WaveDragon [23]

Power [kW]	T_p [s]												
H_s [m]	5	6	7	8	9	10	11	12	13	14	15	16	17
1.0	160	250	360	360	360	360	360	360	320	280	250	220	180
2.0	640	700	840	900	1190	1190	1190	1190	1070	950	830	710	590
3.0		1450	1610	1750	2000	2620	2620	2620	2360	2100	1840	1570	1310
4.0			2840	3220	3710	4200	5320	5320	4430	3930	3440	2950	2460
5.0				4610	5320	6020	7000	7000	6790	6090	5250	3950	3300
6.0					6720	7000	7000	7000	7000	7000	6860	5110	4200
7.0						7000	7000	7000	7000	7000	7000	6650	5740

Dunnett and Wallace (2009) take the following approach calculate the monthly electricity production, ‘create a similar table with the same indices, but providing the expected number of hours that each energy bin occurs instead of power output’ . Therefore ‘Electricity production (in kWh) is simply the expected power output (in kW) for an energy bin multiplied by the expected occurrence (in hours). Summing these products over all energy bins gives the total electricity produced by the WEC at that location for the month.’ Table 3 provides a summary of wave activity organised into the same energy bins as Table 2 performance data.

Table 3: An example of wave activity data (Dunnett and Wallace 2009)

Table 7
Average wave activity in January for Lat 47.63, Long 52.5 near St. John's, Newfoundland, provided by MEDS and summarized by the WaveDragon energy bins

Activity [h]	T_p [s]												
H_s [m]	5	6	7	8	9	10	11	12	13	14	15	16	17
1.0	0.00	1.08	1.08	0.00	1.89	3.78	1.89	1.08	0.54	0.00	0.00	0.00	0.00
2.0	5.41	13.25	10.54	10.27	11.63	34.06	15.95	26.22	11.90	12.98	9.46	2.70	0.27
3.0	4.60	6.76	14.60	12.44	9.73	15.95	15.68	59.48	41.63	38.39	27.31	14.87	8.11
4.0	0.00	0.00	2.70	8.11	7.57	13.79	7.03	22.71	17.57	20.55	17.84	16.22	6.22
5.0	0.00	0.00	0.00	1.62	4.60	4.60	3.78	11.63	5.41	6.49	6.49	5.41	6.22
6.0	0.00	0.00	0.00	0.00	0.54	1.35	1.35	4.33	1.89	0.81	2.16	2.70	1.35
7.0	0.00	0.00	0.00	0.00	0.00	0.54	0.27	0.27	0.27	0.54	1.08	0.54	0.00

The approach used by Babarit et al. (2012) also calculates estimations of the wave energy absorption of a device at a particular location by multiplying the power matrix of this device with the scatter diagrams of wave statistics at this location. A similar matrix method for power analysis will be used in the project design to predict outputs based on selected design criteria.

2.9 Literature Review Summary

From review of the available literature it is obvious that ORE is currently of global interest but highly underutilised. The nature of the energy source is very situational but as the technology matures a degree of standardisation will emerge just as in other energy applications.

There are currently many approaches to the analysis and harvesting of ORE as can be seen in the number of differing methods discussed here. It is important that the project acknowledges the approaches made previously and adopt a method of relating wave characteristics to the physical properties of the design.

The most important question that goes unanswered by the literature is the purpose of this project. An investigation into the viability of small-scale WEC devices in comparison to other alternatives and what would the design and testing of such devices involve.

Chapter 3 – Methodology and Parameters for WEC Device Modelling

3.1 Section Overview

This section introduces and explains the chosen design methodology for the project. It examines important factors that dictate the design requirements, the environmental characteristics and the scope and limitations of the project. Finally, it provides details on the preliminary WEC concepts and how they were evaluated.

3.2 Methodology

The project has adopted the double diamond methodology as a structured approach in generating a solution to the requirement of a small-scale WEC device. The model is systematic in nature, design focused and presents scope for the iterative design of the WEC prototype, all of which suit the nature of the project aim.

This methodology was first introduced by the Design Council in 2004 as a "clear, comprehensive and visual description of the design process" (Design Council, 2020). Since its introduction the model has become extensively adopted and accepted as a tool used to guide the creative process. Figure 6 below shows an example of an adapted double diamond model from an article written by A Stubbs in 2018, taken from online information resource Medium (2020).

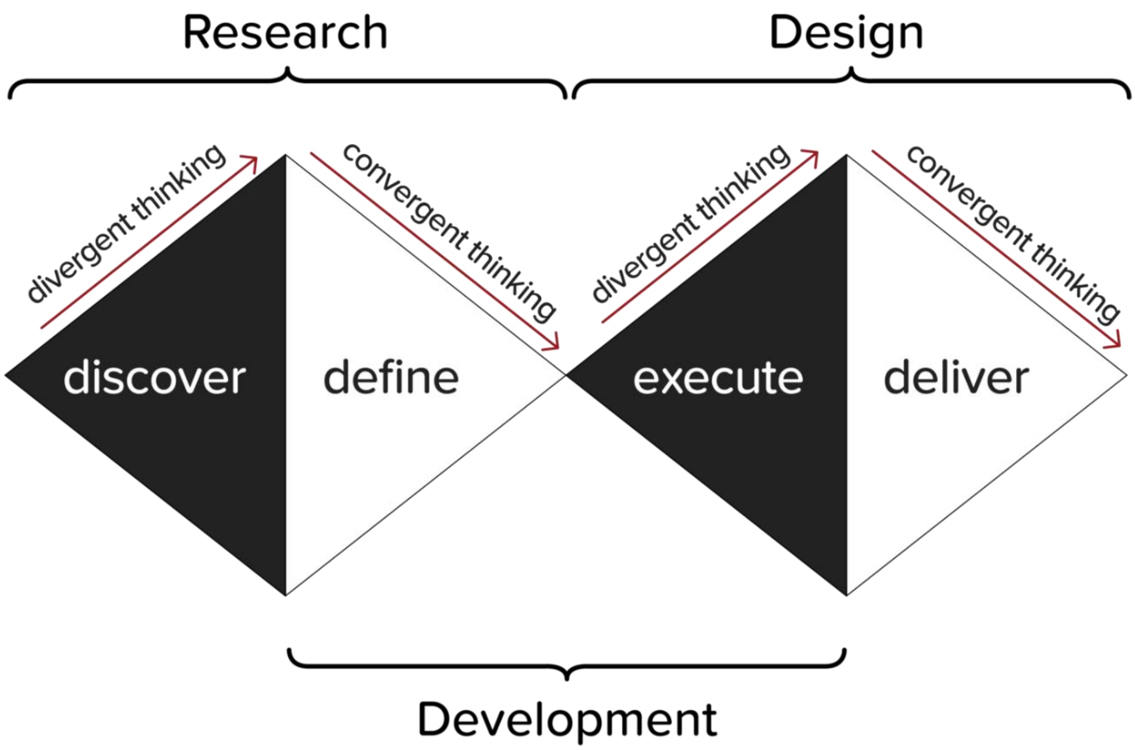

Figure 6: The Double Diamond model (A Stubbs, 2018)

As explained by the Design Council (2020), ‘the two diamonds represent a process of exploring an issue more widely or deeply (divergent thinking) and then taking focused action (convergent thinking)’. Also included within the model, four project stages are undertaken, these are discover, define, execute and deliver. It can be seen that the identified objectives and scope of the project are represented within these four stages.

Discover – This stage involves understanding the what the problem is. This will be undertaken primarily through the completion of the extensive literature review, which will begin quite broadly and serve as a resource for later focus on project outcomes. Additional research here will be conducted on sensor specifications to begin convergence to defining the design more accurately.

Define – The define stage aims to identify what the design outcomes can achieve. It is the result of the identification and analysis of data sets for use in modelling and the theoretical modelling of various harvesting methods to propose a viable design solution.

Execute –This is the stage where physical design and justification as well as physical prototyping and testing will take place as a result of all previous work. The primary tools used in this stage will be Microsoft Excel to carry out the modelling based on the data identified in the define stage. The Computer Aided Design software CREO will be used to generate 3D models of prototype components, verify the assembly of the design and perform finite element analysis.

Deliver – the deliver stage includes the scope for iterative design as the prototype is tested and performance evaluated. It also represents the final convergence in the design process where all data is presented, and the design is finalised.

3.3 Functional and Performance Requirements

As stated, the purpose of the project is to provide persistent power to marine sensors. The CSIRO utilizes a variety of these in their research to measure the essential physical properties of the ocean environment. Measurements made include conductivity, temperature and depth, these sensors are commonly referred to as CTD sensors. Dissolved oxygen, power of hydrogen (pH) and turbidity sensors are also deployed.

These sensors are often deployed in combination with one another in surface, sub-surface or lander configurations, an example of a surface configuration is shown in Figure 7. The most common sensors used are manufactured by Seabird Scientific and include the Seabird 37-SIP (outputting salinity, sound velocity, depth and density data), the 37-SMP (outputting salinity and sound velocity) and the SeaFET (outputting pH data, shown below in figure 8). The data sheets of each may found in appendix F, G and H respectively.

Figure 7: An example of a surface sensor configuration (CSIRO, 2019)

Figure 8: The Seabird SeaFET V2 Ocean pH sensor

These sensors are all already designed to run for extended periods of time, up to 2 years depending on the sampling scheme, collecting hundreds of thousands of samples. Power consumption is typically low when sampling, in the range of sub 3W during a 1.9-2.9 second sample every 6 second to 6-hour interval. They have specifications for external power supplementation that are quite low, indicating that even with multiple sensors drawing from the same source, a reasonably designed WEC device providing an average of 3-10W and an appropriate energy storage system would more than suffice.

In addition to the power requirements many other design factors must be considered. An examination of failure modes, environmental stresses and significantly the practicality of the design within the scope of being a student project, led to the identification of seven primary criteria. An evaluation of each was performed on each identified WEC alternative in order to identify a viable design.

Ease of construction – This relates to the practicality of the device being designed and constructed as part of a student dissertation and then reproduced by the end user, the CSIRO. It also relates to the complexity and size of the device, factors such as the need for hydraulicly or air driven turbine power take-off devices lead to lower scores in this criterion.

Tunability – This relates to the ease at which a device can be optimized, or how well it is able to maintain efficiency to suit different sea states or power requirements.

Transportability – The completed prototype is ideally transportable by 1-2 people in a medium sized vehicle or able to be palletised on a standard pallet for road transport. With several able to be transported together on a reasonably sized marine vessel. Viable devices being of a modular design and easily assembled for deployment.

Mechanical simplicity – Relating to the method of energy harvesting and power transfer. How complex or difficult are the mechanical components of the design.

Electrical simplicity – Relating to power regulation and storage, how complex or difficult are the electrical components of the design.

Durability – How suited is the device to a marine environment. Will it withstand extreme events and also remain maintenance free for prolonged periods.

Scalability – How well does the concept adapt to the small-scale requirements of the design brief.

3.4 Deployment Characteristics

The primary physical ocean dynamics affecting the design of a WEC device are significant wave height and period, as such modelling was carried out with respect the variation of these conditions. As examined in the literature review an effective method is to create a power matrix, which based on the physical geometry of the device and the sea state, will provide theoretical power outputs as well as other important variables such as torque.

Texts such as Renewable Energy (Twidell and Wier, 2015) state that wave periods are most commonly in the 5 to 10 second period range, the AREMI tool was also used to verify the primary operating parameters of the device. This was done through use of the mean annual significant wave height and 50th percentile wave energy period data for prospective deployment areas.

The data of interest was extracted from the following sets;

Renewable energy > Marine > Australian Marine Energy Atlas > Marine Energy Context Layers > Wave Height > Statistics > 50th Percentile of Significant Wave Height

And,

Renewable energy > Marine > Australian Marine Energy Atlas > Marine Energy Context Layers > Wave Period > Statistics > Annual Mean Significant Wave Height

As observed in Figures 9 and 10 below there is a reasonable correlation between wave height and period.

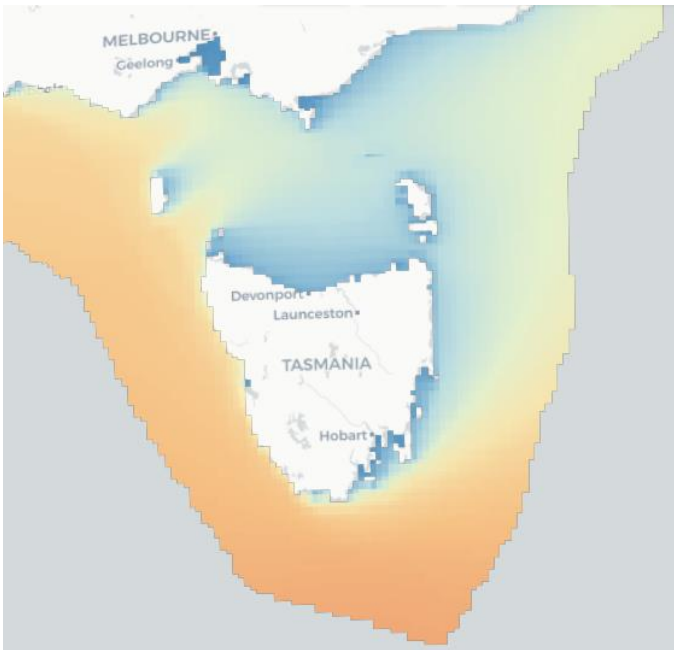

Figure 9: 50th percentile of significant wave height

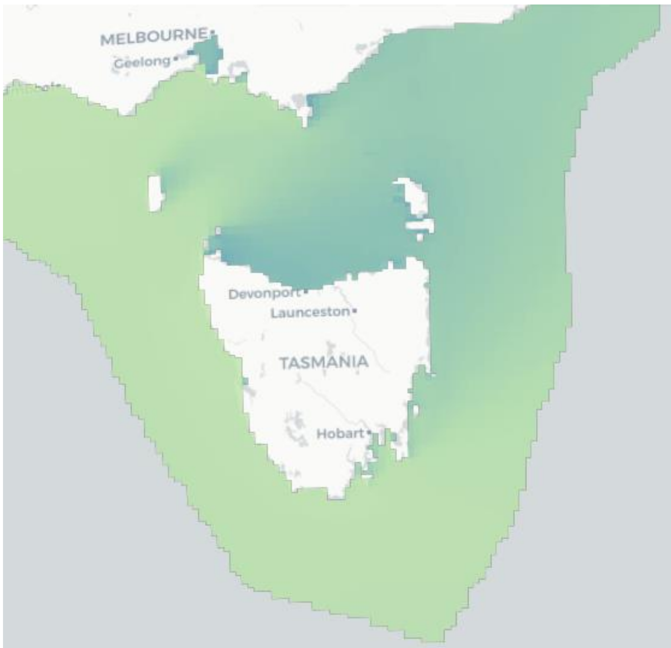

Figure 10: Annual mean of significant wave energy period

Based on the deployment characteristics for reef-based sensing, the generated power matrix extends from 0 to 6-meter wave height and 0 to 12.5 second wave period. The designs expected operational envelope was determined to be sea-states between 2 to 6-meter wave height with a 5 to 10 second wave period.

3.5 Scope and Limitations

The primary objective of the project is the production of a WEC design that can reliably supply power above the required range to meet sensor demands. As such all aspects of the prototype design, testing and data presentation are included within the scope of the project. The section 1.3 Research Objectives outlines the complete scope of the project.

Testing of the prototype with the actual sensors it is to be deployed with as well as in the proposed actual sensor locations is not included within the scope of the project. The focus will remain on its viability for deployment at a later stage following the initial design. Also, while the construction of the device will be documented, detailed examination of mass production requirements will not be examined within this project.

In completing the project it must also be recognised that various limitations and assumptions that must be made. The first of which is that in terms of the information available from previous WEC research there is limited small scale device data available. Secondly, the primary data sets used for modelling have also been limited to simplify analysis, with significant wave height and wave period being selected to characterise wave profiles. Numerical analysis also simplifies the sinusoidal nature of each profile to a linear equivalent for modelling.

To typify conditions at offshore locations, data was extracted from the AREMI on-line tool (https://nationalmap.gov.au/renewables/), specifically the Australian Wave Energy Atlas. The 50% and mean average data is used to represent baseline conditions which should most accurately represent selected deployment locations.

It is also a fact that ocean dynamics are complicated as well as difficult to predict and replicate. Any modelling carried out will be limited in the sense that conditions will be assumed with averaged consistent variables. Although predictions for device performance can be made, actual offshore values could vary significantly. It presents quite a challenge to design a device to suit all ocean conditions as environmental and topographic factors cause drastic differences at any given location that the device might be deployed. Any test locations and conditions used within the project as design proof of concept may ultimately prove incompatible with real world deployment requirements.

Selection and access to deployment locations due to the difficulty and logistics of offshore testing for data gathering in varying conditions must be considered. These selected locations will be affected by the conditions of the day which will also contribute to the range of available data. The ocean is also subject to extreme conditions and although these may be planned for during the design process there will be limited scope to deploy the prototype to such environments to evaluate its tolerance and performance during such events.

There are also factors that limit the physical design of the device. Expected output requirements of the device are assumed based on sensor data sheet and information provided by CSIRO. Power losses related to mechanical, regulation and storage will be tested as far as practical or assumed during theoretical modelling and design. Prototype costs and construction will initially be carried out personally which may limit the complexity and scope of the design, with the desire for an easily modifiable universal design also having an impact.

Finally, the type and quality of data gathering will limit the outcomes of the project. It has already been described how gathering a reliable range of data for modelling comparison may be difficult. Actual recorded data metrics may also be limited but real time logging of power outputs, device rpm, wave height and period would be desirable and require further investigation prior to implementation. Gathered data requires correct analysis and presentation to be considered for inclusion within the project.

3.6 Preliminary Concept Evaluations

Several concepts were initially considered based on the research carried out in the literature review, these were evaluated against the design criteria outlined in Section 3.3 Functional and performance requirements.

Oscillating water column – A wave passes into a partially submerged cavity, this action uses air as a working fluid to drive a wells turbine (a turbine that rotates in one direction regardless of the direction of the air stream).

Oscillating body – Where wave action creates relative movement to a fixed point to extract energy.

Pitching device (Gyroscopic) – Where an angular deflection is used to extract energy.

Pitching device (Gravity referenced) – Where inertia is used to extract energy through the vertical action of the waves.

Attenuator – One or more linked devices, free to move with wave motion, but extract energy from relative motion.

Terminator – Extracts the potential energy of water that is forced above sea level and channelled through an energy extraction device.

A system of evaluation was devised using weighted criteria for each design from 0 to 5, with 0 being poor and 5 being acceptable, in order to identify viable concepts. The final evaluations are provided below in Table 4.

Table 4: Preliminary concept evaluation scores

	Occilating Water Column	Occilating Body	Pitching Device (Gyroscopic)	Pitching Device (Gravity referenced)	Attenuator	Terminator
Ease of construction	1	3	4	2	3	1
Tunability	3	3	4	2	3	2
Transportability	2	4	5	3	4	2
Mechanical simplicity	2	4	4	2	3	2
Electrical simplicity	2	3	3	2	3	2
Durability	2	3	4	2	3	2
Scaleability	1	4	5	2	3	1
Score (%)	37	69	83	43	63	34

3.9 Conclusion

The adopted methodology for the project was systematic and design focused, well suited for the project aim. When completing the discover and design phases of the model it was important to construct a method for identifying and evaluating potential designs. This was achieved through identification of the devices functional and performance requirements, the deployment characteristics and consideration of the project scope and limitations.

The pitching device (gyroscopic) emerged as the clear preferred option in the evaluation process, with most aspects of its design criteria scoring well. The other devices commonly scored poorly due to difficulties with the ease of construction and concept scalability, with several power generation methods being quite complex and the dimensions required not suitable for such a small scale device or ease of transportation.

Chapter 4 – WEC Mathematical Modelling

4.1 Section overview

This section pertains to the mathematical modelling of the gyroscopic WEC prototype. It begins by outlining the assumptions used for the calculations, then presents each variable and details how it was calculated. The results of these calculations are presented in section 7.2 Model Validity Analysis.

Due to the geometry and behaviour of a pendulum device, the primary parameters are the pendulum mass and the distance to the masses centre. The modelling will therefore be dependent on these two variables for the specified combinations of significant wave height and period.

4.2 Assumptions

The modelling does not take any inefficiencies into account. These can be due to mechanical losses, misalignment with the wave field, effects of wind, tethering, ocean currents, wave height and period variability and irregularity, hull dynamics, environmental degradation and extreme weather events.

The primary assumption is made that for a given wave period and height, there is an equivalent near sine wave function, from which an approximate angle of inclination/declination can be calculated, as shown in Figure 11.

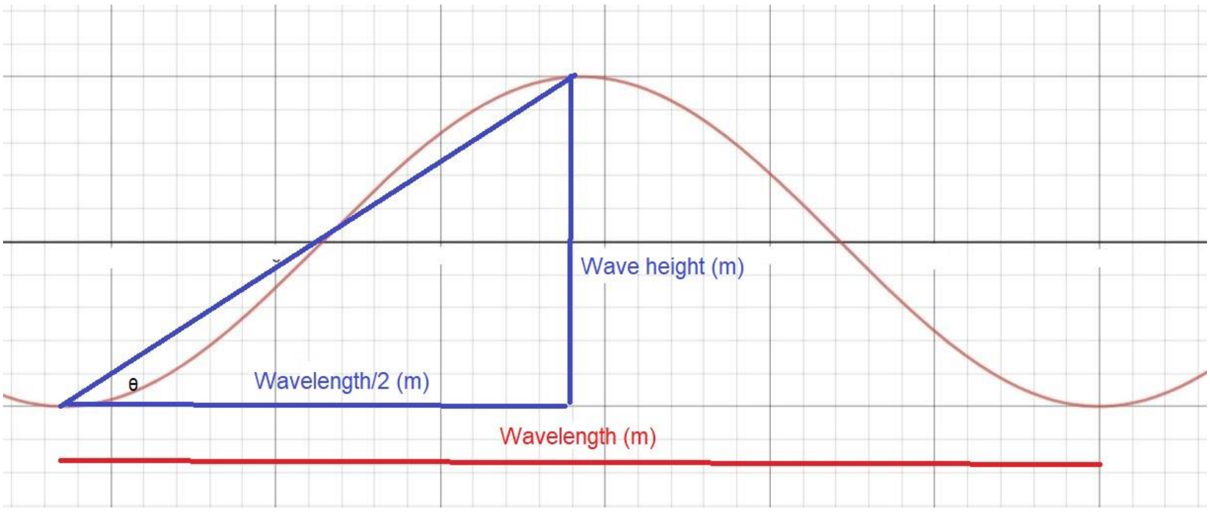

Figure 11: Angle analysis of a wave

The dynamic action of the device is shown in Figure 12. As the body of the device rotates in a clockwise direction from the crest of each wave (when viewed perpendicular to wave motion), the centre of mass (CoM) rotates around the vertical axis to the new lowest possible position. The device is then rotated in a clockwise direction as the wave trough passes, causing the CoM to again rotate around the vertical axis to the new lowest possible position. Any rotation of the CoM drives the power generating mechanism.

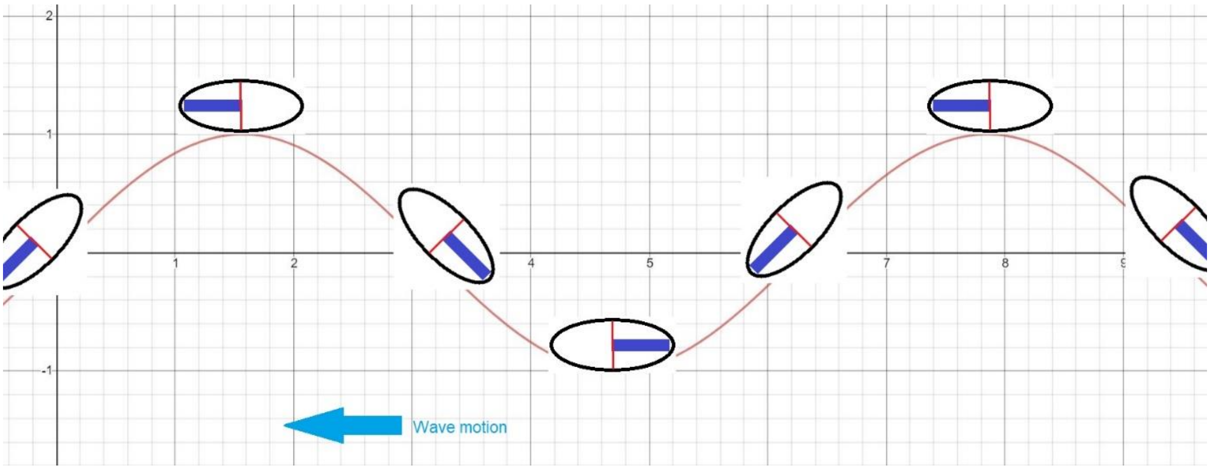

Figure 12: Motion of the vertical axis WEC device

4.3 Wavelength

The wavelength of a wave λ [m] is given by:

$$\lambda = \frac{g}{2\pi} \times T^2 \tag{4.1}$$

where g is the gravitational constant [m.s^{-2}]

T is the wave period [s]

4.4 Wave Angle

The wave angle of a wave θ [degrees] is given by:

$$\theta = ATAN\left(\frac{H}{0.5 \times \lambda}\right) \tag{4.2}$$

where H is the wave height [m]

λ is the wave wavelength [m]

4.5 Effective Height Difference for Potential Energy Evaluation

The effective height of the centre of mass per wave [m] is given by:

$$H_E = 2 \times d \times SIN(\theta) \tag{4.3}$$

where d is the distance to the centre of mass [m]

θ is the angle of the wave [degrees]

4.6 Potential Energy per Wave

The potential energy per wave [J] is given by:

$$PE = m \times g \times H_E \tag{4.4}$$

where m is the mass of the pendulum [kg]

g is the gravitational constant [$m.s^{-2}$]

H_E is the effective height [m]

4.7 Theoretical Wattage

The theoretical wattage output [W] is given by:

$$P = PE / T \tag{4.5}$$

where PE is the potential energy per wave [J]

T is the wave period [s]

4.8 Torque

The torque [Nm] at the pendulum centre of rotation is given by:

$$M = m \times g \times SIN(\theta) \times d \tag{4.6}$$

where *m* is the mass of the pendulum [kg]

g is the gravitational constant [m.s^{-2}]

θ is the angle of the wave [degrees]

d is the distance to the centre of mass [m]

4.9 RPM

The natural RPM (revolutions per minute) [rpm] of the pendulum is given by:

$$RPM = 60 / T \tag{4.7}$$

where *T* is the wave period [s]

4.10 Geared Torque

The torque after gearing [N.m] is given by:

$$M_G = M / R \tag{4.8}$$

where *R* is the gear ratio [Output rpm / Input rpm]

M is the pendulum torque [N.m]

4.11 Geared RPM

The RPM after gearing [rpm] is given by:

$$RPM_G \quad = \quad R \times RPM \tag{4.9}$$

where R is the gear ratio [Output rpm / Input rpm]

RPM is the natural revolutions per minute [rpm]

4.12 Theoretical Ideal Wave Power

The Power carried across a vertical plane per unit width of wave-front [W/m] (Twidell and Weir, 2015) is given by:

$$P' \quad = \quad (\rho \times g^2 \times (H / 2)^2 \times T) / (8 \times \pi) \tag{4.10}$$

where ρ is the density of water [997 kg.m^{-3}]

g is the gravitational constant [m.s^{-2}]

H is the wave height [m]

T is the wave period [s]

4.13 Theoretical Efficiency

The theoretical final efficiency [%] of the device is given by:

$$\eta \quad = \quad P / P' \times 100 \tag{4.11}$$

where P is the theoretical wattage output of the device [W/m]

P' is the ideal wave power per unit width [W/m]

4.13 Conclusion

The derivation of these formulas relied on fundamental physics concepts and an understanding the geometry and motion of the device and the ocean state. Through the use of Microsoft Excel, it is possible to calculate each variable for any combination of wave height and period based on the primary characteristics of pendulum mass and distance to centre of mass.

Chapter 5 – WEC Physical Design

5.1 Section Overview

This chapter details the selection of the device components, as well as major functional and physical characteristics. The primary design parameters are governed by the dimensions of the housings and the rpm and torque specifications of the generator.

5.2 Device Housing

The device is designed to be totally sealed and self-contained when deployed. The housing is composed of two halves, the base of the lower half is attached to the internally positioned inner frame structure, it is fastened by marine grade bolts which are sealed to prevent environmental exposure. Externally on the underside of the base an attachment for tethering would be installed. The lower surface of the upper overhang feature on the lower housing is used to seat and attach the outer frame. The upper surface of the overhang has a rubber seal in place, used provide a sealing surface for the equivalent surface of the upper housing. The two halves are held together by marine grade bolts at regular spacing.

The housings comprise of 2 round pre-formed plastic ponds, designed to be free standing and UV resistant, the model is the Ubbink Victoria – 90 (Creative Pumps, 2020). The size and cost of this component were the main factors in deciding on this particular model. The next larger available selection was over a meter in diameter and 50% more expensive per housing, adding significantly to transportation and base cost. The diameter of the tank provides a primary design constraint for the dimensions of the pendulum and the power able to be generated for a given mass. An image of the housings is shown below in Figure 13, the CREO representation is shown in Figure 14, an engineering drawing is shown in Appendix I while the weight data is presented in section 6.6 Mass and Buoyancy and cost data included in Appendix J.

Figure 13: Image of the device housings

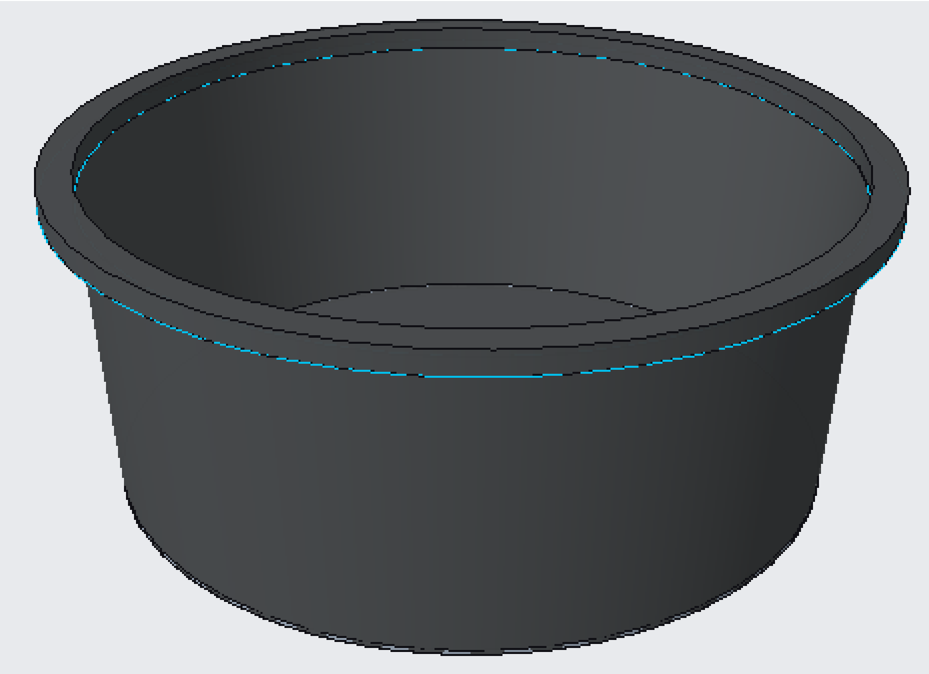

Figure 14: CREO representation of the device housing

The important dimensions of each half of the device housing are as follows:

Height	0.32 m
Width Max	0.88 m
Width Min	0.76 m
Thickness	0.03 m
Weight	5.85 kg
Displacement	150L ~ 0.15 m^3 ~ 150kg

5.3 Outer Frame

The outer frame attaches to the lower surface of the overhang feature of the lower device housing. It is designed in sections for ease of transport and assembly at the deployment site. The frame is made from painted aluminium with plastic floats at the end of each arm. This component has multiple functions, the primary one being to ensure the maximum deflection of the device for every wave event by extending the effective radius of the device. Secondly it acts as a stabilizer to prevent the entire body of the device from rotating due to the action of the pendulum, ensuring its maximum relative motion. Lastly it aids in alignment of the device in the wavefield. The CREO representation of the outer frame is shown in Figure 15, an engineering drawing is shown in Appendix while the weight data is presented in section 6.6 Mass and Buoyancy and cost data included in Appendix J.

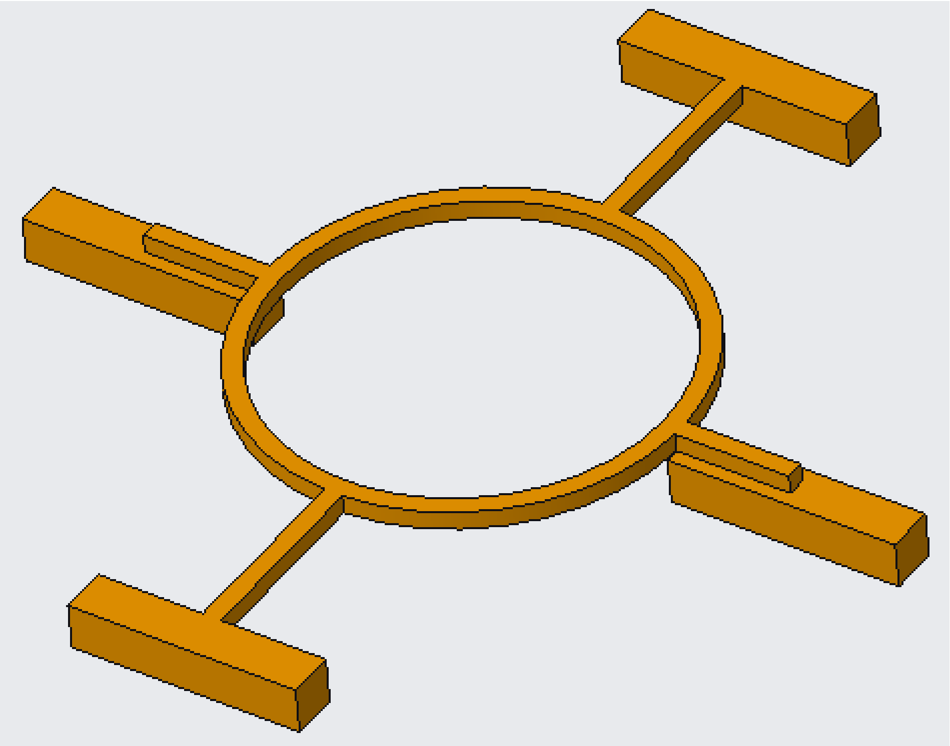

Figure 15: CREO representation of the outer frame

5.4 Inner Frame

The inner frame is designed to support the mechanical and electrical components of the device. It is constructed of painted aluminium 20 x 20 mm square bar and is fixed to the base of the lower device housing. Aluminium 6061 has a yield strength of 276 MPa and an ultimate strength of 310 MPa.

The working component mounting surfaces (bearings and generator) are 10 mm aluminium plate to be able to withstand transmitted forces. Passive components such as the battery and charge regulator are mounted on 3 mm aluminium plate.

The CREO representation of the inner frame is shown in Figure 16, an engineering drawing is shown in Appendix I, while the weight data is presented in section 6.6 Mass and Buoyancy and cost data included in Appendix J.

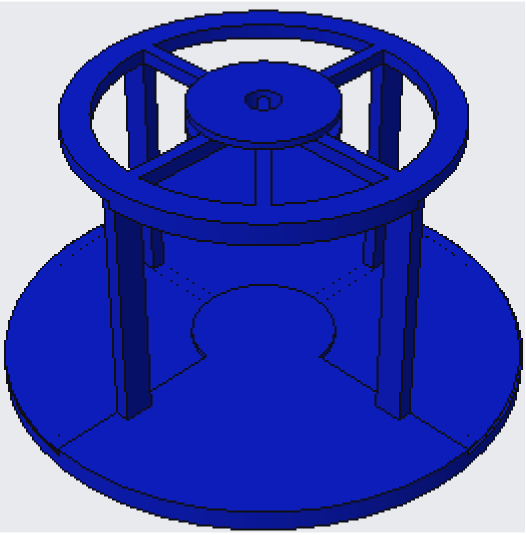

Figure 16: CREO representation of the inner frame

5.5 Generator

The purpose of the generator is to convert mechanical input to an electrical output, the model selection will be a primary driver for other design features based on rpm and torque requirements for the desired output. It is mounted to the lower 10 mm plate of the inner frame of the device and receives input from the compound gear set. The model selected was the NE-100, the device is designed for use in wind turbines and is rated to a nominal output of 100W at 750 rpm, it was the smallest available generator that suited the design requirements and provided performance specifications for use in analysis. The manufacturers device parameters are shown in Figure 17, with the performance graph shown in Figure 18.

Model	NE-100	NE-200	NE-300	NE-400
Rated power	100W	200W	300W	400W
Maximum power	130W	230W	350W	450W
Rated voltage	12/24V			
Rated speed	750rpm	1100rpm	750rpm	950rpm
Net weight	3.5kg	4kg	5kg	5.5kg
Size(Height*Diameter* Shaft length)	65x 145x 28mm		100x 175x 60mm	
lubricating	Fill grease			
Motor	Three-phase permanent magnet synchronous alternator			
Operating temperature	-40~80℃			

Figure 17: Generator parameters

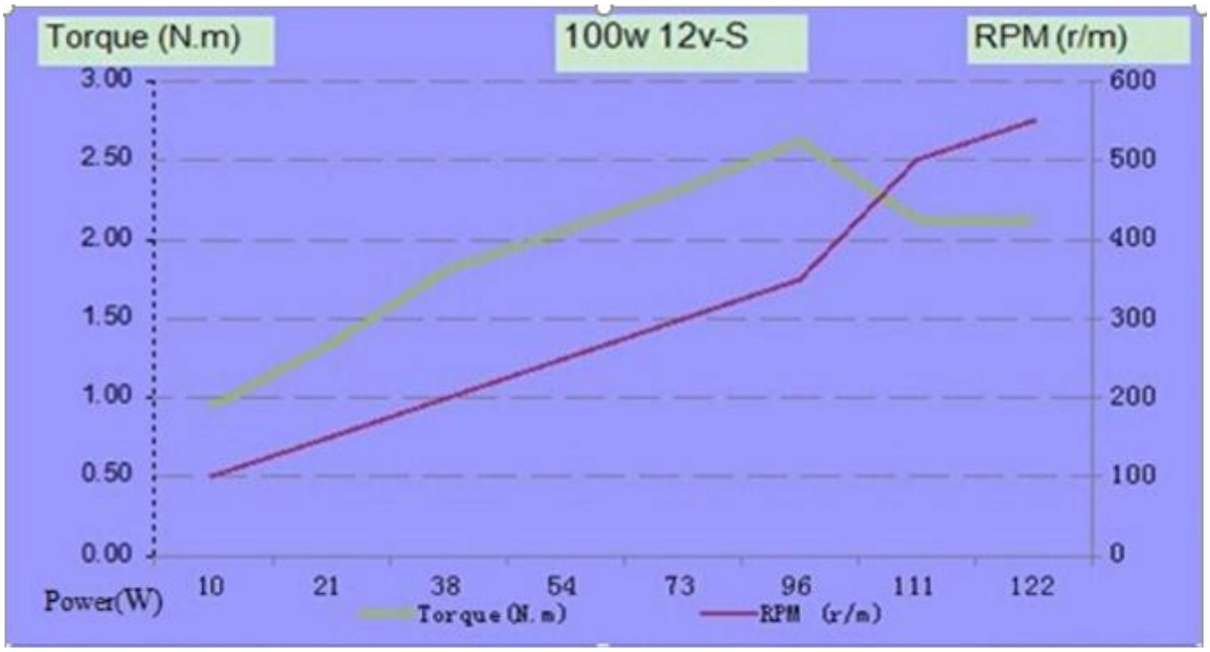

Figure 18: Generator performance chart

From these specifications the target output of up to 10 Watts there is a requirement of 100 rpm and 0.9 Nm of torque. The selected generator is shown in Figure 19, the CREO representation of the generator is shown in Figure 20, an engineering drawing is shown in Appendix I. The weight data is presented in section 6.6 Mass and Buoyancy and cost data included in Appendix J.

Figure 19: The prototype generator

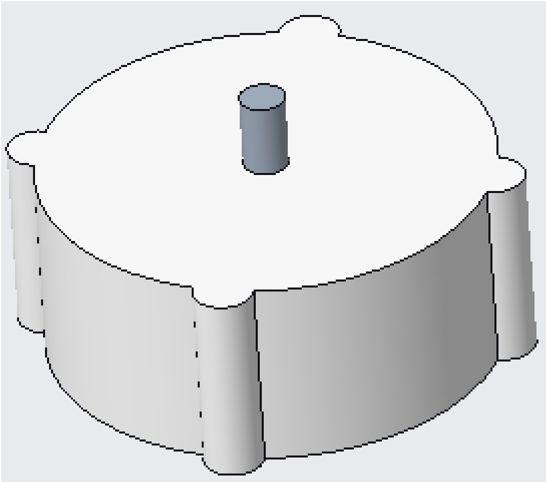

Figure 20: CREO representation of the generator

5.6 Pendulum Design

The pendulum device consists of a steel mass mounted to a steel square hollow bar. The bar is keyed to and mounts to central shaft that connects it to the compound gear set. The steel mass and shaft are designed such that the mass and centre of mass are located as per the mathematical model requirements of power and torque based on the selected generator. The mass is mounted on the bar so that it provides clearance from the compound gear set and is shaped to provide clearance from the housing. The yield strength of steel is given as 350 MPa, while the ultimate strength is 420 MPa.

The pendulum body is designed as a circular segment with the characteristics as shown below in Figure 21. Where *s* is the segment length, *a* is chord length, *h* is the segment height, *r* is the perpendicular distance from the centre of the circle to the chord, *R* is the circle radius and θ is the arc angle.

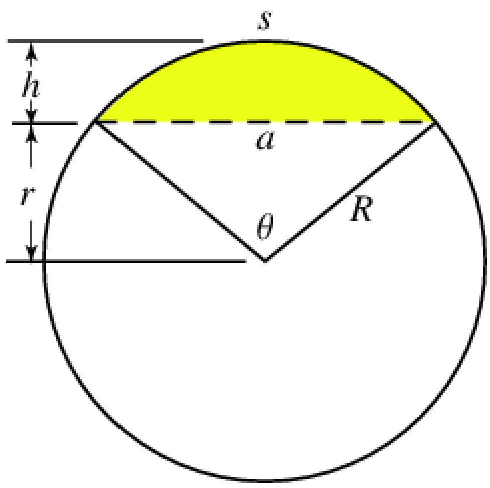

Figure 21: The primary dimensions of a circular segment (Wolfram Mathworld, 2020)

The length of the pendulum arm [m] is given by:

$$r = R \times COS\left(\frac{\theta}{2}\right) \tag{5.1}$$

where *R* is the radius [m]

θ is the arc angle [rad]

For the design, the length of the pendulum arm must be 0.290 m for clearance from inboard components, while the outer diameter of the pendulum must be 0.365 m in order to provide clearance from the outer case. So, from equation 5.1 the arc angle is:

$$0.290 = 0.365 \times COS\left(\frac{\theta}{2}\right)$$

$$\theta = 1.3051\,rad = 74.78°$$

The area of a circular segment [m^2] is given by:

$$A = {}^{1}/_{2} \times R^2 \times (\theta - SIN(\theta)) \tag{5.2}$$

where R is the radius [m]

θ is the arc angle [rad]

For the design the area is:

$$A = {}^{1}/_{2} \times 0.365^2 \times (1.3051 \times SIN(1.3051))$$

$$A = 0.0227 \text{ m}^2$$

The pendulum arm, a steel hollow square bar section measures 0.075 x 0.075 m with a wall thickness of 0.006 m. Its mass is 3.77 kg based on the density of steel being 7850 kg/m^3 for the arm length of 0.290 m. The arm has a keyway cut into it to engage with the gearset mechanism, it has rounded corners to reduce stress concentrators under load. The mass of the pendulum body is therefore 96.23 kg for the 100 kg design requirement. The arm is mounted on the body so as to provide clearance from the upper housing and lower the overall centre of mass of the device to prevent topple.

The required volume of steel [m^3] is given by:

$$V = m / \rho \tag{5.3}$$

where m is mass [kg]

ρ is density [kg/m^3] (7850 kg/m^3 for steel)

So, in the case of the design the required volume is:

$$V = 96.23 / 7850$$

$$V = 0.01226 \text{ m}^3$$

The required height of the mass [m] is given by:

$$H = \frac{V}{A} \tag{5.4}$$

where V is the mass volume [m^3]

A is the segment area [m^2]

So, for the design:

$$H = \frac{0.01226}{0.0227}$$

$$H = 0.540 \text{ m}$$

Given these measurements, the CREO representation of the pendulum is shown in Figure 22, an engineering drawing is shown in Appendix I. The weight data is presented in section 6.6 Mass and Buoyancy and cost data included in Appendix J.

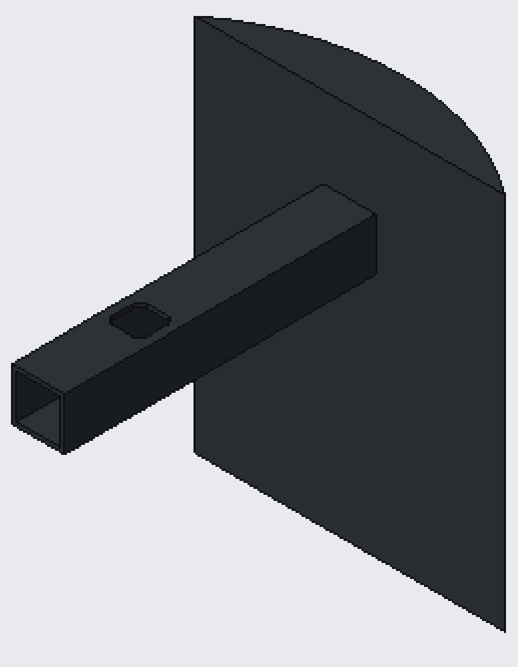

Figure 22: CREO representation of the pendulum

5.7 Compound Gearset

The compound gear set is required to multiply the rpm of the pendulum to a value sufficient to rotate the generator. A compound configuration was chosen to ensure compactness of the design. The gears are fixed to steel 20mm and 25mm circular steel shafts depending on the gear inner diameter, they are housed within the inner frame with input from the pendulum and output going directly to the generator. The section where the pendulum shaft connects to the gear set is made from machined 50 mm steel, it has a square section with rounded corners to reduce stress concentrations and act as a keyway, a threaded top section is used to secure the pendulum arm.

From the generator specifications the required ratio is 1:15 to ensure an rpm average above the minimum 100 rpm for 10W generation as per generator specifications across the operational envelope. The gears were chosen from the Hercus Engineering catalogue (Hercus, 2020). The largest gear tooth choice (MOD 4) was made to ensure design durability, the MOD 4 specification sheet is included in Appendix K. The smallest diameter gear size was 12 teeth, this was selected for clearance reasons and the larger gears subsequently calculated to be as close to one another as possible to achieve the ratio.

Initial ratio:

$$1 : 15$$

Becomes two gear sets of:

$$1 : 4 \quad 4 : 15$$

As the smallest gears are 12 teeth, the ratio becomes:

$$12 : 48 \quad 12 : 45$$

Therefore, the required gears were 2 x 12 teeth gears, 1 x 48 tooth gear and 1 x 45 tooth gear. Images of the two 12 teeth gears are shown in Figure 23, while Figures 24 and 25 show the 45 and 48 tooth gears respectively. The CREO representation of the compound gear set is shown in Figure 26, an engineering drawing is shown in Appendix I. The weight data is presented in section 6.6 Mass and Buoyancy and cost data included in Appendix J.

Figure 23: The 12 toothed gear sets

Figure 24: The 45 toothed gear

Figure 25: The 48 toothed gear

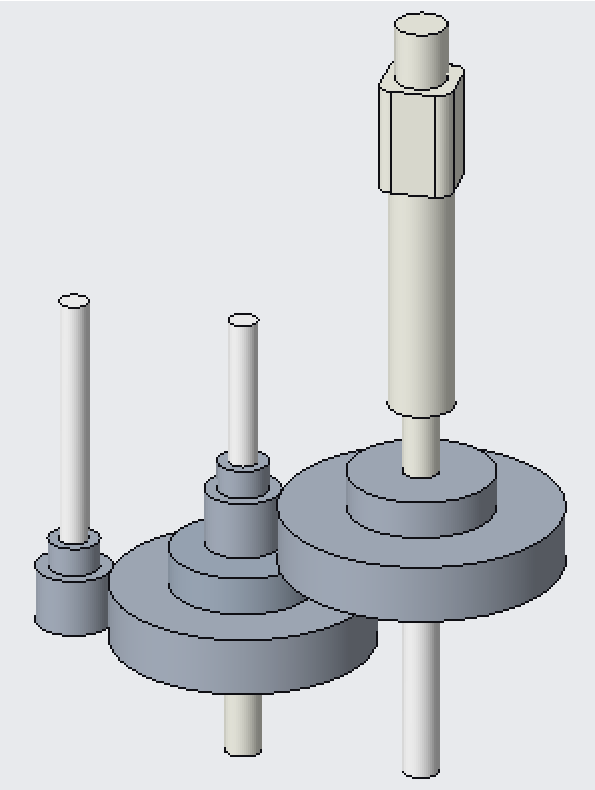

Figure 26: CREO representation of the compound gear set

5.8 Voltage regulator/controller

The voltage regulator/controllers' purpose is to control the charge delivered to the battery; it also prevents overcharging. The device converts the 3-phase power of the generator to single phase for battery charging. The model chosen was the BLW-DC12/24, it is mounted to the inner frame of the device. The regulator is pictured below in Figure 27, the CREO representation is shown in Figure 28, an engineering drawing is shown in Appendix I. The weight data is presented in section 6.6 Mass and Buoyancy and cost data included in Appendix J.

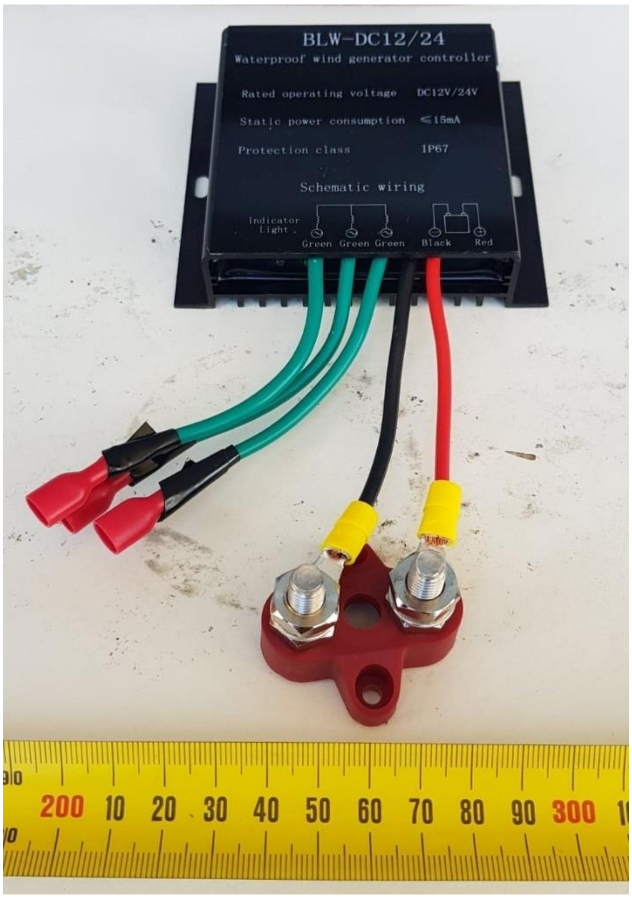

Figure 27: The voltage regulator/controller

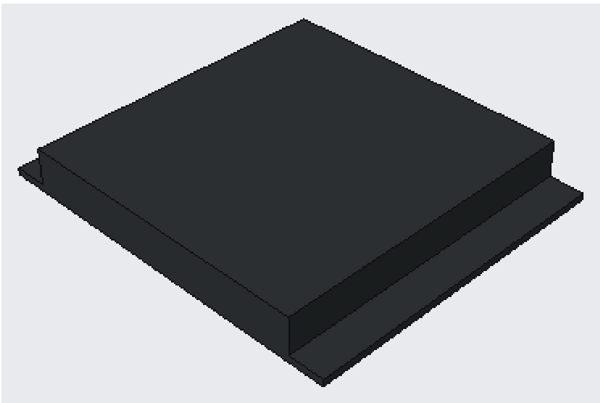

Figure 28: CREO representation of the voltage regulator/controller

5.9 Battery

The purpose of the battery is for power storage and delivery. It will provide sustained 12 Volt DC power to the sensors regardless of the sea-state. For the prototype and testing a relatively small battery was selected, for real-world applications a larger device would be used for extended periods of calm sea-states. The prototype uses a 12 V 9-amp hour battery, mounted to the inner frame of the device.

The battery is pictured below in figure 29, the CREO representation is shown in Figure 30, an engineering drawing is shown in Appendix I. The weight data is presented in section 6.6 Mass and Buoyancy and cost data included in Appendix J.

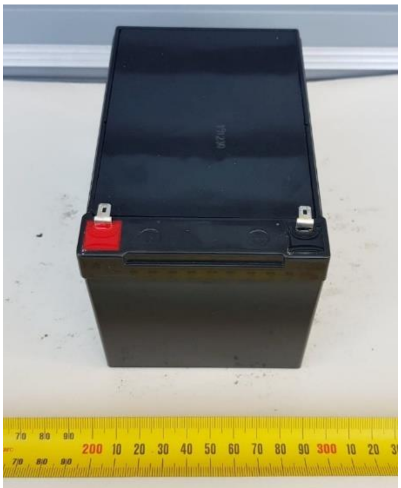

Figure 29: The prototype battery

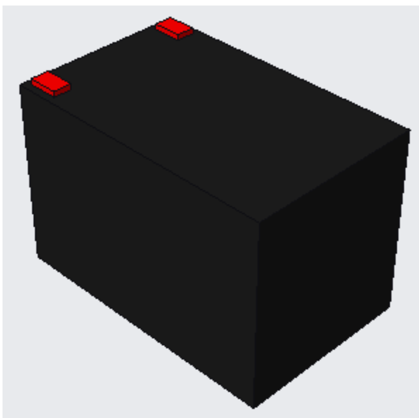

Figure 30: CREO representation of the battery

5.10 Bearings

The bearings are required to support the rotational components of the design. The 2 bolt flange types supporting the compound gear set were selected where clearances demanded and for compactness of the design. The lower most bearing of the input shaft features a 4 bolt flange to aid in load support. The internal diameters are dependent on the shaft sizes required for the gears, being either 20 mm or 25 mm. Where the main input shaft passes through the inner frame however it is supported by 2 four bolt flanged bearings of 45 mm internal diameter. The bearings were all sourced through RS Components. An example of a 25 mm shaft diameter 2 bolt flange bearing is shown below in Figure 31, the bearings CREO representations are shown in Figures 32, 33 and 34. The 2 bolt and 4 bolt flange datasheets are included in Appendixes L and M. The weight data is presented in section 6.6 Mass and Buoyancy and cost data included in Appendix J.

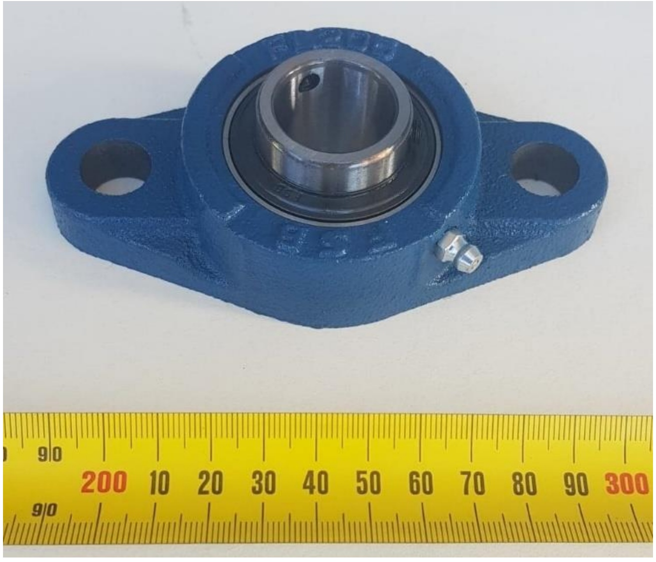

Figure 31: A 25 mm shaft diameter 2 bolt flange bearing

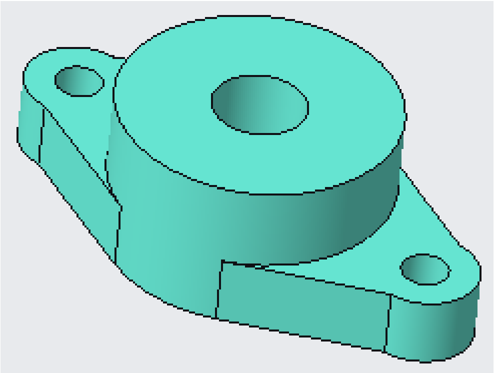

Figure 32: CREO representation of the 2 bolt flange 20mm internal diameter bearing

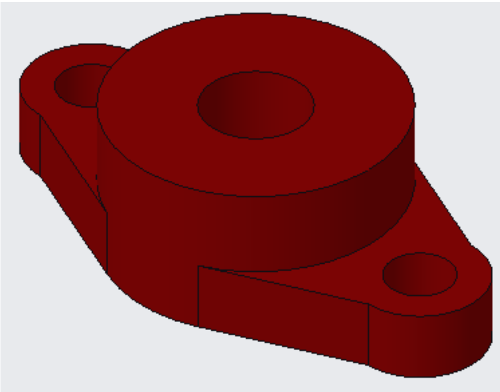

Figure 33: CREO representation of the 2 bolt flange 25mm internal diameter bearing

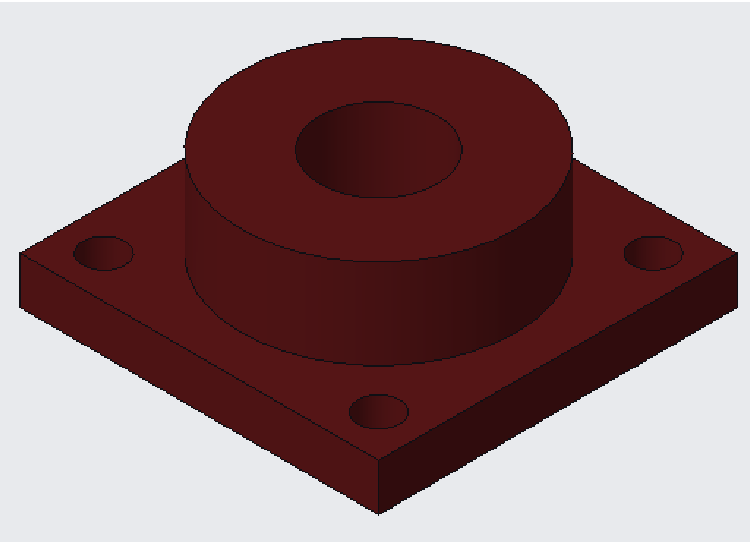

Figure 34: CREO representation of the 4-bolt flange 45mm internal diameter bearing

5.10 Testing equipment

Although not required for final design deployment, it was important to verify the design by what data was available in lieu of assembled device testing. The data of most importance was related to structural integrity and deflection at a given load and the power output of the device for a given rpm. Structural analysis was carried out via the CAD software CREO, power output monitoring and logging was achieved through the use of an automotive battery charge monitor and an rpm sensor used to measure cadence. The sensors were selected for their Wi-Fi and data logging capabilities, such that data could be collected whilst the device was sealed and deployed.

For bench level testing multi-meters and resistors were used to measure generator performance in conjunction with an electric drill and the rpm sensor.

The battery charge monitor selected was a “12V battery monitor with Bluetooth technology” from electronics supplier Jaycar, it is mounted to the inner frame it is pictured below in Figure 35, its CREO representation is in Figure 36. The weight data is presented in section 6.6 Mass and Buoyancy and cost data included in Appendix J.

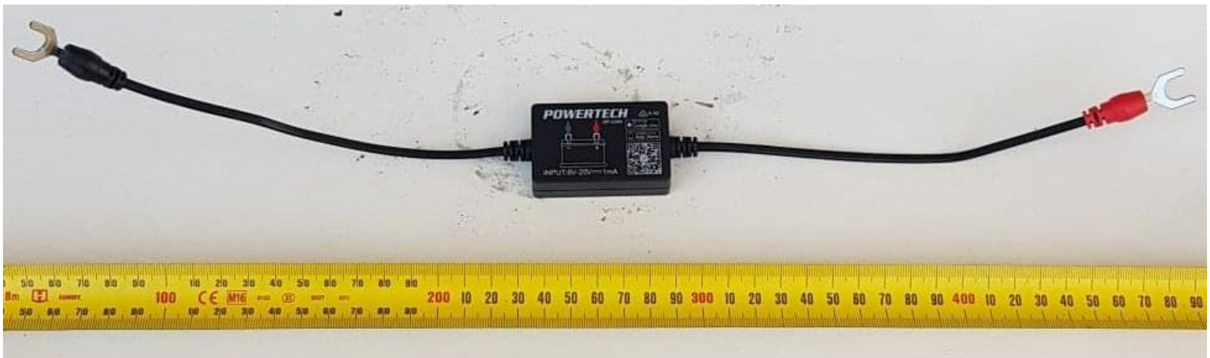

Figure 35: The battery charge monitor

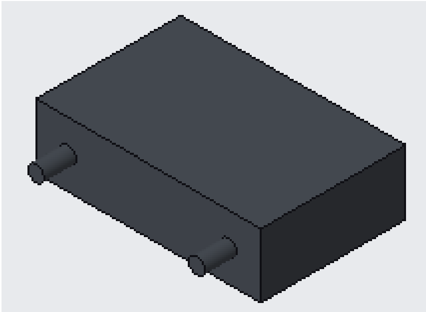

Figure 36: CREO representation of the charge monitor

The battery rpm sensor selected was the "Wahoo RPM Cadence Sensor with Bluetooth/ANT+", it was mounted to the electric drill for bench level testing and to the generator input shaft during deployment. It is pictured below in Figure 37, its CREO representation is in Figure 38. The weight data is presented in section 6.6 Mass and Buoyancy and cost data included in Appendix J.

Figure 37: The rpm monitor

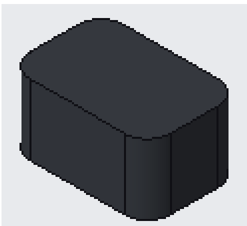

Figure 38: CREO representation of the rpm monitor

5.11 Conclusion

This chapter detailed the major functional and physical characteristics of the device components. Figures 39 and 40 show the final assembled CREO representations of the device. In lieu of real-world testing, component bench level testing was carried out to verify design choices, data for these tests is provided in the following chapter, Chapter 6 - Design Testing.

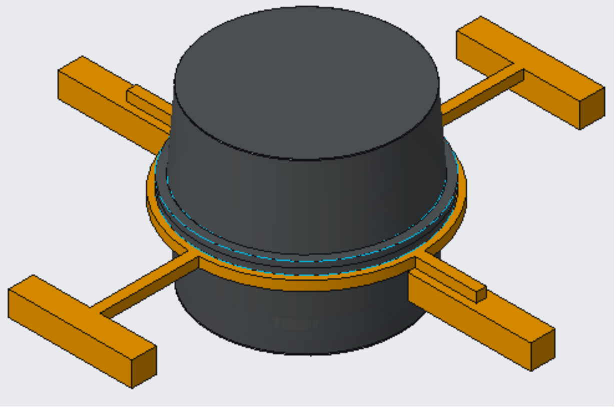

Figure 39: The assembled WEC design

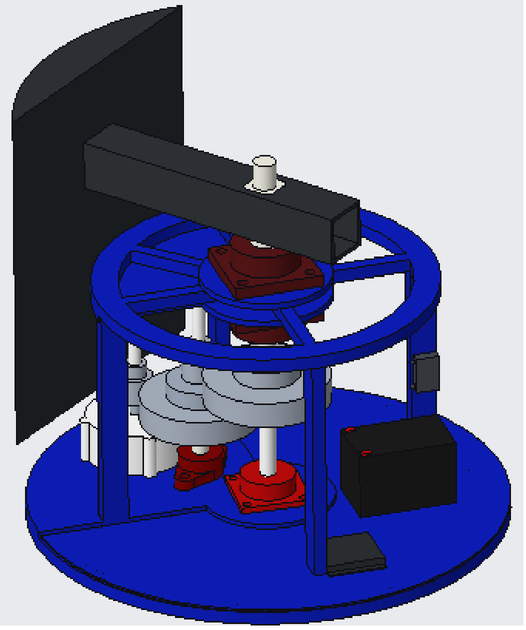

Figure 40: Internal details of the WEC design

Chapter 6 – Design testing

6.1 Chapter overview

This section details the testing of critical design components. It provides an overview of the testing methods and the results; analysis of the data will be carried out in Chapter 7 - Results and Discussion. The design is engineered for a safety factor of 10 to ensure tolerance for large wave events. Simulations were run using CREO computer aided drawing software for the critical design features of the inner frame, input shaft and pendulum device. Bench level testing was carried out on the generator and an analysis of the mass and buoyancy of the completed device carried out.

6.2 Inner frame

Based on the physical properties of the inner frame construction detailed in Section 5.4, Inner Frame, during normal operation or static loading the maximum stress on the inner frame is 9.2 MPa as shown in Figure 41, it is located where the vertical supports connect to the upper frame. There is a maximum deflection of 0.043 mm as shown in Figure 42. The force of 981 N acts through the upper bearing mounting plates through the rest of the inner frame structure. With a steel having a yield strength of 276 MPa, the design is well within requirements. The minor deflection of the inner frame also maintains required clearances.

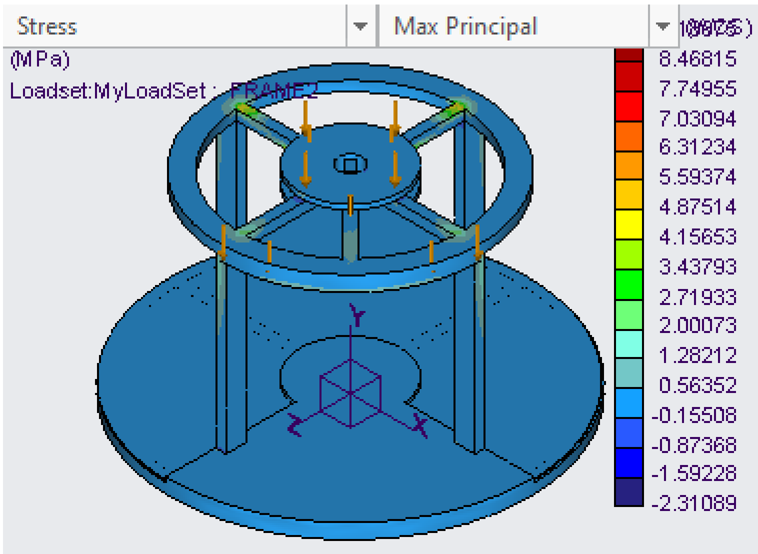

Figure 41: Maximum principle stress (9.2 MPa) of inner frame under normal conditions

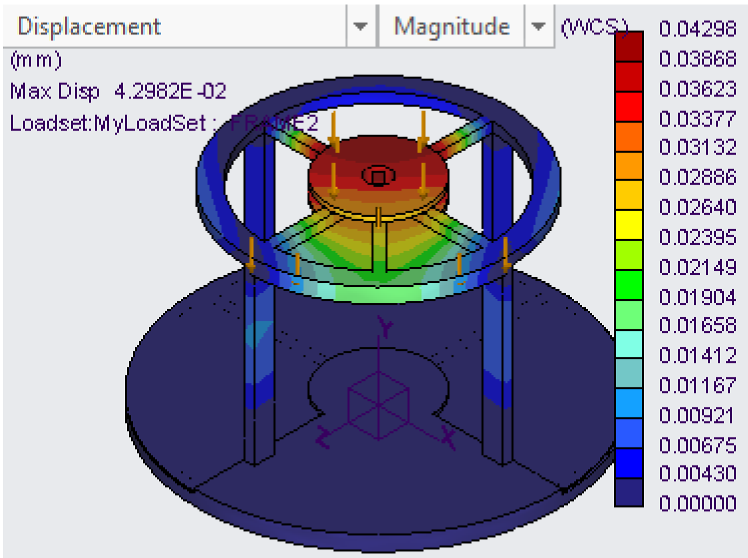

Figure 42: Deflection (0.043 mm) of inner frame under normal conditions

The maximum stress of 251 MPa occurs on the inner frame when the 10g force (9810 N) is applied through the upper mounting plates, perpendicular to the central axis as shown in Figure 43, it is located where the vertical supports connect to the upper frame. This stress remains below the yield stress of 276 MPa for aluminium 6061. The maximum deflection is 2.33 mm as shown in Figure 44, this maintains the required clearances for other components.

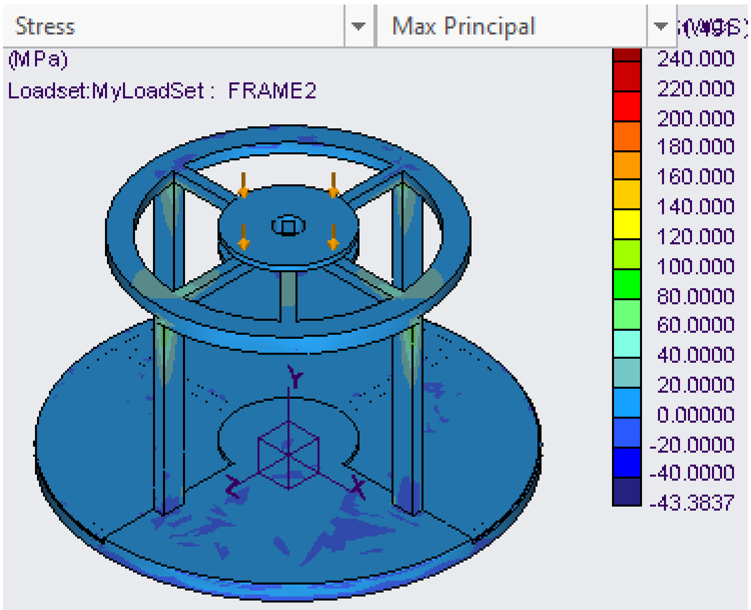

Figure 43: Maximum principle stress (251 MPa) of inner frame subjected to 10g

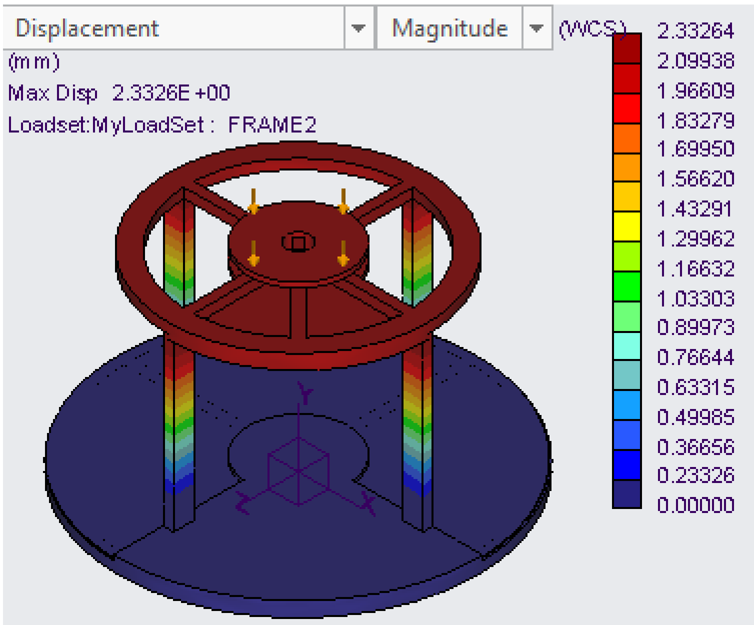

Figure 44: Deflection (2.33 mm) of inner frame subjected to 10g

6.3 Input Shaft

Based on the physical properties of the pendulum shaft as detailed in Section 5.7 Compound Gearset, during normal operation or static loading the maximum stress on the machined steel shaft is 9.96 MPa. It occurs where the shaft exits and is constrained by the upper bearing, as shown in Figure 45. Under these conditions there is a maximum deflection of 0.004 mm as shown in Figure 46.

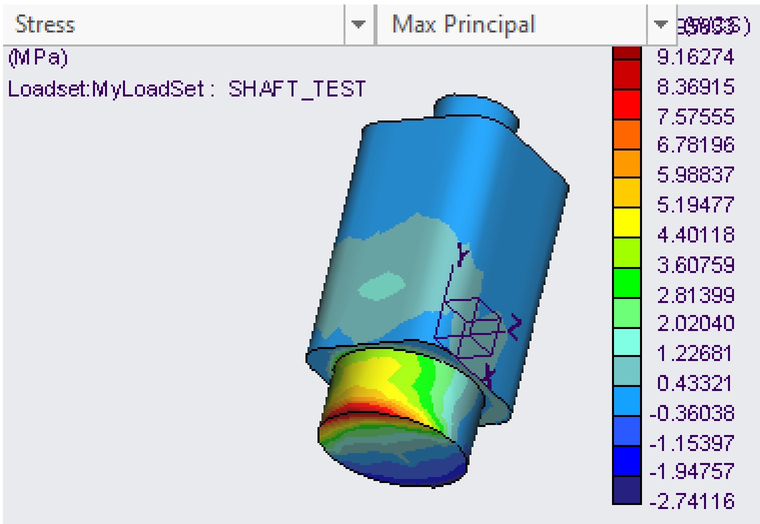

Figure 45: Maximum principle stress (9.96 MPa) of input shaft under normal conditions

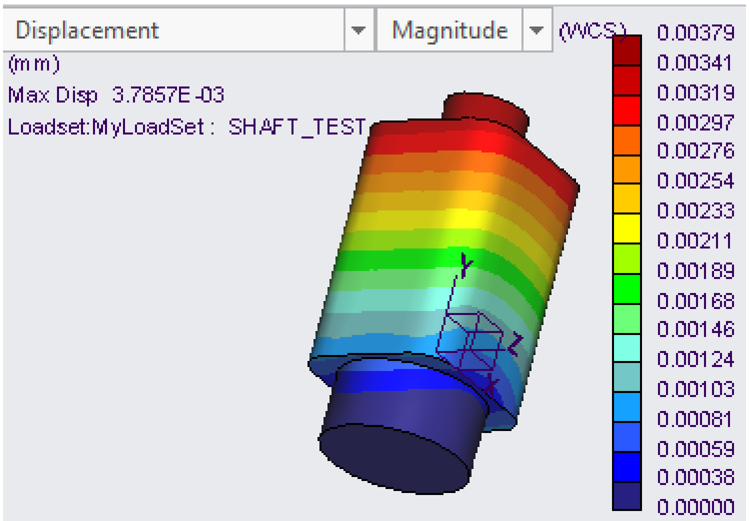

Figure 46: Deflection (0.004 mm) of input shaft under normal conditions

The maximum stress of 314 MPa occurs on the shaft when the 10g force (9810N) is applied through the mass, perpendicular to the flat machined surface and is concentrated where the shaft exits and is constrained by the upper bearing, as shown in Figure 47. This stress is below the yield 350 MPA stress of steel. The maximum deflection is 0.86 mm as shown in Figure 48, this deflection still allows for clearance from other internal components.

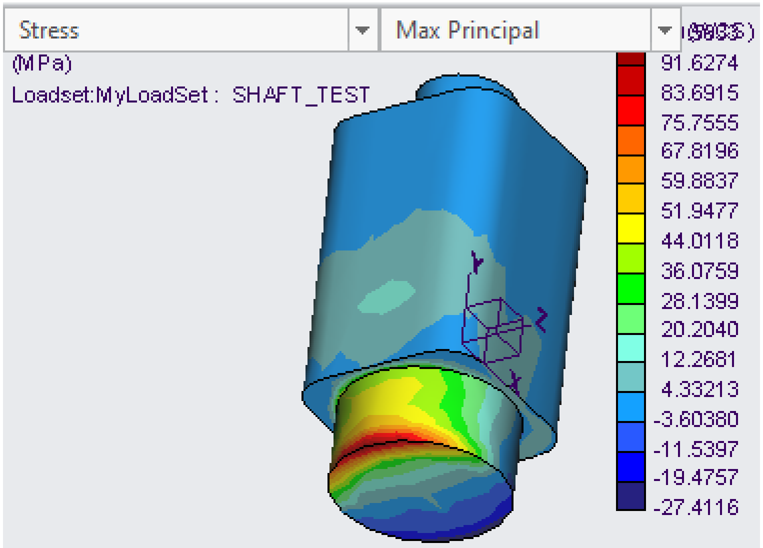

Figure 47: Maximum principle stress (314 MPa) of input shaft subjected to 10g

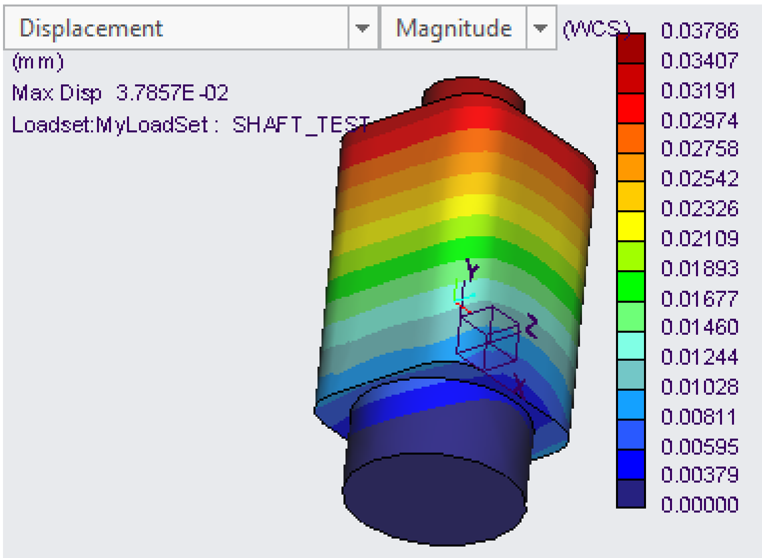

Figure 48: Deflection (0.86 mm) of input shaft subjected to 10g

6.4 Pendulum

Based on the physical properties of the pendulum design as detailed in Section 5.6 Pendulum Design, during normal operation the maximum stress on the pendulum is 31 MPa as shown in Figure 49, with a maximum deflection of 0.086 mm as shown in Figure 50. Stresses are concentrated around the radii of the shaft keyway while the maximum deflection is at the base of the pendulum body.

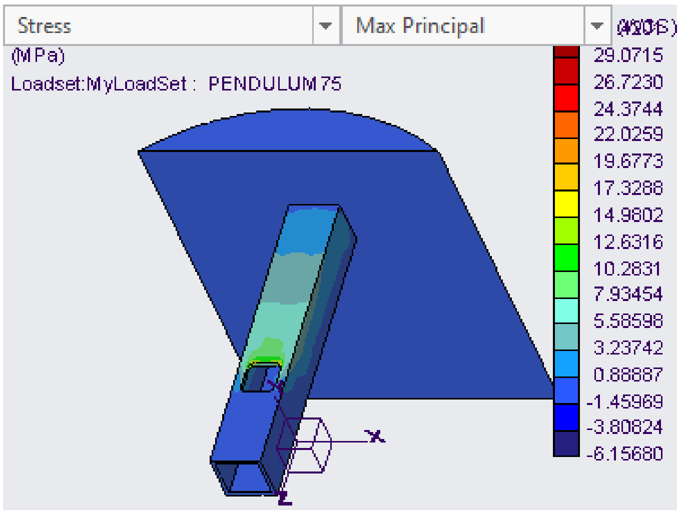

Figure 49: Maximum principle stress (31 MPa) of pendulum under normal conditions

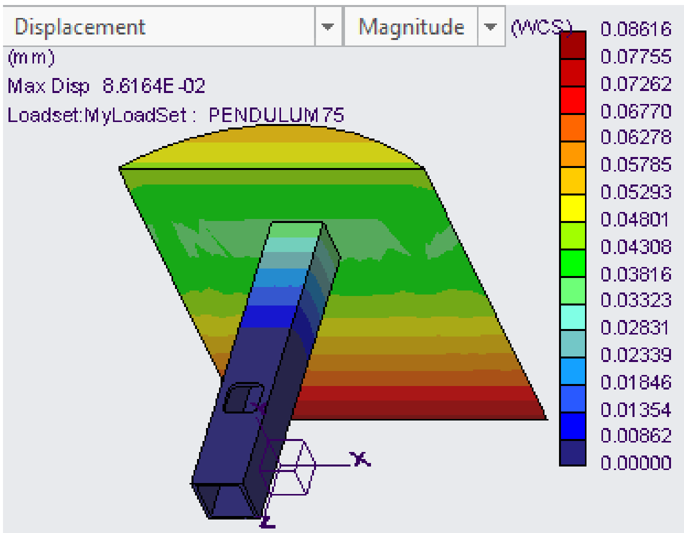

Figure 50: Deflection (0.086 mm) of pendulum under normal conditions

The maximum stress of 314 MPa occurs on the pendulum when the 10g (9810 N) force is applied through the mass, directly downwards, it is located at the corners of the shaft cut out and is shown in Figure 51. This stress is below the 350 MPA yield stress of steel. The maximum deflection is 0.86 mm as shown in Figure 52.

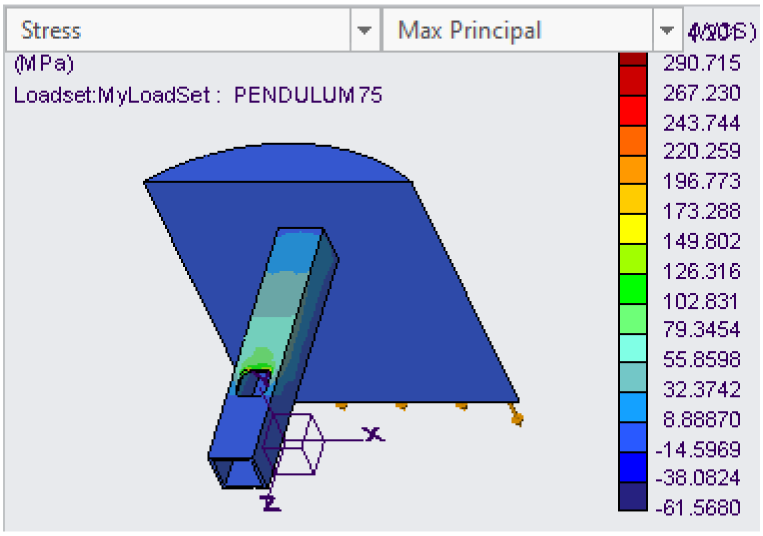

Figure 51: Maximum principle stress (314 MPa) of pendulum subjected to 10g

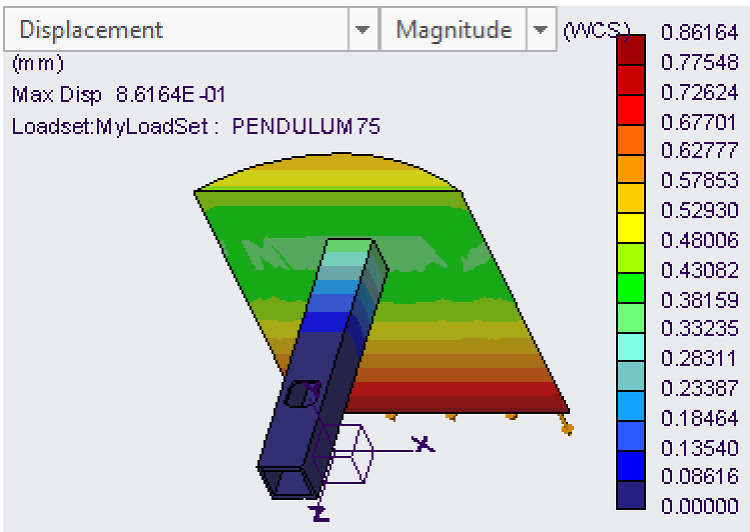

Figure 52: Deflection (0.86 mm) of pendulum subjected to 10g

6.5 Electrical System

The electrical components of the design are the generator, charge controller, rpm sensor and voltage monitor. These components were tested on the bench level to verify the design in lieu of fully assembled testing. A diagram of the test assembly structure is shown below in Figure 53, the physical layout is shown in Figure 54.

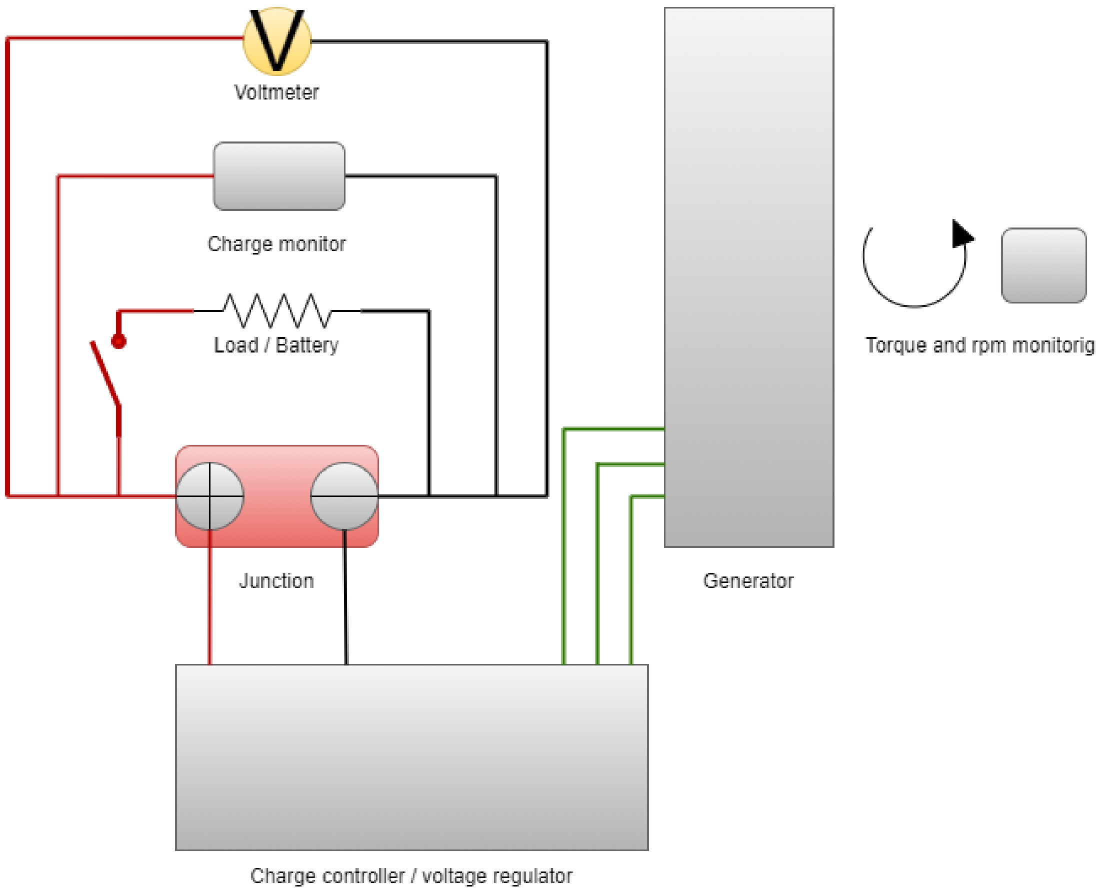

Figure 53: The electrical component test structure

Figure 54: The electrical component test assembly

Testing was performed though input of incremental 10 rpm steps across the operating range of 90 to 180 rpm for a 5 to 10 second wave period, geared 1:15. Using a known resistance, the power output, P in Watts [W] of the generator for a given load could be calculated from equation 6.1.

$$P = V^2 / R \tag{6.1}$$

Where V is the measured voltage [V]

R is the known resistance / load in ohms [Ω]

The results of this analysis are shown below in Table 5.

Table 5: Results of generator performance testing

Resistance (ohm)	1 (1.0 ohm measured)		10 (10.3 ohm measured)	
RPM	Voltage (V)	Calculated Power (W)	Voltage (V)	Calc Power (W)
90	0.665	0.442	1.07	0.116
100	0.832	0.692	1.44	0.209
110	0.98	0.960	1.75	0.309
120	1.143	1.306	2.12	0.454
130	1.389	1.929	2.3	0.534
140	1.534	2.353	2.45	0.606
150	1.728	2.986	2.83	0.809
160	1.92	3.686	3.03	0.927
170	2.2	4.840	3.38	1.154
180	2.56	6.554	3.79	1.451
Average power		2.575		0.657

The average outputs for the 1- and 10-ohm resisters were 2.575 and 0.657 Watts, respectively. The resistors were measured directly at 1.0 and 10.3 ohms. These results will be discussed in Chapter 7 – Results and Discussion.

The user interface for the rpm sensing and logging is through the “wahoo” application. Instantaneous monitoring can be made as shown in Figure 55, while data logging can also be achieved across a period of operation as shown in Figure 56.

Figure 55: Wahoo application user interface for instantaneous rpm monitoring

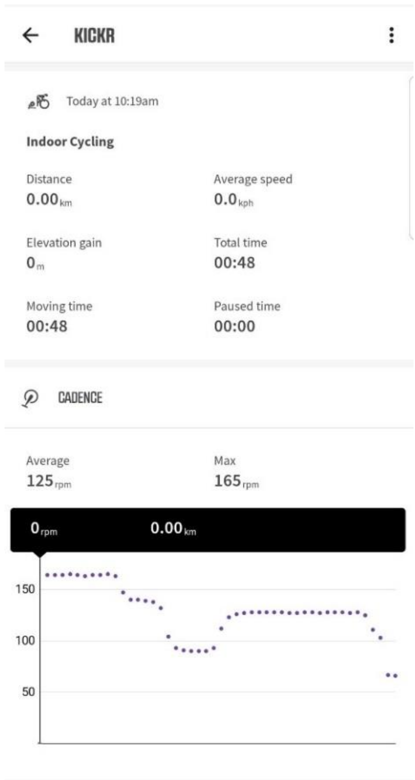

Figure 56: Wahoo application user interface for data logging

The battery charge monitor user interface in use on a vehicle can be seen below in Figure 57. Its purpose is to provide an output of battery charge rate and instantaneous battery voltage. Testing of the device indicated battery voltage accurately, through sustained operation once deployed and under load, the battery level could be monitored and indicate that the WEC device output is sufficient.

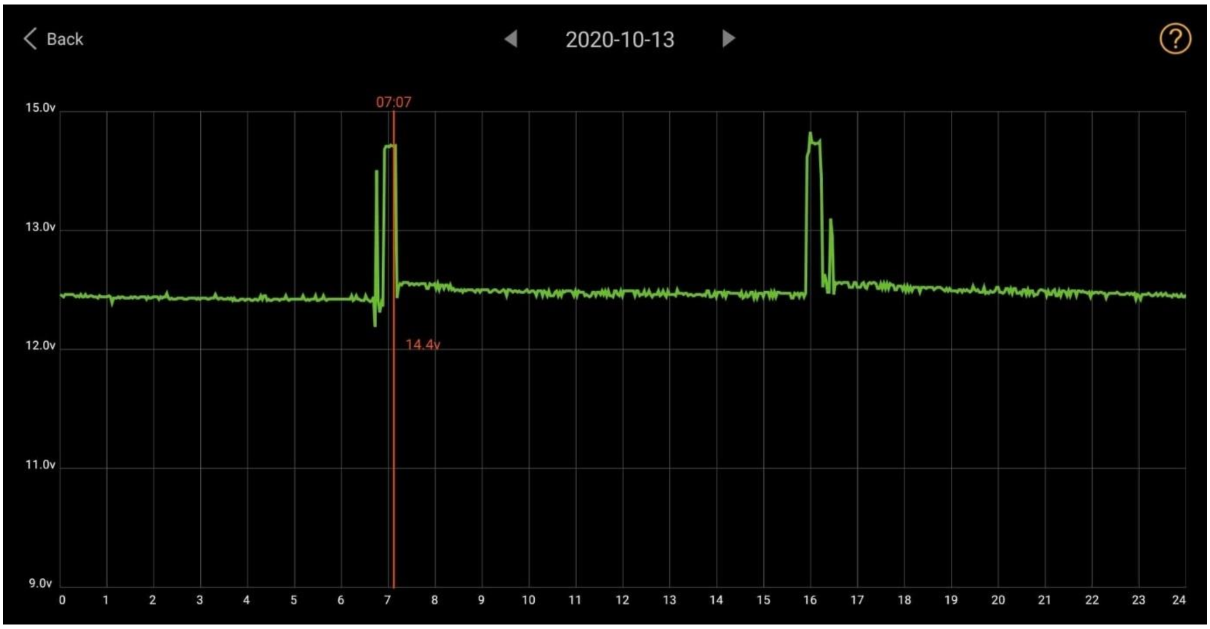

Figure 57: Battery charge monitor interface

6.6 Mass and Buoyancy

The final modelled mass of the assembled WEC is 178.28 kg, as shown in Table 6. Each housing displaces 150 L of water, meaning that the device is sufficiently buoyant under operating conditions.

Table 6: WEC prototype mass data

Item	Qty	Model	Weight each (kg)	Weight total (kg)
Pre-formed pond	2	Victoria-90	5.85	11.70
Aluminium square bar 20x20mm	4	SQR20.00MI4L	4.32	16.81
Aluminium plate 10mm 5x1200x2400	1	S3.012002400MI2FD	39.02	3.72
Aluminium plate 3mm 3x1200x2400	1	S5.012002400MI2FD	23.41	2.21
Steel Plate 75x25	9.743	75x25	15.07	96.23
Steel square tube 75x75mm	0.445	75x75x6	12.00	3.77
Steel shaft 50mm	0.28	50 BLACK ROUND K1045	4.42	1.24
Steel shaft 25mm	0.317	27 BLACK ROUND 300+ AS3679/300	1.46	0.46
Steel shaft 20mm	0.26	20 BLACK ROUND 300+ AS3679/300	0.66	0.17
Sealant	2	1230090	0.30	0.60
Rubber seal	3	3970014	0.30	0.90
Attaching hardware	1	ASSORTED	3.00	3.00
12 toothed gear	2	12M40S	3.54	7.08
45 toothed gear	1	45M40S	8.70	8.70
48 toothed gear	1	48M40S	9.70	9.70
Generator	1	NE-100	3.50	3.50
Voltage regulator	1	BLW-DC12/24	0.63	0.63
Battery	1	SB2487	3.49	3.49
Charge monitor	1	QP2265	0.03	0.03
RPM sensor	1	192296	0.01	0.01
20mm bearing 2 bolt	2	UCFL204	0.44	0.87
25mm bearing 2 bolt	1	UCFL205	0.60	0.60
25mm bearing 4 bolt	1	UCF205	0.65	0.65
45mm bearing 4 bolt	2	UCFC209	0.85	1.70
Electronic components	1	ASSORTED	0.50	0.50
			TOTAL	178.28

6.7 Conclusion

This section detailed the methods used and the results of testing critical design elements of the WEC device. These results will be analysed in the following chapter, Chapter 7 - Results and Discussion.

Chapter 7 - Results and Discussion

7.1 Chapter Overview

This chapter contains an analysis of the validity of the design, it presents an examination of the data generated through mathematical modelling of the WEC performance as detailed in Chapter 4 – Mathematical Modelling. It examines results of the testing performed in Chapter 6 – Design Testing, the limitations of the prototype testing and finally the design cost analysis.

7.2 Model Validity Analysis

The mathematical modelling process has been previously detailed in Chapter 4 – Mathematical Modelling. For the pendulum device, the primary characteristics are the pendulum mass and the distance to the masses centre. The modelling provides outputs for combinations of significant wave height and period. The model ranges from 0 to 6 metres in significant wave height and 0 to 12.5 seconds wave period as per the upper and lower data limits of the AREMI database (AREMI, 2020), these results are presented in full in Appendix N.

In section 3.4 Deployment Characteristics however, it was explained that the designs expected operational envelope was determined to be sea-states between 2 to 6-meter wave height with a 5 to 10 second wave period. Based on a 100kg pendulum mass with a centre of mass of 0.3 meters the expected performance of the WEC design is examined here in Tables 7 through 15.

Table 7: WEC operational envelope wavelength

Wave length (m)											
	50th Percentile of Wave Energy Period (s)										
50th Percentile of Significant Wave Height (m)	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
2.0	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00
2.4	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00
2.8	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00
3.2	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00
3.6	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00
4.0	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00
4.4	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00
4.8	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00
5.2	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00
5.6	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00
6.0	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00

Table 8: WEC operational envelope wave angle

Angle of wave (Degrees)											
	50th Percentile of Wave Energy Period (s)										
50th Percentile of Significant Wave Height (m)	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
2.0	6	5	4	3	3	3	2	2	2	2	1
2.4	7	6	5	4	4	3	3	2	2	2	2
2.8	8	7	6	5	4	4	3	3	3	2	2
3.2	9	8	7	6	5	4	4	3	3	3	2
3.6	10	9	7	6	5	5	4	4	3	3	3
4.0	12	10	8	7	6	5	5	4	4	3	3
4.4	13	11	9	8	7	6	5	4	4	4	3
4.8	14	11	10	8	7	6	5	5	4	4	4
5.2	15	12	10	9	8	7	6	5	5	4	4
5.6	16	13	11	10	8	7	6	6	5	5	4
6.0	17	14	12	10	9	8	7	6	5	5	4

Table 9: WEC operational envelope effective height

Effective height for PE harvesting (m)											
	50th Percentile of Wave Energy Period (s)										
50th Percentile of Significant Wave Height (m)	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
2.0	0.06	0.05	0.04	0.04	0.03	0.03	0.02	0.02	0.02	0.02	0.02
2.4	0.07	0.06	0.05	0.04	0.04	0.03	0.03	0.03	0.02	0.02	0.02
2.8	0.09	0.07	0.06	0.05	0.04	0.04	0.03	0.03	0.03	0.02	0.02
3.2	0.10	0.08	0.07	0.06	0.05	0.04	0.04	0.03	0.03	0.03	0.02
3.6	0.11	0.09	0.08	0.07	0.06	0.05	0.04	0.04	0.03	0.03	0.03
4.0	0.12	0.10	0.08	0.07	0.06	0.05	0.05	0.04	0.04	0.03	0.03
4.4	0.13	0.11	0.09	0.08	0.07	0.06	0.05	0.05	0.04	0.04	0.03
4.8	0.14	0.12	0.10	0.09	0.07	0.07	0.06	0.05	0.05	0.04	0.04
5.2	0.15	0.13	0.11	0.09	0.08	0.07	0.06	0.06	0.05	0.04	0.04
5.6	0.17	0.14	0.12	0.10	0.09	0.08	0.07	0.06	0.05	0.05	0.04
6.0	0.18	0.15	0.13	0.11	0.09	0.08	0.07	0.06	0.06	0.05	0.05

Table 10: WEC operational envelope available PE per wave

Available PE per wave (J)												
		50th Percentile of Wave Energy Period (s)										
		5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
50th Percentile of Significant Wave Height (m)	2.0	120.11	99.43	83.63	71.31	61.52	53.61	47.13	41.75	37.25	33.43	30.17
	2.4	143.80	119.13	100.25	85.51	73.78	64.30	56.53	50.09	44.69	40.11	36.20
	2.8	167.32	138.72	116.81	99.66	86.01	74.97	65.93	58.42	52.12	46.79	42.23
	3.2	190.63	158.21	133.29	113.77	98.22	85.63	75.31	66.74	59.55	53.46	48.25
	3.6	213.72	177.56	149.70	127.84	110.39	96.27	84.67	75.05	66.97	60.12	54.27
	4.0	236.55	196.76	166.02	141.84	122.53	106.88	94.03	83.35	74.38	66.78	60.29
	4.4	259.11	215.80	182.24	155.79	134.63	117.47	103.36	91.63	81.78	73.44	66.30
	4.8	281.37	234.67	198.35	169.67	146.69	128.02	112.67	99.91	89.18	80.08	72.31
	5.2	303.32	253.36	214.36	183.48	158.70	138.55	121.97	108.16	96.56	86.72	78.31
	5.6	324.93	271.84	230.24	197.21	170.66	149.04	131.23	116.41	103.93	93.35	84.30
	6.0	346.20	290.12	245.99	210.86	182.57	159.50	140.48	124.63	111.29	99.97	90.29

Table 11: WEC operational envelope Watts

Watt output (W)												
		50th Percentile of Wave Energy Period (s)										
		5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
50th Percentile of Significant Wave Height (m)	2.0	24.02	18.08	13.94	10.97	8.79	7.15	5.89	4.91	4.14	3.52	3.02
	2.4	28.76	21.66	16.71	13.15	10.54	8.57	7.07	5.89	4.97	4.22	3.62
	2.8	33.46	25.22	19.47	15.33	12.29	10.00	8.24	6.87	5.79	4.92	4.22
	3.2	38.13	28.76	22.22	17.50	14.03	11.42	9.41	7.85	6.62	5.63	4.83
	3.6	42.74	32.28	24.95	19.67	15.77	12.84	10.58	8.83	7.44	6.33	5.43
	4.0	47.31	35.77	27.67	21.82	17.50	14.25	11.75	9.81	8.26	7.03	6.03
	4.4	51.82	39.24	30.37	23.97	19.23	15.66	12.92	10.78	9.09	7.73	6.63
	4.8	56.27	42.67	33.06	26.10	20.96	17.07	14.08	11.75	9.91	8.43	7.23
	5.2	60.66	46.07	35.73	28.23	22.67	18.47	15.25	12.73	10.73	9.13	7.83
	5.6	64.99	49.43	38.37	30.34	24.38	19.87	16.40	13.69	11.55	9.83	8.43
	6.0	69.24	52.75	41.00	32.44	26.08	21.27	17.56	14.66	12.37	10.52	9.03

Table 12: WEC operational envelope peak torque

Peak Torque (Nm)												
		50th Percentile of Wave Energy Period (s)										
		5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
50th Percentile of Significant Wave Height (m)	2.0	30	25	21	18	15	13	12	10	9	8	8
	2.4	36	30	25	21	18	16	14	13	11	10	9
	2.8	42	35	29	25	22	19	16	15	13	12	11
	3.2	48	40	33	28	25	21	19	17	15	13	12
	3.6	53	44	37	32	28	24	21	19	17	15	14
	4.0	59	49	42	35	31	27	24	21	19	17	15
	4.4	65	54	46	39	34	29	26	23	20	18	17
	4.8	70	59	50	42	37	32	28	25	22	20	18
	5.2	76	63	54	46	40	35	30	27	24	22	20
	5.6	81	68	58	49	43	37	33	29	26	23	21
	6.0	87	73	61	53	46	40	35	31	28	25	23

Table 13: WEC operational envelope geared torque

Geared Torque (Nm)											
	50th Percentile of Wave Energy Period (s)										
50th Percentile of Significant Wave Height (m)	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
2.0	2.00	1.66	1.39	1.19	1.03	0.89	0.79	0.70	0.62	0.56	0.50
2.4	2.40	1.99	1.67	1.43	1.23	1.07	0.94	0.83	0.74	0.67	0.60
2.8	2.79	2.31	1.95	1.66	1.43	1.25	1.10	0.97	0.87	0.78	0.70
3.2	3.18	2.64	2.22	1.90	1.64	1.43	1.26	1.11	0.99	0.89	0.80
3.6	3.56	2.96	2.49	2.13	1.84	1.60	1.41	1.25	1.12	1.00	0.90
4.0	3.94	3.28	2.77	2.36	2.04	1.78	1.57	1.39	1.24	1.11	1.00
4.4	4.32	3.60	3.04	2.60	2.24	1.96	1.72	1.53	1.36	1.22	1.11
4.8	4.69	3.91	3.31	2.83	2.44	2.13	1.88	1.67	1.49	1.33	1.21
5.2	5.06	4.22	3.57	3.06	2.65	2.31	2.03	1.80	1.61	1.45	1.31
5.6	5.42	4.53	3.84	3.29	2.84	2.48	2.19	1.94	1.73	1.56	1.40
6.0	5.77	4.84	4.10	3.51	3.04	2.66	2.34	2.08	1.85	1.67	1.50

Table 14: WEC operational envelope rpm

RPM											
	50th Percentile of Wave Energy Period (s)										
	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
RPM	12.00	10.91	10.00	9.23	8.57	8.00	7.50	7.06	6.67	6.32	6.00

Table 15: WEC operational envelope geared rpm

Geared RPM											
Ratio 15	50th Percentile of Wave Energy Period (s)										
	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
RPM	180.00	163.64	150.00	138.46	128.57	120.00	112.50	105.88	100.00	94.74	90.00

The modelling shows that across the operational envelope the average wattage is 18.78 W, with a minimum output of 3 W providing constant output to the battery for power smoothing and storage. These are the peak power figures assuming a constant rpm and regular wave pattern and so the delivery will cycle as a function of the wave frequency and will be lower on average.

The red portion of the Table 13 indicates where the torque requirement of 0.9 Nm at the generator are not met for a 100 rpm design target, a reduced rate of rotation will occur or potentially might not be possible. The momentum of the pendulum would be sufficient in some situations to maintain rotation in these sea states, although long term testing of the deployed device is required to verify this theory.

While the modelling of the design does not take component efficiency into consideration, it is possible to make a comparison based on energy theory as outlined in Chapter 4 – WEC Mathematical Modelling. While the units of wave power are given in W/m of wave front, the WEC design can be said to equate to the same due to its physical dimensions. The results for the operational envelope based on formulas 4.10 and 4.11 for theoretical ideal wave power and theoretical efficiency are shown below in Tables 16 and 17.

Table 16: Operational envelope theoretical ideal wave power

Theroretical ideal wave power (W/m)												
		50th Percentile of Wave Energy Period (s)										
		5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
50th Percentile of Significant Wave Height (m)	2.0	1.91E+04	2.10E+04	2.29E+04	2.48E+04	2.67E+04	2.86E+04	3.05E+04	3.24E+04	3.44E+04	3.63E+04	3.82E+04
	2.4	2.75E+04	3.02E+04	3.30E+04	3.57E+04	3.85E+04	4.12E+04	4.40E+04	4.67E+04	4.95E+04	5.22E+04	5.50E+04
	2.8	3.74E+04	4.12E+04	4.49E+04	4.86E+04	5.24E+04	5.61E+04	5.99E+04	6.36E+04	6.73E+04	7.11E+04	7.48E+04
	3.2	4.89E+04	5.38E+04	5.86E+04	6.35E+04	6.84E+04	7.33E+04	7.82E+04	8.31E+04	8.80E+04	9.28E+04	9.77E+04
	3.6	6.18E+04	6.80E+04	7.42E+04	8.04E+04	8.66E+04	9.28E+04	9.90E+04	1.05E+05	1.11E+05	1.18E+05	1.24E+05
	4.0	7.64E+04	8.40E+04	9.16E+04	9.93E+04	1.07E+05	1.15E+05	1.22E+05	1.30E+05	1.37E+05	1.45E+05	1.53E+05
	4.4	9.24E+04	1.02E+05	1.11E+05	1.20E+05	1.29E+05	1.39E+05	1.48E+05	1.57E+05	1.66E+05	1.76E+05	1.85E+05
	4.8	1.10E+05	1.21E+05	1.32E+05	1.43E+05	1.54E+05	1.65E+05	1.76E+05	1.87E+05	1.98E+05	2.09E+05	2.20E+05
	5.2	1.29E+05	1.42E+05	1.55E+05	1.68E+05	1.81E+05	1.94E+05	2.06E+05	2.19E+05	2.32E+05	2.45E+05	2.58E+05
	5.6	1.50E+05	1.65E+05	1.80E+05	1.95E+05	2.10E+05	2.24E+05	2.39E+05	2.54E+05	2.69E+05	2.84E+05	2.99E+05
	6.0	1.72E+05	1.89E+05	2.06E+05	2.23E+05	2.41E+05	2.58E+05	2.75E+05	2.92E+05	3.09E+05	3.26E+05	3.44E+05

Table 17: Operational envelope theoretical efficiency

Theroretical efficiency (%)												
		50th Percentile of Wave Energy Period (s)										
		5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0
50th Percentile of Significant Wave Height (m)	2.0	1.26E-01	8.61E-02	6.09E-02	4.42E-02	3.29E-02	2.50E-02	1.93E-02	1.51E-02	1.20E-02	9.70E-03	7.90E-03
	2.4	1.05E-01	7.16E-02	5.07E-02	3.68E-02	2.74E-02	2.08E-02	1.61E-02	1.26E-02	1.00E-02	8.08E-03	6.59E-03
	2.8	8.94E-02	6.13E-02	4.34E-02	3.15E-02	2.35E-02	1.78E-02	1.38E-02	1.08E-02	8.60E-03	6.93E-03	5.64E-03
	3.2	7.80E-02	5.35E-02	3.79E-02	2.76E-02	2.05E-02	1.56E-02	1.20E-02	9.45E-03	7.52E-03	6.06E-03	4.94E-03
	3.6	6.91E-02	4.75E-02	3.36E-02	2.45E-02	1.82E-02	1.38E-02	1.07E-02	8.40E-03	6.68E-03	5.39E-03	4.39E-03
	4.0	6.20E-02	4.26E-02	3.02E-02	2.20E-02	1.64E-02	1.24E-02	9.62E-03	7.55E-03	6.01E-03	4.85E-03	3.95E-03
	4.4	5.61E-02	3.86E-02	2.74E-02	2.00E-02	1.49E-02	1.13E-02	8.74E-03	6.86E-03	5.46E-03	4.40E-03	3.59E-03
	4.8	5.12E-02	3.53E-02	2.51E-02	1.83E-02	1.36E-02	1.04E-02	8.01E-03	6.29E-03	5.01E-03	4.04E-03	3.29E-03
	5.2	4.70E-02	3.25E-02	2.31E-02	1.68E-02	1.26E-02	9.54E-03	7.38E-03	5.80E-03	4.62E-03	3.72E-03	3.03E-03
	5.6	4.34E-02	3.00E-02	2.14E-02	1.56E-02	1.16E-02	8.85E-03	6.85E-03	5.38E-03	4.29E-03	3.46E-03	2.82E-03
	6.0	4.03E-02	2.79E-02	1.99E-02	1.45E-02	1.08E-02	8.25E-03	6.39E-03	5.02E-03	4.00E-03	3.22E-03	2.63E-03

The design only accesses a very minor part of total energy of the wave, from this data, on average over its operational envelope the device only potentially harvests 0.022% of what is available.

7.3 Electrical System Analysis

Data collection for bench level testing of the device performance was carried out using resistors in lieu of battery charging and discharging. The resistors were a known variable from which power output was gauged, whereas the battery's internal resistance and charge rate proved too variable to gather reliable data. It was observed that the battery did charge steadily from a discharged state given consistent input. Through prolonged device deployment with an actual intermittent load useful battery charge data could be collected.

The generator performed as expected, increasing outputs as rpm increased as well as higher voltage across larger loads. The calculated watts however increased as the load was reduced, battery internal resistances are typically small, with the test battery measuring at 0.143 ohms at full charge.

The selected data monitoring equipment proved to be intuitive and fit for purpose. It is most suitable for real time performance monitoring as the logging functions lack a degree of fidelity, this is acceptable in the prototype phase of the design as the equipment is not included in the devices final state. The testing served to justify component selection as well as gauge expected performance before assembly and deployment.

7.4 Prototype Dimensions

One of the most important design considerations was maintaining the internal clearances of the device during extreme wave events. The forces and displacement of critical components has been examined up to 10 g previously in Chapter 6 – Design Testing. The primary concern is that combined deflection of the inner frame, shaft and pendulum would lead to contact with either the outer case or the components mounted on the inner frame.

The pendulum was designed with a clearance of 15 mm from the minimum diameter of the outer case and 25 mm from the inner frame components. It has a clearance of 23 mm from the top of the device and 26 mm from the generator below it. FEA analysis indicates that the maximum combined deflection of the device is 4.05 mm in magnitude at the base of the pendulum due to its offset, giving a significant factor of safety in this regard.

The final unassembled height and width of the prototype is 692 mm by 880 mm, standard Australian pallets are 1165 x 1165 mm (ecopallets, 2020). The design is compact enough to be able to transport via standard methods if required once completed.

7.5 Prototype Mass

The final modelled mass of the prototype is 178.28 kg as shown in Table 5 previously. This indicates that the device midpoint will sit slightly below the water line due to each housing displacing 150 L. The design feature of the buoyant outer frame will assist in raising the height of the device in the water and reduce the chance of toppling in extreme wave events. There is an emphasis on the importance of a watertight seal for the device due to this design characteristic.

While the centre of mass of the total device sits below the midline of the housing due to the positioning of the generator and gearset, the centre of mass of the pendulum sits slightly higher, at 51.5 mm above. This assists in magnitude of pendulum angular changes due to wave motion.

7.6 Design Testing Limitations

Unfortunately, the prototype has not been fabricated at this time and so some aspects of the design remain unverified.

In terms of the physical construction of the device, details of the attaching hardware and seals used remain assumed until fabrication takes place. The method used to mount the pendulum to the input shaft requires finalisation to allow for on-site assembly and transportation, the keyway and input shaft may also require redesign for machining considerations. The method used to secure the gears to the shafts as well as the shaft to the bearing requires finalisation. Finally, the theoretical material properties used in modelling such as the density and yield strengths may vary from what is available for construction, requiring modification of the design.

Verification of the torque calculations is also unable to be completed without the constructed prototype. Field testing with known rpm data at the generator for the dimensions of the pendulum is required to determine lower limits for continued rotation.

The devices performance assumes a regular wave height and period, sea state in reality is quite irregular. Extended testing is still required to verify if the modelled data when averaged over time is reasonable under such conditions.

Finally, as discussed in section 7.3 Electrical System Analysis, extended device deployment with an intermittent load is required in order to collect useful battery charge data and gauge the systems capability to power the marine sensor loads persistently.

7.7 Cost Analysis

The final completed cost of the device is $4352.70 following fabrication as detailed in Appendix J. The device weighs 178.28 kgs, occupies 0.205 m^3 and in theory can generate 18.78 Watts consistently over its operational envelope on average. By comparison, an of the shelf 12 Volt 20 Watt (maximum) solar panel available from electronics supplier Jaycar, model ZM9042 costs $59.95, weighs 1.8 kg and occupies 0.00387 m^3, but only produces maximum power during full sunlight (Jaycar, 2020).

An analysis for this performance metric will need to be carried out in regard to the savings made over time for the options of WEC, photovoltaic, additional external battery systems or current sensor deployment practice. This will need to consider the fabrication and deployment costs of a persistent WEC device compared to a photovoltaic option that requires several panels and incur a cost due to frequent cleaning as a result of the marine environment. Investigation into a separate external battery system that requires regular but infrequent servicing might also be justified. These costs will need to be evaluated over time to justify their merits against the current marine sensor internal battery replacement requirements.

7.8 Conclusions

This chapter examined the results of and discussed the modelling and testing carried out previously. It identified where the aspects of the design were validated while highlighting where the design and testing required further investigation. It also performed an examination of the WEC devices performance when compared to a photovoltaic alternative. The final evaluation of the design as well as further work and recommendations is presented in Chapter 8 – Conclusions.

Chapter 8 – Conclusions

8.1 Chapter Overview

This chapter presents the final conclusions of the research and testing undertaken for the small-scale WEC prototype project. It presents a critical evaluation of the design as well as further work and recommendations.

8.2 Project Reflection

The project was an ambitious design undertaking, utilising many engineering principles for its execution. In its current state of completion, the design has proven to be viable and a valuable experience. There were several important project objectives that were unable to be achieved however and would have added significant value.

Of the objectives described in section 1.3 Research Objectives, the majority were satisfactorily completed, with the final fabrication and testing of the assembled device remaining the outcomes not achieved. Towards the end of the project it became clear that the final assembly and testing with the current state of restrictions and delays would not be possible. The project then prioritised the use of FEA to more completely model and analyse the design.

Given the chance to begin the project over, more priority would be given to FEA and analysis of possible design variations rather than such a focus on individual component specification. All of the primary components of the design however have been obtained and bench level testing has carried out in increased detail as a result. The further works required to see the project to its completion are described in section 8.4, Further Work and Recommendations.

8.3 Critical Evaluation of the Design

The greatest design restriction that was encountered during the project was the relatively small diameter of the device housing. Many other restrictions placed on the design would be mitigated through selection of a larger enclosure. This would primarily affect the design dimensions of the pendulum mass and arm. Overall mass could be reduced, clearances increased, more effective height for potential energy conversion could be achieved as well as increases in torque allowing for additional gearing and higher average rpm.

A larger body also displaces more water, ensuring sufficient buoyancy. This revised approach would however add to the difficulty and cost for transportation and deployment, as well as necessitating redesign of much of the device, but this would likely still be offset by the possible design performance improvements.

The generator output was consistently difficult to verify. Design parameters such as gear ratios, torque requirements and expected power output were all derived from the original selection of the NE-100, 100 W rated generator. It was not possible to ascertain or replicate the test conditions under which the manufacturer obtained performance data. Therefore, there could be considerable variation between the expected and actual performance of the device.

The theory behind the design itself is sound, with the primary modelling derived from fundamental physics concepts and an understanding the geometry and motion of the device and the ocean state. These ocean states and operating envelope have been researched and justified from available wave data.

The generator performance specifications provided one of the main drivers of the design's performance targets combined with dimensional restrictions of the relatively small device housing. Very few assumptions have been made in simulating and modelling, with the simulations and tests that were able to be completed verifying design choices.

The efficiency of the design has proven to be a negative contributor to the device's feasibility. The prototype is heavy and expensive, requiring many components and extensive fabrication. Other options such as photovoltaic panels, a floating enclosure of several large batteries or even not relying on external power at all might prove a much more effective option. These options require further evaluation as discussed in section 7.7 Cost Analysis.

8.4 Further Work and Recommendations

In line with the original project plan, critical to further work is the completion of fabrication. This will enable verification of the design through data gathering and direct observation, in the onshore and deployed scenarios.

The final fabrication process will identify any areas that require redesign due to clearance or assembly issues with the component structure. It will allow the gearing and subsequent torque modelling to be verified at bench level using a force gauge on the pendulum body and through observed performance once deployed.

Extended operation in varying wave fields will also be made possible. This testing will involve subjecting the battery to a small load, similar to marine sensor requirements, while constantly monitoring battery voltage and charge rate. This will finally determine whether the selection of generator, charge controller and battery are sufficient to supply persistent power to the load over irregular sea states, including periods of calm.

The project would benefit from further analysis that the effects of a larger device housing will have on performance and viability. Conceptually the modelling would remain the same but allow for increased variation in pendulum characteristics as well as requiring modification and FEA of the primary structures.

Although the monitoring and data logging methods proved sufficient at the conceptual stage of the prototype, ideally the systems related to battery charge, voltage and rpm at the generator would be specifically designed for the device. Investigation of incorporation of Arduino components or similar to fulfil this function could be undertaken. This further work could be justified to fully verify the completed prototype, or if the data is of particular interest to the final user.

Finally, a cost benefit analysis should be undertaken to fully compare the economic viability of the design when compared to a similar concept with a larger device housing, photovoltaic panels, external battery banks or persisting with current marine sensor internal battery power supply.

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Appendix A – Project Specification

ENG4111/4112 Research Project

Project Specification

For: Peter Courtis

Title: An investigation of small-scale wave energy converters for marine sensors

Major: Mechanical Engineering

Supervisors: Dr Steven Goh

Scott McGarry, CSIRO

Sponsorship: CSIRO

Confidentiality: Restricted public access until 2022 or until CSIRO has completed project works on this topic.

Enrolment: ENG4111 – EXT S1, 2020

ENG4112 – EXT S2, 2020

Project Aim: To investigate and propose a design for a small-scale wave energy conversion device in order to power marine sensors.

Programme: Version 1, 21st March 2020

1. Research marine sensor types, power characteristics and the various stakeholder requirements.

2. Research wave data, wave characteristics, current wave energy converters (WEC) technologies and mechanical and electronic methods for harvesting and power delivery.

3. Devise a computational model for viable methods based on wave data variables.

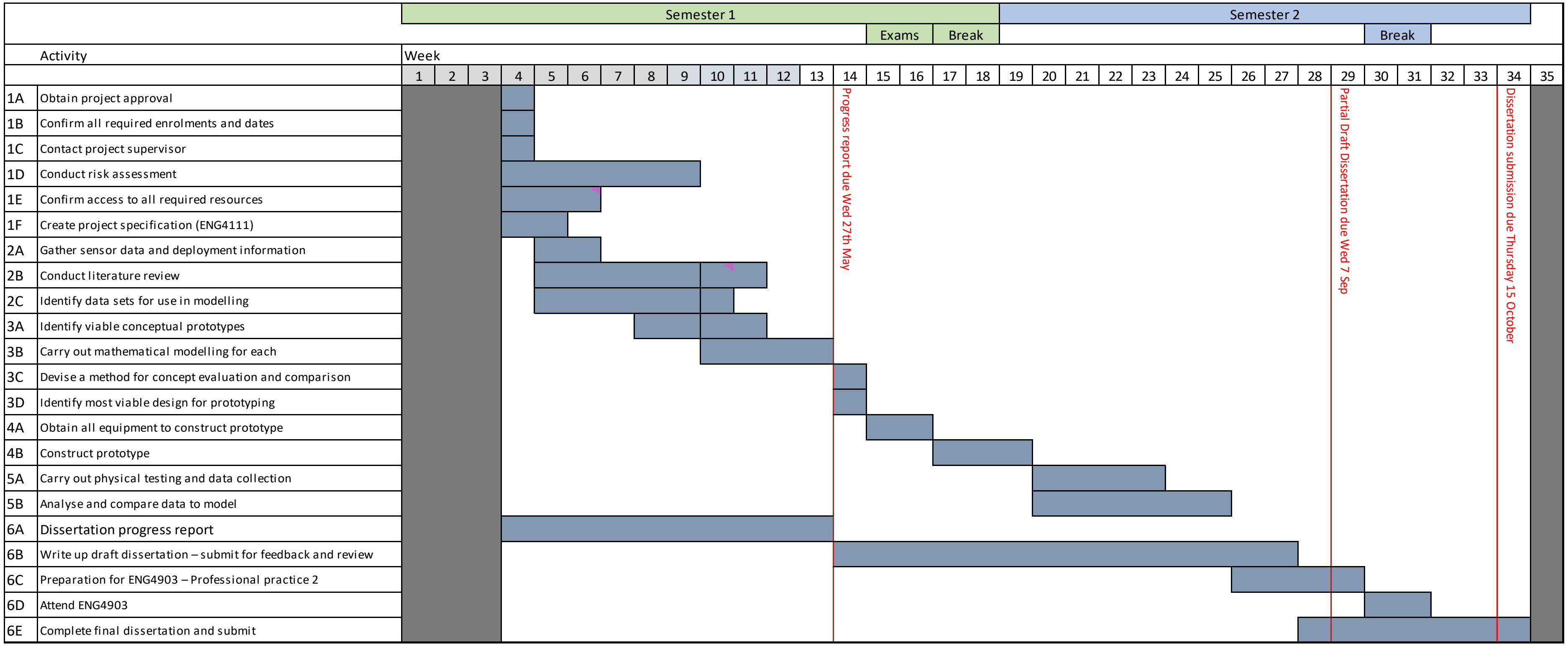
4. Create conceptual prototypes for viable designs, evaluate the modelling and prototypes using a weighted score system and manufacture the most viable design.

5. Carry out testing and data comparison.

6. Adjust Prototype and reiterate step 5 as many times as practical, logging progress.

7. Present the analysis and evaluation, and recommend a final viable design.

Appendix B – Project Timeline



Appendix C – Project Risk Assessment

Phase	Task	Hazard	Rating	Risk Management
ALL	Deadlines and task timings	Not meeting deadlines or inadequate progress	EXTREME -11-	Conform to project plan and set early target deadlines
ALL	Resource acquisition	Required resources unavailable or delayed	EXTREME -11-	Set early deadlines and devise other viable alternatives case by case
ALL	Data storage	Data/information loss could prove disastrous at any stage of the project	EXTREME -11-	Regular data back up and communication with project sponsor
ALL	Extensive IT usage	RSI/ergonomic/eye strain	MEDIUM -5-	Regular breaks and an ergonomic workspace set up
ALL	Manual handling	RSI/injury	MEDIUM -6-	Correct lifting/handling techniques. Appropriate PPE
ALL	Project cost	Aspects of the project are financially unjustifiable	MEDIUM -3-	Keep costs to a realistic minimum. Consult CSIRO for reimbursement
1A	Obtain project approval	Insufficient preparation	HIGH -10-	Conform to project approval guidelines
		Rejection of project idea	HIGH -10-	Thoroughly outline project processes and outcomes
1B	Confirm all required	In correct enrolment or deadlines could jeopardise project completion	HIGH -10-	Examine and record all enrolments and project dates

	enrolments and dates	Incorrect planning as a result of not complying to important dates	HIGH -10-	Record dates on a separate calendar and set early deadlines
1C	Contact project supervisor	Insufficient communication	MEDIUM -6-	Communicate clearly, establish regular communication schedule and keep a communications log
1D	Conduct risk assessment	Risk assessment insufficient	MEDIUM -6-	Consider all aspects individually and review other assessments for comparison
		Risk assessment guidelines not followed	MEDIUM -6-	Conform to guidelines and submit drafts to supervisor for review if possible
1E	Confirm access to all required resources	Insufficient foresight into project requirements	MEDIUM -6-	Forecasting resource requirements as much as reasonably practical. Identification of alternatives as required
1F	Create project specification (ENG4111)	Assessment guidelines not correctly addressed	MEDIUM -4-	Conform to guidelines and submit drafts to supervisor for review if possible
		Individual assessment components are inadequate	MEDIUM -4-	Address each component as an individual task for completion
2A	Gather sensor data and deployment information	Data not readily available for public access	MEDIUM -3-	Generalise sensor requirements within reasonable limits for modelling

2B	Conduct literature review	Assessment guidelines not correctly addressed	HIGH -8-	Conform to guidelines and submit drafts to supervisor for review if possible
		Not meeting academic standards for a dissertation	HIGH -8-	Comprehensive planning for structure and content. Draft submissions and review of other available dissertations
2C	Identify data sets for use in modelling	Data sets insufficient for project modelling	MEDIUM -6-	Use only verified data sources
		Data sets unreliable or improperly interpreted	MEDIUM -6-	Ensure data is applicable through research and consultation with sponsors
3A	Identify viable conceptual prototypes	Insufficient research of viable options	MEDIUM -6-	Ensure comprehensive literature review and sensor data targets
3B	Carry out mathematical modelling for each	Limitations in individual understanding and skillset	HIGH -8-	Conduct appropriate research. Liaise with supervisor and CSIRO contacts.
		Over-simplification of mathematical aspects in modelling	MEDIUM -5-	Conduct appropriate research. Liaise with supervisor and CSIRO contacts.
3C	Devise a method for concept evaluation and comparison	Bias influencing model evaluation	MEDIUM -5-	Conduct appropriate research. Liaise with supervisor and CSIRO contacts.
3D	Identify most viable design for prototyping	A flawed evaluation and comparison model will	MEDIUM -5-	Ensure concept evaluation and comparison processes

		influence choice of viable design for further research		are sufficient before proceeding
4A	Obtain all equipment to construct prototype	Equipment is not fit for task	HIGH -8-	Anticipate equipment requirements early. Have alternate sources available where appropriate
		Prototype revisions have excessive equipment burdens	MEDIUM -5-	Ensure revisions and resources are kept to a realistic level. Seek CSIRO guidance on support early.
4B	Construct prototype	Construction is beyond current abilities/resource availability	HIGH -8-	Ensure prototype design is kept realistic for the nature of the project
5A	Carry out physical testing and data collection	Testing is beyond current abilities/resource availability	HIGH -8-	Ensure prototype design is kept realistic for the nature of the project
5B	Analyse and compare data to model	Physical test data is insufficient for comparison	HIGH -8-	Ensure that the data required for comparison is able to be analysed
6A	Dissertation progress report	Assessment guidelines not correctly addressed	EXTREME -11-	Conform to guidelines and submit drafts to supervisor for review if possible
6B	Write up draft dissertation – submit for feedback and review	Assessment guidelines not correctly addressed	EXTREME -11-	Conform to guidelines and submit drafts to supervisor for review if possible
6C	Preparation for ENG4903 –	Assessment guidelines not correctly addressed	EXTREME -11-	Conform to guidelines and submit drafts to supervisor for review if possible

	Professional practice 2			
6D	Attend ENG4903	Restrictions on travel and gatherings still in place	MEDIUM -5-	Keep up to date with national, state and university advice/requirements
		Unable to attend due to other commitments	EXTREME -11-	Liaise with workplace to ensure leave is available. Avoid making other commitments close to practical phase
6E	Complete final dissertation and submit	Assessment guidelines not correctly addressed	HIGH -10-	Conform to guidelines and submit drafts to supervisor for review if possible
POST	Injury	Injury as a direct result of the prototype design	HIGH -10-	Eliminate risks through design. Provide clear instruction for device handling and operation
POST	Prototype not suitable for purpose	CSIRO may have no use for or desire to utilize project outcomes	MEDIUM -4-	Liaise with CSIRO project contact

Appendix D - Wave Energy Resource and Development in Australia

A.1 Wave Energy Resource in Australia

Australia's long southern-facing coastline gives rise to arguably the largest wave energy resource of any country in the world. A comprehensive assessment of wave-energy resource in Australia estimates the total wave-energy flux across the depths of 25, 50 and 200 m to be 1796, 2652 and 2730 TW h/year, respectively (Hemer et al., 2016). This available energy is an order of magnitude larger than the 248 TW h electricity generated in Australia in 2013–2014 (Department of Industry and Science, 2015), and indicates that the magnitude of the wave resource is not a constraint to its future uptake. The vast majority of this resource is available to the southern coastal region with 1455 TW h/year estimated at the 25-m depth contour (the depth around which many wave devices are presently being tested), from 29°S on the Western Australian coast to 148°E on the southern tip of Tasmania including western Victoria. By contrast, the wave-energy resource over northern Western Australia (north of 23.5°S) and Northern Territory at the 25-m contour is 61 TW h/year.

Wave variability is also an important consideration for wave-energy extraction. An assessment of wave variability at the 25-m isobath indicates that much of the southern, mid-latitude coastal region is also favourable because it displays relatively low variability in wave energy with respect to the total available wave energy. In other words, large waves are generally not much greater than the wave height at which most energy is received, and episodes of minimum wave heights and energy ($H_s<1$ m) are relatively short-lived, typically exhibiting durations of less than a day and are relatively uncommon with typically >100 days between events. Conversely, in the tropical north, the lower available wave resource is also characterised by a larger ratio of large waves to mean wave height. This is due to the occurrence of tropical cyclones. This region also experiences periods of minimal wave energy that are more frequent and of longer duration (Hemer et al., 2016).

A.2 Wave Energy Development in Australia

Globally, a wide variety of WEC device designs are under development. Over the past 10 years, Australia has been the setting for a number of marine renewable energy developments. Using the internationally-accepted Technology Readiness Level system (e.g. Makin, 2009) in which the developing technology is rated from 1 (Basic principles observed and reported) to 9 (Actual system proven in environment), ocean trials in Australia have demonstrated technology at up to a TRL of 7 (System prototype demonstration in environment). The locations of the various trials that have been undertaken in Australia are shown in Figure 1 and indicates that trials to date have occurred along the wave energy-rich coastlines of the southern half of the continent. Each of the devices that have been trialled have different conditions to which they are ideally suited, and can be deployed in a range of situations from on the shoreline, to near-shore water depths, and offshore in water depths exceeding 100 m.

WEC design is important since it determines the WECs suitability for different operating environments including the optimal depth of deployment, wave energy potential of the device and distance to shore. These considerations in turn determine the feasibility of the wave energy project.

Wave Energy Converter (WEC) technologies derive energy from the reciprocating motion of ocean waves, which can be harnessed in a variety of different ways (Falcao, 2010; Manasseh et al, 2017a) and accordingly different classification systems have emerged for categorising the various device designs (Manasseh et al, 2017b). The first categorisation, referred to as the Directional Classification (DC) is based on the influence that the WEC has on the wave field. This classification describes devices as point absorbers, attenuators and terminators. The second classification system, referred to as the Morphological Classification (MC) divides devices according to their physical structure such as oscillating water columns, heaving buoys, overtopping converters and so on. A third proposed classification system described in Manasseh et al. (2016) refers to the physical operating principal (Operating Classification – OC) on which the device is designed. For example, devices may be classified as point absorbing linear resonators, wavelength-tuned linear resonators or absorbers. The OC classification also describes whether the basic operating principal is that of a pendulum (01) or a spring (02) and whether the device is large, medium or small in relation to the typical wavelength of the wave field it is deployed in. This latter classification therefore embeds more detail around the engineering aspects of the device than the DC classification.

The characteristics of the devices trialled around Australia as shown in Figure 1 are also summarised in Table A.1 in terms of the MC and OC classification systems. For a detailed history of these developments, the reader is referred to Manasseh et al. (2017a).

Appendix E - Planning and Legislative Considerations

The planning and development of wave energy projects requires approvals from authorities within different levels of government at different stages of the project cycle. Projects operating within 3 nautical miles offshore and the coastal high water mark fall under State Government controls whereas those operating beyond the 3 nautical model limit fall under Commonwealth controls. Shore cable connection of these offshore deployments will span State and Local Government waters, and are therefore subject to coinciding controls. Table 2 provides a summary of relevant state-based information. Wave energy converter deployments typically target particular depths, with many designs targeted at depths of ~25-30 m. This targeted depth aims to capture the energy of the waves before it is lost through sea-bed friction processes. The 25-30 m depth contour often coincides closely with the 3 nm limit and so wave energy projects may require Commonwealth approvals, in addition to those required from Local and State Government associated with shore connections. Local and State Government processes differ by jurisdiction, with some regions having more mature process than others. Guidance and information on the processes required for obtaining approvals to conduct wave energy projects across Australia is provided below. A wave energy project cycle typically consists of the following stages (Govt. WA, 2010); • Preliminary evaluation; • Feasibility study; • Project design; and • Implementation and operation. The preliminary evaluation stage involves an exploration of options such as an assessment of the wave energy resource at potential sites of interest and a preliminary financial evaluation typically based on information from comparable projects and incorporating potential revenue streams such as Renewable Energy Certificates. Relevant information at this stage such as wave energy resource, proximity to the electricity grid, other marine resource users and so on can be obtained from the Australian Wave Energy Atlas (AWavEA) (http://nationalmap.gov.au/renewables/). Other considerations are the selection of appropriate technology for the project, access to land, relevant approvals and access to the energy market. The feasibility stage will involve a detailed assessment of the technical and economic viability of the project including potential barriers to the project. Relevant information at this stage includes a detailed project assessment including a site assessment that considers factors such as proximity to sensitive environmental areas and infrastructure access. Other factors to consider are local community issues, the intended uses of the energy produced, access to a workforce. A preliminary engineering assessment typically will consider capital costs and costs of supporting infrastructure, operation, electrical connection, revenue streams from energy and Renewable Energy Certificates (RECs), an environmental impact assessment and assessment of relevant legislation and policies. A timetable for implementation of the project should also be developed. The project design phase involves finalising agreements and approvals such as a Power Purchase Agreements (PPA) and securing investment and funding from financiers. At this stage a Project Definition Document (PDD) is developed that provides detailed technical information, details of the PPA, environmental and planning approvals and investment information and support from government agencies. Following approval and sign-off of the PDD, the project can proceed to the implementation stage. This involves entering formal contractual arrangements with relevant entities, undertaking the detailed design, construction and commissioning of the project.

Table 3 State-based guidance material available to support the development of wave energy projects

State	Relevant Information	Comments
Victoria	Guideline for Marine Energy Tenures on Crown Land	Available from Victorian Department of Environment, Land, Water and Planning (nicola.waldron@delwp.vic.gov.au)
WA	Renewable Energy Handbook (2010)	available from https://www.finance.wa.gov.au/cms/index.aspx
NSW	NSW regulatory framework for marine energy deployments	Available from NSW Department of Industry (susan.shaw@industry.nsw.gov.au)
SA	General information on renewable energy including investors guide	http://www.renewablessa.sa.gov.au/

Appendix F – Sea-Bird Scientific 37-SIP Datasheet

SEA·BIRD SCIENTIFIC

seabird.com
seabird@seabird.com

SBE 37-SIP
MicroCAT CT(D)

The SBE 37-SIP pumped MicroCAT is a high-accuracy conductivity and temperature (pressure optional) recorder with Serial interface (RS-232 or RS-485), memory, and integral Pump. Externally powered, it can be used for moored applications requiring fast sampling. The MicroCAT is useful as a stand-alone monitoring device and is easily integrated with other instrumentation platforms.

Data is output in real-time and can be recorded in memory; memory capacity exceeds 530,000 samples. Measured data and derived variables (salinity, sound velocity, depth, density) are output in engineering units.

Deploy in orientation shown (connector end down) for proper operation

Features

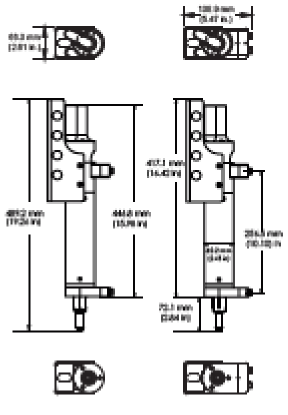
- Moored Conductivity, Temperature, and Pressure (optional), with user-programmable sampling — 6-sec to 6-hour intervals, or continuous (0.9 sec/sample without pressure, 1.3 sec/sample with pressure).
- Integral pump.
- RS-232 or RS-485 interface.
- Internal memory, external power.
- Expendable anti-foulant devices, unique flow path, and pumping regimen for bio-fouling protection.
- 350 m plastic or 7000 m titanium housing.
- Seasoft® V2 Windows software package (setup, data upload, and data processing).
- Field-proven MicroCAT family, with more than 10,000 instruments deployed.
- Five-year limited warranty.

Components

- Unique internal-field conductivity cell permits use of expendable anti-foulant devices, for long-term bio-fouling protection.
- Aged and pressure-protected thermistor has a long history of exceptional accuracy and stability.
- Optional strain-gauge pressure sensor with temperature compensation is available in eight ranges (maximum depth 7000 m).
- Pump runs for 1 second for each sample, providing improved conductivity response and bio-fouling protection.

Options

- Plastic (350 m) or titanium (7000 m) housing.
- RS-232 interface.
- No pressure, or strain-gauge pressure sensor in one of 8 ranges.
- XSG or wet-pluggable MCBH connector.
- Factory-supplied mount, wire mounting clamp and guide, or brackets for mounting to a flat surface.



Standard Without Mounting Hardware

Optional Wire Mounting Clamp and Guide

Measurement Range

Conductivity	0 to 7 S/m (0 to 70 mS/cm)
Temperature	-5 to 45 °C
Optional Pressure	20 / 100 / 350 / 600 / 1000 / 2000 / 3500 / 7000 (meters of deployment depth capability)

Initial Accuracy

Conductivity	± 0.0003 S/m (0.003 mS/cm)
Temperature	± 0.002 °C (-5 to to 35 °C); ± 0.01 °C (35 °C to 45 °C)
Optional Pressure	± 0.1% of full scale range

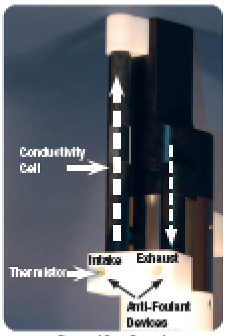
Typical Stability

Conductivity	0.0003 S/m (0.003 mS/cm) per month
Temperature	0.0002 °C per month
Optional Pressure	0.05% of full scale range per year

Resolution

Conductivity	0.00001 S/m (0.0001 mS/cm)
Temperature	0.0001 °C
Optional Pressure	0.002% of full scale range

Acquisition Time	0.9 - 3.0 sec/sample (see manual)
External Power	0.25 Amps at 9-24 VDC
Memory Capacity	530,000 samples CTD
Housing, Depth Rating, & Weight	Plastic: 350 m With pressure, without clamps 2.3 kg in air, 1.4 kg in water With pressure, with clamps 2.5 kg in air, 1.6 kg in water Titanium: 7000 m Without pressure or clamps 3.0 kg in air, 1.8 kg in water



Pumped flow through conductivity cell (conductivity cell guard removed)

SEA-BIRD SCIENTIFIC
seabird@seabird.com
+1 425 643 9466

Appendix G – Sea-Bird Scientific 37-SMP Datasheet

SEA-BIRD SCIENTIFIC

seabird.com
seabird@seabird.com

SBE 37-SMP
MicroCAT CT(D)

The SBE 37-SMP pumped MicroCAT is a high-accuracy conductivity and temperature (pressure optional) recorder with Serial interface (RS-232 or RS-485), internal batteries, Memory, and integral Pump. The MicroCAT is designed for moorings or other long-duration, fixed-site deployments.

Data is recorded in memory and can be output in real-time. Measured data and derived variables (salinity, sound velocity) are output in engineering units.

Memory capacity exceeds 530,000 samples. Battery endurance varies, depending on sampling scheme. Sampling every 2-1/2 minutes, the MicroCAT can be deployed for 2 years (425,000 samples).

Deploy in orientation shown (connector end down) for proper operation

Features

- Moored Conductivity, Temperature, and Pressure (optional), at user-programmable 6-sec to 6-hour intervals.
- Integral pump.
- RS-232 or RS-485 interface.
- Internal memory and battery pack (can be powered externally).
- Expendable anti-foulant devices, unique flow path, and pumping regimen for bio-fouling protection.
- 350 m plastic or 7000 m titanium housing.
- Seasoft® V2 Windows software package (setup, data upload, and data processing).
- Field-proven MicroCAT family, with more than 10,000 instruments deployed.
- Five-year limited warranty.

Components

- Unique internal-field conductivity cell permits use of expendable anti-foulant devices, for long-term bio-fouling protection.
- Aged and pressure-protected thermistor has a long history of exceptional accuracy and stability.
- Optional strain-gauge pressure sensor with temperature compensation is available in eight ranges (maximum depth 7000 m).
- Pump runs for 1 second for each sample, providing improved conductivity response and bio-fouling protection.

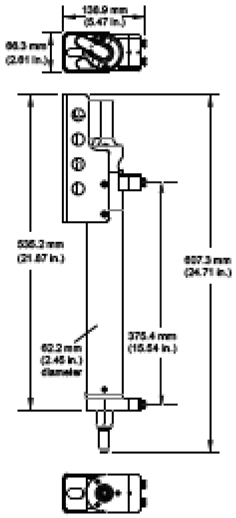
www.seabird.com sales@seabird.com +1 425-643-9866

SEA-BIRD SCIENTIFIC

SBE 37-SMP MicroCAT

Options

- Plastic (350 m) or titanium (7000 m) housing.
- RS-232 or RS-485 interface.
- No pressure, or strain-gauge pressure sensor in one of 8 ranges.
- XSG or wet-pluggable MCBH connector.
- Wire mounting clamp and guide or brackets for mounting to a flat surface.



Standard Wire Mounting Clamp and Guide

Measurement Range

Conductivity	0 to 7 S/m (0 to 70 mS/cm)
Temperature	-5 to 45 °C
Optional Pressure	20 / 100 / 350 / 600 / 1000 / 2000 / 3500 / 7000 (meters of deployment depth capability)

Initial Accuracy

Conductivity	± 0.0003 S/m (0.003 mS/cm)
Temperature	± 0.002 °C (-5 to to 35 °C); ± 0.01 °C (35 °C to 45 °C)
Optional Pressure	± 0.1% of full scale range

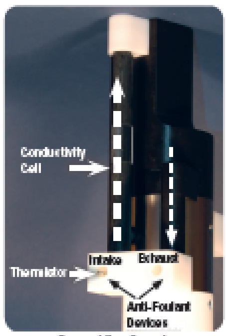
Typical Stability

Conductivity	0.0003 S/m (0.003 mS/cm) per month
Temperature	0.0002 °C per month
Optional Pressure	0.05% of full scale range per year

Resolution

Conductivity	0.00001 S/m (0.0001 mS/cm)
Temperature	0.0001 °C
Optional Pressure	0.002% of full scale range

Acquisition Time	1.9 - 2.9 sec/sample (see manual)
Power Supply & Consumption	7.8 Amp-hour (nominal) battery pack (derated for calculations) 425,000 samples CTD (see manual)
Optional External Power	0.25 Amps at 9-24 VDC
Memory Capacity	530,000 samples CTD
Housing, Depth Rating, & Weight	Plastic: 350 m, 3.4 kg in air, 1.6 kg in water Titanium: 7000 m, 3.7 kg in air, 2.2 kg in water



Pumped flow through conductivity cell (conductivity cell guard removed)

SEA·BIRD SCIENTIFIC
Sea-Bird Scientific
+1 425-643-9866
sales@seabird.com
www.seabird.com

Appendix H – Sea-Bird Scientific SeaFET V2 Datasheet

SEA·BIRD SCIENTIFIC

seabird.com
seabird@seabird.com

SeaFET™ V2
Ocean pH Sensor

The SeaFET™ V2 is the next generation pH sensor, featuring an ion sensitive field effect transistor (ISFET) pH sensor. This class of device has been used for pH sensing in industrial processes, food processing, clinical analysis, and environmental monitoring. The advantages of the ISFET include robustness, stability and precision that make it suitable for ocean pH measurement at low pressure.

Unlike traditional methods of measuring pH, the SeaFET™ V2's superior stability and rapid sampling facilitate longer deployments than glass electrode sensors and greater data density than colorimetric measurement techniques; the SeaFET™ V2 can obtain roughly 1 million pH samples in a single year before service/recalibration.

Features

- Solid state ISFET sensor
- Dual reference electrodes (external AgCl and internal KCl)
- Calibrated using natural seawater
- Internal logging and scheduling
- Internal battery pack

Applications

- Ocean Acidification research
- Coral reef physiology and sensitivity analyses
- Near-shore biological research
- Environmental monitoring

Flexible Operating Modes

- Interval sampling mode – samples at pre-programmed interval
- Scheduled mode – begins sampling at internally stored date/time
- Polled mode – sample upon receiving commands

SeaFET™ V2

Specifications

Measurement Range	6.5 to 9.0 pH
Initial Accuracy	± 0.05 pH
Precision	0.004 pH
Stability	0.003 pH/month

Environmental

Operating Temperature Range	0 to 50 °C
Storage Temperature Range	2 to 55 °C
Salinity Range	20 to 40 psu
Depth Range	50 m

Electrical

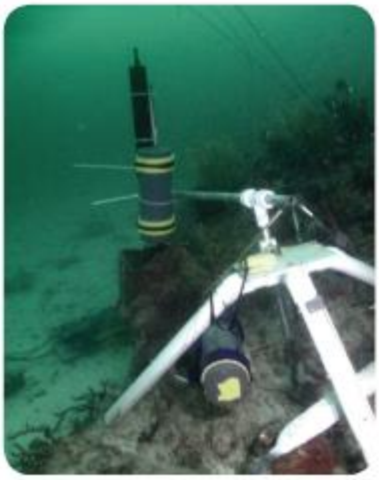
Supply Voltage Range	6 to 18 VDC
Power Consumption: Sampling	340-400 mW
Power Consumption: Sleep	10 µA
Batteries	12 x 1.5 V Alkaline D-Cells
Optional Pump Power	12 V, 650 mA

Mechanical

Dimension: Housing	508 mm L x 114 mm D (20.00 in x 4.48 in)
Dimension: Overall	549 mm L x 114 mm D (21.63 in x 4.48 in)
Weight in air	5.4 kg (w/batteries)
Weight in water	0.1 kg (w/batteries)
Displacement	5300 cm³
Housing Material	PVC

Communication

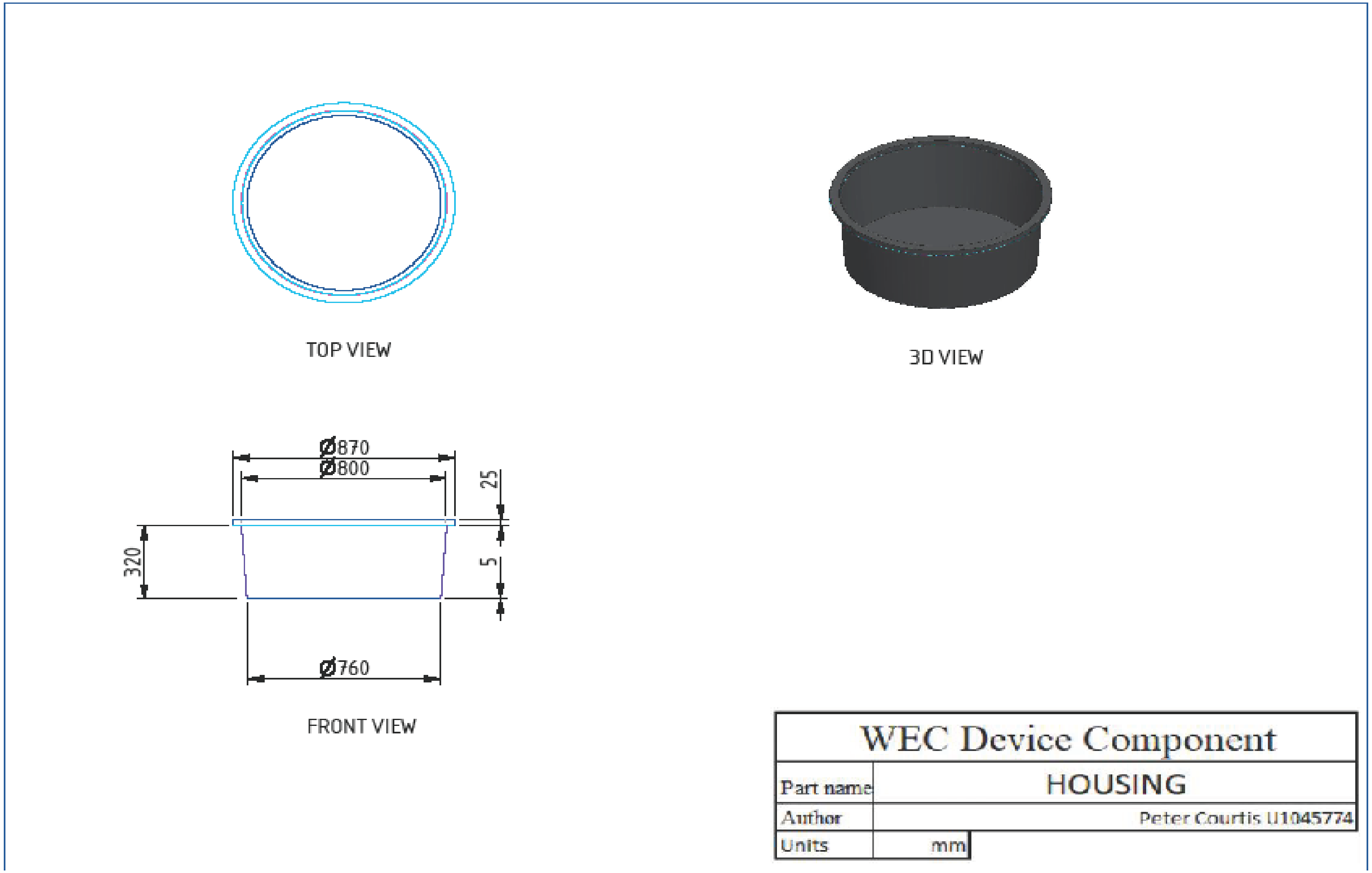
External Connector	MCBH 8M
Telemetry	RS-232 (9600-115200 baud)
Storage	32 MB (over 1240000 samples)

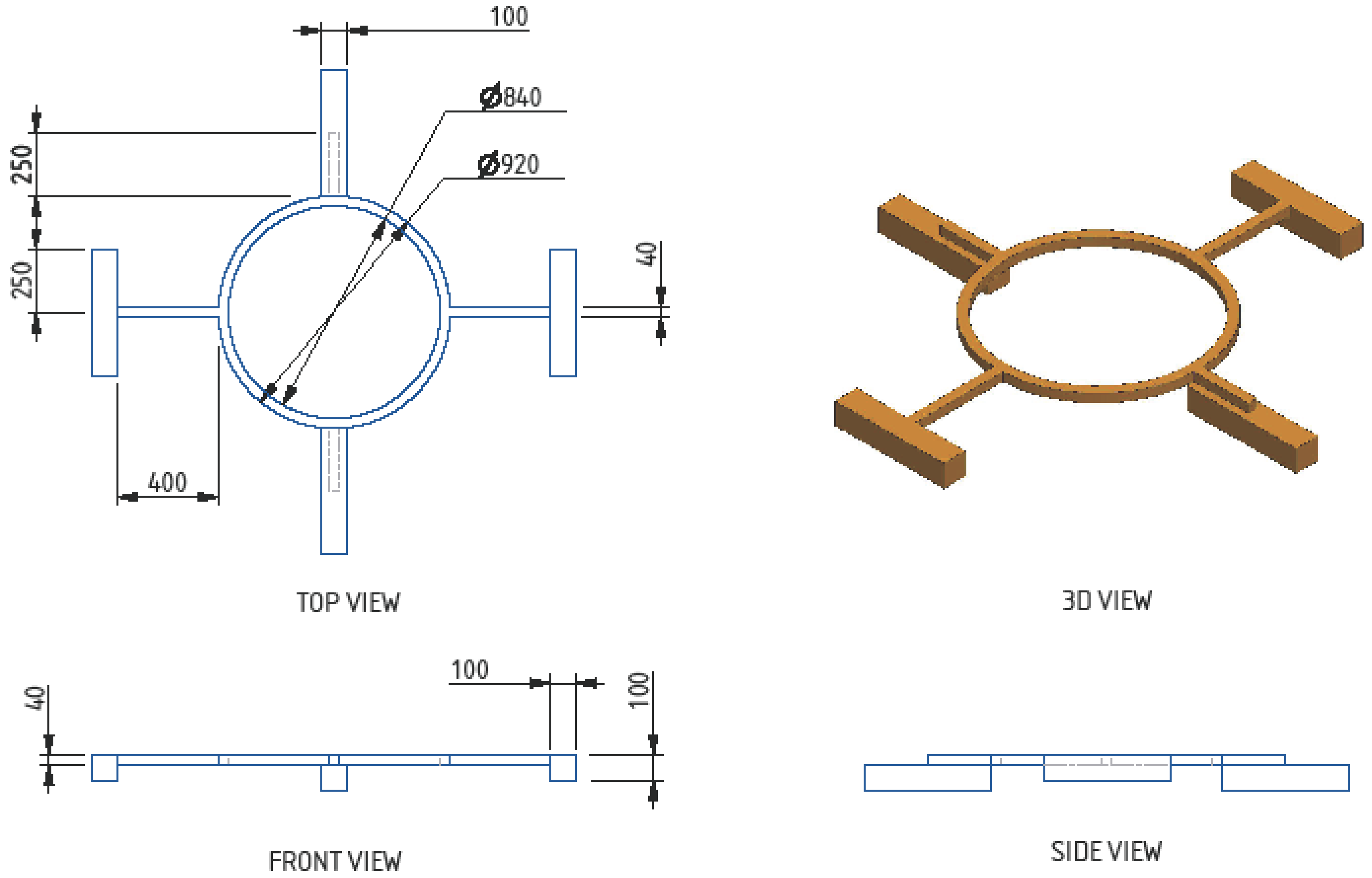


SEA-BIRD SCIENTIFIC

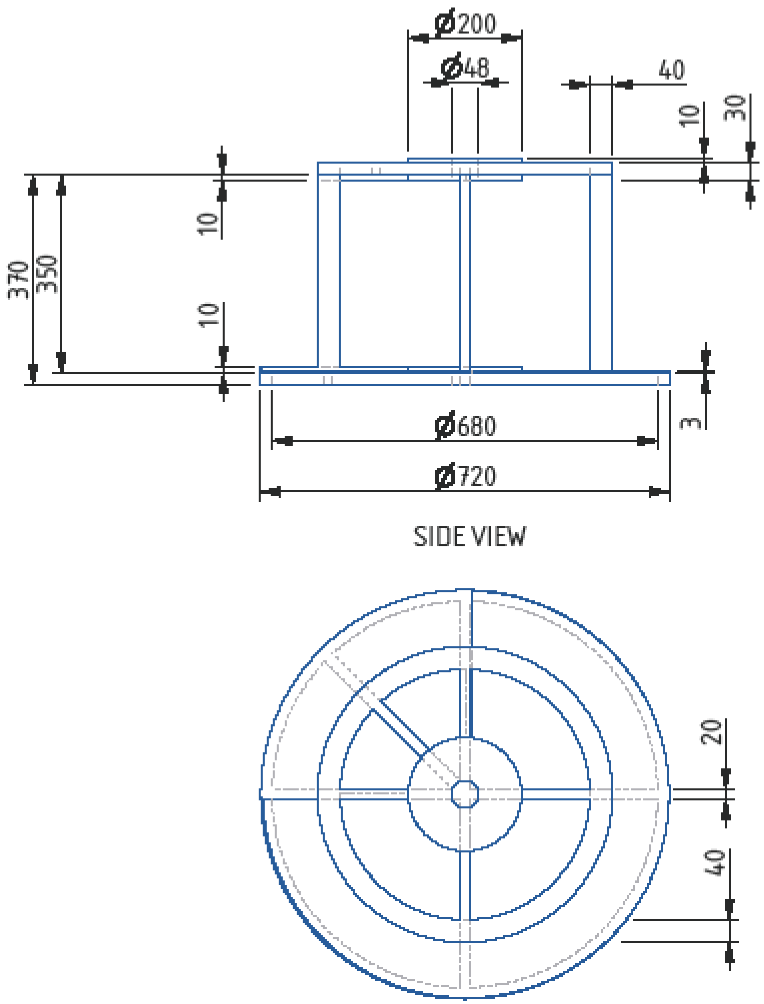
Sea-Bird Scientific
+1 425-643-9866
sales@seabird.com
www.seabird.com

Appendix I – Engineering Drawings



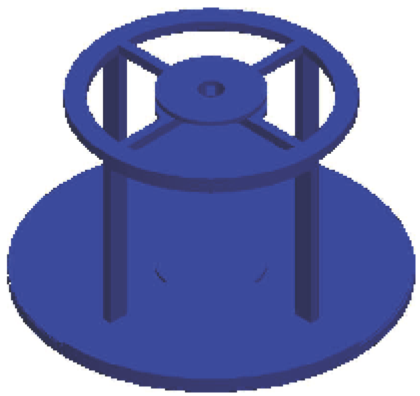


WEC Device Component	
Part name	OUTER FRAME
Author	Peter Courtis U1045774
Units	mm



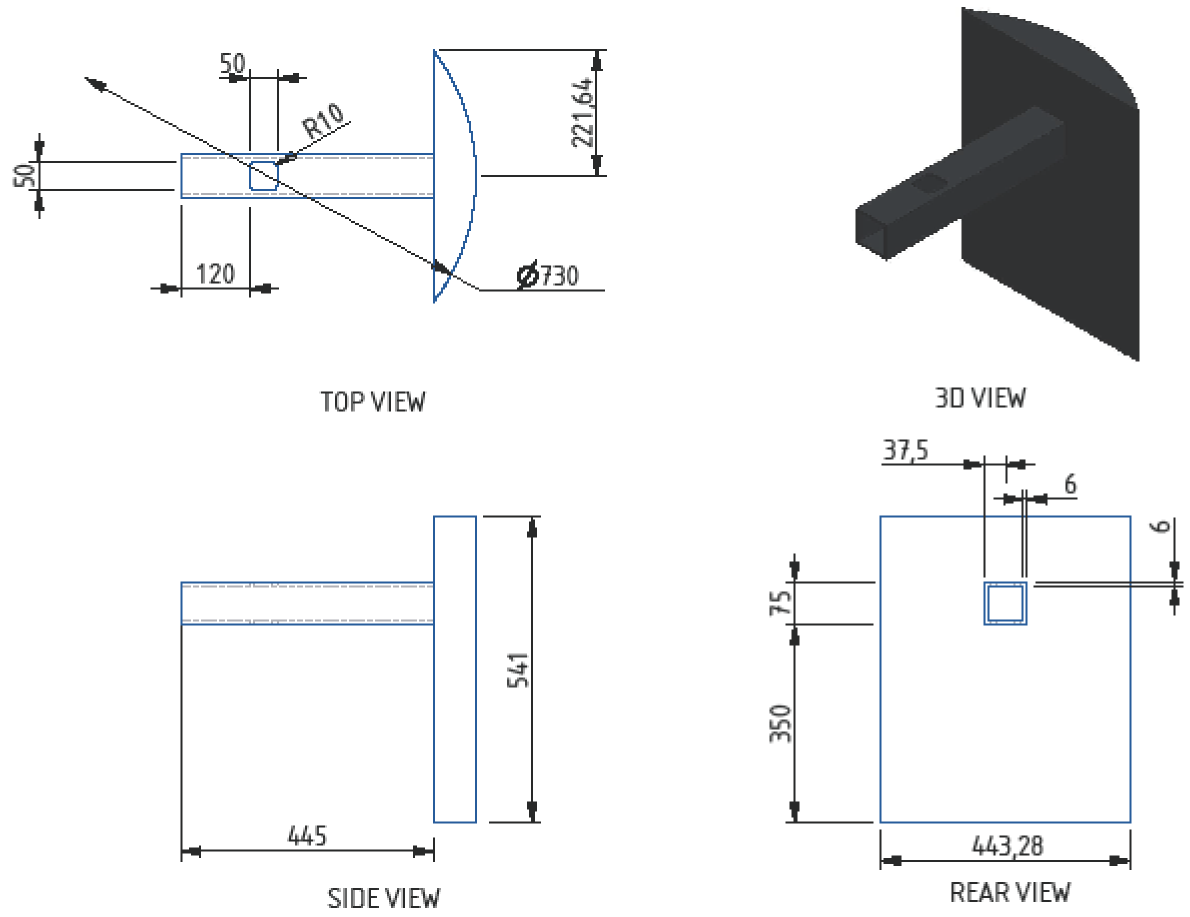
SIDE VIEW

TOP VIEW

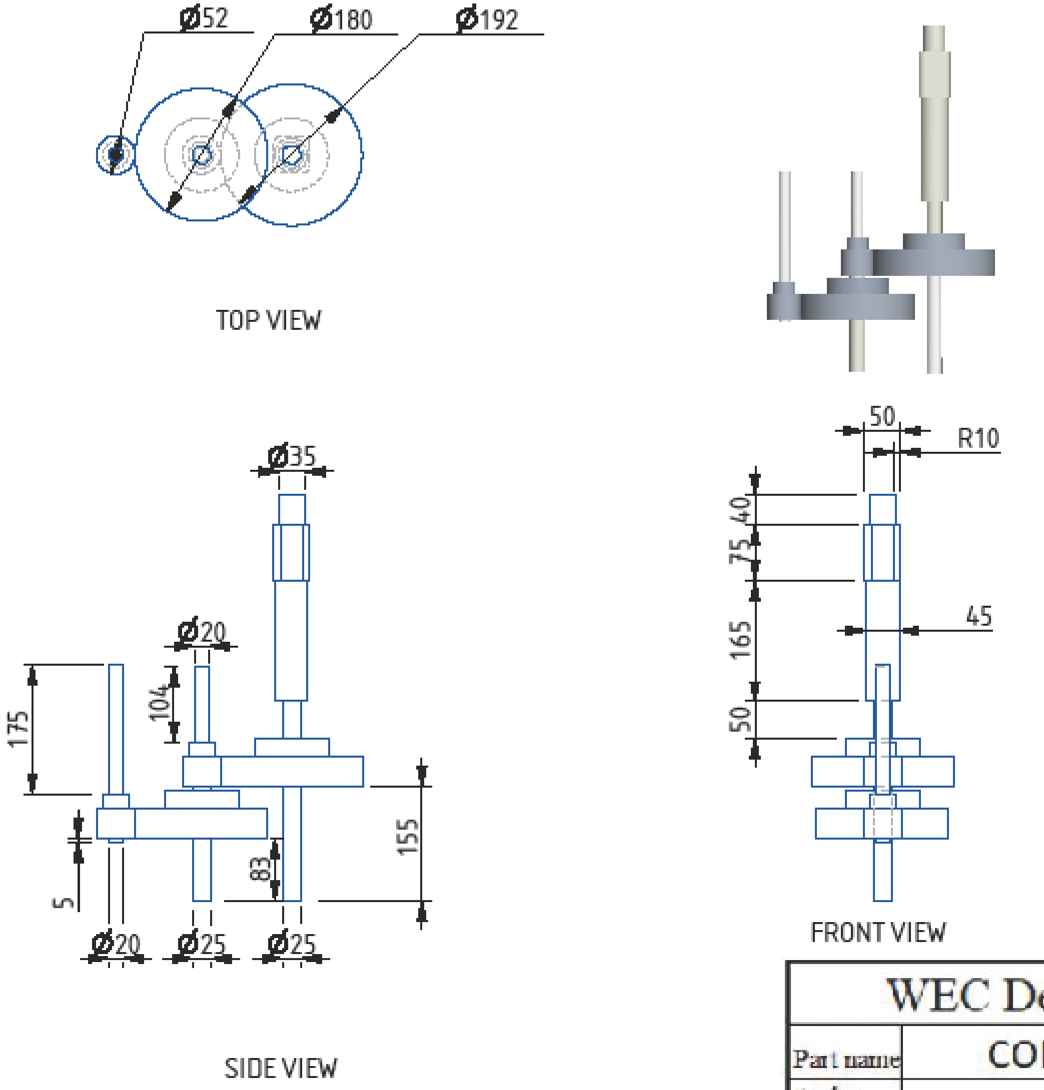


3D VIEW

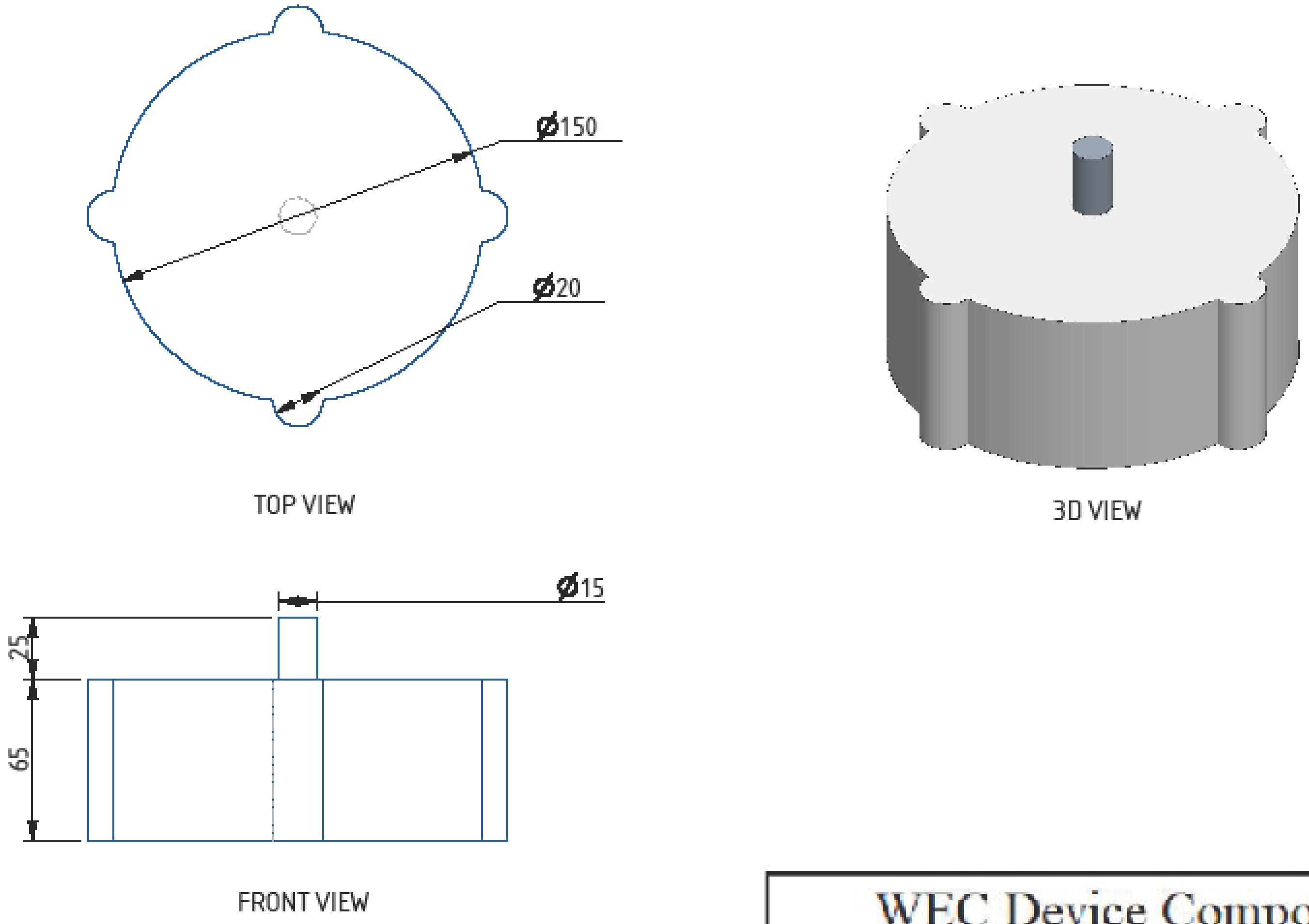
WEC Device Component	
Part name	INNER FRAME
Author	Peter Courtis U1045774
Units	mm



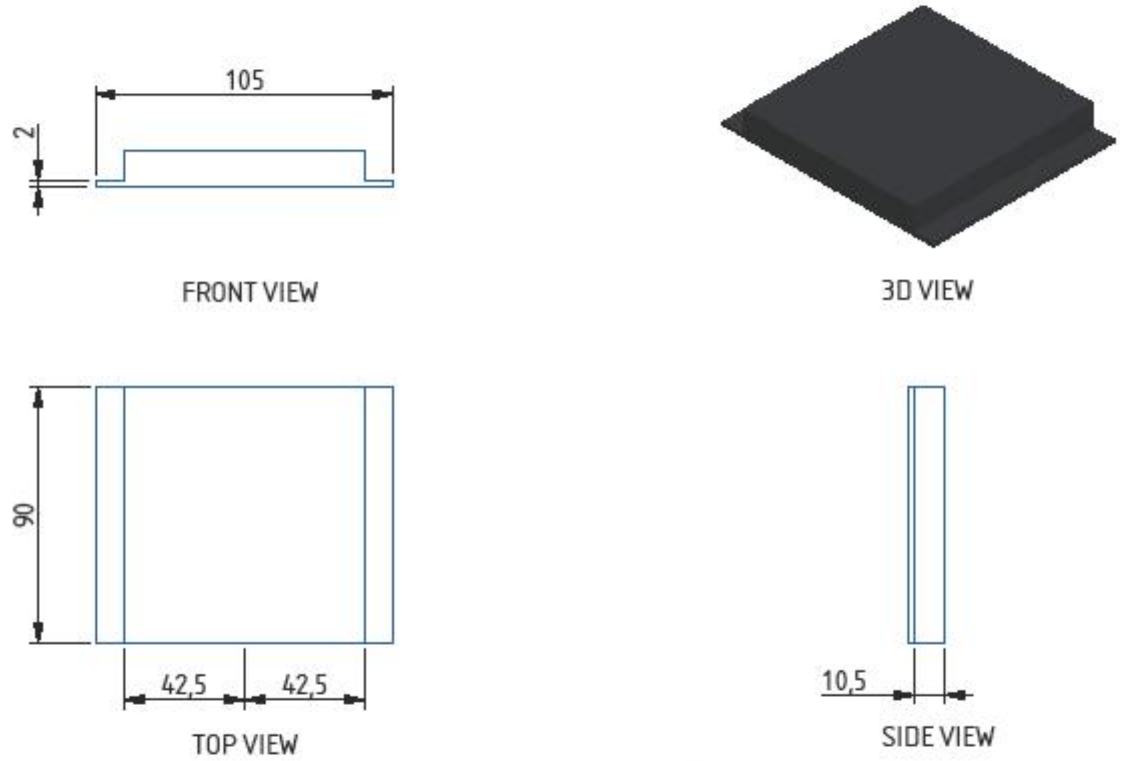
WEC Device Component	
Part name	PENDULUM
Author	Peter Courtis U1045774
Units	mm



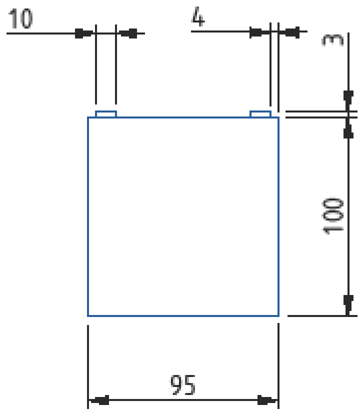
WEC Device Component	
Part name	COMPOUND GEAR SET
Author	Peter Courtis U1045774
Units	mm



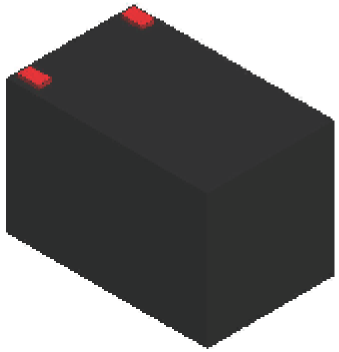
WEC Device Component	
Part name	GENERATOR
Author	Peter Courtis U1045774
Units	mm



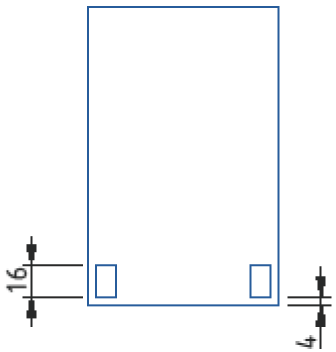
WEC Device Component	
Part name	VOLTAGE REGULATOR
Author	Peter Courtis U1045774
Units	mm



FRONT VIEW



3D VIEW



TOP VIEW

WEC Device Component	
Part name	BATTERY
Author	Peter Courtis U1045774
Units	mm

Appendix J – Cost Data

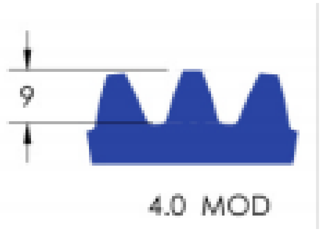
Item	Model	Qty	Cost ea	Total cost	Supplier	Address
Pre-formed pond	Victoria-90	2	$148.00	$296.00	Creative Pumps	https://creativepumps.com.au/
Aluminium square bar 20x20mm	SQR20.00MI4L	4	$40.50	$162.00	Ulrich Aluminium	https://www.ullrich.com.au/
Aluminium plate 10mm 5x1200x2400	S3.012002400MI2FD	1	$480.00	$480.00	Ulrich Aluminium	https://www.ullrich.com.au/
Aluminium plate 3mm 3x1200x2400	S5.012002400MI2FD	1	$125.00	$125.00	Ulrich Aluminium	https://www.ullrich.com.au/
Steel Plate 75x25	75x25	9.743	$44.77	$436.19	Handy Steel Stocks	https://handysteel.com.au/
Steel square tube 75x75mm	75x75x6	0.445	$34.14	$15.19	Handy Steel Stocks	https://handysteel.com.au/
Steel shaft 50mm	50 BLACK ROUND K1045	0.28	$50.48	$14.13	Handy Steel Stocks	https://handysteel.com.au/
Steel shaft 25mm	27 BLACK ROUND 300+ AS3679/300	0.317	$12.20	$3.87	Handy Steel Stocks	https://handysteel.com.au/
Steel shaft 20mm	20 BLACK ROUND 300+ AS3679/300	0.26	$6.89	$1.79	Handy Steel Stocks	https://handysteel.com.au/
Sealant	1230090	2	$13.79	$27.58	Bunnings	https://www.bunnings.com.au/
Rubber seal	3970014	3	$10.75	$32.25	Bunnings	https://www.bunnings.com.au/
Attaching hardware	ASSORTED	1	$100.00	$100.00	Bunnings	https://www.bunnings.com.au/
12 toothed gear	12M40S	2	$65.00	$130.00	Hercus	http://www.hercus.com.au/
45 toothed gear	45M40S	1	$246.00	$246.00	Hercus	http://www.hercus.com.au/
48 toothed gear	48M40S	1	$279.00	$279.00	Hercus	http://www.hercus.com.au/
Generator	NE-100	1	$130.71	$130.71	Ebay	https://www.ebay.com.au/
Voltage regulator	BLW-DC12/24	1	$32.18	$32.18	Ebay	https://www.ebay.com.au/
Battery	SB2487	1	$44.95	$44.95	Jaycar	https://www.jaycar.com.au/
Charge monitor	QP2265	1	$49.95	$49.95	Jaycar	https://www.jaycar.com.au/
RPM sensor	192296	1	$57.99	$57.99	Pushys	https://www.pushys.com.au/
20mm bearing 2 bolt	UCFL204	2	$20.06	$40.12	RS Components	https://au.rs-online.com/web/
25mm bearing 2 bolt	UCFL205	1	$24.64	$24.64	RS Components	https://au.rs-online.com/web/
25mm bearing 4 bolt	UCF205	1	$21.43	$21.43	RS Components	https://au.rs-online.com/web/
45mm bearing 4 bolt	UCFC209	2	$30.86	$61.72	RS Components	https://au.rs-online.com/web/
Electronic components	ASSORTED	1	$40.00	$40.00	Jaycar	https://www.jaycar.com.au/
Fabrication	APEX	1	$1,500.00	$1,500.00	Apex machining	http://apexmachiningservices.com.au
				$4,352.70		

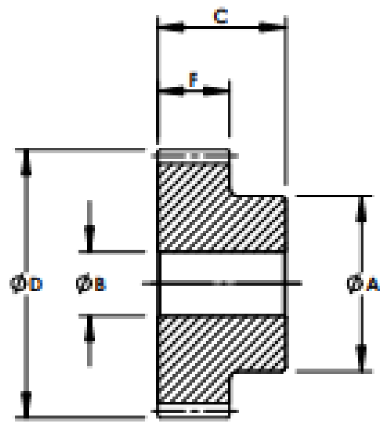
Appendix K – MOD 4 Gear Specifications

F.W. Hercus Pty. Ltd.
12 Camira Street
Regency Park
South Australia, 5010

Phone: (08) 8346 5522 Fax: (08) 8346 5811 e-mail: hercus@hercus.com.au Website: www.hercus.com.au

STOCK SPUR GEARS
PITCH - 4.0 MOD





Face Width – 'F' = 40mm.
Material - S1045 Steel
Tooth Pressure Angle - 20°
Gear Accuracy Conforms To AGMA Class 8

Catalogue No.	No. Teeth	Pitch Dia.	A	B	C	D
12M4.0S	12	52.00	35.0	20.00	60.0	60.00
14M4.0S	14	60.00	40.0	20.00	60.0	68.00
15M4.0S	15	64.00	45.0	20.00	60.0	72.00
16M4.0S	16	68.00	50.0	20.00	60.0	76.00
18M4.0S	18	72.00	55.0	20.00	60.0	80.00
19M4.0S	19	76.00	60.0	20.00	60.0	84.00
20M4.0S	20	80.00	65.0	20.00	60.0	88.00
24M4.0S	24	96.00	80.0	20.00	60.0	104.00
30M4.0S	30	120.00	100.0	20.00	60.0	128.00
36M4.0S	36	144.00	100.0	22.00	56.0	152.00
40M4.0S	40	160.00	100.0	25.00	56.0	168.00
44M4.0S	44	176.00	100.0	25.00	56.0	184.00
45M4.0S	45	180.00	100.0	25.00	56.0	188.00
48M4.0S	48	192.00	100.0	25.00	56.0	200.00
54M4.0S	54	216.00	100.0	30.00	56.0	224.00
60M4.0S	60	240.00	110.0	30.00	56.0	248.00

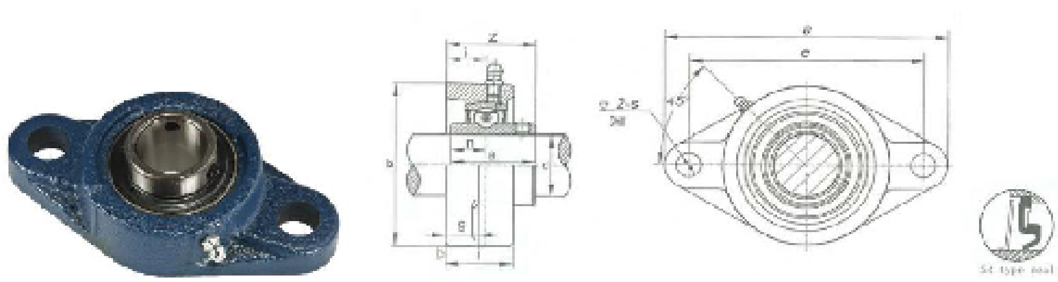
Dimensions in mm.

Note:- To give added strength and improved tooth action all pinions having 16 teeth or less have had their effective meshing pitch diameter increased by one addendum. Centre distance for any two gears is the sum of their pitch diameters as shown in the table, divided by two.

Appendix L - Hercus 2 Bolt Flange Bearing Specifications

ENGLISH

2 Bolt Flange Bearing unit – Metric

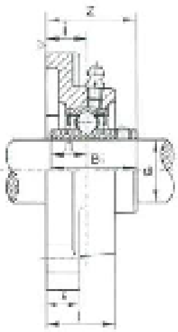


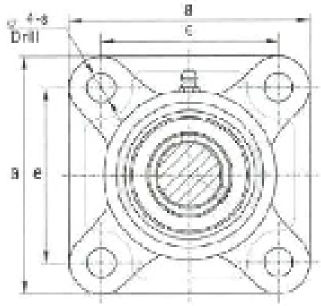
RS Article no.	Bearing unit No.	Shaft Dia. d mm	Dimension (mm)										Bolt used (mm)	Bearing No.	Housing No.	Weight (kg)
			a	e	i	g	l	s	b	z	Bi	n				
[illegible]	UCFL201	12	113	90	15	12	25.5	12	60	33.3	31.0	12.7	M10	UC201	FL201	0.40
[illegible]	UCFL202	15	113	90	15	12	25.5	12	60	33.3	31.0	12.7	M10	UC202	FL202	0.40
[illegible]	UCFL203	17	113	90	15	12	25.5	12	60	33.3	31.0	12.7	M10	UC203	FL203	0.40
[illegible]	UCFL204	20	113	90	15	12	[illegible]	12	60	33.3	31.0	12.7	M10	UC204	FL204	0.40
[illegible]	UCFL205	25	130	99	16	14	27.0	16	68	35.7	34.0	14.3	M14	UC205	FL205	0.63
[illegible]	UCFL206	30	148	117	18	14	31.0	16	80	40.2	38.1	15.9	M14	UC206	FL206	0.94
[illegible]	UCFL207	35	161	130	19	16	34.0	16	90	44.4	42.9	17.5	M14	UC207	FL207	1.2
[illegible]	UCFL208	40	175	144	21	16	36.0	16	100	51.2	49.2	19.0	M14	UC208	FL208	1.6
[illegible]	UCFL209	45	188	148	22	18	38.0	19	108	52.2	49.2	19.0	M16	UC209	FL209	1.9
[illegible]	UCFL210	50	197	157	22	18	40.0	19	115	54.6	51.6	19.0	M16	UC210	FL210	2.2
[illegible]	UCFL211	55	224	184	25	20	43.0	19	130	58.4	55.6	22.2	M16	UC211	FL211	3.2
[illegible]	UCFL212	60	250	202	29	20	48.0	23	140	68.7	65.1	25.4	M20	UC212	FL212	4.1

Appendix M - Hercus 4 Bolt Flange Bearing Specifications

ENGLISH

4 Bolt Flange Bearing unit - Metric





RS Article no.	Bearing unit No.	Shaft Dia.	Dimension (mm)									Bolt used	Bearing No.	Housing No.	Weight (kg)
		d (mm)	a	e	i	g	l	s	z	Bi	n	(mm)			
[illegible]	UCF201	12	86	64	15	12	25.5	12	33.3	31.0	12.7	M10	UC201	F201	0.63
[illegible]	UCF202	15	86	64	15	12	25.5	12	33.3	31.0	12.7	M10	UC202	F202	0.63
[illegible]	UCF203	17	86	64	16	12	26.5	12	33.3	31.0	12.7	M10	UC203	F203	0.62
[illegible]	UCF204	20	86	64	15	12	25.5	12	33.3	31.0	12.7	M10	UC204	F204	0.63
[illegible]	UCF205	25	95	70	16	14	27.0	12	35.7	34.0	14.3	M10	UC205	F205	0.82
[illegible]	UCF206	30	108	83	18	14	31.0	12	40.2	38.1	15.9	M10	UC206	F206	1.1
[illegible]	UCF207	35	117	92	19	16	34.0	14	44.4	42.9	17.5	M12	UC207	F207	1.5
[illegible]	UCF208	40	130	102	21	16	36.0	16	51.2	49.2	19.0	M14	UC208	F208	1.8
[illegible]	UCF209	45	137	105	22	18	38.0	16	52.2	49.2	19.0	M14	UC209	F209	2.3
[illegible]	UCF210	50	143	111	22	18	40.0	16	54.6	51.6	19.0	M14	UC210	F210	2.5
[illegible]	UCF211	55	162	130	25	20	43.0	19	58.4	55.6	22.2	M16	UC211	F211	3.4
[illegible]	UCF212	60	175	143	29	20	48.0	19	68.7	65.1	25.4	M16	UC212	F212	4.4

Appendix N – Modelling data

Wave length (m)																										
	50th Percentile of Wave Energy Period (s)																									
50th Percentile of Significant Wave Height (m)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5
0.0	0.00	0.39	1.56	3.51	6.24	9.75	14.04	19.11	24.96	31.59	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00	171.99	188.76	206.31	224.64	243.75
0.4	0.00	0.39	1.56	3.51	6.24	9.75	14.04	19.11	24.96	31.59	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00	171.99	188.76	206.31	224.64	243.75
0.8	0.00	0.39	1.56	3.51	6.24	9.75	14.04	19.11	24.96	31.59	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00	171.99	188.76	206.31	224.64	243.75
1.2	0.00	0.39	1.56	3.51	6.24	9.75	14.04	19.11	24.96	31.59	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00	171.99	188.76	206.31	224.64	243.75
1.6	0.00	0.39	1.56	3.51	6.24	9.75	14.04	19.11	24.96	31.59	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00	171.99	188.76	206.31	224.64	243.75
2.0	0.00	0.39	1.56	3.51	6.24	9.75	14.04	19.11	24.96	31.59	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00	171.99	188.76	206.31	224.64	243.75
2.4	0.00	0.39	1.56	3.51	6.24	9.75	14.04	19.11	24.96	31.59	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00	171.99	188.76	206.31	224.64	243.75
2.8	0.00	0.39	1.56	3.51	6.24	9.75	14.04	19.11	24.96	31.59	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00	171.99	188.76	206.31	224.64	243.75
3.2	0.00	0.39	1.56	3.51	6.24	9.75	14.04	19.11	24.96	31.59	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00	171.99	188.76	206.31	224.64	243.75
3.6	0.00	0.39	1.56	3.51	6.24	9.75	14.04	19.11	24.96	31.59	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00	171.99	188.76	206.31	224.64	243.75
4.0	0.00	0.39	1.56	3.51	6.24	9.75	14.04	19.11	24.96	31.59	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00	171.99	188.76	206.31	224.64	243.75
4.4	0.00	0.39	1.56	3.51	6.24	9.75	14.04	19.11	24.96	31.59	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00	171.99	188.76	206.31	224.64	243.75
4.8	0.00	0.39	1.56	3.51	6.24	9.75	14.04	19.11	24.96	31.59	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00	171.99	188.76	206.31	224.64	243.75
5.2	0.00	0.39	1.56	3.51	6.24	9.75	14.04	19.11	24.96	31.59	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00	171.99	188.76	206.31	224.64	243.75
5.6	0.00	0.39	1.56	3.51	6.24	9.75	14.04	19.11	24.96	31.59	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00	171.99	188.76	206.31	224.64	243.75
6.0	0.00	0.39	1.56	3.51	6.24	9.75	14.04	19.11	24.96	31.59	39.00	47.19	56.16	65.91	76.44	87.75	99.84	112.71	126.36	140.79	156.00	171.99	188.76	206.31	224.64	243.75

Angle of wave (Degrees)																										
	50th Percentile of Wave Energy Period (s)																									
50th Percentile of Significant Wave Height (m)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.4	0	64	27	13	7	5	3	2	2	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
0.8	0	76	46	25	14	9	7	5	4	3	2	2	2	1	1	1	1	1	1	1	1	1	0	0	0	0
1.2	0	81	57	34	21	14	10	7	5	4	4	3	2	2	2	2	1	1	1	1	1	1	1	1	1	1
1.6	0	83	64	42	27	18	13	10	7	6	5	4	3	3	2	2	2	2	1	1	1	1	1	1	1	1
2.0	0	84	69	49	33	22	16	12	9	7	6	5	4	3	3	3	2	2	2	2	1	1	1	1	1	1
2.4	0	85	72	54	38	26	19	14	11	9	7	6	5	4	4	3	3	2	2	2	2	2	1	1	1	1
2.8	0	86	74	58	42	30	22	16	13	10	8	7	6	5	4	4	3	3	3	2	2	2	2	2	1	1
3.2	0	87	76	61	46	33	25	19	14	11	9	8	7	6	5	4	4	3	3	3	2	2	2	2	2	2
3.6	0	87	78	64	49	36	27	21	16	13	10	9	7	6	5	5	4	4	3	3	3	2	2	2	2	2
4.0	0	87	79	66	52	39	30	23	18	14	12	10	8	7	6	5	5	4	4	3	3	3	2	2	2	2
4.4	0	87	80	68	55	42	32	25	19	16	13	11	9	8	7	6	5	4	4	4	3	3	3	2	2	2
4.8	0	88	81	70	57	45	34	27	21	17	14	11	10	8	7	6	5	5	4	4	4	3	3	3	2	2
5.2	0	88	81	71	59	47	37	29	23	18	15	12	10	9	8	7	6	5	5	4	4	3	3	3	3	2
5.6	0	88	82	73	61	49	39	30	24	20	16	13	11	10	8	7	6	6	5	5	4	4	3	3	3	3
6.0	0	88	83	74	63	51	41	32	26	21	17	14	12	10	9	8	7	6	5	5	4	4	4	3	3	3

Effective height for PE harvesting (m)

50th Percentile of Significant Wave Height (m)	50th Percentile of Wave Energy Period (s)																									
	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.4	0	0.54	0.27	0.13	0.08	0.05	0.03	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.8	0	0.58	0.43	0.25	0.15	0.10	0.07	0.05	0.04	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00
1.2	0	0.59	0.50	0.34	0.22	0.14	0.10	0.07	0.06	0.05	0.04	0.03	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
1.6	0	0.60	0.54	0.40	0.27	0.19	0.13	0.10	0.08	0.06	0.05	0.04	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
2.0	0	0.60	0.56	0.45	0.32	0.23	0.16	0.12	0.09	0.08	0.06	0.05	0.04	0.04	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01
2.4	0	0.60	0.57	0.48	0.37	0.27	0.19	0.15	0.11	0.09	0.07	0.06	0.05	0.04	0.04	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01
2.8	0	0.60	0.58	0.51	0.40	0.30	0.22	0.17	0.13	0.10	0.09	0.07	0.06	0.05	0.04	0.04	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.01	0.01
3.2	0	0.60	0.58	0.53	0.43	0.33	0.25	0.19	0.15	0.12	0.10	0.08	0.07	0.06	0.05	0.04	0.04	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02
3.6	0	0.60	0.59	0.54	0.45	0.36	0.27	0.21	0.17	0.13	0.11	0.09	0.08	0.07	0.06	0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.02
4.0	0	0.60	0.59	0.55	0.47	0.38	0.30	0.23	0.18	0.15	0.12	0.10	0.08	0.07	0.06	0.05	0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.02	0.02	0.02
4.4	0	0.60	0.59	0.56	0.49	0.40	0.32	0.25	0.20	0.16	0.13	0.11	0.09	0.08	0.07	0.06	0.05	0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.02	0.02
4.8	0	0.60	0.59	0.56	0.50	0.42	0.34	0.27	0.22	0.17	0.14	0.12	0.10	0.09	0.07	0.07	0.06	0.05	0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.02
5.2	0	0.60	0.59	0.57	0.51	0.44	0.36	0.29	0.23	0.19	0.15	0.13	0.11	0.09	0.08	0.07	0.06	0.06	0.05	0.04	0.04	0.04	0.03	0.03	0.03	0.03
5.6	0	0.60	0.59	0.57	0.52	0.45	0.37	0.30	0.25	0.20	0.17	0.14	0.12	0.10	0.09	0.08	0.07	0.06	0.05	0.05	0.04	0.04	0.04	0.03	0.03	0.03
6.0	0	0.60	0.59	0.58	0.53	0.47	0.39	0.32	0.26	0.21	0.18	0.15	0.13	0.11	0.09	0.08	0.07	0.06	0.06	0.05	0.05	0.04	0.04	0.03	0.03	0.03

Available PE per wave (J)

50th Percentile of Significant Wave Height (m)	50th Percentile of Wave Energy Period (s)																									
	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.4	0	1058.16	537.18	261.60	149.70	96.27	66.97	49.24	37.71	29.80	24.14	19.95	16.77	14.29	12.32	10.73	9.43	8.36	7.45	6.69	6.04	5.48	4.99	4.56	4.19	3.86
0.8	0	1143.71	842.88	488.28	292.39	190.63	133.29	98.22	75.31	59.55	48.25	39.89	33.52	28.57	24.64	21.46	18.86	16.71	14.90	13.38	12.07	10.95	9.98	9.13	8.38	7.73
1.2	0	1161.96	987.02	664.45	422.59	281.37	198.35	146.69	112.67	89.18	72.31	59.79	50.26	42.84	36.94	32.18	28.29	25.06	22.35	20.06	18.11	16.43	14.97	13.69	12.58	11.59
1.6	0	1168.55	1058.16	793.10	537.18	367.10	261.60	194.42	149.70	118.64	96.27	79.64	66.97	57.09	49.24	42.90	37.71	33.41	29.80	26.75	24.14	21.90	19.95	18.26	16.77	15.45
2.0	0	1171.64	1096.74	884.84	635.29	446.81	322.55	241.18	186.28	147.88	120.11	99.43	83.63	71.31	61.52	53.61	47.13	41.75	37.25	33.43	30.17	27.37	24.94	22.82	20.96	19.32
2.4	0	1173.33	1119.56	950.24	717.75	519.95	380.82	286.78	222.31	176.84	143.80	119.13	100.25	85.51	73.78	64.30	56.53	50.09	44.69	40.11	36.20	32.84	29.93	27.38	25.15	23.18
2.8	0	1174.36	1134.02	997.46	786.26	586.31	436.13	331.05	257.71	205.48	167.32	138.72	116.81	99.66	86.01	74.97	65.93	58.42	52.12	46.79	42.23	38.31	34.91	31.94	29.34	27.04
3.2	0	1175.02	1143.71	1032.16	842.88	645.99	488.28	373.84	292.39	233.75	190.63	158.21	133.29	113.77	98.22	85.63	75.31	66.74	59.55	53.46	48.25	43.78	39.89	36.50	33.52	30.90
3.6	0	1175.48	1150.50	1058.16	889.60	699.31	537.18	415.05	326.27	261.60	213.72	177.56	149.70	127.84	110.39	96.27	84.67	75.05	66.97	60.12	54.27	49.24	44.87	41.06	37.71	34.76
4.0	0	1175.80	1155.44	1078.00	928.22	746.72	582.80	454.58	359.30	289.00	236.55	196.76	166.02	141.84	122.53	106.88	94.03	83.35	74.38	66.78	60.29	54.70	49.85	45.61	41.90	38.62
4.4	0	1176.05	1159.13	1093.43	960.28	788.74	625.19	492.39	391.42	315.90	259.11	215.80	182.24	155.79	134.63	117.47	103.36	91.63	81.78	73.44	66.30	60.15	54.82	50.17	46.08	42.47
4.8	0	1176.23	1161.96	1105.62	987.02	825.93	664.45	528.44	422.59	342.29	281.37	234.67	198.35	169.67	146.69	128.02	112.67	99.91	89.18	80.08	72.31	65.61	59.79	54.72	50.26	46.33
5.2	0	1176.37	1164.18	1115.39	1009.44	858.81	700.70	562.72	452.77	368.12	303.32	253.36	214.36	183.48	158.70	138.55	121.97	108.16	96.56	86.72	78.31	71.05	64.76	59.27	54.44	50.18
5.6	0	1176.49	1165.94	1123.33	1028.36	887.89	734.11	595.24	481.94	393.38	324.93	271.84	230.24	197.21	170.66	149.04	131.23	116.41	103.93	93.35	84.30	76.50	69.73	63.81	58.62	54.03
6.0	0	1176.58	1167.38	1129.86	1044.43	913.64	764.85	626.02	510.07	418.03	346.20	290.12	245.99	210.86	182.57	159.50	140.48	124.63	111.29	99.97	90.29	81.94	74.69	68.36	62.80	57.88

Watts

50th Percentile of Wave Energy Period (s)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5
RPM	0.0	120.0	60.0	40.0	30.0	24.0	20.0	17.1	15.0	13.3	12.0	10.9	10.0	9.2	8.6	8.0	7.5	7.1	6.7	6.3	6.0	5.7	5.5	5.2	5.0	4.8
50th Percentile of Significant Wave Height (m)																										
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.4	0	2116.31	537.18	174.40	74.85	38.51	22.32	14.07	9.43	6.62	4.83	3.63	2.79	2.20	1.76	1.43	1.18	0.98	0.83	0.70	0.60	0.52	0.45	0.40	0.35	0.31
0.8	0	2287.43	842.88	325.52	146.19	76.25	44.43	28.06	18.83	13.23	9.65	7.25	5.59	4.40	3.52	2.86	2.36	1.97	1.66	1.41	1.21	1.04	0.91	0.79	0.70	0.62
1.2	0	2323.92	987.02	442.97	211.30	112.55	66.12	41.91	28.17	19.82	14.46	10.87	8.38	6.59	5.28	4.29	3.54	2.95	2.48	2.11	1.81	1.56	1.36	1.19	1.05	0.93
1.6	0	2337.11	1058.16	528.74	268.59	146.84	87.20	55.55	37.42	26.36	19.25	14.48	11.16	8.78	7.03	5.72	4.71	3.93	3.31	2.82	2.41	2.09	1.81	1.59	1.40	1.24
2.0	0	2343.29	1096.74	589.89	317.65	178.73	107.52	68.91	46.57	32.86	24.02	18.08	13.94	10.97	8.79	7.15	5.89	4.91	4.14	3.52	3.02	2.61	2.27	1.98	1.75	1.55
2.4	0	2346.67	1119.56	633.50	358.88	207.98	126.94	81.94	55.58	39.30	28.76	21.66	16.71	13.15	10.54	8.57	7.07	5.89	4.97	4.22	3.62	3.13	2.72	2.38	2.10	1.85
2.8	0	2348.71	1134.02	664.97	393.13	234.52	145.38	94.58	64.43	45.66	33.46	25.22	19.47	15.33	12.29	10.00	8.24	6.87	5.79	4.92	4.22	3.65	3.17	2.78	2.44	2.16
3.2	0	2350.04	1143.71	688.11	421.44	258.40	162.76	106.81	73.10	51.94	38.13	28.76	22.22	17.50	14.03	11.42	9.41	7.85	6.62	5.63	4.83	4.17	3.63	3.17	2.79	2.47
3.6	0	2350.95	1150.50	705.44	444.80	279.72	179.06	118.59	81.57	58.13	42.74	32.28	24.95	19.67	15.77	12.84	10.58	8.83	7.44	6.33	5.43	4.69	4.08	3.57	3.14	2.78
4.0	0	2351.61	1155.44	718.67	464.11	298.69	194.27	129.88	89.83	64.22	47.31	35.77	27.67	21.82	17.50	14.25	11.75	9.81	8.26	7.03	6.03	5.21	4.53	3.97	3.49	3.09
4.4	0	2352.09	1159.13	728.95	480.14	315.50	208.40	140.68	97.86	70.20	51.82	39.24	30.37	23.97	19.23	15.66	12.92	10.78	9.09	7.73	6.63	5.73	4.98	4.36	3.84	3.40
4.8	0	2352.46	1161.96	737.08	493.51	330.37	221.48	150.98	105.65	76.06	56.27	42.67	33.06	26.10	20.96	17.07	14.08	11.75	9.91	8.43	7.23	6.25	5.44	4.76	4.19	3.71
5.2	0	2352.75	1164.18	743.59	504.72	343.52	233.57	160.78	113.19	81.80	60.66	46.07	35.73	28.23	22.67	18.47	15.25	12.73	10.73	9.13	7.83	6.77	5.89	5.15	4.54	4.01
5.6	0	2352.97	1165.94	748.89	514.18	355.16	244.70	170.07	120.48	87.42	64.99	49.43	38.37	30.34	24.38	19.87	16.40	13.69	11.55	9.83	8.43	7.29	6.34	5.55	4.88	4.32
6.0	0	2353.16	1167.38	753.24	522.22	365.46	254.95	178.86	127.52	92.90	69.24	52.75	41.00	32.44	26.08	21.27	17.56	14.66	12.37	10.52	9.03	7.80	6.79	5.94	5.23	4.63

Peak Torque

50th Percentile of Wave Energy Period (s)	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5
RPM	0.0	120.0	60.0	40.0	30.0	24.0	20.0	17.1	15.0	13.3	12.0	10.9	10.0	9.2	8.6	8.0	7.5	7.1	6.7	6.3	6.0	5.7	5.5	5.2	5.0	4.8
50th Percentile of Significant Wave Height (m)																										
0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.4	0	265	134	65	37	24	17	12	9	7	6	5	4	4	3	3	2	2	2	2	2	1	1	1	1	1
0.8	0	286	211	122	73	48	33	25	19	15	12	10	8	7	6	5	5	4	4	3	3	3	2	2	2	2
1.2	0	290	247	166	106	70	50	37	28	22	18	15	13	11	9	8	7	6	6	5	5	4	4	3	3	3
1.6	0	292	265	198	134	92	65	49	37	30	24	20	17	14	12	11	9	8	7	7	6	5	5	5	4	4
2.0	0	293	274	221	159	112	81	60	47	37	30	25	21	18	15	13	12	10	9	8	8	7	6	6	5	5
2.4	0	293	280	238	179	130	95	72	56	44	36	30	25	21	18	16	14	13	11	10	9	8	7	7	6	6
2.8	0	294	284	249	197	147	109	83	64	51	42	35	29	25	22	19	16	15	13	12	11	10	9	8	7	7
3.2	0	294	286	258	211	161	122	93	73	58	48	40	33	28	25	21	19	17	15	13	12	11	10	9	8	8
3.6	0	294	288	265	222	175	134	104	82	65	53	44	37	32	28	24	21	19	17	15	14	12	11	10	9	9
4.0	0	294	289	270	232	187	146	114	90	72	59	49	42	35	31	27	24	21	19	17	15	14	12	11	10	10
4.4	0	294	290	273	240	197	156	123	98	79	65	54	46	39	34	29	26	23	20	18	17	15	14	13	12	11
4.8	0	294	290	276	247	206	166	132	106	86	70	59	50	42	37	32	28	25	22	20	18	16	15	14	13	12
5.2	0	294	291	279	252	215	175	141	113	92	76	63	54	46	40	35	30	27	24	22	20	18	16	15	14	13
5.6	0	294	291	281	257	222	184	149	120	98	81	68	58	49	43	37	33	29	26	23	21	19	17	16	15	14
6.0	0	294	292	282	261	228	191	157	128	105	87	73	61	53	46	40	35	31	28	25	23	20	19	17	16	14

Geared Torque

Ratio	15	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5
		50th Percentile of Wave Energy Period (s)																									
	RPM	0.0	1800.0	900.0	600.0	450.0	360.0	300.0	257.1	225.0	200.0	180.0	163.6	150.0	138.5	128.6	120.0	112.5	105.9	100.0	94.7	90.0	85.7	81.8	78.3	75.0	72.0
50th Percentile of Significant Wave Height (m)	0.0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0.4	0	17.64	8.95	4.36	2.49	1.60	1.12	0.82	0.63	0.50	0.40	0.33	0.28	0.24	0.21	0.18	0.16	0.14	0.12	0.11	0.10	0.09	0.08	0.08	0.07	0.06
	0.8	0	19.06	14.05	8.14	4.87	3.18	2.22	1.64	1.26	0.99	0.80	0.66	0.56	0.48	0.41	0.36	0.31	0.28	0.25	0.22	0.20	0.18	0.17	0.15	0.14	0.13
	1.2	0	19.37	16.45	11.07	7.04	4.69	3.31	2.44	1.88	1.49	1.21	1.00	0.84	0.71	0.62	0.54	0.47	0.42	0.37	0.33	0.30	0.27	0.25	0.23	0.21	0.19
	1.6	0	19.48	17.64	13.22	8.95	6.12	4.36	3.24	2.49	1.98	1.60	1.33	1.12	0.95	0.82	0.72	0.63	0.56	0.50	0.45	0.40	0.36	0.33	0.30	0.28	0.26
	2.0	0	19.53	18.28	14.75	10.59	7.45	5.38	4.02	3.10	2.46	2.00	1.66	1.39	1.19	1.03	0.89	0.79	0.70	0.62	0.56	0.50	0.46	0.42	0.38	0.35	0.32
	2.4	0	19.56	18.66	15.84	11.96	8.67	6.35	4.78	3.71	2.95	2.40	1.99	1.67	1.43	1.23	1.07	0.94	0.83	0.74	0.67	0.60	0.55	0.50	0.46	0.42	0.39
	2.8	0	19.57	18.90	16.62	13.10	9.77	7.27	5.52	4.30	3.42	2.79	2.31	1.95	1.66	1.43	1.25	1.10	0.97	0.87	0.78	0.70	0.64	0.58	0.53	0.49	0.45
	3.2	0	19.58	19.06	17.20	14.05	10.77	8.14	6.23	4.87	3.90	3.18	2.64	2.22	1.90	1.64	1.43	1.26	1.11	0.99	0.89	0.80	0.73	0.66	0.61	0.56	0.51
	3.6	0	19.59	19.18	17.64	14.83	11.66	8.95	6.92	5.44	4.36	3.56	2.96	2.49	2.13	1.84	1.60	1.41	1.25	1.12	1.00	0.90	0.82	0.75	0.68	0.63	0.58
	4.0	0	19.60	19.26	17.97	15.47	12.45	9.71	7.58	5.99	4.82	3.94	3.28	2.77	2.36	2.04	1.78	1.57	1.39	1.24	1.11	1.00	0.91	0.83	0.76	0.70	0.64
	4.4	0	19.60	19.32	18.22	16.00	13.15	10.42	8.21	6.52	5.27	4.32	3.60	3.04	2.60	2.24	1.96	1.72	1.53	1.36	1.22	1.11	1.00	0.91	0.84	0.77	0.71
	4.8	0	19.60	19.37	18.43	16.45	13.77	11.07	8.81	7.04	5.70	4.69	3.91	3.31	2.83	2.44	2.13	1.88	1.67	1.49	1.33	1.21	1.09	1.00	0.91	0.84	0.77
	5.2	0	19.61	19.40	18.59	16.82	14.31	11.68	9.38	7.55	6.14	5.06	4.22	3.57	3.06	2.65	2.31	2.03	1.80	1.61	1.45	1.31	1.18	1.08	0.99	0.91	0.84
	5.6	0	19.61	19.43	18.72	17.14	14.80	12.24	9.92	8.03	6.56	5.42	4.53	3.84	3.29	2.84	2.48	2.19	1.94	1.73	1.56	1.40	1.27	1.16	1.06	0.98	0.90
	6.0	0	19.61	19.46	18.83	17.41	15.23	12.75	10.43	8.50	6.97	5.77	4.84	4.10	3.51	3.04	2.66	2.34	2.08	1.85	1.67	1.50	1.37	1.24	1.14	1.05	0.96

RPM

		50th Percentile of Wave Energy Period (s)																									
		0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5
	RPM	0	120.00	60.00	40.00	30.00	24.00	20.00	17.14	15.00	13.33	12.00	10.91	10.00	9.23	8.57	8.00	7.50	7.06	6.67	6.32	6.00	5.71	5.45	5.22	5.00	4.80

Geared RPM

Ratio	15	50th Percentile of Wave Energy Period (s)																									
		0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5
	RPM	0	1800.00	900.00	600.00	450.00	360.00	300.00	257.14	225.00	200.00	180.00	163.64	150.00	138.46	128.57	120.00	112.50	105.88	100.00	94.74	90.00	85.71	81.82	78.26	75.00	72.00