Engineering Doctorate

The transfer of Oil and Gas Technology and Skills to the conceptual design and development of a novel low cost modular Tidal Energy Conversion deployment system

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This thesis is submitted in part fulfilment of the requirements for the degree of Doctor of Engineering at The Robert Gordon University

This project is confidential

Abstract

This thesis outlines the use of a new design of Tidal Energy Conversion device which has application in near shore shallow water. The design is applicable for use by coastal communities, either to generate revenue through power sales or just a stand alone system to generate off grid electricity.

Previous work conducted on large scale tidal installations have shown that they suffer from excessive costs and time lines, due to their up front design philosophy. This thesis discusses the reasons behind such cost/time overruns and concludes that several technologies and techniques can be incorporated from the subsea oil and gas industry. The early ethos in the offshore oil industry in the 1970's and 1980's was to build large offshore structures such as steel and concrete platforms. This has now been replaced by a field development philosophy that looks at simple lower cost subsea well infrastructure as the most cost effective route to exploit a reservoir. The emerging tidal industry has not learned this lesson, yet.

A set of new Tidal Energy exploitation designs are proposed and Patented. The chief advantages of this new design are their modular nature, fabrication simplicity, lower build and installation cost. Prototype work is described and further work also highlighted.

Acknowledgements

I am indebted to my Supervisor Professor Peter Robertson for his help, support and encouragement throughout this project. Peter, without your help, this work would have been far more difficult.

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Shell International Exploration and Production

Galloway Engineering

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List of Abbreviations

AC	Alternating Current
API	American Petroleum Institute
ARC	Atlantis Resources Corporation
BERR	Department for Business Enterprise and Regulatory Reform
BiFab	Burntisland Fabrication
BOP	Blow Out Preventer
CAD	Computed Aided Design
CAPEX	CAPital EXpenditure
cc/l	Cubic centimetre per litre
CFD	Computational Fluid Dynamics
DC	Direct Current
DGB	Drilling Guide Base
EDP	Emergency Disconnect Package
EMEC	European Marine Energy Centre
EU	European Union
ft	Feet
GoM	Gulf of Mexico
GRP	Glass Reinforced Plastic
GW	Gigawatt
H_2S	Hydrogen Sulphide
HOST	Hinge Over Subsea Template
Hz	Hertz
IC	Impressed Current
kg	Kilograms
kN	Kilo Newton
KV	Kilovolts
kW	Kilowatts
kWh	Kilowatt hour
lb/ft	Pounds per Foot
LRP	Lower Riser Package
m	metres

m/s	metres per second
MCT	Marine Current Turbines
MLS	Magnetic Locking System
MT	Metric Tonne
MW	Megawatts
OD	Outside Diameter
PGB	Production Guide Base
ppm	Parts Per Million
psi	Pounds per Square Inch
PSL	Production Specification Level
RNLI	Royal National Lifeboat Institution
ROC	Renewable Obligation Certificate
RoI	Return on Investment
ROT	Remotely Operated Tool
ROV	Remotely Operated Vehicle
RP	Rapid Prototyping
RPM	Revolutions Per Minute
RT	Running Tool
S/N	Stress versus Number of cycles
SCC	Stress Corrosion Cracking
STL	Stereo Lithography
SWL	Safe Working Loads
TCRT	Tree Cap Running Tool
TEC	Tidal Energy Converter
TIB	Transport and Installation Barge
TW	Terrawatt
TWh/y	Terrawatt hours per year
UK	United Kingdom
USA	United States of America
V	Volts

1 Introduction

1.1 Introduction to chapter

This chapter commences by outlining the problems addressed by the EngD research project. The aims and objectives are described and the innovative ideas developed during this work are highlighted. A breakdown of each chapter of this thesis is also included.

1.2 The nature of the problem

The market for renewable energy products and services is expanding rapidly, on a global scale. In recent years it has been acknowledged that tidal energy, or energy derived from marine currents, is set to be an interesting future part of the renewable energy portfolio. However, the tidal "industry" is still in its infancy and the majority of research and development is still at the prototype stage. There are numerous devices worldwide that are at various stages in their development, from laboratory sized models to full scale pre-commercial systems.

The majority of tidal systems being developed are suffering from the "quest" to achieve a nominal one megawatt output device. This philosophy seems to be driving the development of so called economic systems. However, to achieve this one megawatt nameplate is involving massive injections and private and government investment. In just Europe, the sum invested in tidal research on prototype devices must easily be over £100 million, and yet there is not one economic system in the water. Most of the devices are structurally very large and heavy, and hence are burdened with excessive build and deployment costs.

The mentality of many tidal developers is that they are working in an industry akin to the oil and gas operators, where profits are large and hence development money is easy to come by. Very few tidal developers seem to consider that the price of electricity is very low (as produced by large power stations) and that to compete with this needs a low cost approach. The large one megawatt devices are proving that they cannot compete with the economics of existing generation systems.

When any marine device is structurally very large and heavy, it will be difficult to construct and also install. The device will require the use of purpose built vessels like heavy lift barges, which are used in the oil and gas industry. Instantly, the tidal industry is then competing with another industry for vessel rental. The high costs available in the oil industry rental market are then put across into the tidal market. This makes viable tidal economics difficult to achieve.

Therefore, the main aim of this EngD project was to transfer elements of technology from existing subsea equipment installation procedures that are used in the oil and gas industry and combine these with a novel design of a lower cost tidal energy exploitation device. The overall aim was to develop a lower powered (100 kilowatt) tidal exploitation system, and low-cost modular solution for securing marine energy devices to the seabed, in shallow water. A 100 kW device that can be easily installed with conventional in-shore installation workboats would much improve project economics and make the system viable for use by coastal communities, as an example.

1.3 Aims and Objectives

The main aim of the research was to critically review existing tidal energy exploitation devices and their installation methods, and compare them to existing subsea oil and gas installation technologies and techniques. In addition, attempt to develop small scale prototypes and perform conceptual testing.

To achieve the aim of the project the following objectives were set for this EngD;

1. Produce a brief review of the emerging tidal energy market, and related business opportunity.
2. Critically review tidal technology deployment activities and compare oil & gas installation techniques to several tidal technology installation techniques.
3. Critically review existing subsea oil and gas technology and attempt to derive a lower cost system for use in tidal devices.

4. Produce a concept for a simple non-hydraulic locking device, using magnetic force as opposed to hydraulic force.
5. Build small scale prototypes of a magnetically operated lock, and concept test these under different conditions (laboratory and in water).
6. Build scaled prototypes of a new style of rotor, and perform early stage testing and analysis under different conditions.

1.4 Novel aspects of this research

Although tidal energy device research and development is advancing quickly, most researchers have tried to develop their own systems, especially with regard to installation. Many developers have no experience of working in the offshore / marine sector, which is obviously a distinct disadvantage when it comes to considering installation. The author has tried to critically review what others are doing in various industries and attempt to transfer technologies and techniques and mould them into an innovative new system for tidal energy exploitation**.**

There are several unique aspects to the approach used in this EngD project research. The most important of these are;

- An innovative modular tidal energy exploitation system was developed, using proven tools and techniques from another industry
- Experimental results show that the new system has several distinct advantages and adds new knowledge to the field.
- A Patent was received in 2006 for initial research completed leading up to the EngD experimental stage, and a description is included in the Appendices. The award of this Patent proves the application of an innovative step.
- Two further patents are now pending, these were filed as the EngD project progressed.

- An economics approach proving that the system could be an attractive renewable energy system for coastal communities

The patent awarded is shown in Figure 1.1.

Certificate of Grant of Patent

Patent Number: GB2400632

Proprietor(s): Anthony T Morse

Inventor(s): Anthony T Morse

This is to Certify that, in accordance with the Patents Act 1977,

a Patent has been granted to the proprietor(s) for an invention entitled **"Subsea energy generation"** disclosed in an application filed **16 April 2004**.

Dated 26 April 2006

Ron Marchant
Comptroller General of Patents, Designs and Trade Marks
UNITED KINGDOM PATENT OFFICE

The attention of the proprietor(s) is drawn to the important notes overleaf.

Figure 1.1: UK patent Award 2006

1.5 Thesis Structure

An overview of each chapter is included below;

Chapter 2. Literature Search

This chapter provides a survey, review and critical comment of the existing tidal and subsea oil and gas industries, and the relevant technologies being used.

Chapter 3. Conceptual design for new Modular Tidal Generator

This chapter introduces the new tidal energy exploitation system designs and explains their construction and function in detail.

Chapter 4. Early stage practical work

This chapter explains the initial work conducted in order to provide early proof of concept of the designs.

Chapter 5. Engineering and Cost Analysis

This chapter compares the results from the various prototype tests and provides an outline engineering and economic analysis on the new designs.

Chapter 6. Discussion, **Conclusions**

This final chapter revisits the aims and objectives of the project and critically assesses the success of this EngD project. It suggests the further work that is required.

1.6 Chapter Summary

This chapter commences by outlining the problems addressed by the EngD research project. The aims and objectives are described and the innovative ideas developed during this work are highlighted. A breakdown of each chapter of this thesis is also included. The published Patent and additional information are included in the Appendices.

This EngD submission covers a project submission to the Robert Gordon University Aberdeen. This tidal energy research and part time project has been ongoing for 6 years and started with the filing of a patent in 2004, and its subsequent award in 2006. In 2008, the EngD project secured a grant of £47,000 from Scottish Enterprise's Marine Energy Support Fund to develop a scaled prototype of a novel underwater locking system for its seabed-mounted modular tidal stream turbine. The part funded project commenced in April 2008 and was successfully completed at the end of March 2009. The remainder of the project has been funded by the author.

2 Literature Search

This chapter reviews and discusses the following as part of the literature survey for the thesis research:

- Review of global tidal energy market potential
- Overview of Subsea Oil & Gas Production systems
- Review of Subsea Well Systems
- Review of tidal Energy Devices and Installation Methods
- Chapter summary

2.1 Review of global tidal energy market potential

Worldwide energy demand is growing phenomenally and is predicted to increase by 55% between 2005 and 2030 if current government policies are maintained(1). At the same time, there is an unprecedented level of awareness of the need to break away from dependence on unsustainable and environmentally harmful sources of energy.

Governments around the world are setting targets for generation of renewable energy and implementing policies to support their achievement. There is a baseline EU target of 20% of energy to be derived from renewable sources by 2020(2) and the newly elected US president has pledged a target of 25% by 2025. Scotland, with its plentiful natural energy resources, has already achieved over 20% of electricity generated from renewable resources (predominantly conventional hydro), with pressure to progress towards its own national targets of 31% by 2011 then 50% by 2020. Thus the proportion of renewable energy is growing rapidly but there is pressure for it to continue to do so exponentially in order for the mandatory targets to be achieved.

Note: The Scottish Government website(3) recently announced (October 2010) that it wishes to achieve 100% of it's generation capacity by 2050.

Tidal stream energy, from marine currents, is a vast resource capable of generating significant proportions of energy demand in locations where the tides provide a rich source of power. The resource is concentrated in northerly and southerly latitudes in areas that include the UK, Russia, N America, NE Asia, Australasia and S America. There is a massive market for clean energy in these areas.

Worldwide, resource estimates vary. The global tidal stream resource is thought to be in excess of 100 Gigawatts (GW)(2) and the potential is generally limited only by the economic viability of extraction. This will change as the technology develops and as energy economics evolve through the 21st century.

ABPmer were commissioned by the UK government to study the country's tidal resource potential. They concluded(4) that the total technically extractable resource in UK waters up to 40m deep is capable of yielding 94 Terrawatt hours per year (TWh/y), requiring 200,000 installed devices. This emphasises the need to differentiate between theoretical, technical and economically extractable resource figures. The parameters used and assumptions made are also critical in determining estimates. ABPmer examined different scenarios including one for exploitation over the next five to ten years of the ten best UK sites, using devices in 30 Megawatts (MW) arrays totalling an installed capacity of 1.5GW. This was estimated to yield over 4.3TWh/y, dependent on economic, political and technological factors.

The Carbon Trust's "Future Marine Energy" study (2) reported that the UK has the technical potential to generate 18TWh/y of tidal stream energy, equivalent to 10-15% of the worldwide known resource. Of this figure, 63.2% is derived from waters at a depth greater than 40m(4). The same Carbon Trust report estimated the economic installed capacity for tidal stream energy in the UK to be 2.8GW.

The Sustainable Development Commission corroborated these claims to an extent, with an estimate that the technical resource of the top ten tidal stream sites in the UK is equivalent to generation of 17.5TWh/y(5).

In Scotland, the Strategic Environmental Assessment for wave and tidal energy published in 2007(6) concluded that between 475MW and 800MW of marine energy could be installed sustainably in Scottish waters by 2020. This forms a valuable component of the stated target of 1.3GW of Scottish marine energy development by 2020.

The UK's tidal stream resource distribution is illustrated in Figure 2.1 & Figure 2.2 and for spring and neap flows respectively; these figures are taken from the Department for Business Enterprise and Regulatory Reform's (BERR) Atlas of UK Marine Renewable Energy Sources(7). As can be seen, the resource is concentrated in particular sites, primarily around certain headlands, islands, channels and inlets. Sites that have the highest estimated capacity include the Pentland Firth, the Channel Islands, Anglesey and areas around Islay and SW Scotland.

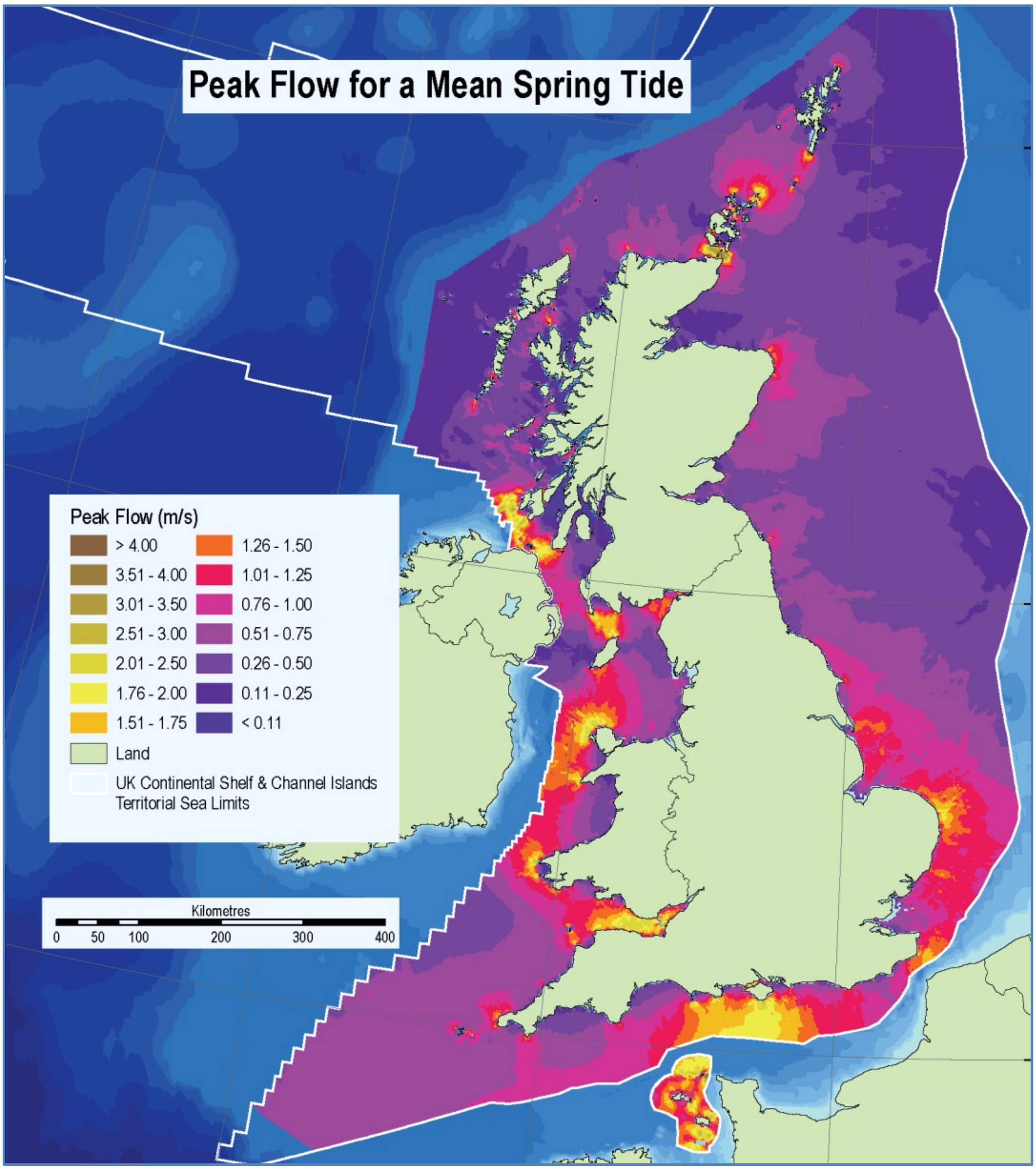


Figure 2.1: Map illustrating peak Mean Spring Tides in UK waters(7)

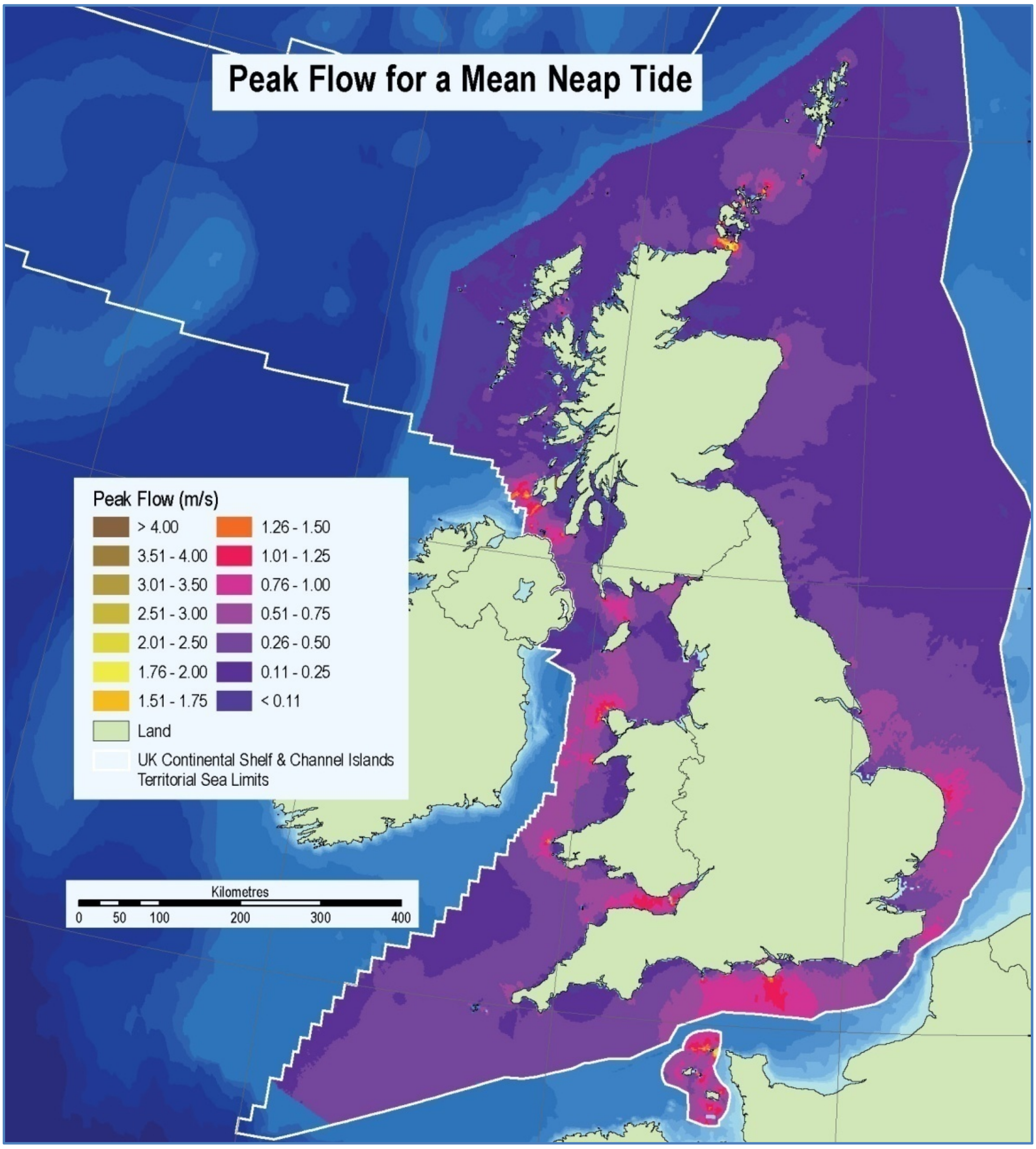


Figure 2.2: Map illustrating peak Mean Neap Tides in UK waters(7)

Higher magnification reveals more detail of specific tidal sites, for example the Pentland Firth as shown in Figure 2.3. Bathymetric and tidal velocity profiles are being built up from the surveying work conducted. These are enabling increased understanding of the geographical interactions and thus the optimum sites for tidal power capture.

There are numerous other smaller sites with more localised high-velocity tidal streams that could additionally be exploited if it was economically viable to do so. This viability will follow the cost trends in the energy industry.

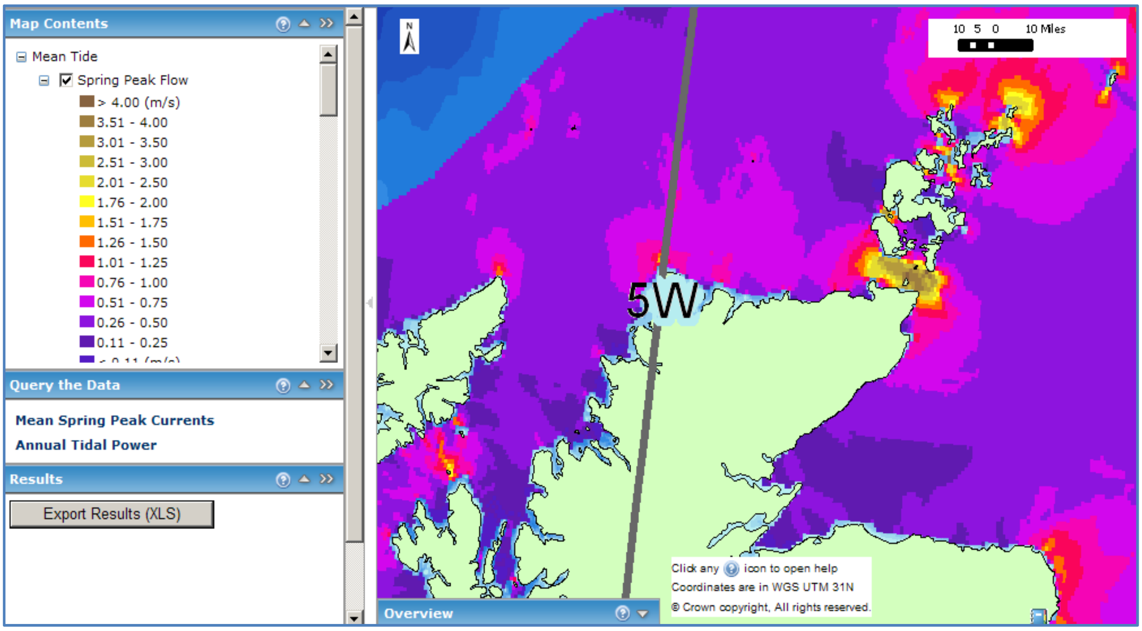


Figure 2.3: Mean Spring Tides in Northern Scotland(7)

There is also a significant tidal stream resource in North America, concentrated in certain areas along the north-eastern and north-western coasts of the USA and in several locations in Canada.

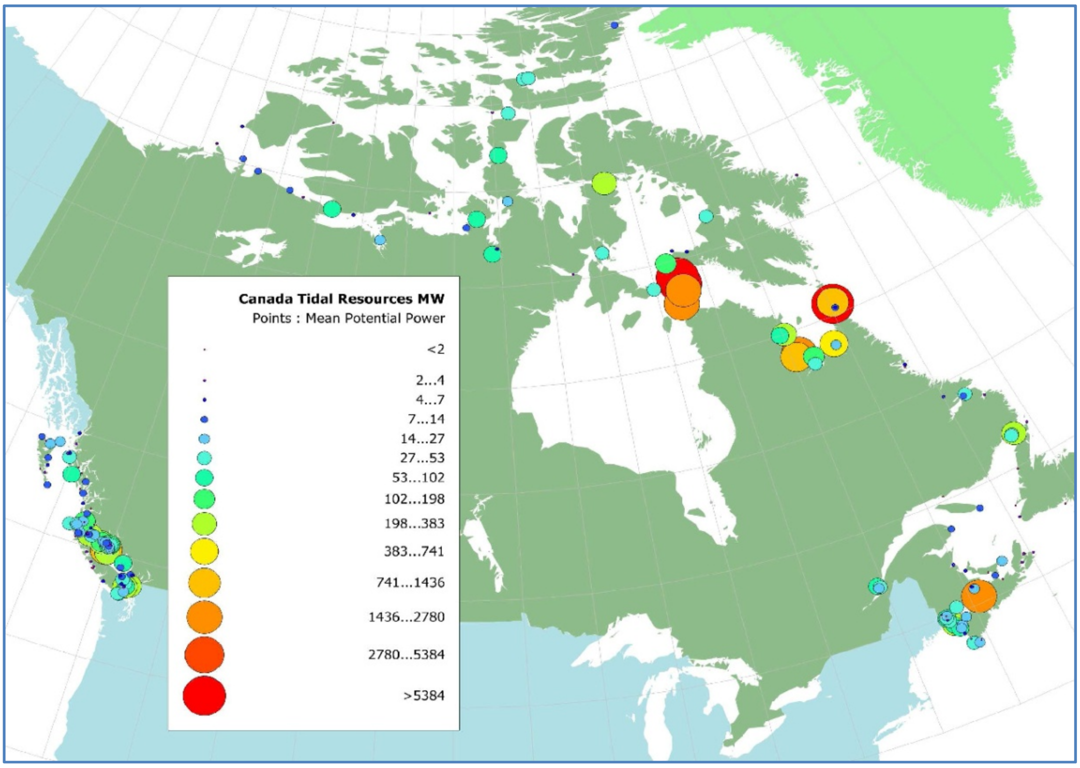


Figure 2.4: Map of Canada showing areas of significant estimated tidal stream resource(8)

The map (Figure 2.4) was produced following a study by Triton Consultants Ltd (8), which calculated that Canada had a theoretical tidal stream resource of up to 42GW. However this did not take into account seasonal and physical constraints, such that much of this resource is situated in unfeasible northern locations. There remain, nonetheless, sites of concentrated potential in British Columbia and the eastern provinces.

Being in its early stages in a very dynamic market, the value of the tidal energy industry is not straightforward to predict with any degree of economic accuracy. However, various research studies have been conducted and comparisons have been drawn with the development of the wind industry in order to aid extrapolation of future figures.

A joint report from Greentech Media and the Prometheus Institute(9) states that, “While today fewer than 10 MW of ocean power capacity has been installed worldwide, we believe that in six years the industry has the potential to break 1GW of installed capacity on an annual market size of over $500 million. More than $2 billion will be invested in that time in commercial production and installation. Based on current trends, a similar amount will be invested in research, design and development during that time.”

The Carbon Trust, by contrast, quotes a much larger estimate for the size of the marine renewable market as a whole: it states that the value of worldwide electricity revenues from wave and tidal stream projects could ultimately be between £60billion/year and £190billion/year(2). The Carbon Trust acknowledges that there is a lot of technology-dependent variation in the calculated cost of energy for tidal stream projects. There is also uncertainty involved in predicting future costs. However the “Future Marine Energy” report(2) concluded that the cost-competitiveness of tidal technology would increase as capacity grows and learning occurs. Thus tidal stream energy could, from an estimated baseline of 12p/kilowatt hour (kWh) to 15p/kWh for initial tide farms, become competitive with base costs of electricity (4p/kWh at the time of publication) within the economic installed capacity for the UK, estimated at 2.8GW.

As well as electricity revenues, there is a potentially massive market arising from tidal device manufacture, construction, installation, operation and maintenance services. The wide-ranging economic benefits arising from the stimulation of the renewable energy sector as a whole are widely recognised and are being encouraged by the Scottish Government.

Worldwide, it is clear that there is increasing political determination to support the development of marine renewables, with financial incentives and revenue support being offered by various governments to assist these capitally intensive technologies to become better established. In the UK, the Renewables Obligation is due to provide support for renewable energy generation at least until 2027, with the level increasing until 2016. A recent announcement by the Scottish Government allocated a minimum of triple Renewables Obligation Certificates (ROCs) for tidal stream generation(10). This is due to be expanded to 5 ROCs for Tidal, making it equivalent to Wave Power. There are also Levy Exemption Certificates (LECs) currently valued at 0.43p/kWh of clean energy generated.

Increased carbon trading in the future is only likely to increase the value of power produced from tidal sources. However it is the effects of massive growth in global energy demand and diminishing supplies of fossil fuels that will have the most far-reaching impacts on the economics of the renewable energy sector. The tidal energy market value will inevitably be driven upwards as the global energy industry transforms to meet the demands of this next phase.

2.2 Overview of Subsea Oil & Gas Production systems

Subsea Oil & Gas systems are now a conventional way for operating companies to development hydrocarbon resources. They provide an alternative to high cost fixed steel or concrete platforms. There are many subsea technologies used to exploit resources and in the past 20 years considerable experience has been gained in their use.

Figure 2.5 shows a schematic of commonly used subsea production systems.

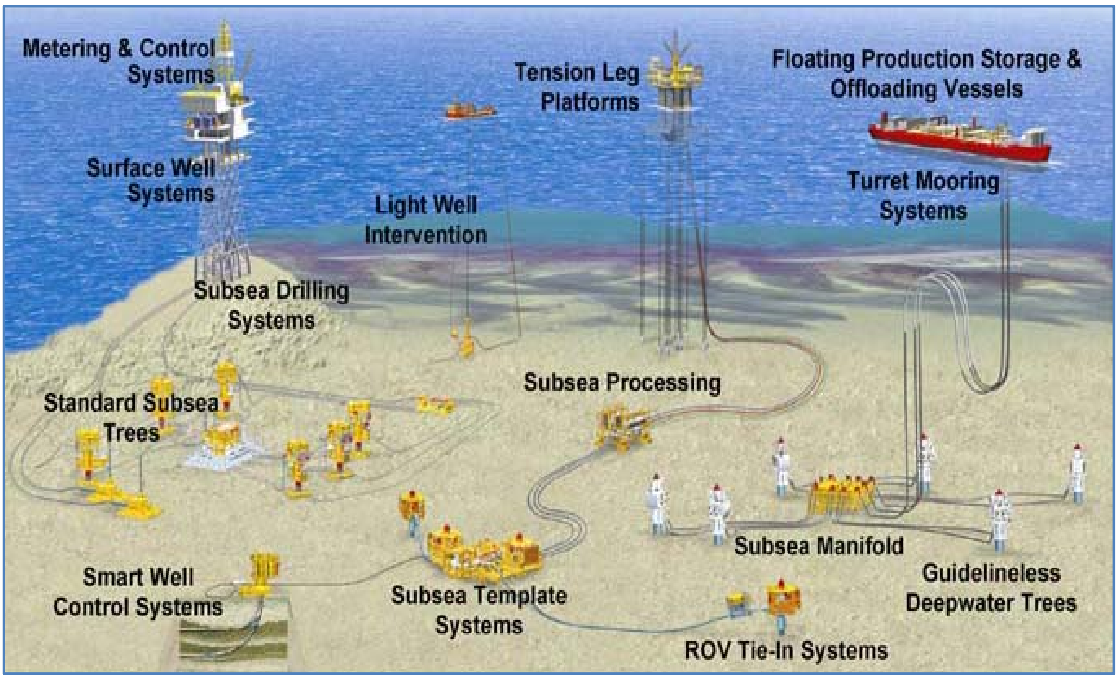


Figure 2.5: Subsea Development (11)

It is possible to develop a small field using single wellheads and subsea trees, to developing a large field using multiple wells tied together via a central manifold or template structure. From the seabed the wells are connected to a process facility, on a platform or on land, by pipelines. Chemical injection via subsea umbilicals is used to assist flow management.

Specialised equipment is used to assist the installation and operation of subsea equipment, much of it quite different from technologies used above water. Dedicated vessels such as drillships, semi-submersible rigs and crane barges are used to assist the drilling and installation of subsea wells and equipment. These vessels come at high daily rental costs, typically £100,000 per day to £400,000 per day.

Figure 2.6 shows a comparison of two styles of subsea development, these are the single well and also numerous wells placed on a single template.

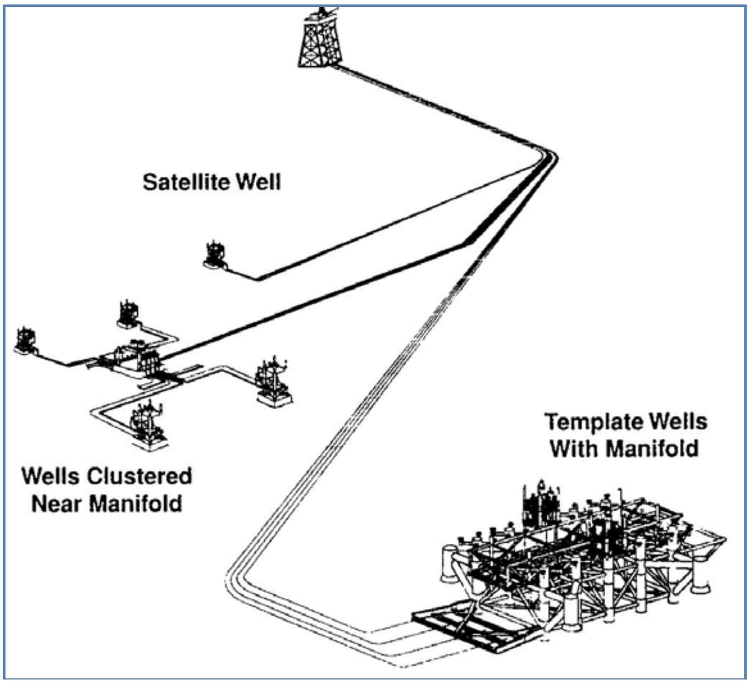


Figure 2.6: Basic Subsea system configuration (Hansen and Rickey 1994(12))

The global quest for energy is causing operators to search in deeper waters, and this quest is continually pushing forward new technology development. Considerable advances in technology are being made each year.

2.2.1 History of development

The first Subsea development was off California in 1961. These wells were accessible to divers (20m). The design allowed for remote operation in an attempt to deeper water capability. When the well was abandoned the subsea tree was recovered in good condition with no significant corrosion damage(12).

Through the 1960's several new subsea fields were trialled, and example being the Molino gas field off California. A robot (called MOBOT) was used to assist intervention(13).

In the 1970's, Louisiana West Delta Block 73 pilot test brought the use of the first subsea template, with 3 wells(14). This pilot test proved that diverless technology could be used on subsea wells(15).

Through the 60's and 70's, about 200 subsea wells with basic subsea technology were installed worldwide. As a result of the establishment of technology developed off North America, the North Sea became the next arena for subsea technology(16).

The first Norwegian North Sea Subsea development was The Ekofisk production system, commissioned for testing in the 1971. The field was developed with four satellite wells producing to a Jack-up rig modified for production and processing. The completion of the subsea wells was performed through diver-assisted technology in 71m (230 ft) of water(16).

The Norwegian Espoir field in 1982 was another successful test of subsea development in the North Sea(12). The Argyll Field project, in 77m (250ft) of water, the world first application of a Floating production Vessel (FPS) and the UK's first North Sea oil producer, was a massive advancement in Subsea for The North Sea. The field was brought on stream in 1975 and abandoned in 1992(17). The UK Buchan field was developed with the introduction of pre-drilling template technology and multiple subsea manifolds(12). In the Norwegian deepwater sector, the Tordis field was developed remotely about the same time as the Balmoral project using clustered well approach (12).

Globally, developments in Brazil, Nigeria and US Gulf of Mexico pushed subsea limits even further. By early 1980's, subsea technology was vastly utilized in many field projects worldwide(12).

By 1993, subsea wells were been completed in maximum water depth of 790m (2562ft) in the Campos Basin and 680m (2245ft) in the Gulf of Mexico(18). Commissioned in 2010 at 2450m (8000ft) of water in the

Gulf of Mexico, Shell Perdido offshore subsea system became one of the world's deep – subsea system installed(19). Today, subsea systems are now designed for 3000m (10,000 ft) of water.

Deepwater developments of major fields such as Ormen Lange in North Sea, Europa in Gulf of Mexico, Bonga in Nigeria, Kizomba in Angola, Gorgon in Western Australia, etc are today indications of successful advancement in subsea technology.

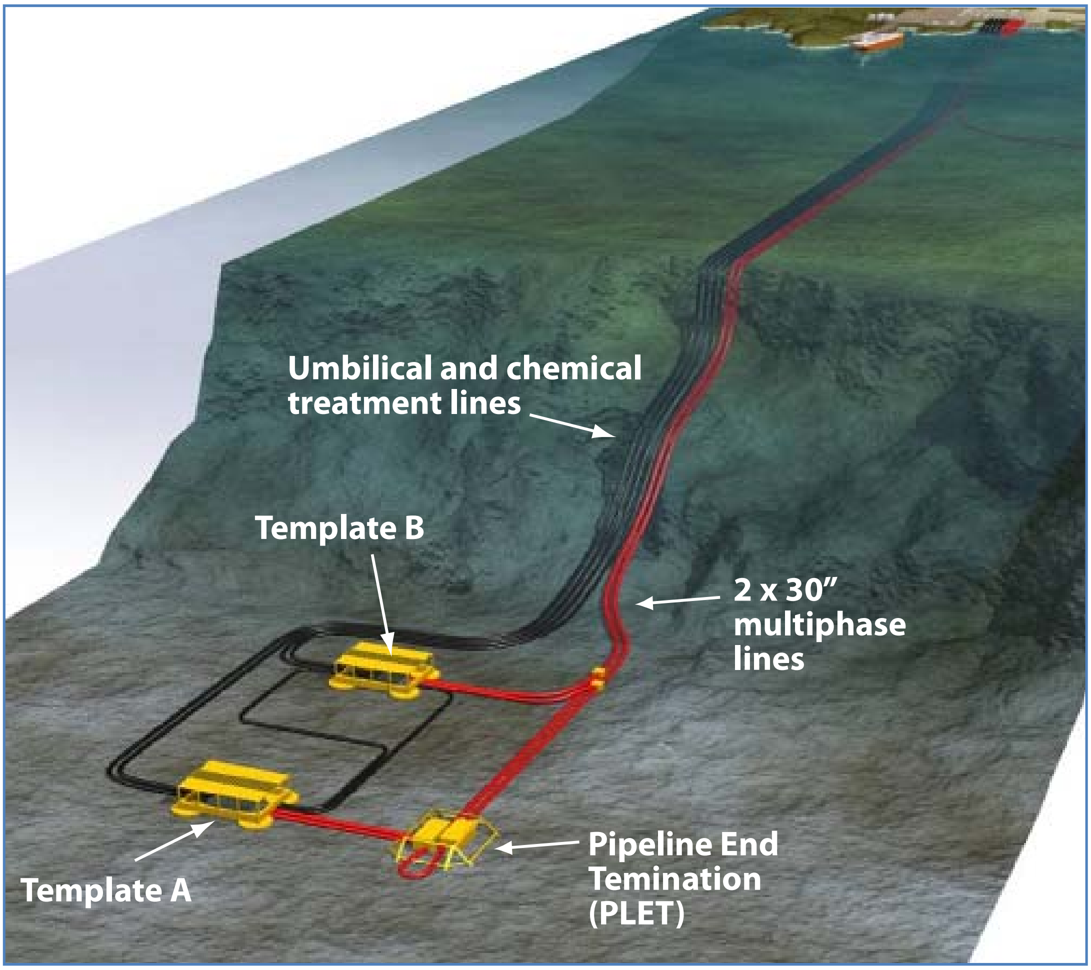


Figure 2.7: Ormen Lange Subsea production system (20)

2.2.2 Subsea Wells

In the UK, there are more than 700 subsea wells in operation (21).

Subsea trees Figure 2.8 provide a conduit to allow a controlled flow of produced or injected fluid through a series of valve systems. It also allows interface of the control umbilical and flowline connectors.

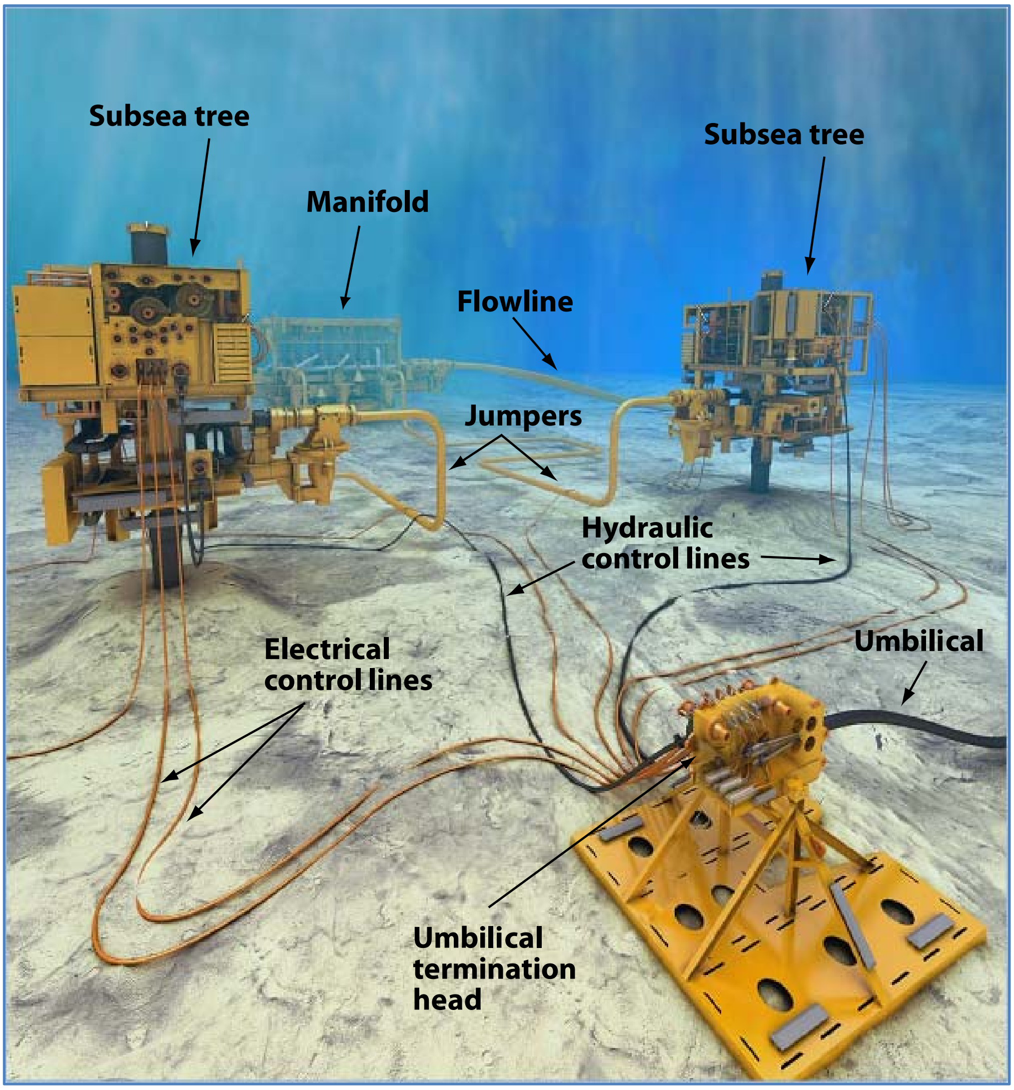


Figure 2.8: Figures showing two subsea trees connected to seabed mounted equipment (22)

A subsea control system provides for electrical and hydraulic control subsea, at the wellhead and/or manifold.

Jumpers are short flowlines used to connect subsea production equipment, such as trees to manifolds. Umbilicals helps to transmit controls to subsea equipment. A flowline is used to transport produced fluid, or to allow for injection of fluids such as water.

2.2.3 Subsea Templates & Manifolds

Conventional subsea templates consist of a structure founded on the seabed by some means suitable for the soil conditions at the installation site, and combine the functions of a drilling template and support for the subsea trees, a commingling production or injection manifold, the associated pipe work, connection systems and controls and chemical injection equipment.

Figure 2.9: Subsea Template attached to four structures (called 'mudcans') to provide stability on seabed (11)

The template structure may or may not be designed to protect the equipment from trawling activities and dragging anchors, in the form of an over-trawlable structure, depending on the level of fishing activity at the location. It will almost certainly be designed to provide protection from dropped objects, generally limited to lighter objects such as drill pipe which are liable to be dropped from a vessel during installation and intervention activities. This dropped object protection is normally achieved by means of roof panels which are hinged to permit access for intervention activities, either by Remotely Operated Vehicles (ROV) or Remotely Operated Tools (ROT).

The well bay isolation valves in a production or injection manifold are normally remote controlled hydraulic operated valves with ROV override, like the subsea tree valves.

The largest conventional template ever installed was the Saga Snorre template off Norway, which had a 20 well capacity and fully over-trawlable protection structure. Its total weight was approx. 2,200 tonnes.

As an alternative to the integrated template, in which the wells, subsea trees and manifolds are all contained within a single structure, a well cluster may be employed. This consists of a central manifold containing the well bay control valves, the umbilical termination unit and control and chemical distribution systems. The choke valves and even the subsea tree control modules may also be included in some designs. The wells are remote from the manifold centre, by anything from a few metres to several kilometres, depending on the specific field requirements.

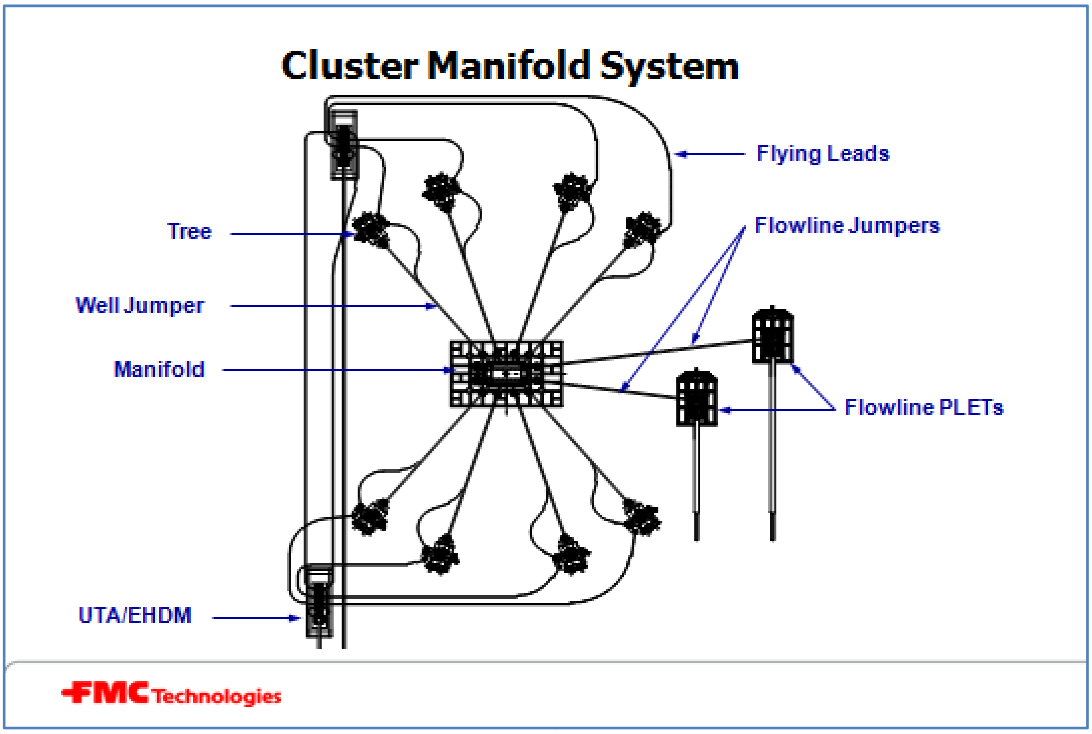


Figure 2.10: Plan view of cluster concept showing how subsea trees are arranged, and connected to, a central production manifold (11)

Figure 2.11: Example of central manifold surrounded by, and connected to, subsea trees (23)

The advantages of this system are that it permits smaller, lighter structures to be used, the connection of the subsea trees to the manifold is simpler, since there is sufficient distance between the two to allow tolerances to be accommodated. A cluster layout conveys more flexibility since wells may be sited in the optimum location rather than on a single drilling centre. The figure below shows that quite a complex subsea layout can be achieved.

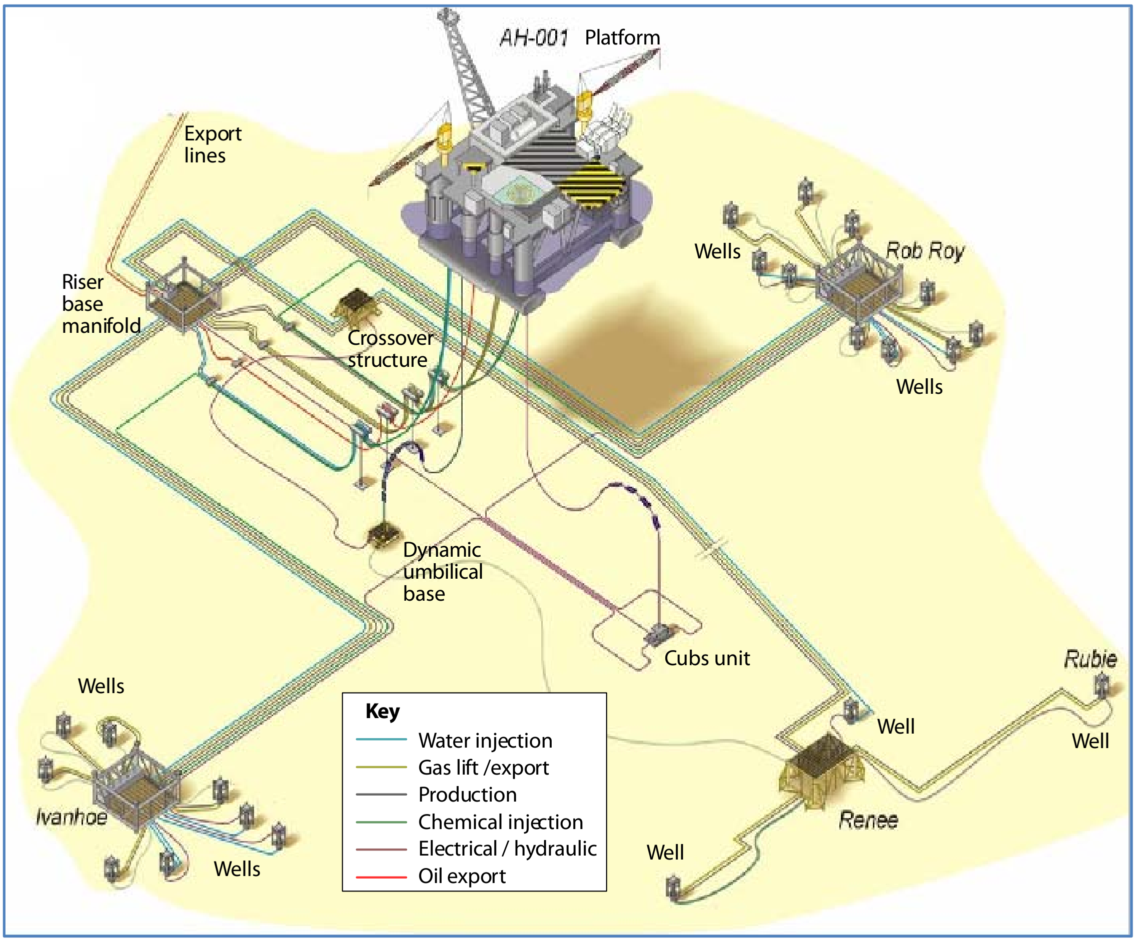


Figure 2.12: Cluster configuration of Ivanhoe and Rob Roy (24)

The disadvantages are that more subsea connections must be made, (there is one to be made up at each end of every in-field flowline jumper), there are in-field jumpers and umbilicals to lay and more drilling rig moves may be involved.

A comparatively recent development has been the development of templates and manifolds capable of being installed through the moonpool of a drilling rig. The objective of employing this installation method is to eliminate the requirement for a heavy lift vessel and therefore reduce the development costs.

There are a number of proprietary concepts on the market, the most successful of which is the Hinge Over Subsea Template (HOST) developed by FMC Kongsberg(11). As the name conveys, this consists of a central rectangular section on which a number of “wing” sections (normally 4) are hinged. During installation through the moonpool, the “wings” are hinged upwards into a vertical position. After installation of the structure onto its pre-installed foundation, the “wings” are hinged down into the horizontal position, each one then forming a well bay foundation.

The wells are drilled and completed and the subsea trees run in the normal manner.

A manifold module is then installed on the central bay and the subsea tree flowlines connected by some means, horizontal in the case of HOST, vertical in some other similar concepts.

Both template and cluster systems require careful consideration be given to intervention and repair and maintenance activities during the life of the field. Although the reliability of subsea components has increased over time, a failure, which results in loss of production from a field, even temporarily, cannot be allowed. Therefore, a great many of the more vulnerable components, particularly in the control system, have inherent redundancies built in.

Not withstanding this, subsea control modules are designed to be retrieved and replaced either by diver, ROV or dedicated remotely operated tool. The same principle is adopted for all other modular units such as multi-phase meters etc.

Other components liable to failure such as choke valves, and well bay control valves, are available with inserts, which can be removed and replaced by special tooling without recovering the whole valve body.

All remotely operated valves should be fitted with ROV overrides so that, in the event of failure of the remote control system, production can be maintained by ROV intervention.

Finally, it is good practice to design the complete manifold module to be recoverable without retrieving the subsea trees as a last resort in the event of failure of a non-retrievable component.

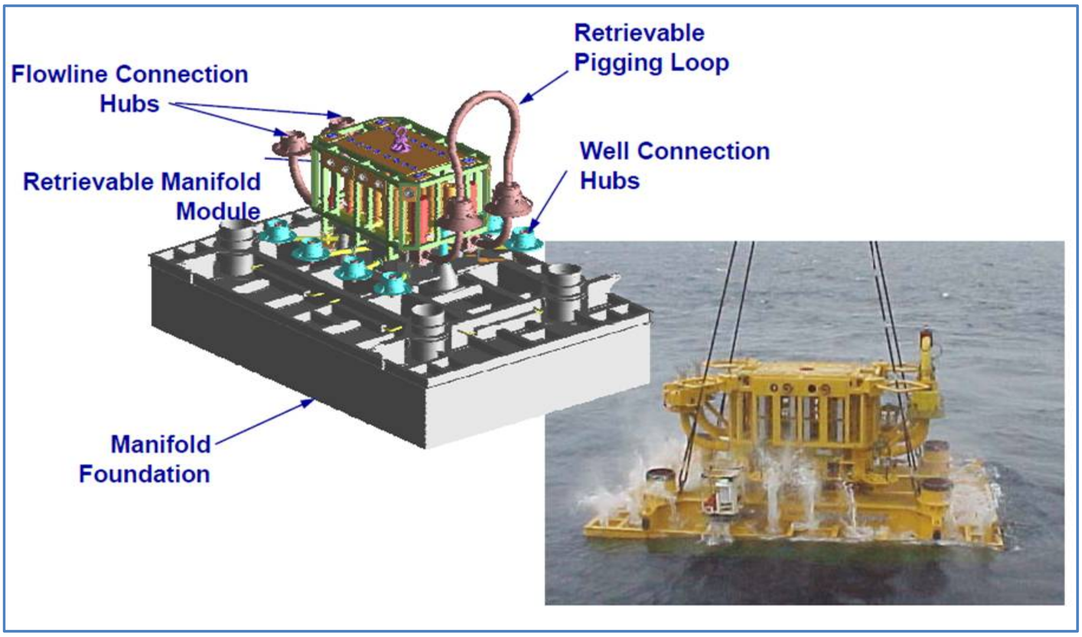


Figure 2.13: Cluster Manifold System (11)

All of these intervention activities and their access requirements need to be given full consideration in the design of templates and manifolds and proven during the system integration testing onshore. Mistakes in deep water especially can be very expensive to rectify.

The template or manifold must fulfil the following primary functions:

Provide a solid foundation for the equipment to be installed, capable of withstanding all imposed loads including:

- Static equipment loads
- Dynamic installation loads, during template and equipment installation
- Drilling loads, dynamic and static
- Dropped object loads
- Snagging loads, normally 60 Tons - the breaking load of a normal trawl wire
- Provide protection to the installed equipment from impact by dropped or dragged objects

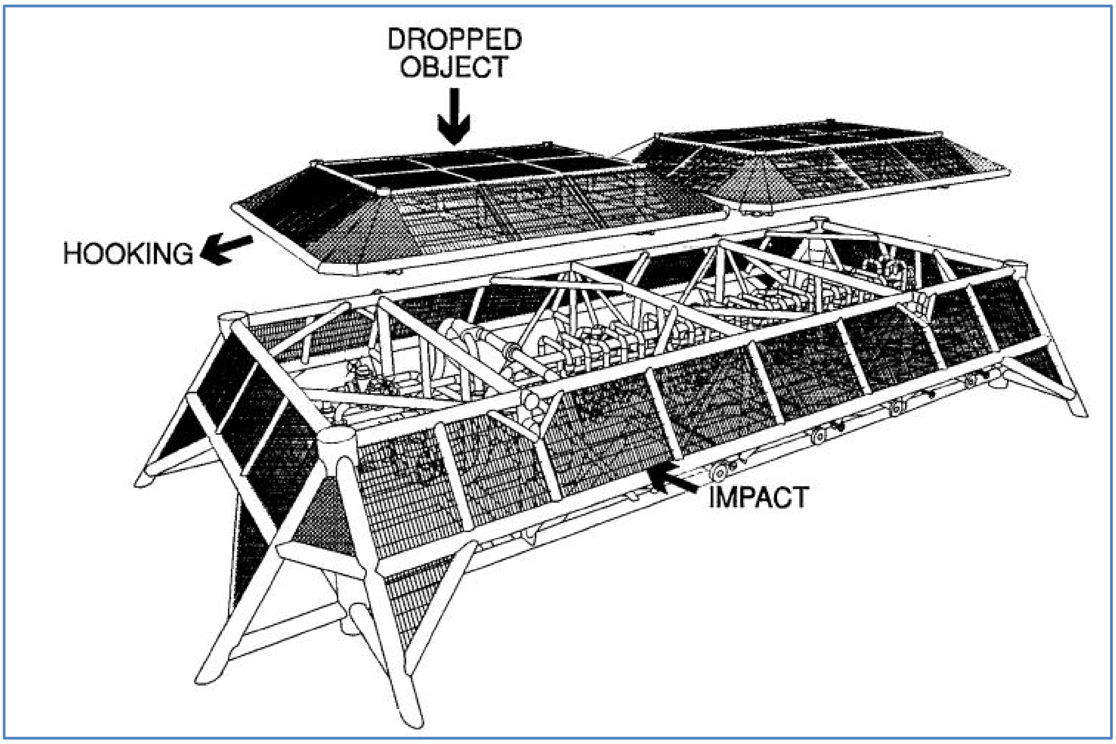


Figure 2.14: Manifold protection system (25)

Provide access to permit all routine operational, intervention, repair and maintenance activities to be carried out by the specified means, whether this be diver, ROV or ROT

Be as light in weight and compact in overall dimensions as possible to permit installation by the smallest possible vessel, and if possible by the drilling rig.

2.2.4 Summary

In the late 1970s and 1980s, subsea templates ware an optimum option for subsea field development, especially where additional reservoir data are essential and first oil needs to be accelerated as it allows for pre-drilling operations while platforms were under construction[(26)]. The templates allowed the drilling of wells from same location while production was fed into the centre manifold located on the template. The methodology was considered to be cost effective for subsea field development and was used to augment project economics. As the technology was increasingly utilized with much field experience, template designs were optimised to allow remote installations by mobile drilling vessels and provide terminal assemblies for connections (27).

With further offshore field discovery, increasing subsea engineering, and more demands on oil and gas products, templates designs became very massive. Challenges involving deployment, reserve distribution, and high Capital Expenditure, (CAPEX) etc. prompted operators to explore the alternative use of subsea manifolds. The manifolds were considered to have extended reservoir reach with top-hole location advantages in disperse fields while reducing the challenges of dropped objects experienced with templates. Subsea wells were then clustered around the manifolds (28).

In recent years, with the advances in subsea technologies and the increase in decommissioning cost of offshore structures, operators have revisited the production template layout in subsea development. Selection of the subsea system and its configuration is now heavily linked to optimising production operations. The decision for this selection is more challenging as there is no basic and single standard set for use in the industry. This forces major operators' decision in subsea development into the hands of the oil and gas service specialists (consultants or service companies as often called). This selection is now often conceded based on short-term project economic benefits and technical competencies rather than coupling with long-term technical feasibility and project economic view.

It has taken nearly 50 years for subsea systems to become fully developed for all conventional water depths. It did, however, take the first 20 years (from 1961) to research and develop the first commercial subsea technologies, even with the massive cash injections possible from the oil majors. It is only in the last 20 years, from 1990, that subsea technology has truly accelerated in its use.

If this timeline is placed on the new Tidal Energy technologies, then we would have a start date of say 2003 (Marine Current Turbines installation in Severn Estuary). The first 20 years would then place us past 2020. Following this is the "technology growth period". This, of course, assumes that there will be massive cash injections into the fledgling tidal industry, akin to the investment from the oil industry. Massive cash injections into the tidal sector will not happen on the scale seen in the oil industry, as most of the tidal developments are supported via grants from governments. In these cash challenged times, it is doubtful whether the tidal industry will receive substantial cash investments of the levels required to accelerate new technologies. The 20 year timeline will also not meet the clean energy targets being set by governments, which are quite aggressive.

Taking the above into account the author saw the need to look at the subsea oil and gas technologies in detail, with the remit of identifying tools, technologies and techniques that could be applicable to the tidal industry. In effect, a technology and ideas transfer, but without the oil industry costs.

A simpler approach to tidal development is proposed, aiming at coastal community infrastructures rather than large grid connected systems.

2.3 Review of Subsea Well systems

Following the review of the main aspects of subsea systems it was prudent to then focus on certain detailed aspects of subsea systems that may have greater applicability to the tidal energy sector. The aspect requiring additional focus are subsea well technologies and techniques. The subsea well and completion is a critical part of the whole Subsea Production System. It is the conduit which carries produced fluids from the reservoir to the seabed. Subsea Completions can be used to produce oil or gas / gas condensate reservoirs and can also be used for injection purposes (water or gas).

As previously mentioned, subsea wells have been used in many areas of the world to access production from marginal fields that, in many cases, cannot warrant the cost of a fixed platform. In recent years, the use of subsea wells in conjunction with a floating production vessel has become an increasingly common lower cost way of developing oil and gas fields. The technology is well developed.

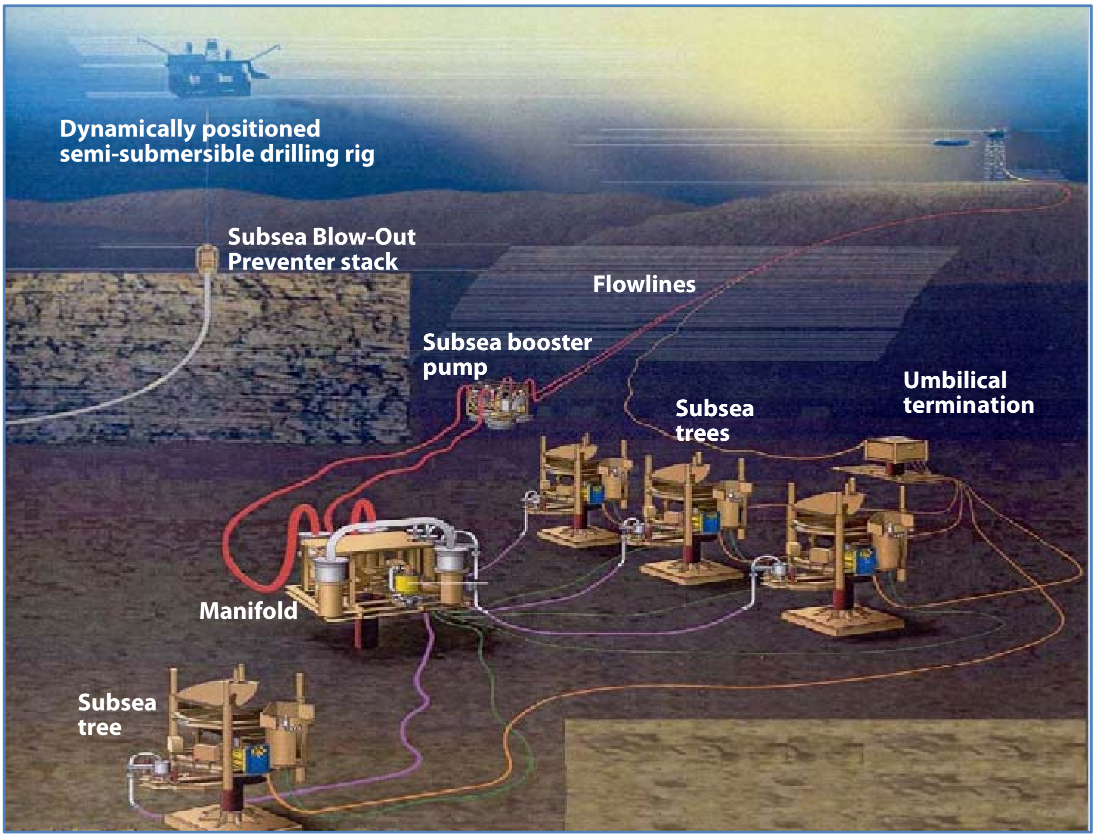


Figure 2.15: Subsea production system showing subsea trees and manifold (29)

The effective design of a subsea completion is of primary importance to the success of a Subsea Field Development, and considerable emphasis is placed on the correct selection of technology and installation techniques. There are many areas which need particular attention during the design of Subsea Completions. Included in these are, maintaining well integrity, design for minimal intervention, reliability.

Should well intervention be required there are two methods currently available to the operator. The commonly used intervention technique is to use a Semi-Submersible Drilling Rig, or Drillship in deeper waters (>500m) - these systems can perform most of the tasks required on a well intervention. The industry is now moving towards lower cost vessels with cranes (a so called Vessel of Opportunity) because of the high daily cost of conventional vessels. Conventional rigs typically cost between $200-500,000 per day, and on a typical subsea well completion lasting 30 days this can add up to a considerable amount of money, circa. $15 million for a deepwater Drillship! Obviously, there is no way the tidal industry can accept such high costs, as there would never have been a Return on Investment (RoI) achieved. Therefore, the tidal industry must look at alternative vessels, more like in-shore civil engineering support vessels, costing a few thousand pounds per day.

Figure 2.16: Drillship costing $500,000 per day (20)

Figure 2.17: Semi-Submersible costing $250,000 per day (20)

2.3.1 Subsea Wellheads, Guide Bases and Subsea Trees

The subsea wellhead housing provides the interface between, and support for, for well casing strings and Blow Out Preventer (BOP) equipment. At a later stage it also provides a hang off point for the well production completion. The wellhead housing is positioned on the seafloor (or mudline) and is locked into a previously run 30" diameter conductor pipe.

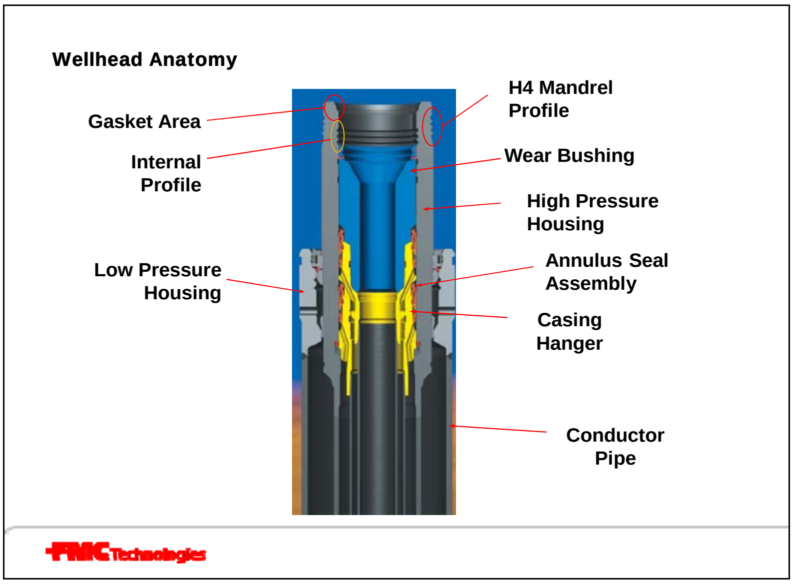


Figure 2.18: Cut away schematic of subsea wellhead (11)

Figure 2.19: Picture of subsea wellhead (11)

Subsea wellheads are available in a number of sizes, types, and pressure ranges. The most common type used is a conventional 18 ¾" outside diameter, 10,000 psi rated wellhead housing (oilfield units). The wellhead housing are designed to withstand very large operational loadings. Not only do they have to withstand loads exerted by hanging casings from them, but also supporting BOP and riser loads above, bending moments from the riser, internal pressures, etc. For example, the bending loads allowed are up to three million kilograms (over three thousand tons). Many of the wellhead systems in use today employ four guidelines / guideposts attached to the wellhead housing base sometimes called a Drilling Guide Base (or DGB). The guidelines are attached to the DGB and the floating rig above. They provide a simple and effective system for guideing tools from the rig to the seabed.

Figure 2.20: Picture of drilling / production guidebase (11)

The DGB will remain in place during the subsea drilling operation. When it comes to the requirement of running the production completion, the DGB can be removed and replaced by the Production Guide Base. Alternatively, it can be left in position and production pipework attached to it. The primary function of the Production Guide Base (PGB) is to provide the initial alignment and orientation for the subsea tree, to ensure that it is centralised over the wellhead and orientated relative to the tubing hanger. It also provides guidance for the Tree deployment equipment, namely the Lower Rise Package (LRP), Emergency Disconnect Package (EDP) and Tree Cap Running Tool (TCRT). The PGB is designed to carry a minimum static load of 780,000 Newtons (175,000 pounds) or approximately 80 Tonnes.

Figure 2.21: Schematic of subsea guidebase(11)

The PGB has four guideposts positioned at 90 degrees apart on a standard American Petroleum Institute (API) 6ft radius (oilfield units). The posts have an outside diameter of 8-$^{5}/_{8}$", and are a minimum of 8ft long (oilfield units). The guideposts are designed to allow for their replacement subsea. Provisions are made to attach guidelines to the top of the guideposts. These provisions are capable of being released automatically and re-established, by ROV or diver.

The following loads are considered in selection of a PGB:

- Flowline pull-in, connection, or installation loads
- Ballast
- Guideline tension
- Environmental

Subsea Specification API 17D(30) provides the general design requirements relating to the production guide base.

The subsea Christmas tree is the main component which sits on the production guidebase once installed. The tree is effectively a “tap” which controls the flow from the well completion. There are two main versions of a Subsea Tree, the “Conventional” type and the “Horizontal or Spool” type. For the purposes of this thesis only the Conventional type will be described. Conventional subsea trees have been in common use for thirty or more years in one form or another. Over the years the designs have evolved, with the most common being a tree with a 5" production bore and 2" annulus bore. There are numerous other variations in operation around the world.

Figure 2.22: A simple subsea tree being deployed from a rig, down the guidewires (20)

As stated, the main function of the conventional subsea tree is to control the flow of a producing well and to allow complete well shut in. Two vertical bores exist through the tree. These allow vertical access to the downhole production tubing and to the annulus at least down to the tubing hanger level.

In certain cases a control pod and either one or two chokes could be mounted on the tree. Normal control of the tree in production mode is via the electrohydraulic control system with the main control panel on the host facility. The pod routes hydraulic control fluid to the various tree actuated valves and choke and also processes pressure and temperature electrical signals from surface and downhole gauges. Most tree control systems can now be run and recovered using a Remotely Operated Vehicle (ROV) intervention only.

Water depth plays an important part in the design of a subsea trees. Since the end of the last decade, ROV technology has come of age and is cheaper than using a diver for performing the same task. Thus the majority of new subsea trees are designed for ROV intervention even though the water depth for their installation is less than 200m/600 ft. For water depths that exceed 500 m/1,500 ft, it is impractical to use guide wires to provide guidance during installation. The guide posts on the tree frame will be replaced by a large diameter funnel attached to the outside diameter of the Wellhead which captures the Tree Connector when it lands. This type of subsea tree is known as Guidelineless subsea tree. The type of field development for the subsea tree to be installed on also plays an important part in the layout of a subsea tree.

Figure 2.23: Guidelineless tree being installed with winch (20)

Installation of the shallow subsea tree is usually carried out from a semi-submersible drilling rig. It is lowered and locked onto the wellhead and guide base using a dual bore workover riser package. Landing of the tree is a fairly sensitive operation because of the number of interfaces being made up simultaneously. There can be a multitude of hydraulic stingers within the tree connector which must mate with their respective pockets in the tubing hanger and there may also be a flowline connector which has to make up to a hub on the guide base / flowbase. Once landed, locked and pressure tested, downhole operations can take place.

Figure 2.24: Tree being tested on dummy production guidebase (20)

The principal components of the conventional subsea tree are:

- Tree Connector and Tree Frame
- Valve Block
- Loose Valves
- Choke
- Flowloops
- Flowline Connectors
- Control Pod
- Power connectors
- Tree Intervention Panel
- Tree Cap

- Tree Handling Tool

For the purposes of this research the only items of interest that could be utilised in a proposed Tidal Energy Converter (TEC) design are:

- Tree Connector and Tree Frame
- Control Pod
- Power Connectors

2.3.1.1 Tree Connector and Tree Frame

The tree connector is a specific example of a typical connector. It is used to land and lock the tree to the wellhead. The locking profile will match the specified wellhead profile. It may be flanged to the tree body or it may be integral with the tree body. It will provide a metal to metal environmental seal with the wellhead. A port will be provided for testing between the environmental seal and the tubing hanger stabs, this may be in the connector or in the tree body.

Tree connectors may be actuated by hydraulic mechanisms which are integral with the connector or by hydraulic mechanisms mounted in the tree running tool. A mechanical locking device may be provided as back up to the primary locking method. Secondary release mechanisms and external visual indication of the connector locking status will also be supplied.

The tree connector is connected to the Tree Frame. This frame gives the tree its structural integrity and several designs are used. In its basic form, the frame is designed around four equally spaced funnels / tubes. These tubes are designed to slot over the corresponding four posts of the wellhead guide base.

When the tree connector is landed onto the wellhead, it is functioned hydraulically by driving the locking sleeve downwards and subsequently collapsing the split locking ring to mate with the profile on the wellhead. This locking mechanism ensures that the required tree connector/wellhead pre-load is achieved. In the unlocking function, the reverse motion takes place, allowing the split locking ring to expand to its starting position. These vertical motions are provided by annular pistons, where the connector unlocking force will be greater than the locking force.

Mechanical lockdown devices on the connector hold the locking sleeve in position, preventing the accidental release of the connector due to vibration and thermal load changes. In the event of a hydraulic failure from the surface, the connector may be released by a secondary hydraulic piston functioned by a subsea hot stab, or an overpull from the surface through override rods connected to the locking sleeve. Both of these methods will shear a sleeve within the mechanical lockdown assembly, allowing the connector to unlock. This sleeve also acts as a position indicator for the connector.

The tree connector will be designated by size, pressure rating, and the profile type of the subsea wellhead to which it will be attached. The pressure rating should be equal to or greater than the maximum operating control pressure of the down hole safety valve (typically 5000 pounds per square inch in oilfield units).

The following loads and conditions should be considered when designing the connector:

- Well pressures
- Mechanical pre-loads
- Riser bending and tension loads
- BOP loads
- Thermal expansion
- Environmental loads
- Fatigue conditions

Pressure separation loads will be based on worst case sealing conditions, where leakage to the largest redundant seal diameter shall be assumed. Consideration should be given to testing all primary seals in the connector cavity, and to testing and flushing the connector hydraulic chambers.

The hydraulically actuated connector will be designed to prevent release from the subsea wellhead due to a hydraulic failure from the surface. It must be capable of a release force which is at least 25% above the locking force, in the event that the normal operating release pressure is inadequate to effect the connector unlock function. A secondary release method should also be provided.

The Standard, API 17D(30) provides the specific design requirements related to a subsea tree connector.

2.3.1.2 Control Pod

The purpose of the control system on a subsea well is to allow an operator located on the surface facility to control tree valves, downhole safety valves, chokes and chemical control and metering valves. It is also used to monitor process variables such as pressure, temperature, flow rate and valve and choke position.

2.3.1.3 Power connectors

Power connectors are used extensively in the subsea industry. For subsea oil and gas it is common to see both dry connectors and wet connectors.

Figure 2.25: Subsea power connector (20)

Figure 2.26: Subsea power wet connector (20)

Power Connectors are available to carry out many different types of operation, and there is an array of connector capacities (KV, amps, etc) available. A subsea tree will commonly have two+ power connectors from the main control umbilical to the control module or pod. One connector will typically be low voltage, the other high voltage. If a down hole electric pump is being used, there will be a dedicated third connector for this. The wet connectors are designed to be made up "in water". For example, this could be with an ROV, diver or even when equipment is mated together during deployment.

The subsea tree intervention panel is fitted to the subsea tree guide frame to facilitate support by a remotely operated vehicle (ROV). It is the interface between the tree functions and the ROV tooling package. The panel will provide a means for the ROV to attach itself to the tree and manipulate valves by linear or rotary actuation, and to inject fluid. The panel will be clearly marked with valve identifications and positions for ROV visual verification.

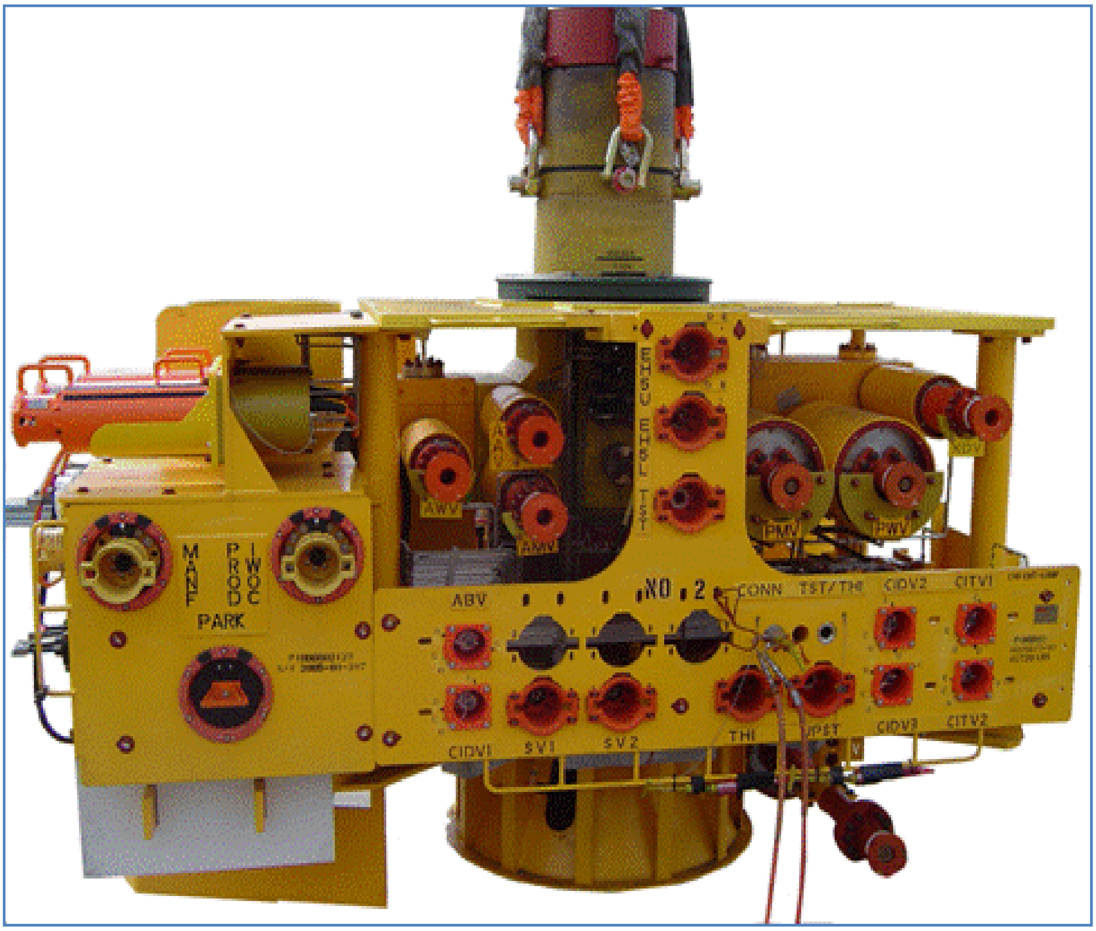


Figure 2.27: Tree showing ROV interface panel (20)

The panel will be furnished with either a grabber bar or docking receptacles which will allow the ROV to latch onto the tree in a defined position. The ROV manipulation tool will then engage with an intervention fixture on the panel to open or close a valve as required. This actuation may be linear by means of a push/pull rod, or rotary by applying a torque to operate the valve. The valve position indicator shall clearly show whether the valve is open or closed, for visual confirmation by the ROV camera. The type of docking and intervention fixtures on the panel will be dependent on the ROV tooling package.

Pressure balanced fluid couplings may also be incorporated into the intervention panel. These allow the ROV to access hydraulic circuits, through a hot stab, and perform such tasks as an interspace test between seals, or the emergency release of a connector in the event of hydraulic failure from the surface.

The ROV's overall configuration must be considered when designing the tree frame and intervention panel to ensure that access is not restricted. The panel will have bold permanent markings which must be non reflective.

Linear and rotary intervention fixtures are designed to withstand the required axial and moment forces respectively. Fluid couplings are made of corrosion resistant material and do not have seals.

Removable dummy stabs are provided to protect the fluid couplings from damage, debris and marine growth when not in use.

The subsea tree handling tool provides the means of hoisting the fully assembled subsea tree through a single point lift. It facilitates the lifting of the subsea tree onto and off road and sea transport, test stumps and for general workshop use.

The handling tool lands on the subsea tree hub upper profile and is locked or unlocked mechanically to the hub via a split ring and cap screw retention feature. A lift lug which shoulders against the upper plate, is designed for use with the required safe working load shackle. A single leg sling may also be provided, which is long enough to overcome offshore structure crane limitations.

The handling tool is designed and tested in accordance with a documented industry standard such as the 'Lloyds Register of Shipping Code for Lifting Appliances in a Marine Environment'. The lift lug has a design safety factor of 4 or greater based on the minimum specified ultimate material strength at the maximum rated pick up angle. A back up safety feature may also be incorporated to prevent the inadvertent release of the tree.

For the purposes of this document the other items of subsea tree equipment that will not be required in any proposed Tidal Energy Converter (TEC) design are;

Valves and valve block

Designed to allow control of production / injection through the subsea tree. Not applicable to TEC requirements so will not be discussed.

Choke

As above. Designed to allow control of production / injection through the subsea tree. Not applicable to TEC requirements so will not be discussed.

Flowloops

Designed to allow the subsea tree to connect to the manifold pieplines and jumper lines. Not applicable to TEC requirements so will not be discussed.

Flowline Connectors

Designed to allow the subsea tree to connect to the flowloops. Not applicable to TEC requirements so will not be discussed.

Tree Cap

Engaging the tree cap allows the subsea tree to be operated from the Control Pod . Not applicable to TEC requirements so will not be discussed.

Tree running will commence once the tubing hanger has been installed and the drilling guide base replaced by the production flowbase. Handling arrangements will differ from rig to rig, however the basic procedure is to latch a riser package to the top of the tree, and then latch the emergency disconnect package to the top of the Lower Riser Package (LRP).

This assembly must then be positioned beneath the rotary table of the rig and the stress joint lowered through the table and made up to the Emergency Disconnect Package (EDP).

Figure 2.28: Subsea tree, LRP and EDP stack up suspended from rig (20)

The main workover umbilical will then be attached and a full function test carried out. Drift checks will also be done to ensure clear passage through each bore and all stinger and wellhead seals renewed. Upon completion of tests, the tree will be lowered through the splash zone with no delay.

Figure 2.29: Subsea tree, LRP and EDP below rig floor being deployed (20)

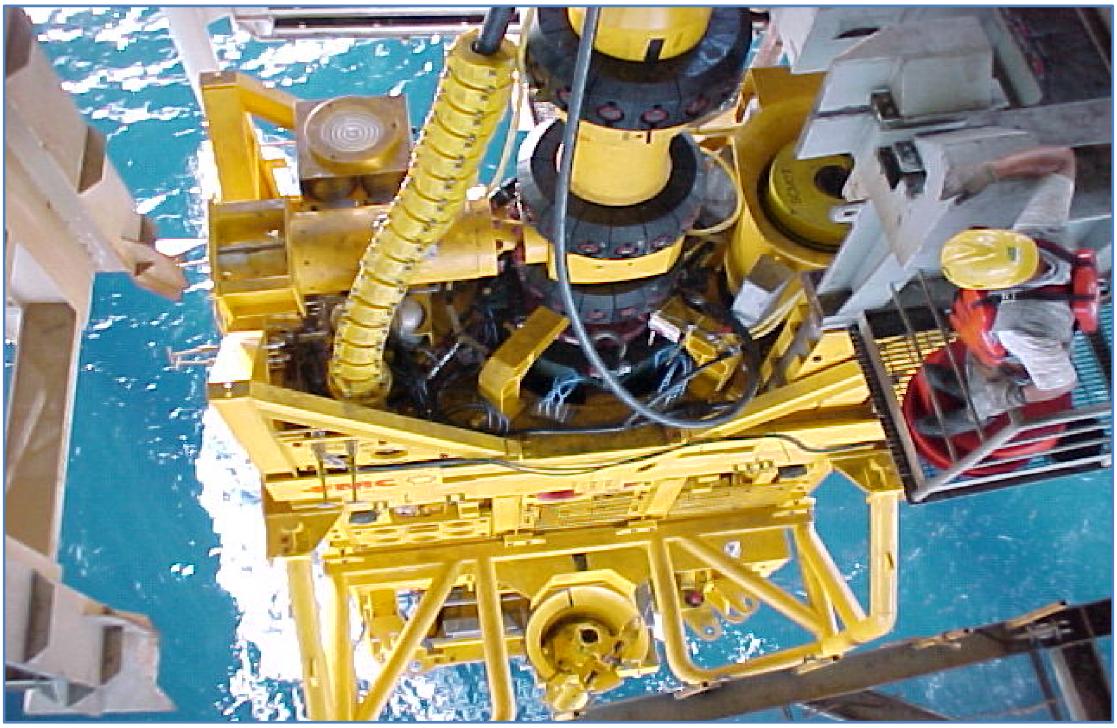


Figure 2.30: Riser stress joint being made up to EDP during deployment (20)

The tree/LRP/EDP stack is run through the water column on standard riser joints with a main hydraulic control umbilical being made up to each joint. The tension joint is made up to the last standard riser joint and the surface joint and surface tree assembly made up to the top of the tension joint.

Tensioner cables are made up to a tension ring situated in the cellar deck of the rig and a nominal tension applied to the ring. The remaining weight, minus the allowable set down weight, is taken by the heave compensator on the rig. The tree is then lowered down over the guide posts and onto the wellhead until it is observed that the tree has fully landed.

Figure 2.31: Subsea tree nearing production guidebase (31)

Pressure is then applied to the tree connector lock function and the connector locked to the wellhead. An overpull is then taken to confirm that the connector is locked. Pressure tests are then carried out on all functions to ensure that no damage has occurred to the interface stingers during landing. Upon completion of satisfactory tests, the wireline plugs in the tubing hanger can be removed and any well intervention work performed before the well is shut in and the LRP disconnected. The LRP/EDP and riser is then recovered and the tree cap run. Control of the tree can then be handed over to the host facility and production can then commence through the main flowline.

Figure 2.32: Final condition. Subsea tree attached to wellhead, ready for production (31)

2.3.2 Global standards covering subsea design : The API Standards

Standards published by the American Petroleum Institute (API) are readily available, which cover most aspects of Oilfield related equipment. These standards were initially created initially, to maximise the interchangeability of equipment supplied from a variety of manufacturers, but have since evolved to include design, quality and reliability issues as part of their compliance requirements.

These specifications offer a guide to Product design and form base level acceptance criteria for primary component parts and assemblies. They are not intended to be a panacea for all aspects of design, nor do they reference every component item within a product assembly. Their use does however create a standardised level of acceptability.

The specific API standard which relates to subsea Wellhead and Subsea tree equipment is API 17D(30). This specification also closely references API 6A(30) (for surface equipment systems) from which it was developed. There are also additional referenced standards contained within the API 17D(30) document, some of which are API specifications, and others, which are issued by other Standards Authorities.

Two levels of equipment supply are referenced within the Standard. These are called Product Specification Levels (PSL) and comprise PSL 2 or PSL 3. These two levels designate the assured quality to which a component or assembly is manufactured, which in turn will depend on its proposed service criticality.

Additional Information

DESCRIPTION	API Standard	ISO Standard
Surface wellhead and tree equipment	Spec 6A	10423
Drill-Through Equipment	Spec 16A	13533
Casing and Tubing	Spec 5CT	10426
Materials for H_2S Service	NACE MR-01-75	15156
Design and operation of subsea systems	RP 17A	13628-1
Flexible pipe	RP 17B	13628-11
TFL systems	RP 17C	13628-3
Subsea wellhead and tree equipment	Spec 17D	13628-4
Production control umbilicals	Spec 17E	13628-5
Subsea controls	Spec 17F	13628-6
Design & operation of completion/workover risers	RP 17G	13628-7
ROV interfaces	RP 17H	13628-8
Unbonded flexible pipe	Spec 17J	13628-2
Bonded flexible pipe	Spec 17K	13628-10
ROT Intervention System	RP 17M	13628-9
Dynamic Risers	RP 2RD	13628-12

Web Sites

- www.akerkvaerner.com
  - Aker Kvaerner
- www.api.org
  - American Petroleum Institute
- www.camerondiv.com
  - Cameron
- www.dril-quip.com
  - Dril-Quip
- www.fmctechnologies.com
  - FMC Technologies
- www.offshore-technology.com/projects
- www.vetco.com
  - Vetco Gray

FMC Technologies

Figure 2.33: Required subsea standards (11),

The structure of the standard deals initially with the Design and Performance of the equipment (inclusive of pressure testing), followed by Materials, Welding and Quality Control requirements. Storage and Shipping criteria are also referenced. Thereafter, the individual component parts and assemblies which make up Wellhead and Subsea Tree equipment are referenced for each of the above parameters. Finally, a series of non-mandatory Appendices offer guidance on additional features of equipment supply (i.e. Coating systems, Torquing, Intervention fixtures etc.).

These API equipment specifications, when used in conjunction with the API Q1 specification, (which deals with the manufacturer's Quality Assurance system), are designed to produce a product which gives a high level of design integrity, has been manufactured to a high quality standard and which will interface satisfactorily with equipment supplied by others.

It must always be borne in mind that equipment which has been designed and manufactured to API design codes and standards does not in any way justify its use or applicability for any given application. These standards maintain a good basis for design, but it is the responsibility of the Engineer to apply his expertise and judgement to develop the optimum solution for its particular application.

Typically, other National standards or specifications may exist which require additional design considerations (e.g. UK Statutory Requirements and Norwegian Petroleum Directives). These may involve additional Quality Control measures, product verification testing and / or Independent Design Review (e.g. Lloyds Register, DNV, etc.) to satisfy the legislative requirements for safety critical equipment installed in that location. The engineer is required to be aware of these needs when designing his equipment. Fortunately, a significant database has been developed over a number of years which highlights these additional requirements.

For the marine renewables industry there has been discussion over several years now regarding design and manufacturing standards for the new industry. Recent publications by the European Marine Energy Centre (EMEC)(32) include new Standards. It is interesting to note that none make reference to API 17D (33), which is a global standard for subsea oil and gas equipment. One would have considered it useful to review what peers in the main subsea industry (oil and gas) would have been using?

2.4 Review of tidal energy devices and installation methods

Being in its early stages of development, the marine energy industry has not yet established standard practice for device installations and mooring methods. Device developers that are farthest ahead have trialled their own solutions, with varying degrees of success in terms of efficiency and cost. The most prominent of these developments are outlined in this research. The marine energy sector can also look to the offshore oil and gas industry and offshore wind turbine industry for technologies and methodologies that may be transferred to marine renewables with some adaptations. Some of the issues affecting technology choices are common to all and are also included below.

There appears to be a shift in understanding occurring in the industry about the need to consider installation and maintenance as being integral to the device design from the outset. This is perhaps in light of one or two publicised cases of device installations floundering in the face of enormous costs and practical challenges that outweigh the potential performance of the device itself.

A chapter from Tocardo BV's "Pentland Firth Pre-Feasibility Report" on 'Foundation, Installation and Decommissioning Techniques' includes the following:

> *"Various technologies and vast experience has emerged from the history of offshore oil and gas exploitation. A major constraint to applicability of mooring technology is its cost; for present tidal device designs, installation and foundation costs are expected to compose more than 50% of its total lifecycle costs." ... & ... "skills and technology should be 'downgraded' to a level of simplicity that allows marine renewable energy to be generated at an affordable level."*

The report goes on to suggest that an investigation of a joint approach in development of mooring, installation and decommissioning techniques would be of benefit to the industry. Specifically, it states that shared technology matching the requirements for the Pentland Firth would result in cost savings for individual developers.

The author of this research has been a proponent of such a philosophy since the start of this decade, and the award of UK patent GB2400632

(2004) shows that the author was promoting the transfer of such skillsets early on.

2.4.1 Tidal Device Installations Achieved

Openhydro, foreseeing the difficulty and expense of installing their tidal turbine, have undertaken a bold move by commissioning their own specialist installation vessel. Launched in September 2008, the vessel required an investment of EUR 5 million and was assigned to the deployment of the company's Open-Centred Turbine. The current turbine prototype model has a 6m diameter. It is moored on a triangular gravity base which is lowered down from the barge using cables.

Figure 2.34: Openhydro specialist installation vessel (34)

For its earlier prototype deployment, Openhydro used a twin-piled test structure installed at EMEC. The turbine, positioned between the piles, could be raised and lowered in and out of the water. However this structure is mainly for ease of testing; commercial deployments of the

Open-Centred Turbine will be seabed-mounted. A similar system was deployed off Nova Scotia, Canada.

The company proposes a 16m diameter turbine, and are seeking funds to build another deployment vessel.

Figure 2.35: Openhydro test structure (34)

Cost estimates from Openhydro prototypes to date seem to indicate a cost ratio of approximately £8-12 million per megawatt, not including the cost of the deployment vessel.

Lunar Energy's ducted Rotech Tidal Turbine (35) sits on the frame of a three-legged ballast-filled gravity base. The turbine duct for the 1MW unit measures 15m in diameter and has a length of 19.2m. The design includes a removable cassette containing key components that can be lifted out for maintenance and replaced. Lunar Energy claims that the use of the gravity base allows rapid deployment, including in water depths of more than 40m, requiring only minimal seabed preparation.

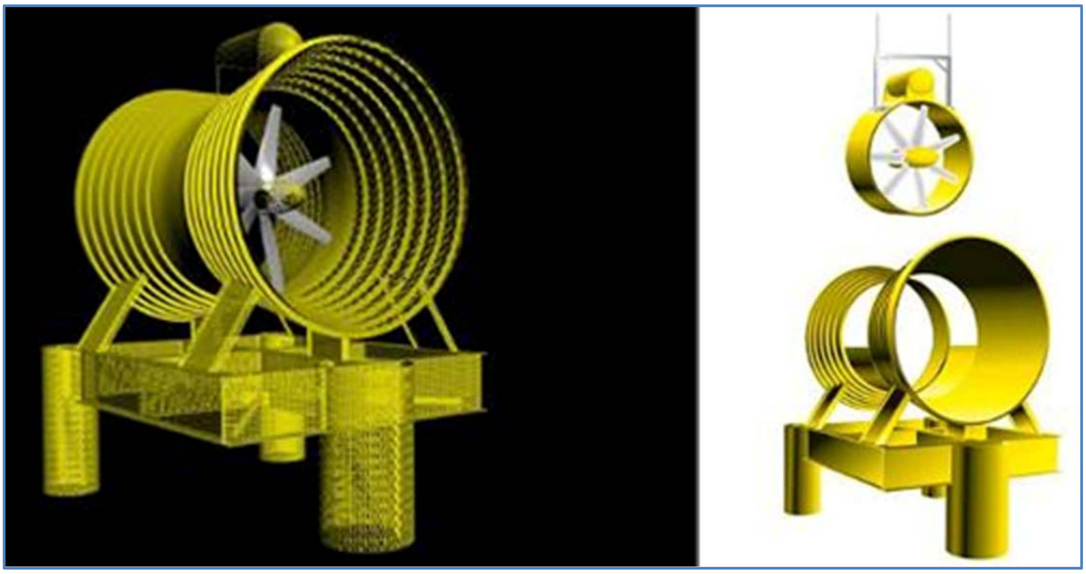


Figure 2.36: Rotech Tidal Turbine with removable cassette (35)

The size and weight of the base structure (2000MT) makes the Rotech Turbine one of the most unwieldy devices for installation and demands the use of a large heavy-lift vessel. The modular cassette design reduces the vessel requirements for maintenance, although with a diameter of 11.5m the turbine still weighs a large number of tonnes (suspected as being 200 tons). Further information or footage from the actual prototype installation are not available from Lunar Energy. The cost of a crane barge to install such a device would be over $100,000 per day, immediately making the system uneconomic.

Marine Current Turbines (MCT) (36) are probably the leaders in the field with regard to installations. Two main prototype phases have been achieved: Seaflow (300kW) in 2003 and SeaGen (1.2MW) in 2008. Pictured below is the jack-up rig Excalibur of project partner Seacore Ltd, conducting a geotechnical survey for the SeaGen project.

For the Seaflow project, the specification of the piles was limited to the capabilities of the biggest barge available from Seacore at the time. MCT revealed installation solutions that had been considered, including a ('Plan 'B'') solution involving a quadrapod foundation pinned with 1m piles, using a crane barge.

Figure 2.37: Jack-up rig 'Excalibur', (37)

The solution employed included drilling and grouting operations, as illustrated:

Figure 2.38: MCT Installation Operation (36)

As discovered in the earlier Seaflow prototype project, seabed drilling requires strong geotechnical evidence that the seabed can support sockets of the size required. Localised weak spots can be encountered, with severe consequences. MCT found that a steel casing had to be inserted to prevent the socket from collapsing.

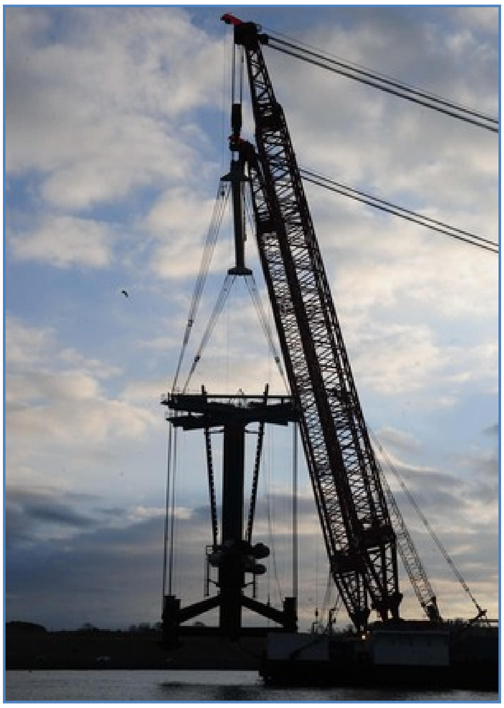


Figure 2.39: Seagen Turbine being unloaded (38)

The following is a news article on the MCT SeaGen installation, from April 2008 (39):

[See **bold sections** re installation]

"At approximately 4.00 am this morning the 1.2MW SeaGen tidal turbine was offloaded from the massive crane-barge, Rambiz, so that it is now standing on the seabed of the fast flowing waters in Strangford Narrows, Northern Ireland.

It is now correctly positioned and ready for the installation process to be completed so that it can be connected to the grid. The SeaGen tidal turbine has been developed by the pioneering renewable energy company Marine Current Turbines Ltd and is the first commercial system in the world capable of collecting clean energy from tidal or other marine currents.

SeaGen is sited roughly 1km south of the ferry route between Strangford and Portaferry, approximately ***400m from the shoreline****. When fully operational later in the summer, its* ***16m diameter, twin rotors*** *will operate for up to 18-20 hours per day to produce enough clean, green electricity, equivalent to that used by a 1000 homes.*

It is four times greater than any other tidal stream project so far built, including Marine Current Turbines' own earlier 300kW Seaflow system installed off Lynmouth, Devon in 2003 which was hitherto the joint largest tidal turbine.

Commentating after the successful phase of work, Martin Wright, Managing Director of Marine Current Turbines said: 'SeaGen is a hugely exciting project, as well as an historic achievement for both Marine Current Turbines and for renewables in the UK and Ireland. No other system can harness the power of the tidal currents in the way this one can. Tidal energy has the great advantage of being predictable. We take great pride and see enormous potential in the technology and hope it will eventually make a significant contribution to the future energy needs of the British Isles, Ireland and beyond.'

Secretary of State for Energy, John Hutton added: 'It is great news that Marine Current Turbines and British innovation are leading the world in the development of marine energy technologies. It's this sort of project which will help the UK meet our ambitious targets to significantly increase the amount of energy from renewable sources. I am proud that my department has played a part in the development of SeaGen, ***granting £5.2 million of funds to help take it from the drawing board****. Marine power has the potential to make a significant contribution to our energy generation needs, and I hope the success of this project will inspire others to follow its lead.'*

SeaGen had its final assembly at the Harland & Wolff dockyard ***in Belfast. Here it was winched onto the crane barge, 'Rambiz', owned and operated by the Belgium company Scaldis, and then transported to Strangford Narrows*** *on Sunday (30th March).*

The installation went according to plan but ***several days delay were caused by extreme weather which held up Rambiz's arrival at Belfast*** *and which led to another 24 hours delay for lowering the turbine into the Narrows*

The deployment by the Rambiz and the subsequent installation work is being overseen by MCT's in-house engineering team and ***being managed by marine engineering specialists SeaRoc Ltd****.*

The quadropod base of SeaGen's structure, which sits on the seabed is currently being pin piled. Each of the four pins that secure the structure will be drilled to a depth of about 9 metres. This work is being carried out by Fugro Seacore Ltd.

Following the pin-piling operation there will be an approximately 12-week commissioning phase to connect the tidal system up to the local electricity network for commercial use*. ESB Independent Energy, the retail subsidiary of Ireland's ESB, generating utility has offered a Power Purchase Agreement to supply to its customers in the island of Ireland with electricity from SeaGen."*

A further article on the same topic (40) states that the SeaGen turbine weighs 1,000t and that the Rambiz has a capacity of 3,300 t.

> *"Completing the installation of the turbine will take around two weeks. Fugro Seacore will use four 9m pin piles to secure the legs of the turbine to the ocean floor."*

Costs for the operation are difficult to come by, as the company holds them confidentially. However, several comments have been heard which indicate the recent MCT installation has cost way over £12 million per megawatt equivalent installed. Again, it is impossible to achieve a payback on such investment. The cost of the vessels involved in the project range from £30,000 per day for the jack-up rig to over £100,000 per day for the lift barge Rambiz. Looking at the timings of the project, one can easily estimate that the operational cost in vessel hire alone will be close to £5 million pounds. Without heavy government subsidy, future projects like this can be made economic. A megawatt of "green electricity" on the markets is worth about £50-£100, depending upon subsidy. Therefore the 1.2 MW MCT turbine would deliver about £1,000 per day into the grid, assuming it works for 12 from 24 hours (accounting for tidal flows). An investment of £12 million divided by £1,000 is 12,000 days for payback (simplified), or 32 years. With investors looking for about 5 -10 year paybacks one can see that this concept is not going to happen.

Interestingly, the company is now promoting several "alternative" designs. One alternative approach being considered for the mooring of a next generation MCT tidal array is shown below. No accompanying indication of an installation methodology was given.

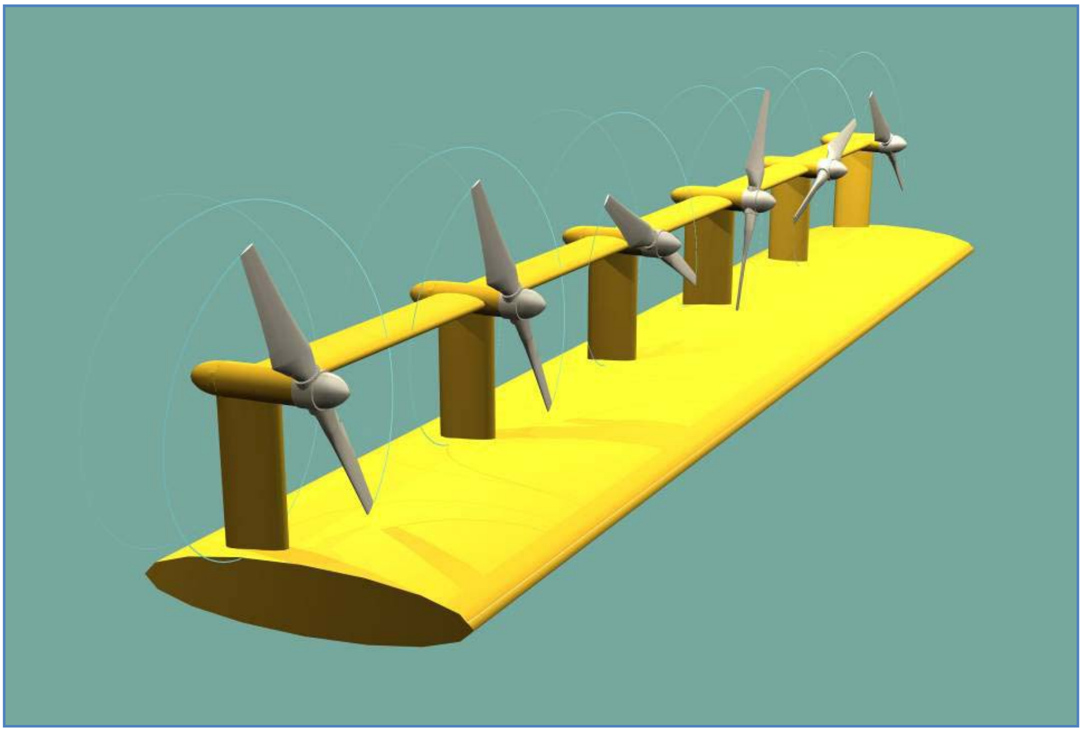


Figure 2.40: Possible alternative next generation MCT mooring design (36)

Hammerfest Strom (41)**,** another long-standing tidal industry player, has had a grid-connected prototype device in/out the water since 2003. It uses a gravity base with a tubular frame supporting a horizontal-axis propeller.

Figure 2.41: Drawing of Hammerfest Strom's installed turbine (41)

Figure 2.42: A Hammerfest Strom prototype being installed (42)

No data is available as to the costs and times of installation, although industry sources say the installation was very problematic and took several weeks. Recently, Burntisland Fabrication Ltd. (BiFab) were awarded a £2 million contract for manufacture of the gravity base.

Verdant Power's primary project has been in New York City East River. Installation (43)therefore has been achievable without significant offshore operations. The turbines installed are triple-bladed propellers with 5m diameter blades, rated at 35kW. A video and photographs on the Verdant Power website show a jack-up barge and crane being used, as shown:

Figure 2.43: New York East River installation (43)

This installation looks much more sensible, with smaller turbines and a much smaller installation barge. No costs are available for comparison. The Verdant approach has its merits, whereby the company promotes multiple small turbines placed in tidal flows.

The latest **Atlantis Resources Corporation** (ARC) project is a test installation (44), at the EMEC Orkney site, of their AK-1000 turbine design. The device is a very large structure, measuring over 25 metres in height, and is claimed to have the largest diameter rotor currently installed a marine environment.

Figure 2.44: AK-1000 turbine on keyside, and support support base structure being loaded aboard installation vessel (45)

The turbine is rated at 1MW, weighs 1,300 tonnes and has an estimated development cost of £25 million (45).

The installation of the device was carried out by Hallin Marine Subsea International Ltd, using the newly constructed (2010) anchor handling vessel Skandi Skolten.

Figure 2.45: Installation vessel, Skandi Skolten (46)

It is reported(47) that the installation was completed within budget but there is no information on what the actual budget was.

2.4.2 Tidal Installation Activities conducted by Academic Institutions.

A review was carried out on tidal installations conducted by academic institutions. The following universities have performed some proof of concept work:

- The Robert Gordon University (RGU), Aberdeen
- Swansea University
- University of Hull / Humberside
- University of Strathclyde, Glasgow

With the exception of RGU and Swansea University, the other devices are moored in mid-water or at the surface and are therefore not included in this study. The Swansea University device is close to the MCT design, and is therefore not described further.

The RGU device is called the Sea Snail(48). In effect it is a seabed mounted design to host a turbine or other underwater platform (e.g. sensors etc.). The novel aspect of this design is the hydrofoil attachments which provide a downward force as the water flows across the structure.

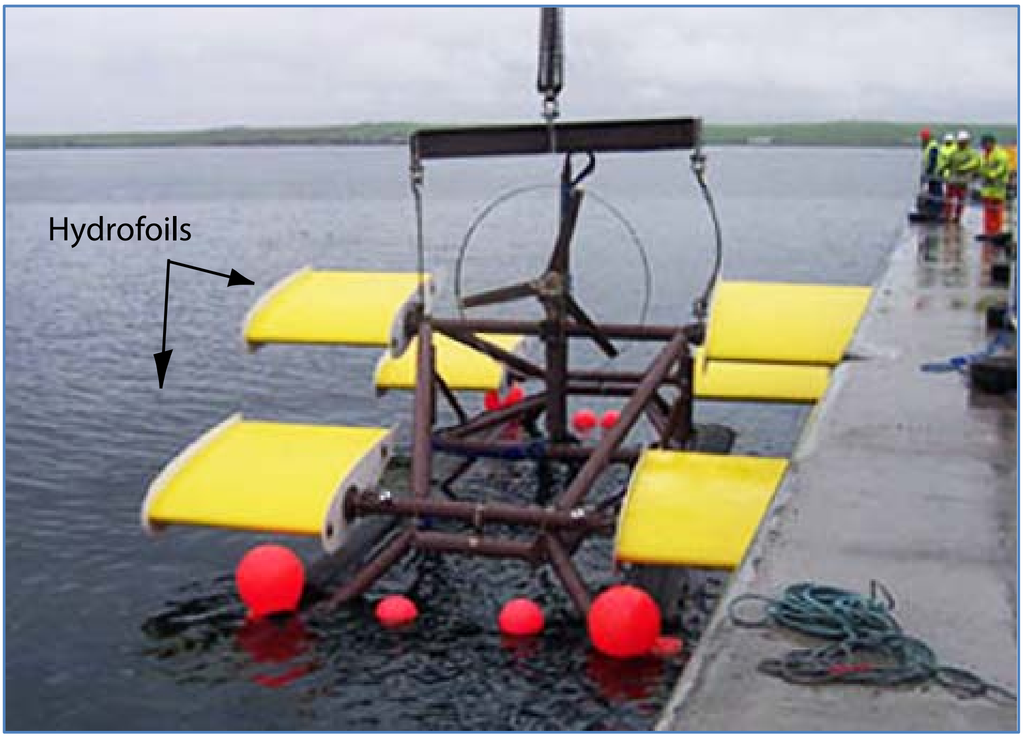


Figure 2.46: Sea Snail at quayside (49)

Work conducted by Dr. Alan Owen and Professor Ian Bryden proved, in prototype form, the efficiency of the device under tidal loading conditions. A PhD submitted by Dr Owen covers the detailed mathematical analysis performed on the concept / device(50).

Of interest, the philosophy of design follows a similar pattern to that of this research. In effect, a lower cost, lower weight modular tidal system that can be scaled to suit site conditions or client requirements.

It would be most interesting to look at further work between RGU and the author, whereby a hybrid between the two could be designed. Logically, there are innovative aspects between both devices and these could be developed into a hybrid design. This could be the subject of further work.

As a comparison, trends in technology for **offshore wind turbine foundations** are outlined in the following slide:

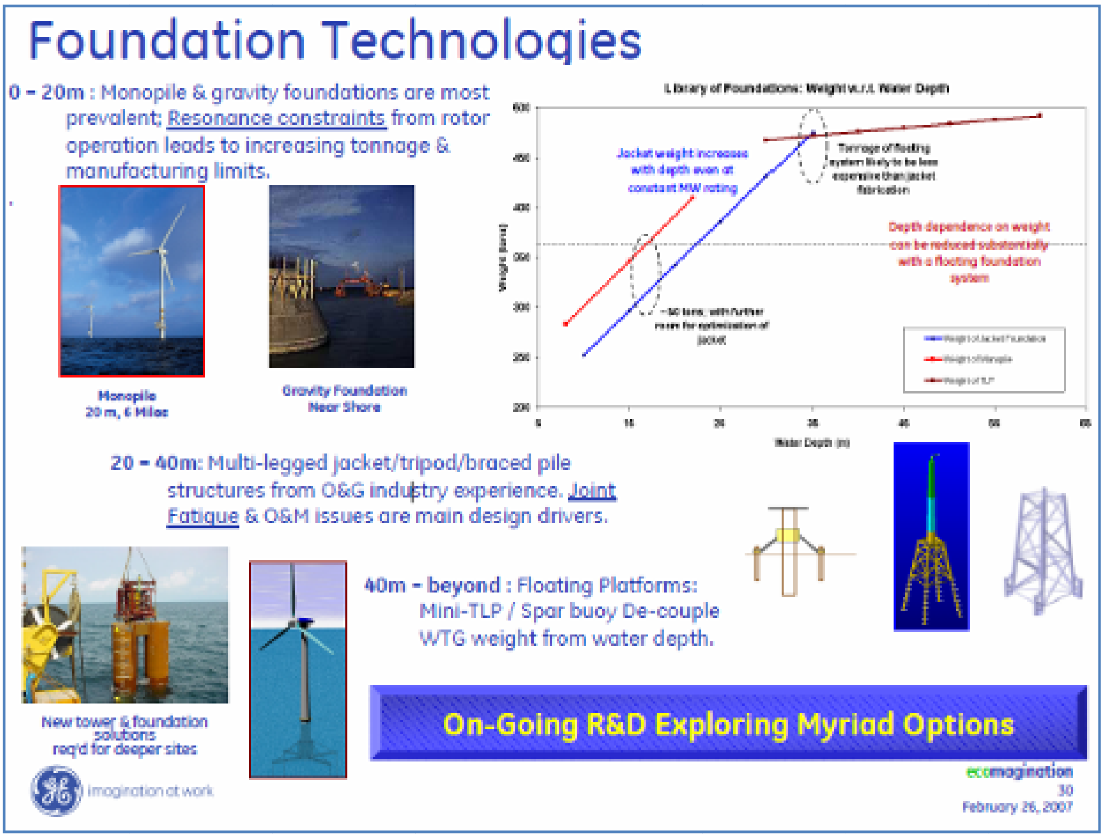


Figure 2.47: Offshore wind turbine foundation technology(51)

Compared to offshore wind turbines, the drivers for tidal turbine moorings vary due to the types of load and vibrations. Other factors are fatigue life and corrosion of additional subsea components.

However, parallels exist with the offshore wind industry which benefits from being further ahead in its development and about which more information is generally available.

Like the infant marine renewable industry, it is being set back by the competition for vessels, as mentioned in the following extract (52)

"European offshore wind installers were expecting to soak up surplus capacity from depleted North Sea natural gas fields, but those vessels are now in service in India and Brazil. Short supply and high prices add to the already outsize installation costs for offshore wind, which have caused a number of major developers to put some big projects on hold. This has sent investment return opportunities tumbling, making offshore renewables projects even less attractive than before. Shell stepped out of the 1 GW London Array, citing equipment shortages and spiralling construction costs. Both Vestas and General Electric have slowed production of their offshore units because of shrinking sales. Vestas, for example, hasn't sold an offshore turbine since late 2006. There are currently $120 billion of offshore wind projects in Europe that are stalled because of high construction costs and installation vessel shortages. As long as costs remain high and vessel availability remains uncertain, it is unlikely most offshore renewables projects will get built. This will certainly impact the EU's goal of meeting 20 percent of its electricity demand from renewables by 2020. However, lessons from Europe should give American renewables developers and drilling opponents another kind of ammunition in their fight to expand renewables capacity and limit the future development of fossil fuels."

In light of this, Gifford, in collaboration with BMT Group and others, have proposed a solution for offshore wind turbines based on concrete gravity foundations, which they believe to be competitive given current trends. A dedicated Transport and Installation Barge (TIB) is proposed to be used to ship a heavy concrete foundation block to the site, before being submerged for the positioning of the block on the seabed.

2.5 Chapter summary

High costs, delays and cost variance are the most significant factors for economic marine renewable installations, as competition with the offshore wind and oil and gas industries for appropriate jack-up and heavy-lift vessels has become particularly intense.

The disadvantages of offshore assembly and installation using large floating barges include potential delay from adverse weather conditions, besides the high dayrate costs (over £100,000 per day in many cases). Further specialist installation vessels suffer from similar susceptibility.

Physical challenges also exist when using jack-up barges in tidal zones where the currents are a much more serious consideration than in areas used for offshore wind farms. A European study (53) reported on MCT's Seaflow project that:

> *"Currents impose significant drag loads on the legs of a jack up, and may also induce vibrations in the whole structure from vortex shedding off the round legs". (53)*

Therefore, for the project in question, fairings were put on the jack-up barge's legs during tidal operations, at much increased cost.

The nature of tidal sites means that the vast majority of the most amenable/suitable sites are near land (e.g. headlands, islands and inlets) in relatively shallow waters. This is suitable for most jack-up barges, but also increases the viability of using in-shore work vessels such as illustrated below. Furthermore, it reduces the competition with offshore industry technology developed for deepwater installations. Use of vessels such as these does, however, mean that the tidal energy industry needs to concentrate on small modular tidal systems which have an installed capacity of up to 100kW, and not megawatt machines. In the author's view, this is the only way the tidal industry is going to become economic and be able to attract investor support.

Figure 2.48: Damen 24m Multicat with twin 10MT cranes (54)

The marine energy industry approach seems currently to be to avoid subsea operations where possible. From the information available, not much use of ROV technology is highlighted. The lack of crossover with the familiar technologies of the offshore service industry is apparent. Although ROVs have become highly sophisticated and can potentially save much time in conducting interventions, the unknown factors involved, as well as geographical constraints for quick deployment, are possible disincentives to their use.

Complete mooring solutions for marine energy applications are being proposed by some of the offshore service companies. For example, First Subsea offer a ball and taper connector for use in the marine energy industry. The company has a track record of designing and supplying over 200 mooring solutions for a variety of oil and gas applications, including in deep water. It requires a small amount of ROV use for installation and supports a quick release mechanism. No uptake from the marine energy industry has yet been publicised.

Experience from other offshore industries is claimed to be leverageable rather than (in many cases) directly transferable to the marine renewable sector.

The review of the literature covering the technologies and techniques employed in the subsea oil and gas industry for the past 20 years indicates that there are many aspects of the existing subsea industry that could, potentially, be transferred to the emerging tidal industry. Of importance here, is to seek technologies and techniques that could be crossed over without the huge costs involved with subsea oil and gas capex and opex. Innovative thinking and re-use of existing concepts will help bring improved economics to the tidal sector.

This thesis proposes the use of the following ideas and concepts in the tidal industry:

- Subsea well head technology, such as the production guidebase
- Subsea tree technology, such as the tree frame, guidewires, sacrificial anode systems for corrosion protection, electrical power wet connects
- Subsea equipment deployment technology, such as deployment risers and through water winches.
- Subsea field layout designs, such as well cluster around manifolds, daisy chain layouts.

3 Conceptual design for new Modular Tidal Generator

3.1 Introduction

Following the literature search and trials with small prototype concepts the author designed and tested two innovative systems that are applicable to extraction of energy from flowing water. Both designs take concepts and ideas from the subsea oil and gas industry, and incorporates these into two new systems that are expected to offer a lower cost alternative to existing tidal energy extraction devices.

This chapter introduces a subsea or underwater deployed, seabed mounted magnetic locking system that can be activated or deactivated remotely. Activation of the system is either by electrical pulse or pneumatic pulse. It is not operated using conventional electromagnetism. This design is patent pending (# 0921513.8) and was filed on 9th December 2009(55). These publications are included in Appendix one.

The chapter also introduces and describes a modular subsea energy production apparatus that is deployed underwater. It can be sea bed or river bed mounted and generates electricity from the kinetic energy in flowing water. It is a design which includes a sea bed or river bed mounted base structure onto which an underwater frame structure is locked into place. The frame structure can typically include a twin set of rotors and generators linked together by a shaft, gearbox and, or a set of flexible shafts. A power cable is used to export electricity. This design is patent pending (# 1001122.9) and was filed on 25th January 2010(56).

These systems use information and technology descriptions from existing UK patent, number GB2400632(57). This Patent was filed by author and is included in Appendix one. This initial patent award covered a Vertical Axis Design for deeper water (> 50m) from which these two shallow water systems have been developed.

Chapter 3 will discuss these new designs, based on Patent descriptions, and Chapter 4 will describe the laboratory and field trial work on the prototype systems.

3.2 Marine Locking System and Deployment frame

Conventional oil and gas subsea locking systems are designed to lock and secure various devices to the seabed. Typically, these devices operate either mechanically or, more commonly, hydraulically. This design relates to a remotely operated underwater magnetic locking and holding system apparatus that can be used to connect components together, either permanently or temporarily

Activation of the system is either by electrical pulse or pneumatic pulse, as opposed to the use conventional electromagnetic technology. The main components of the apparatus are the underwater frame structure and the underwater base structure.

The author has appreciated that conventional subsea and underwater locking devices have shortcomings. The present design has been devised in light of this appreciation. The design provides for modular flexibility in order to deploy different modules onto the seabed or underwater structures, and permanently or temporarily lock these structures and modules into place. A subsea landing piston is included in the system, to allow for slow make up of frame and base components as they are being connected underwater.

The design comprises:

1. A magnetic locking device incorporated into an underwater landing frame structure: and,
2. A set of modular electrical power connectors linked to the magnetic locking device, either internally to, or externally arranged around the magnets.
3. A subsea landing piston, which allows for a slow connection speed when the landing frame is lowered to the sea bed or river bed base structure.

4. An underwater landing frame structure which contains the above.
5. A base structure that hosts the underwater landing frame

The system will be modular in nature and besides the primary function of locking two mechanical components together, it will also have the ability to allow simple removal and repositioning of the following;

- Electrical power cables, connectors and umbilicals
- Hydraulic power cables, connectors and umbilicals
- Signal and fibre-optic cables
- Chemical lines and umbilicals
- Underwater mechanical tools
- Underwater Remotely Operated Vehicle tooling
- Underwater sensors
- Underwater cameras
- Underwater explosives and cutting tools

Figure 3.1 shows the fully constructed underwater landing frame structure. It is comprised of a series of individual magnet segments 1 which are attached to the top of a tubular subsea piston structure 2. The subsea piston structure allows for the underwater landing frame to slow its descent as it is lowered over the corresponding metal plate on the underwater base structure 4. There may be a single magnet module to lock the frame or structure in place, or a multiple of magnet modules utilised in a single frame.

Incorporated in the underwater landing frame structure are also guide tubes 3, and structural cross members 6. The underwater frame structure may be arranged in other ways, according to the requirements of the system being deployed. For example, a variety of flanged and metal plate orientations may be used. Materials used may include non-metallic components, such as fibreglass, carbon fibre materials and Kevlar materials.

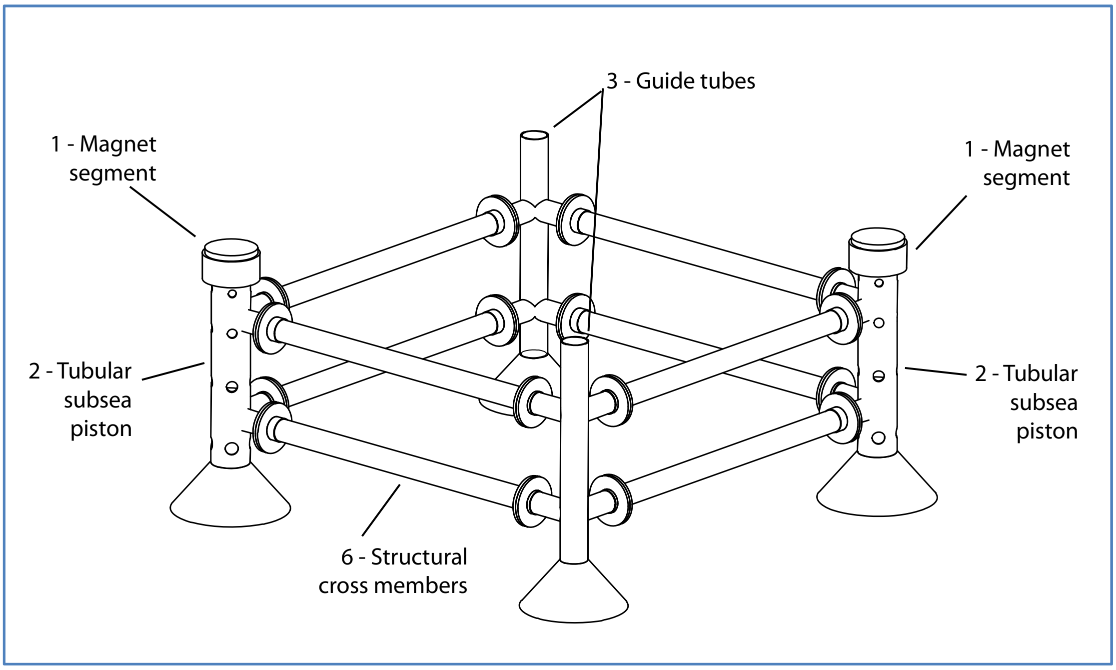


Figure 3.1: Schematic representation of frame structure

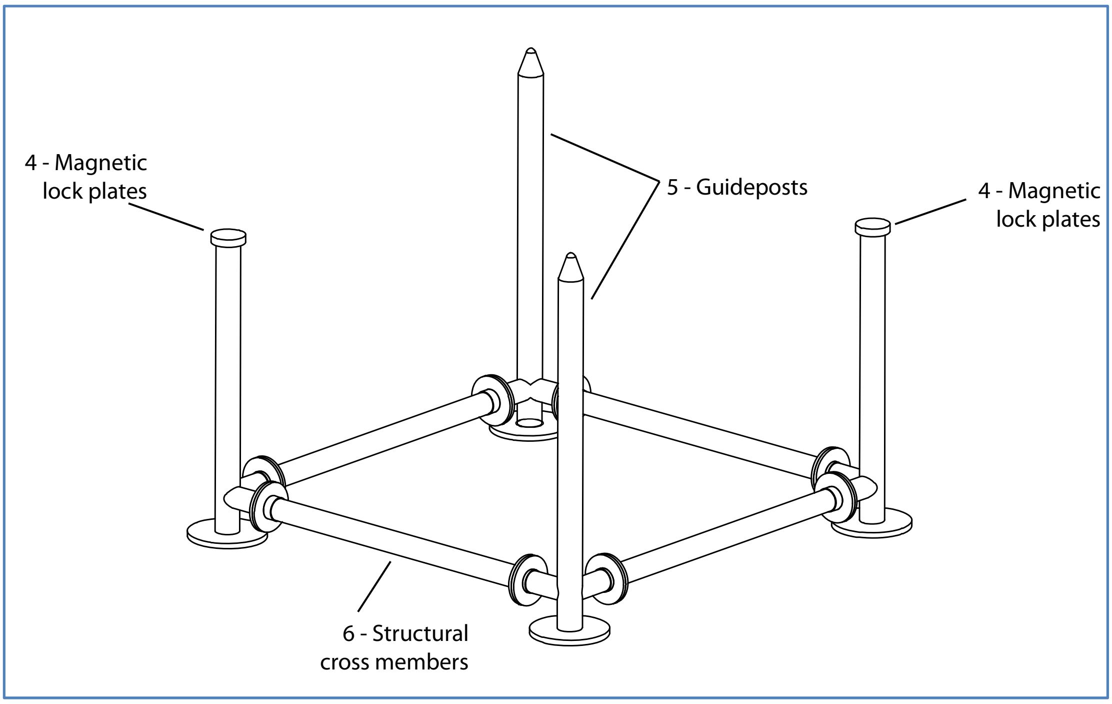


Figure 3.2: Schematic representation of base structure

Figure 3.2 shows the fully constructed underwater base unit. This structure may be constructed from tubular and, or box steel members. Steel plate structural members may also be included. Materials used will also vary according to the use required.

Incorporated in the underwater base unit are four vertical posts. These posts will either function as guide posts 5 for the upper frame structure or magnetic lock plates 4 to match the upper magnets 1 in the upper frame structure.

The underwater base unit, as in Figure 3.2, would be attached to a suitable gravity structure. The underwater base unit and gravity structure would then be deployed to the seabed. The fully constructed apparatus will be placed such that it can act as a base unit for deploying the underwater frame structure onto.

Once in position on the seabed there would be the option of attaching one, or several, guidewires to the underwater base structure. Each guidewire would attach to the top of guidepost 5. The top of the guidewires would then be attached to the vessel or fixed surface structure being used for the deployment operation. Depending upon the site conditions there may be the option of not using the guidewire method.

Once the underwater base structure was secure and the guidewires attached then the underwater frame structure would be deployed. The guidewires are positioned inside guide tubes 3.

Figure 3.3 and Figure 3.4 show side views of the frame and base structures;

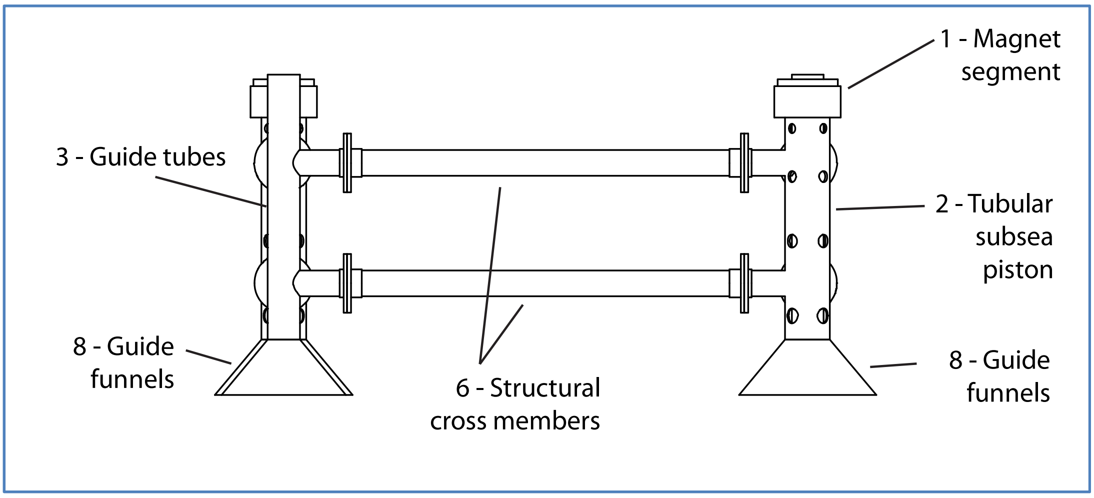


Figure 3.3: Side view of frame

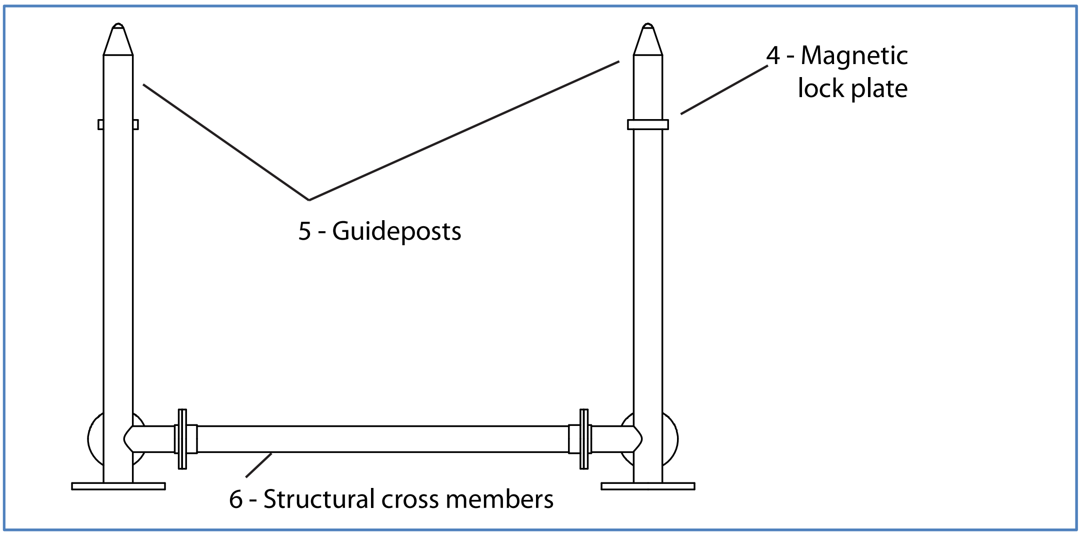


Figure 3.4: Side view of base structure

Figure 3.5 shows an example of a running tool to be used on top of the underwater frame structure. This running tool has magnets 7 for locking on to the top of the underwater frame magnets, and guide funnels for 8 for placing over the guide tubes 3, and associated guidewires. It also makes the connection between the control umbilical, used to operate the magnets.

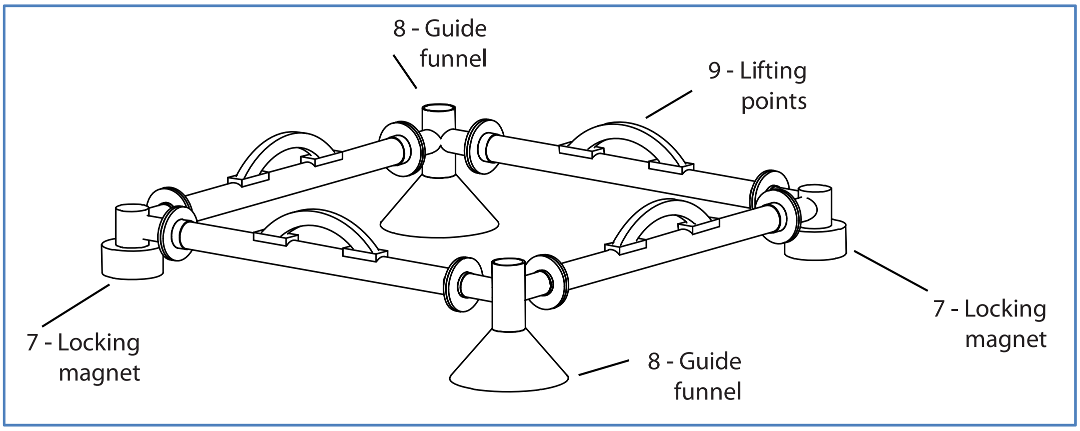


Figure 3.5: Frame running tool

The running tool would be magnetically locked to the top on the underwater frame structure and the whole assembly run to the sea or river bed, using the guidewires to assist in accurate deployment to the base structure.

The running tool would be lowered using a suitable cable from the surface vessel. Lifting points 9, of various known designs, are attached to the running tool. Attached to this cable would be the control umbilical for the magnets.

As the underwater frame structure reaches the base unit, the guide tubes and subsea piston tube will commence running down over posts 4 and 5. The magnet lock plate on the top of post 4 will immediately slow down the underwater frame structure as water will be forced out of the holes in the subsea piston structure 2, due to the piston effect of the magnet lock plate moving up the inside of the subsea piston 2. The holes in 2 can be sized according to the landing speed required. The subsea piston structure is acting like a motion compensation device at this point.

An option with the magnet module 1 in the underwater frame structure will be to incorporate an electrical power wet connect feature. This can be made integral to the magnet module, or attached to the side of the magnet module. Figure 3.6 indicates different views of this option. The electrical wet connectors are indicated as 10 and 11. Besides electrical power connectors other connectors of known design could be used, for example fibre optic signal cables.

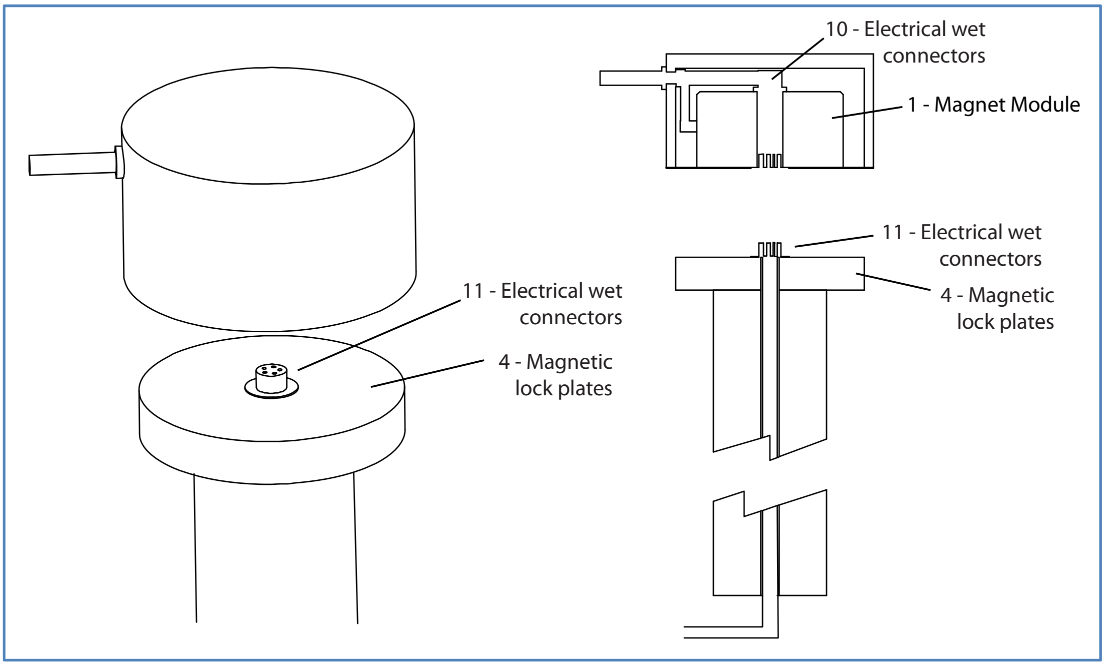


Figure 3.6: Electrical power connector options

Once the underwater frame structure is located on the base structure then the magnets would be energised by using either an electric pulse or by a pneumatic pressure pulse. Several magnets would be controlled from one power or pneumatic source. Magnets can be energised at different set electrical voltages, or different pneumatic pressures.

Following confirmation that the underwater frame structure was locked onto the underwater base structure (by using an overpull) the magnets in the running tool would be unlocked. The running tool would then be retrieved to surface, followed by retrieving the guidewires by known methods.

The fully constructed segmented apparatus and associated equipment, as shown in Figure 3.7, can be parametrically scaled, as required.

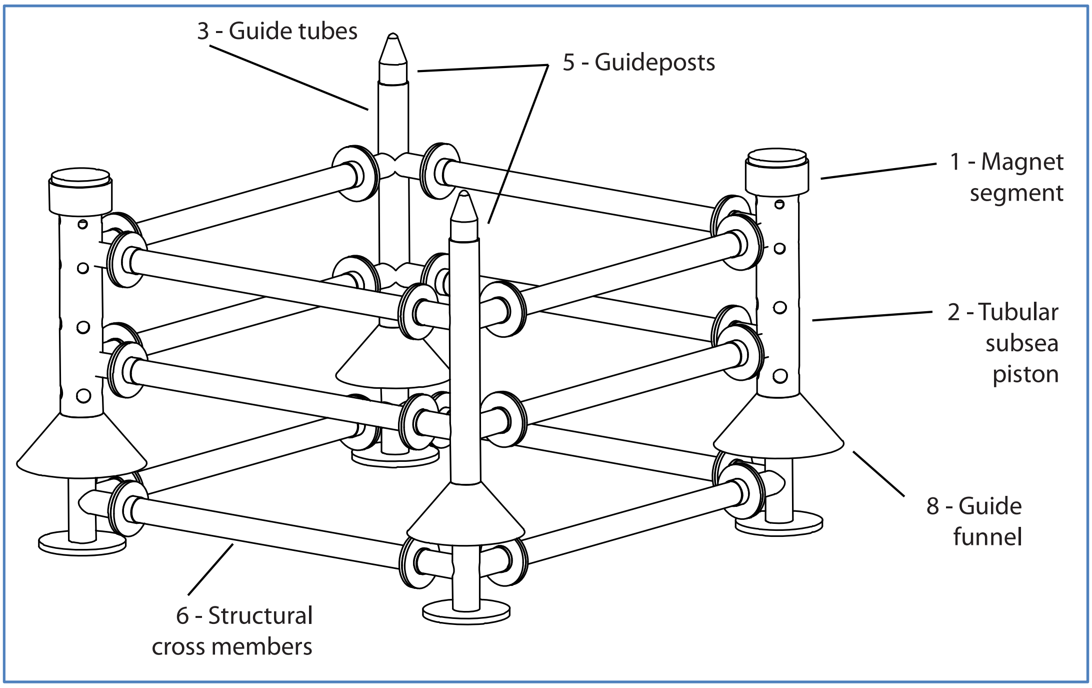


Figure 3.7: Schematic of frame and base connected

To retrieve the frame structure the magnets will have to be unlocked, using an electrical current applied through the running tool, or independently via a ROV or diver.

3.3 Modular Tidal Energy System

This design relates to a modular subsea energy production apparatus that is deployed underwater. It can be sea bed or river bed mounted and generates electricity from the kinetic energy in flowing water.

It is a design which includes a sea bed or river bed mounted base structure onto which an underwater frame structure is locked into place. The frame structure can typically include a twin set of rotors and generators linked together by a shaft, gearbox and, or a set of flexible shafts. A power cable is used to export electricity.

This system uses information and technology descriptions from existing UK patent, number GB2400632(57)

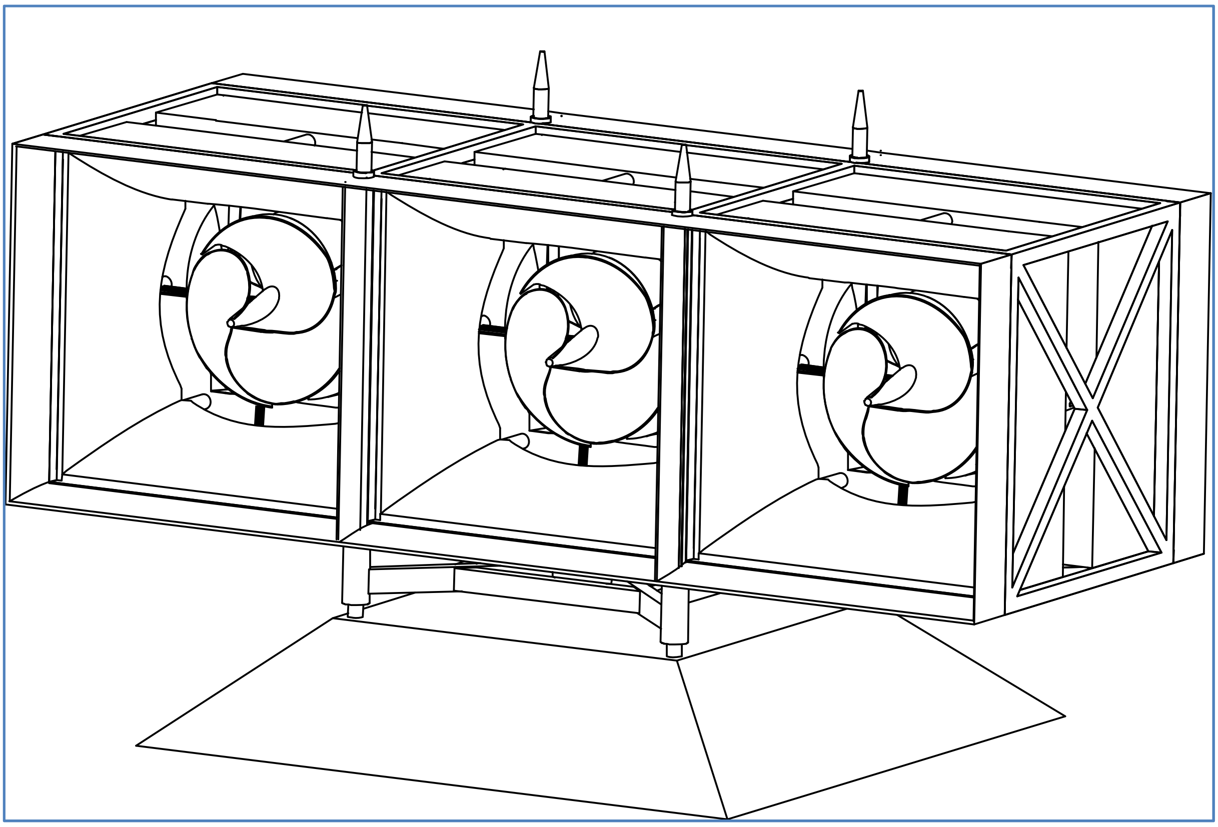


Figure 3.8: Representation of modular tidal energy system

Conventional horizontal axis systems are designed to extract energy from flowing water (either river, tidal flows or ocean currents) by using propeller type rotor blades. The rotor, or turbine, blade is directly attached via a solid shaft to either an electrical or hydraulic generator.

This design describes a new type of rotor design and an improved way of linking several rotors and generators together, by using flexible shaft technology. The author appreciated that conventional horizontal axis devices have shortcomings, especially with regard to the rotor design and also the method of connection of rotor to generator. The present design provides modular flexibility in order to deploy different modules onto the seabed or underwater structures, and permanently or temporarily lock these structures and modules into place.

According to a first aspect of the present invention, there is provided a seabed or underwater kinetic energy conversion system operable as at least an electricity production system, the apparatus comprising:

1. A single, or set of horizontal axis rotors of a new design incorporated into an underwater landing frame structure: and,
2. A set of modular generator units that can be independently connected to the rotor structure.
3. Allows for a plurality of rotor frame structures and generators may be connected together with flexible shaft technology.
4. All can be configured into an underwater frame structure for deployment.
5. The underwater frame structure would lock on to a base structure.

The tidal system will be modular in nature and besides the primary function of converting the kinetic energy in flowing water to electrical energy, it will also have the ability to allow simple connection, removal and repositioning of the following;

- Electrical and hydraulic power cables, connectors and umbilicals
- Signal and fibre-optic cables
- Underwater mechanical tools
- Underwater Remotely Operated Vehicle tooling
- Underwater sensors
- Underwater cameras

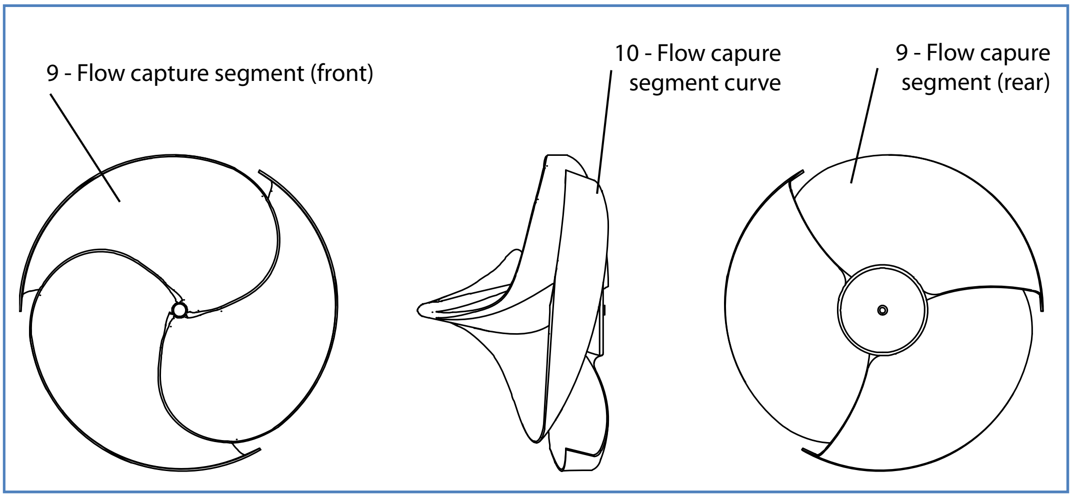


Figure 3.9: Depiction the new rotor blade / turbine blade design

Figure 3.9 (centre), shows a side view of the rotor blade. The design addresses the shortcomings of traditional propeller type rotor designs. Figure 3.9 (centre) shows the elongated nose of the rotor extending outwards into an angled set of individual flow capture segments. Three, or more flow capture segments, 9, can be linked together on the central cone to form the complete rotor blade system. The central cone taper angle can be modified to suit underwater flow conditions and power output requirements. Each segment is shaped to maximise flow across the whole surface area of the rotor blade. The elongated nose reduces abrupt back pressure effects and aids deflection of the flow towards the outer diameter of the flow capture segments. This design helps minimise the risk of marine strike injury through the reduction of leading edges on the blade.

Figure 3.9 also depicts how the rear surfaces of the rotor flow capture segments are curved over to face the incoming flow, 10. This curved portion, or segment wing tip, can be of varying thickness and variable angle of attack to the oncoming water flow. An option would be to make this part of the flow capture segment a pressure adjustable system, to maximise flow capture under variable water speeds.

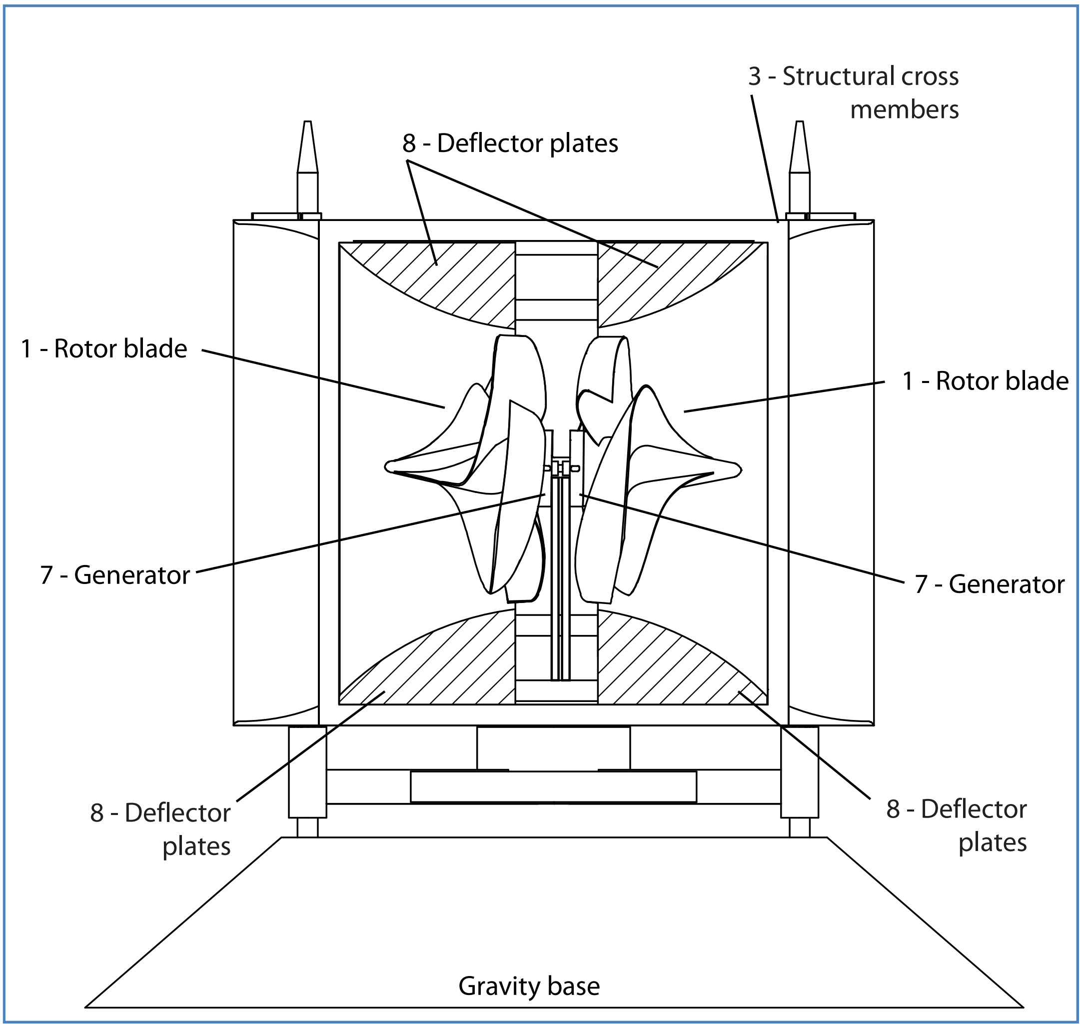


Figure 3.10: Side view (cut-away) of one module

Figure 3.10 shows a side view on one of the underwater rotor / generator modules on the base structure. The twin rotors are shown, 4, with a set of individual generators, 7, directly attached to the rear of each rotor blade arrangement. Internal to each module will be a set of deflector plates, 8, the purpose of these will be to help direct the water flow directly onto the rotor or turbine blades. The deflector plates may, or may not, have side openings in them to allow for the egress of water after it has passed over the rotor blades. The deflector plates may, or may not, extend beyond the structural cross members, 3, of each individual module. The deflector plates may, or may not, be pressure flexible and therefore capable of automatically adjusting themselves to the velocity of the water flow, in order to influence the rotational speed of the rotor blade

Figure 3.11 shows an example of the fully constructed apparatus, viewed from a frontal aspect. It is comprised of a series of individual rotor and generator modules 1, which are connected together as three sets as in this example. Single or Multiple modules, 1, may be linked together, depending upon site conditions and power generation requirements.

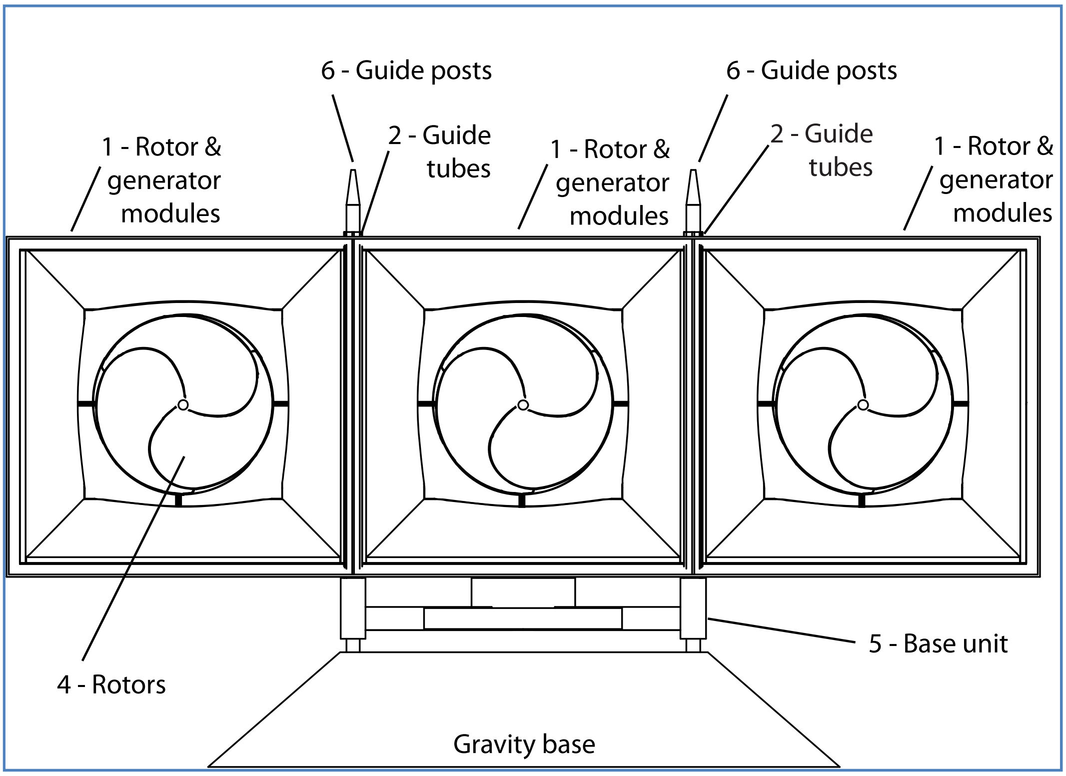


Figure 3.11: Front view of modular tidal energy system

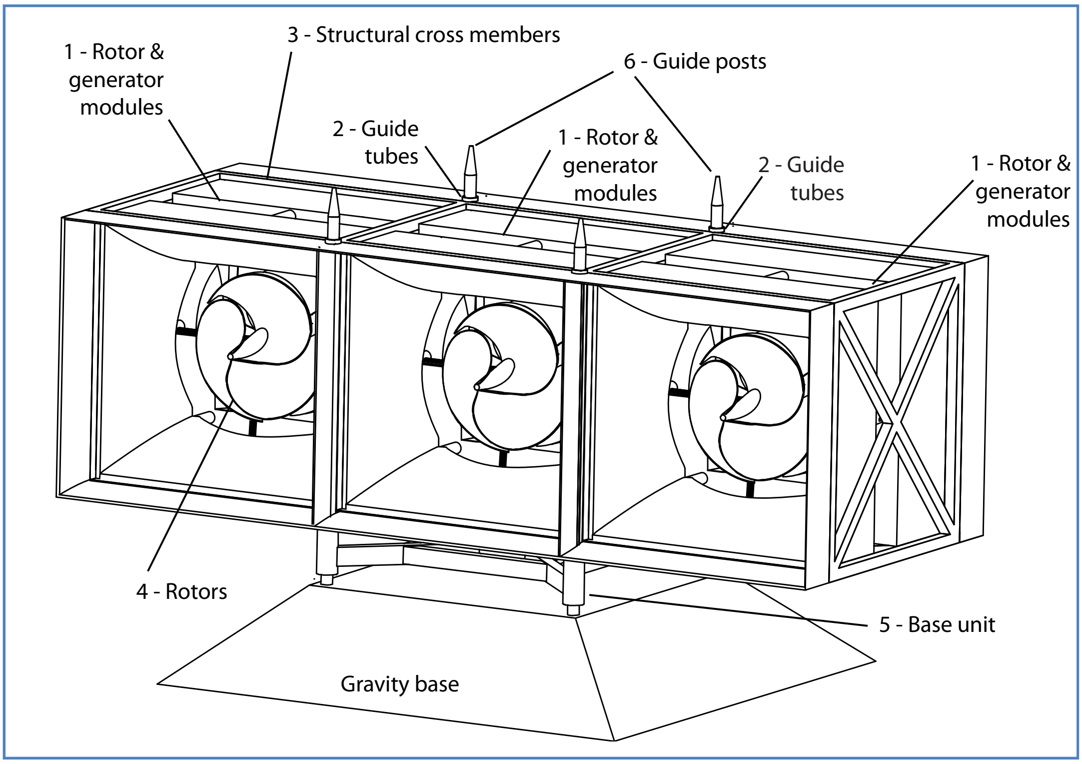


Figure 3.12: Perspective view of modular tidal energy system

Incorporated in the individual modules also guide tubes 2, and structural cross members 3. The underwater frame structure may be arranged in other ways, according to the requirements of the system being deployed. For example, a variety of flanged and metal plate orientations may be used. Materials used may include non-metallic components, such as fibreglass, carbon fibre materials and Kevlar materials.

To prevent debris, an appropriate sized mesh would be included. Fouling is prevented by anti foul paints and coating.

There may be a single rotor in a module for uni-directional flow such as in a river, or a multiple of rotors and generators utilised in a single frame, such as in a tidal environment.

Figure 3.11 also shows a fully constructed triple module on an underwater base unit. This base structure may be constructed from tubular and, or box steel members. Steel plate structural members may also be included. Materials used will also vary according to the use required. It also shows how multiple underwater rotor / generator modules can be linked together; in this case it depicts three modules.

The modules can be linked horizontally or vertically, or a combination of both. Single modules are also possible.

Incorporated in the underwater base unit are four vertical guideposts, 6. These posts will either function as guide posts for the upper modules or as locations where power cables and locking mechanisms may be incorporated.

The underwater base unit, 4, as in Figure 3.11, would be attached to a suitable gravity structure, commonly made from concrete or steel. This may also contain ballast. The underwater base unit and gravity structure would then be deployed to the seabed. The fully constructed apparatus will be placed such that it can act as a base unit for deploying the rotor / generator modules onto.

Once in position on the seabed there would be the option of attaching one, or several, guidewires to the underwater base structure, to aid in deployment operations. Each guidewire would attach to the top of guidepost 6. The guidewire attachments are of known design. The top of the guidewires would then be attached to the vessel or fixed surface structure being used for the deployment operation. Depending upon the site conditions there may be the option of not using the guidewire method.

Once the underwater base structure was secure and the guidewires attached then the underwater rotor / generator modules would be deployed. Running tools and cables of known design would be used.

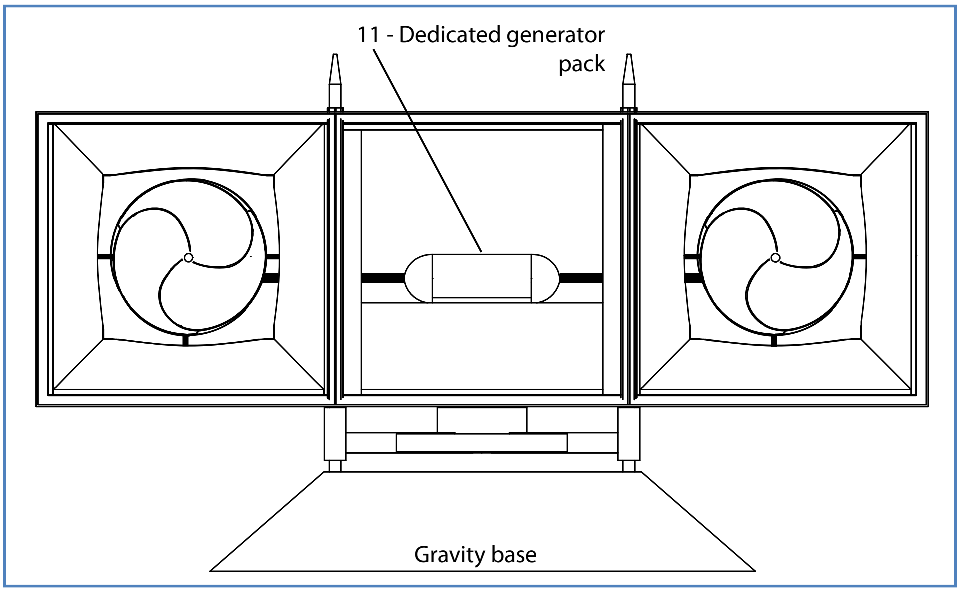


Figure 3.13: Front view showing generator placed in central module

Figure 3.13 shows a front view of two underwater rotor / generator modules linked to a third housing containing a dedicated generator pack, 11. This option allows for a larger generator to be used, by driving it with two rotors as opposed to a single rotor. The generator, 11, would be connected to the rotors by utilising a solid rotating shaft or a flexible rotating shaft. An integral gearbox option could be used on the ends of either type of shaft, or the gearbox or gear head may be part of the generator module.

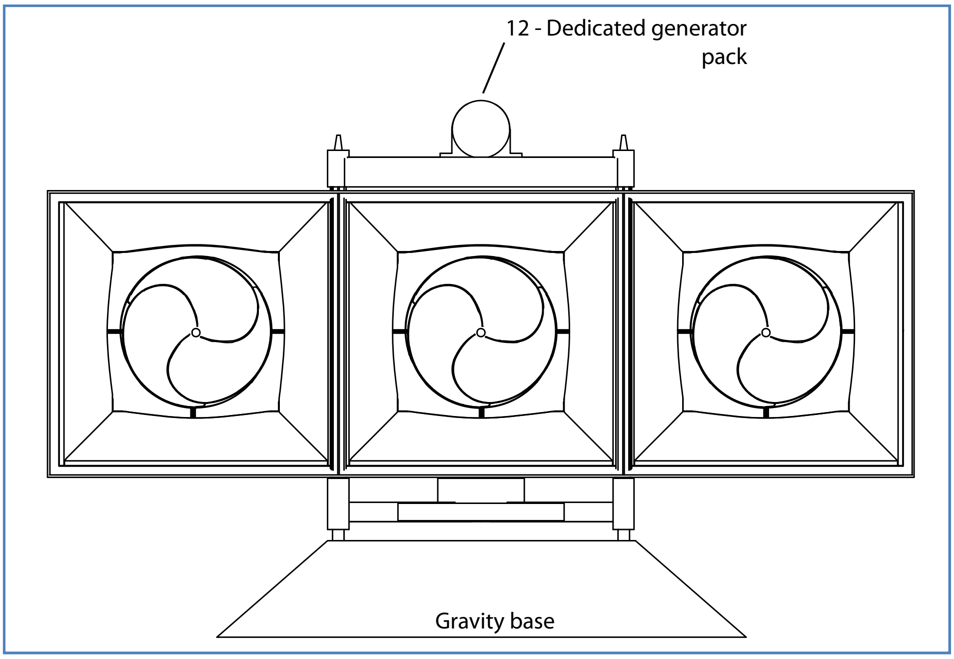


Figure 3.14: Front view showing generator placed above rotor modules

Figure 3.14 shows a front view of three underwater rotor / generator modules linked to a fourth module containing a dedicated generator pack, 12. This option allows for a larger generator to be used, by driving it with three rotors as opposed to a single or dual rotors. The generator, 12, would be connected to the rotors by utilising a solid rotating shaft or a flexible rotating shaft. An integral gearbox option could be used on the ends of either type of shaft, or the gearbox or gear head may be part of the generator module.

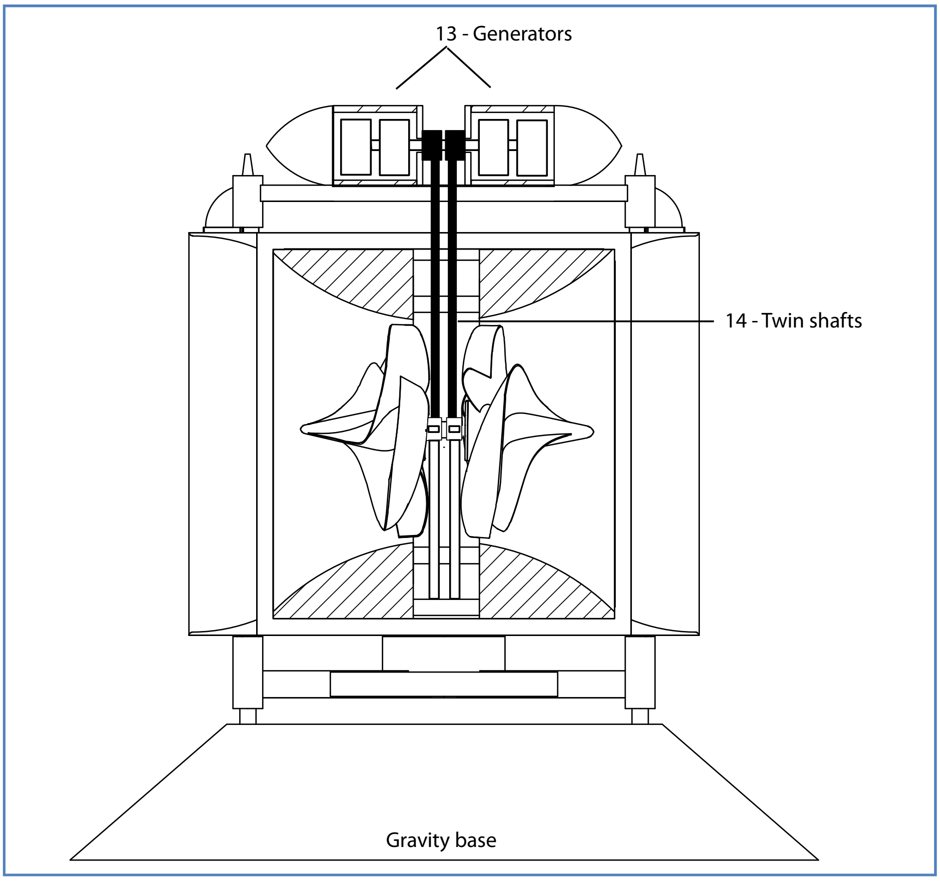


Figure 3.15: Cut-away view showing shafts attached to generator module

Figure 3.15 shows a side view of Figure 3.14. The generators, 13, are attached to the twin blade rotors by using a set of twin solid or flexible steel shafts (14). An integral gearbox option could be used on the ends of either type of shaft, or the gearbox or gear head may be part of the generator module. An option would be to make this generator part, 13, of the system retrievable, without the need to remove each of the underwater rotor / generator modules.

The fully constructed segmented apparatus and associated equipment, as shown in figure 3.12, can be also attached to a floating structure such as a boat or dedicated barge, or to a rigid structure such as bridge pillars. The rotor and generator modules will also have the ability to be retro-fitted to other industry designs, such as the RGU Sea Snail(48).

The following figures show the first prototype rotor/generator module following construction. More detail is included in Chapter 4

Figure 3.16: Prototype rotor/generator module

3.4 Chapter summary

This chapter introduced a subsea or underwater deployed, seabed mounted magnetic locking system that can be activated or deactivated remotely. Activation of the system is either by electrical pulse or pneumatic pulse. It is not operated using conventional electromagnetism.

The chapter also introduced and describes a modular subsea energy production apparatus that is deployed underwater. It can be sea bed or river bed mounted and generates electricity from the kinetic energy in flowing water. It is a design which includes a sea bed or river bed mounted base structure onto which an underwater frame structure is locked into place. The frame structure can typically include a twin set of rotors and generators linked together by a shaft, gearbox and, or a set of flexible shafts. A power cable is used to export electricity.

Chapter 3 discussed these new designs and Chapter 4 will describe the laboratory and field trial work on the prototype systems.

4 Early stage practical work

4.1 Introduction

For the experimental stage of testing the design concepts the required tasks were split into a series of project specific stages. The project stages covered comprised Final Definition of Project Scope, Feasibility/Concept Reviews and a start to Design Development. A brief description of stages involved are listed below;

- The top level project schedule was reviewed and split into sub task levels in sufficient detail to identify start and end dates (and the resources required) of individual task groups critical to each sub-project timeline.
- Conceptual design sketches of the assembly and sub-assemblies were prepared in preparation for review, along with outline requirements and objectives of the project
- Job steps contained within the project plans tasks and sub-task levels were summarized in bullet point form providing a step by step reminder of activities required to complete a task/sub-task.
- A risk register (example Appendix two) was opened for review and update throughout the project.
- A list of suppliers/potential suppliers was created detailing the relevant component ranges.
- Time based and capital based expenditure was confirmed using the detailed work plan and supplier cost estimates.
- The outline Statement of Requirements (SOR) of the sub-projects was reviewed and more fully defined.
- A review of the current state of play in the industry was undertaken to produce an outline market opportunity awareness.
- Addition requirements to the existing SOR were considered in light of the outline market opportunity review.
- Equipment required was listed and its design parameters and functionality outlined.

- An outline description of the type and extent of trials to be carried out was completed, including an overview of procedures for conducting the trials.
- Sub assembly and assembly trials were discussed, looking at details of the trials to be conducted including the type, location, extent and purpose of the trials.
- The outline procedure for each sub-project trial was discussed to ensure that each trial can be performed in a manner appropriate to the trial's outline description.
- The outline scope of equipment and services was firmed up.
- Design development was commenced with CAD assemblies/sub-assemblies being constructed from the conceptual designs. These were reviewed and set-up was undertaken of the initial fluid dynamics/stress analysis models.

The following primary sub-projects were conducted;

1. Magnetic Locking System Experimentation
2. Design and test of new rotor concept
3. Design and test marinised generator options
4. System Integration Analysis and Cost Estimates
5. Summary

The sub-projects are all included in this Chapter.

4.2 Magnetic Locking System Experimentation

4.2.1 Design Work

The project proposed to design a structure that would incorporate electrically switchable permanent magnets to provide a means for anchoring a Tidal / River Turbine to the seabed. Based on standard oil and gas industry equipment, the structure was intended to be a simple modular frame (section 3.2) that would provide sufficient strength to withstand tidal energy forces whilst minimising deployment costs. Other specifications were that the system should operate without ROV or diver support, require minimal pre-assembly and be capable of deployment from a Vessel of Opportunity. The full requirements for the project were developed as part of the preliminary project design.

The original scope was to include a demonstration of the running procedure within the project: this would entail the design of a soft-landing system. The removal procedure also required features compatible with the quick release of the magnet lock and subsequent retrieval of the frame. High factors of safety and some redundancy were to be incorporated into the design. The design was to be modelled using a half-scale functional prototype.

Figure 4.1: Pneumatically switchable permanent magnet being checked (copyright author)

It was an objective to produce a standardised design, capable of being tailored to a wide range of applications including other tidal and wave energy devices. The design process was planned to undergo a number of iterative stages of concept review, design development, refinement and technical review, prior to a firm design being frozen and taken forward for trialing and subsequent finalisation.

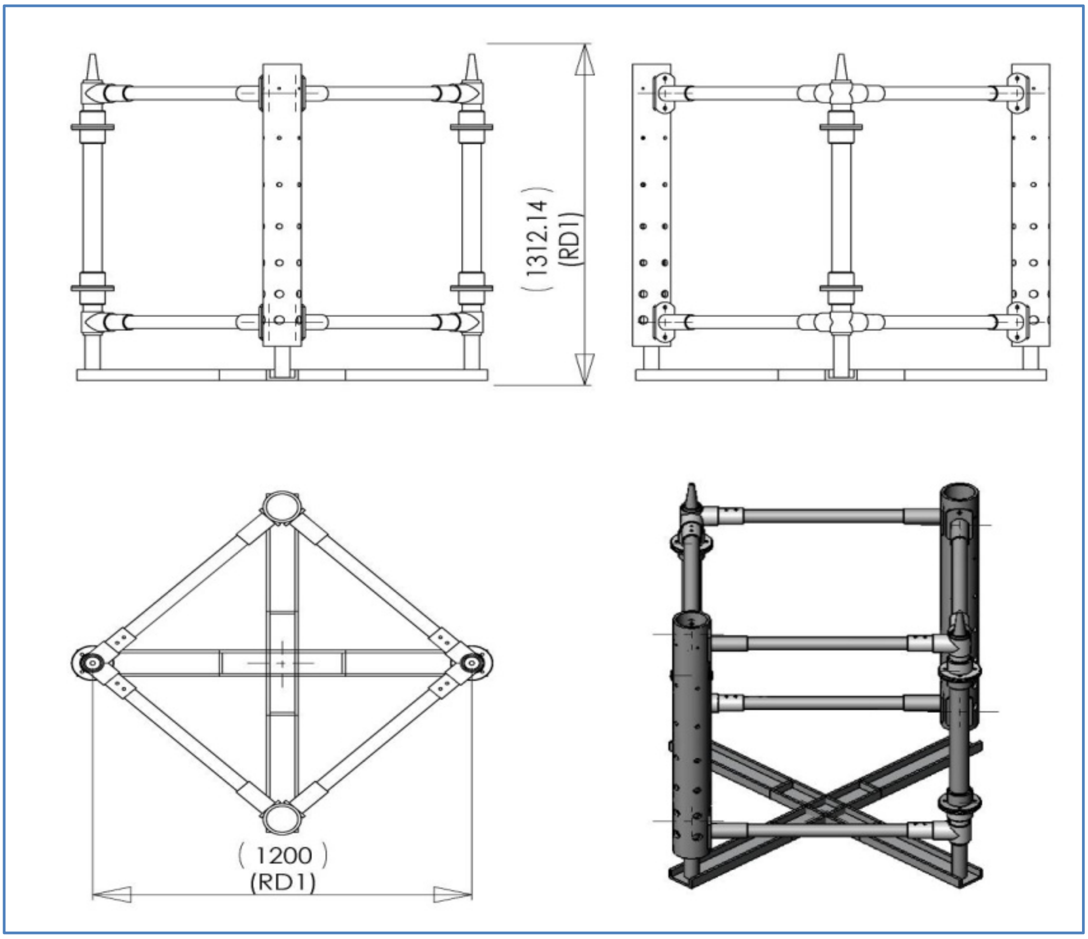


Figure 4.2: CAD design of frame and base structures (copyright author)

4.2.2 Development

The actual design fulfils its mandate of providing a robust means of securing a device to the seabed. The locking frame is modular and is made from standard steel pipe (tubular) which are widely used in the oil and gas industry. It is thus cost-effective. Simple calculations indicate that it provides sufficient strength to hold a tidal device firmly against tidal forces, when used with a guidebase securely embedded in a gravity base. The design has maintained similarity to a wellhead frame structure and the installation procedure should therefore be familiar to the subsea service industry.

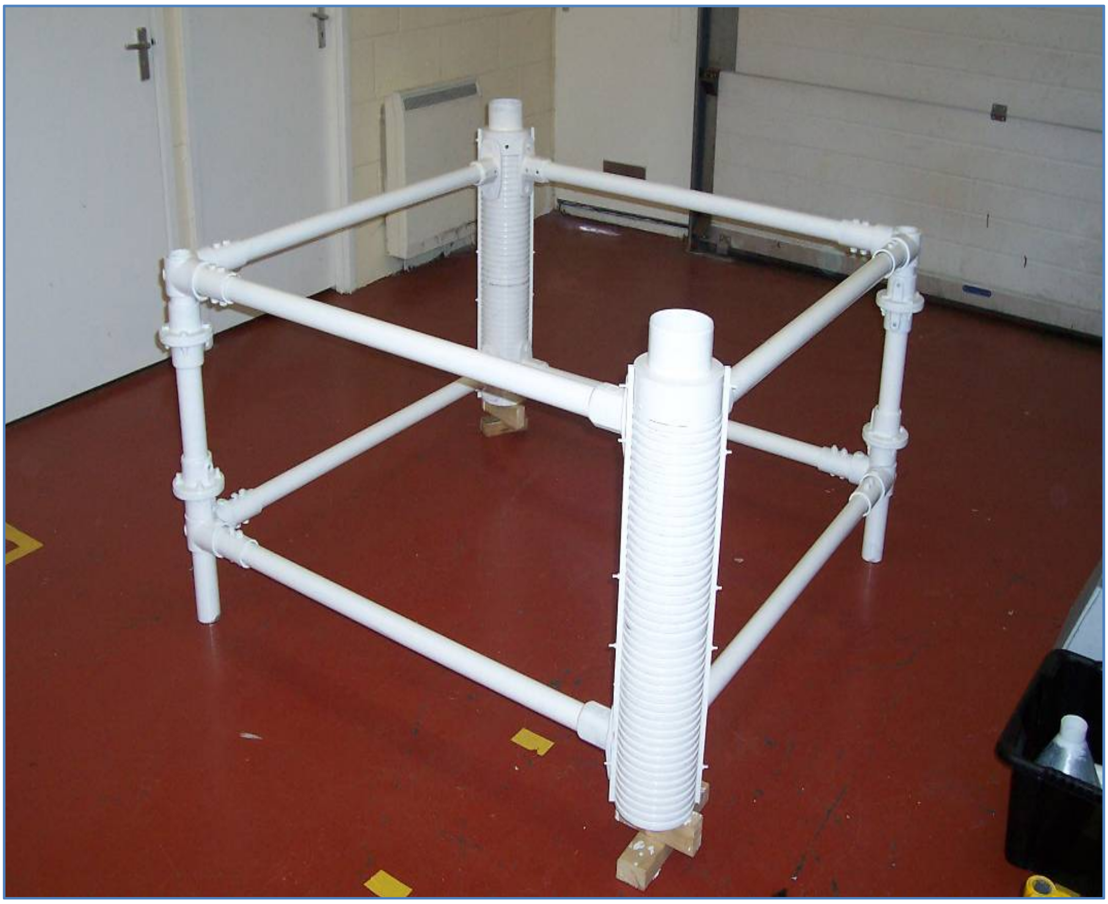


Figure 4.3: Frame assembly (copyright author)

The requirement for guidewires and magnets on the corner-posts led to a solution using two of each, after discussion and sketching of alternative options. Further redundancy can still be added. Design adaptations for other applications have not yet been fully explored but there remains scope to apply variations.

Figure 4.4: Guidepost and magnet housing corner-post sub-assemblies (copyright author)

A soft-landing system to enable a smooth running procedure was eventually deemed to be beyond the financial resources of this project. Possibilities were sketched and will be worked on in future.

The design cycle was not as iterative as it could have been as, due to the need to order materials and test within a short timeframe and with a limited budget, there was not much opportunity to make changes. As it was, the design did not require significant revision after the final review.

The use of CAD tools and software analysis was conducted according to plan. The use of Rapid Prototype models were extremely beneficial and reduce cost / time at several points in this stage of the project.

4.2.3 Tow Tank Testing

A period of testing at Strathclyde University tow tank was envisaged in order for the frame prototype to be fully tested in a controlled flow environment. The towing carriage was expected to operate at up to 4m/s. Runs could therefore be conducted at a range of flow speeds with the underwater frame mounted at different angles to the flow. The intention was to determine any limitations of the MLS under different configurations and to inspect the system after each set of runs to check for any change in the performance of the magnetic locking. An oscillation test and a water impact test were also discussed early on. Underwater video footage and photographs were to be obtained of all tests;

Strathclyde University also promoted the use of various displacement, force and flow sensors.

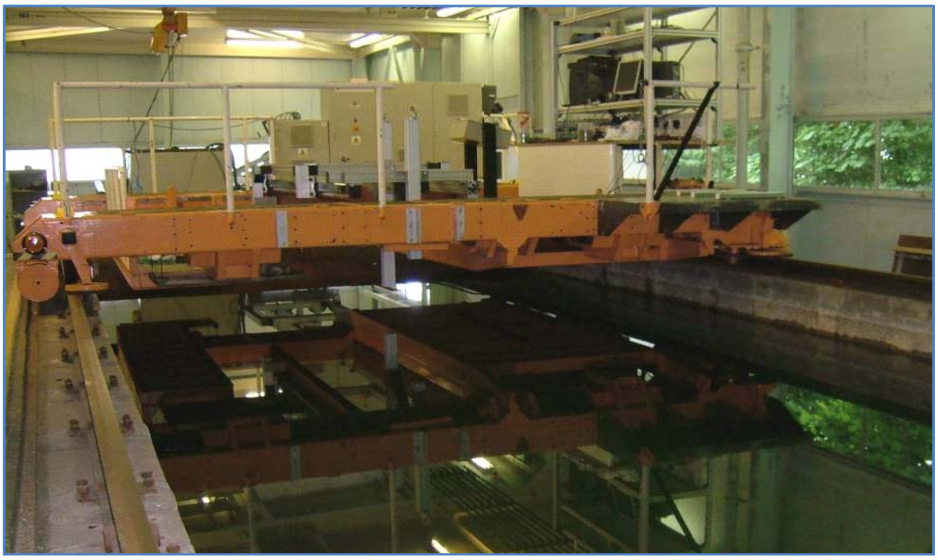


Figure 4.5: Strathclyde tow tank facility, showing towing carriage (copyright author)

The tank facility was visited and planning meetings held with Strathclyde University staff as per the project plan. After due discussion, it was decided that one day of focused testing was necessary to conduct a thorough tow test on the underwater frame and magnets in a cost-effective manner.

A test rig was designed with a two-part sting with an agreed interface to allow quick connection between the frame rig and Strathclyde's apparatus.

Figure 4.6: Construction of the base support structure, being attached to the base. Magnet locking plates shown (copyright author)

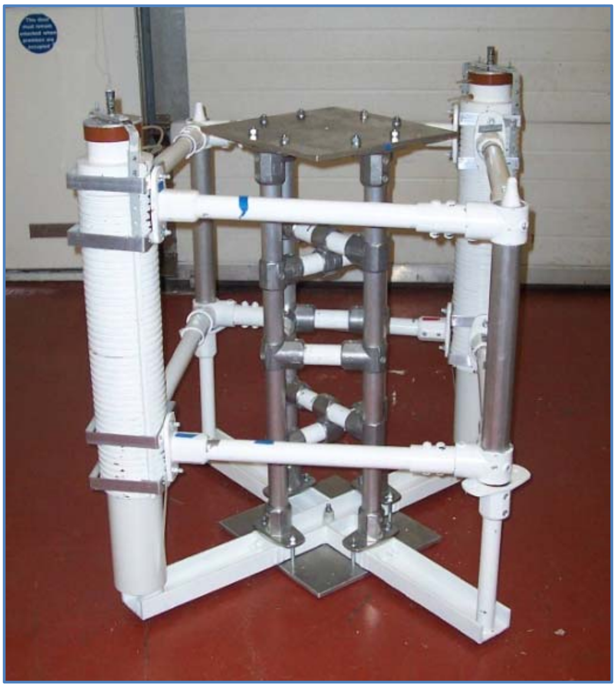


Figure 4.7: Completed frame, with guidebase and testing support structure (copyright author)

However, upon arrival at the site, Strathclyde's part of the sting (that was designed to allow angled mounting) was found to be too weak so a redesign using a large steel beam had to be hastily arranged. This was eventually attached by a more cumbersome method than had been intended.

Figure 4.8: Underwater Frame unit being hoisted into position at Strathclyde University tow tank, prior to being attached to the sting structure and submerged (copyright author)

Removal of the underwater frame was therefore a time-consuming operation meaning that it was impractical to remove the frame for inspection after each batch of runs. The unlock-pull-lock test was therefore conducted in situ and inspection was limited to what could be seen using the video cameras followed by a final examination upon completion of testing. Control runs were also conducted with the magnets unlocked.

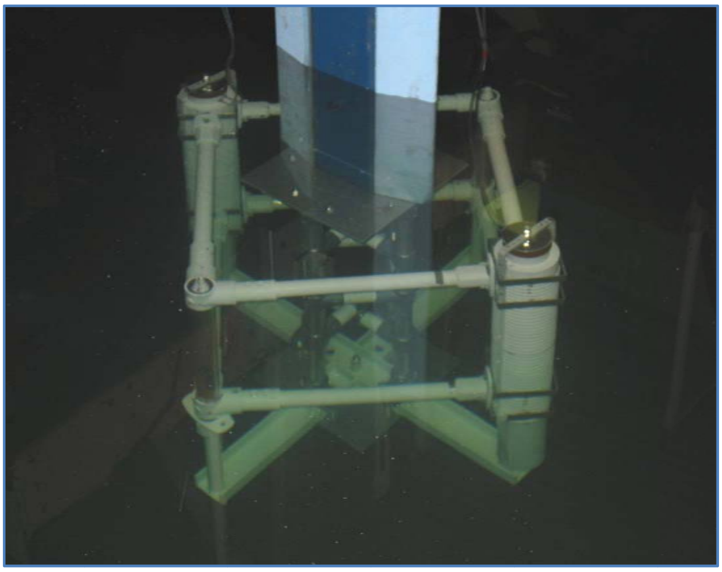


Figure 4.9: Underwater frame submerged in position beneath the towing carriage, ready for test runs (copyright author)

The maximum speed at which Strathclyde University were happy to operate the carriage was 3 m/s, however no vibrations were observed up to this point. The oscillation function for the carriage had not been commissioned by the time of the test day, following the installation of a new carriage drive. In any case the period of oscillation was not the most useful for applying the desired vibrations.

It was decided not to apply the water impact test either, due to the size of the frame, fear of damage and the time-consuming nature of such a test; it was also felt it would be of limited use due to unknown scale effects.

Despite having discussed plans and been shown drawings, staff at Strathclyde University were surprised by the eventual size of the MLS prototype.

4.2.4 Results

The tests themselves went very successfully and no problems were encountered with the test procedures undertaken, however the service provided by the contractor could have been more efficient and thus led to some restrictions. Despite the practical limitations, the day of testing was very successful in verifying the operation of the underwater frame according to procedures that were carefully planned and safely implemented.

The following results in Table 4.1 were recorded, where the 'movement observed' column relates to the magnet attached to the top of the post;

Table 4.1: MLS Test Runs

Run	Carriage Speed (m/s)	Movement Observed@ magnet (mm)
1	0.5	0.00
2	1.0	0.00
3	1.5	0.00
4	2.0	0.00
5	2.5	-
6	3.0	-

Note: Runs 5 & 6 subject to some vibrations from carriage. Results therefore inconclusive, but magnets did not separate visually.

4.2.5 RGU Wave Tank Experimentation

To confirm the deployment methodology of the system using a dummy riser and running tool it was decided to rig up a deeper water test in the RGU wave tank. The water depth was approximately 2m. Guidewires were attached to a magnet rig up in an attempt to mimic a real life deployment scenario.

The rig up as shown in Figure 4.10 was constructed for the test.

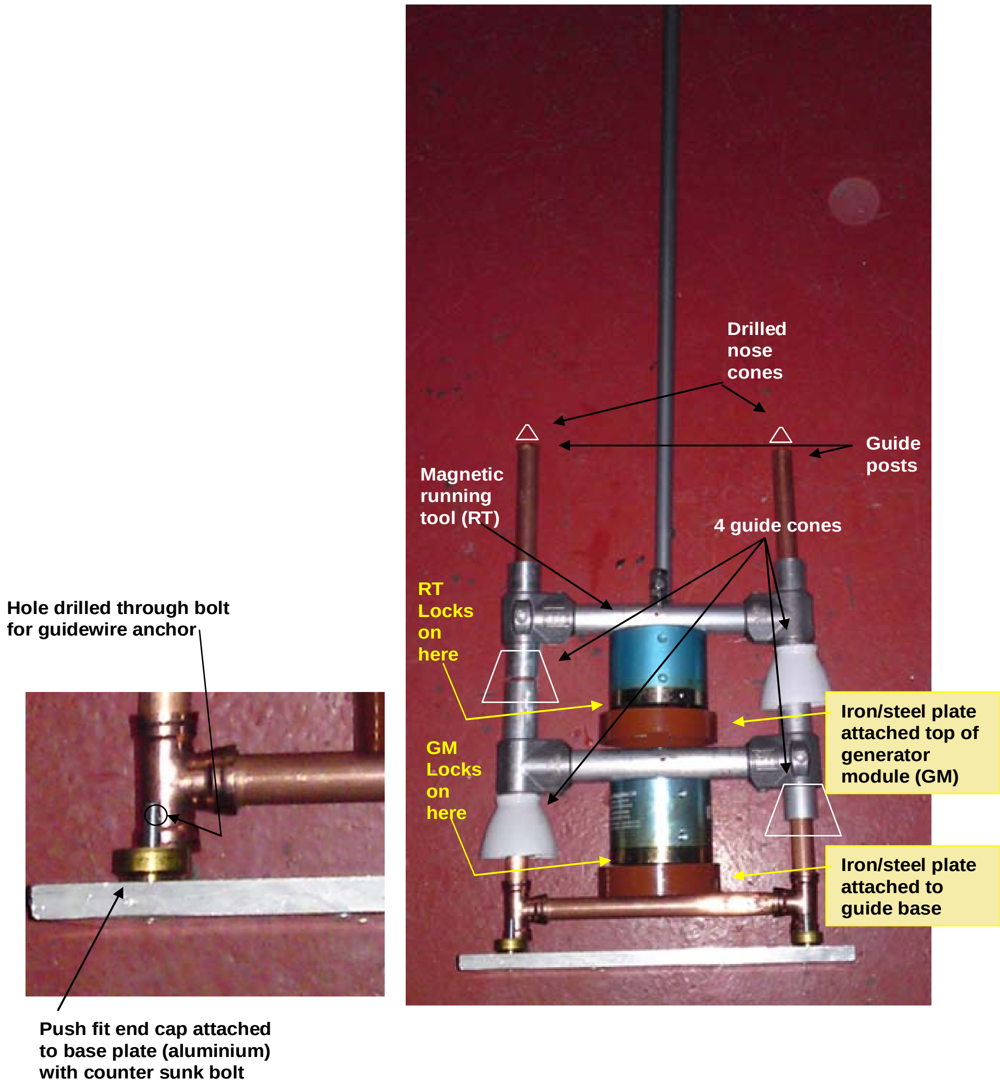


Figure 4.10: Rig up used in RGU Wave tank (copyright author)

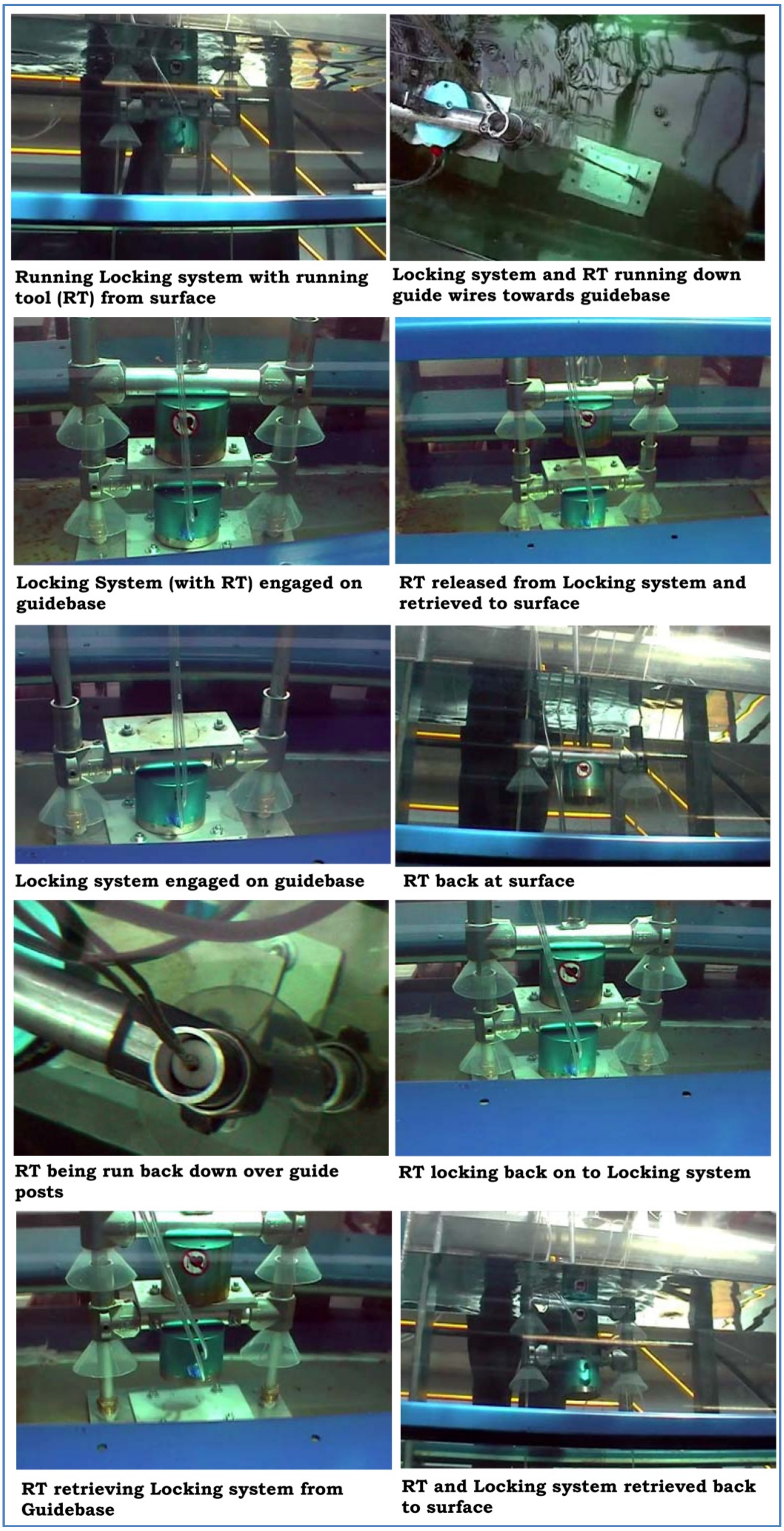


Figure 4.11: RGU Wave tank test sequence (copyright author)

The tests were conducted over a period of one day at RGU. The tests involved deploying the various magnet assemblies several times in / out the wave tank. Multiple locking runs were conducted, all of which were successful.

A short DVD clip is available to support the testing.

4.2.6 Open Water Magnet testing

Following the work in the respective University tanks the project was able to move ahead mainly with the modified flow/corrosion and running trials.

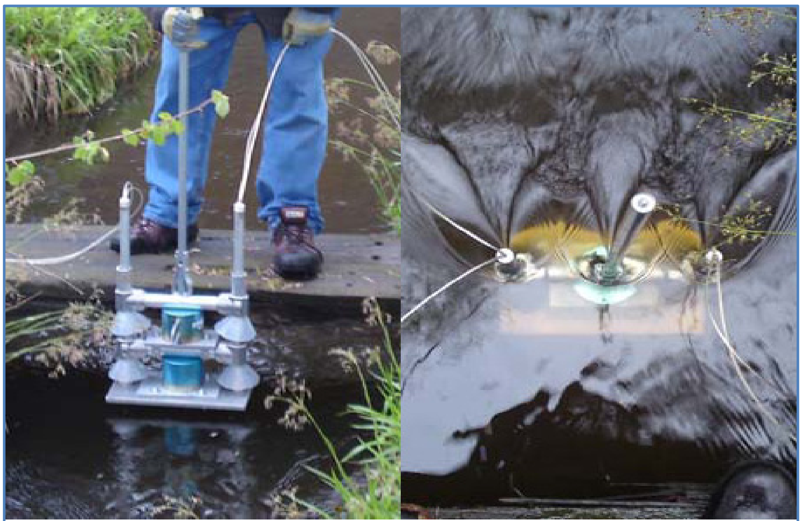
The open water tests were conducted at a river lade site (near Kirriemuir, Angus) and at a sea site (Fife Ness). A series of small scale rig ups were constructed for the open water sites, to reduce complexity and cost and also to ensure safety (not handling heavy weights).

The first tests were run in a river lade site with a fast flowing, safe source of water. The water flow was turbulent and approximately 3 m/sec.

Figure 4.12: Magnet rig up testing sequence photographs, turbulent flow (copyright author)

The above rig up (Figure 4.12) demonstrated the robustness of the locking concept, which was installed, locked and unlocked in various flow conditions including highly turbulent flow.

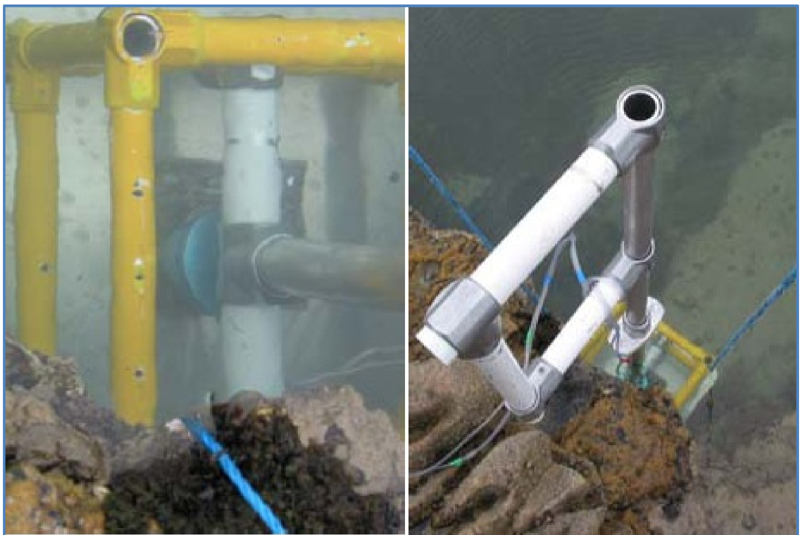
The other rig-up (below) demonstrated the running procedure (in milder flow conditions), this uses a second locking system on top of the first one to act as a running tool.



Locking system with locking running tool | Locking system and locking running tool in flow

Figure 4.13: Locking system and running tool in mild flow conditions (copyright author)

A third rig-up was used for corrosion testing at a secluded marine site, here the device was run on to a base plate after which lock and unlock cycles were performed. The device was then left locked on the seabed for increasing periods of time and the locking unlocking cycle checked.



Device is locked on to base plate | Close up of device locked on to base plate

Figure 4.14: Corrosion testing in marine environment (copyright author)

A period of testing at a near shore shallow marine site in order for the Magnet rig up to be fully tested in a controlled marine environment. There were no tidal currents at the site (Fife Ness), but it was subject to localised wave action. The intention was to determine any limitations of the Magnet rig up under different configurations and running scenarios, and to inspect the system after each set of runs to check for any change in the performance of the magnetic locking. Video footage and photographs were to be obtained of all tests. The Magnet rig up was then to be left on site for one month, in order to determine if the magnet performance was affected by salt water immersion.

A test rig was designed with a three-part assembly (base, frame, running tool), with an agreed interface to allow quick connection/disconnect.

At the site, a series of runs were performed as a proof of concept of the Magnet rig up lock and unlock function in a seawater environment. The runs were performed in a set order, to mimic how a full scale system would be deployed from an offshore vessel using a crane winch / A Frame. Control runs were also conducted with the magnets unlocked.

A fully locked frame-base assembly was left immersed in the sea for one month, and checked once per week to ensure it was still on location. After one month, the running tool was deployed and locked onto the frame. The frame to base plate magnet was then unlocked successfully first time, and the whole assembly retrieved to surface. As a control, the frame was locked onto the base plate again, to confirm the lock operation. This was successful.

The magnet assembly that was left submerged at the coastal site was retrieved and inspected for damage / corrosion. No visual effects of marine corrosion were observed, although it was evident that a small amount of marine growth (algae) was covering the whole assembly (magnets and aluminum framework).

The assembly was cleaned down and the lock/unlock tests were repeated in the RGU Wave Tank, a few days later. All components functioned according to plan, showing that there was not adverse effect on magnet performance due to salt water immersion.

The magnet manufacturer was provided with information on the performance of the magnets during the sea and wave tank trials. Of interest to Eclipse were the one month immersion tests, as this has never been conducted before on any of their systems. A magnet was sent to Eclipse for stripping down and inspection. Verbal communication from the company suggests that there was no evidence of leakage or deterioration of the magnetic components.

Figure 4.15: Recovering base plate at coastal site (copyright author)

Figure 4.16: Magnet frame retrieved following one months submersion in seawater (copyright author)

4.2.7 Results

No significant issues were identified with all devices performing as expected. Minor difficulties were experienced with some valve fittings but since these are not part of the full prototype design this would be manufactured out.

4.2.8 Magnetic Locking capabilities

To confirm the capability of the magnets under actual loading conditions a test rig was constructed at the Concrete Research Lab at Dundee University. The University allowed the author free use of their facilities for several days, and this is appreciated. The magnet rig up was designed to mimic the placement of magnets to confirm the following;

- Magnets were capable of holding under dummy load conditions
- Confirm the best magnet placement for use in the underwater frame
- Determine best size of magnets
- Determine effect of air gap

Magnet data sheets were provide by Eclipse magnets for use in the analysis trials. These are included in appendix 3. A set of three different sized magnets were purchased for the research. The magnets used were the electrically excited permanent magnets, as opposed to the pneumatic ones as used last time. As there was no water involved, it was safe to use the more powerful magnets.

Note; if the electrical magnets are to be used underwater then the company, Eclipse, will have to include power breakers in their control module. This is not available in their standard design. Also, the magnets will have to be encapsulated in resin, to provide for corrosion resistance.

The magnets used were the following outside diameter sizes: 75, 100, and 125mm. Energising power from the control module of 110V, 50Hz. 5.6 Amps (variable according to magnet) for 0.5 seconds is required to fully energise the magnets. Once the magnets are energized, they are effectively “switched on”, and no further current is required. The control unit can be disconnected if required. Applying another burst of current switches the magnets off, effectively depolarizing them and rendering them inert.

The magnet data sheets registered the “pull force” for each magnet under different air gaps and different test piece thickness. The best “pull” is achieved with 0mm air gap and 50mm test piece. Increasing the air gap by a small amount will decrease the pull quite quickly. However, this data applies to the test magnets supplied only. The manufacturers can adjust the magnetic flux strength to account for air gap issues (such as corroded metal surfaces).

The best factory registered "pull" of the test magnets was;

75mm Magnet on clean 50mm plate = 275 kg

100mm magnet on clean 50mm plate = 495 kg

125mm magnet on clean 50mm plate = 697 kg

150mm magnet on clean 50mm plate = 940 kg

Note: the 150 mm magnet was not available from the supplier for this test.

The rig up designed for the analysis test was as follows;

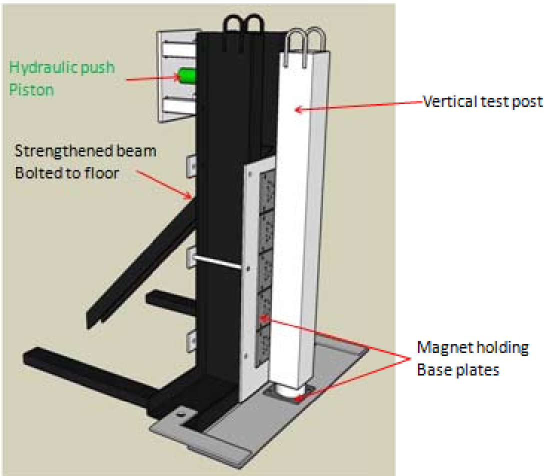


Figure 4.17: Initial Design of test rig

The magnets were bolted to base plates on the strengthened beam, in various vertical arrangements. A magnet was also bolted horizontally to the floor, facing upwards. A vertical test post was then positioned against the magnets and the magnets were then activated. The test post was designed to mimic one of the guideposts on the tidal underwater frame base unit. The vertical post was held by a lifting strop hung from an overhead gantry crane, to improve safety.

A load cell (Force Logic 100kN) was attached to the hydraulic piston and the output read off electronically, via a H120 portable load indicator.

The hydraulic piston "push pad" was attached to the vertical post, and hydraulic pressure applied. This had the effect of trying to push the vertical post off the magnets. The kN loading was recorded for each test. The test set up is seen in **Error! Reference source not found.** below.

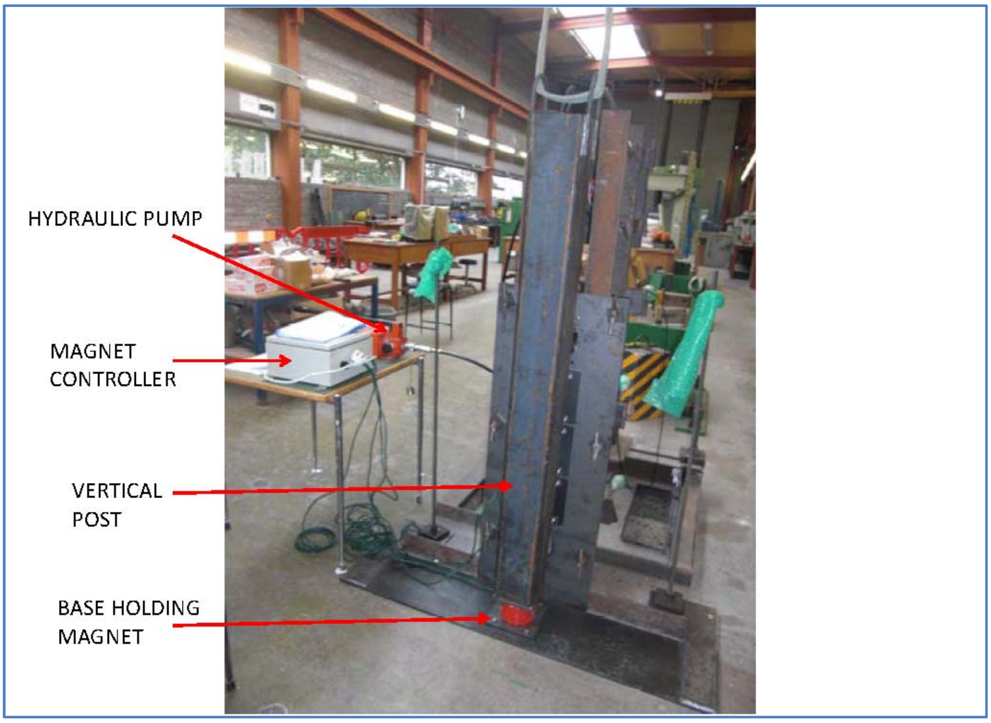


Figure 4.18: Actual test rig, front view (copyright author)

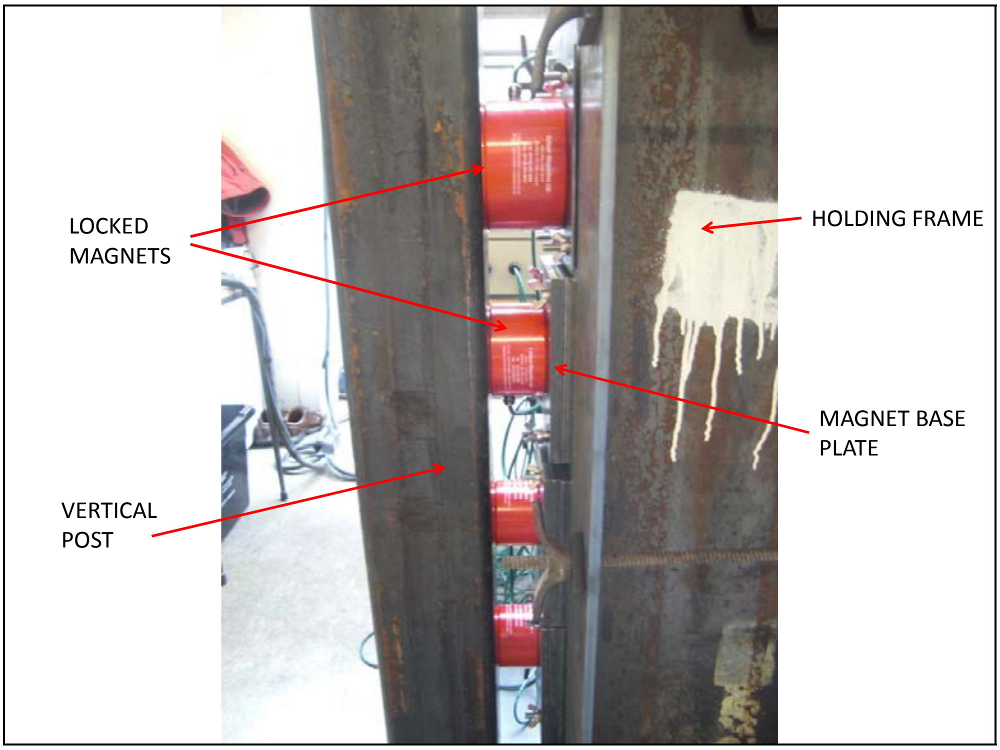


Figure 4.19: Actual test rig, side view, showing test magnets locked (copyright author)

Figure 4.20: Actual test rig, front view, showing base magnet locked (copyright author)

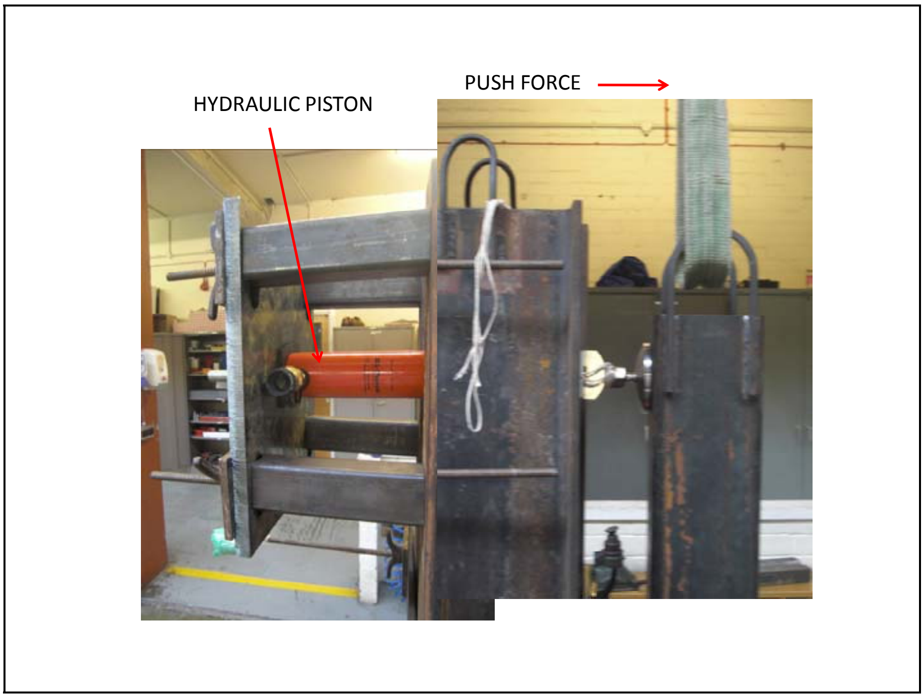


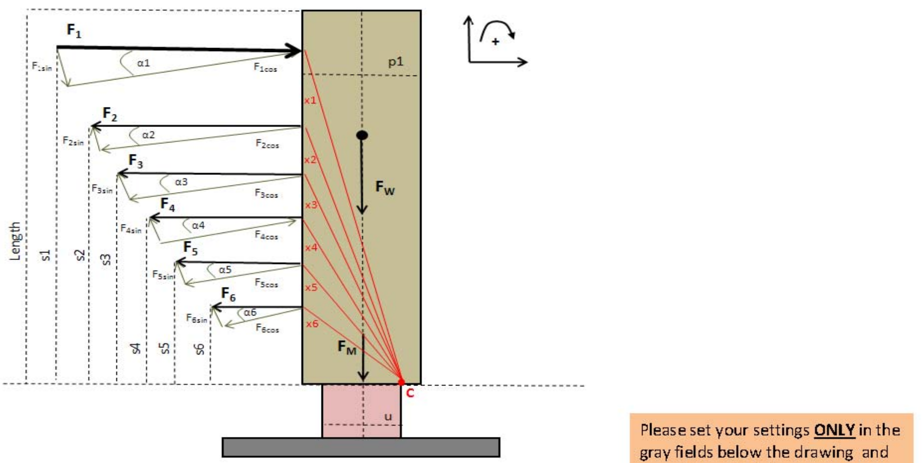
Figure 4.21: Side view of hydraulic piston and "pusher pad" against vertical post (copyright author)

Once each trial had been completed the vertical test post was removed, the magnets de-energised and then the magnet arrangement was altered. For example, the figure below shows the two larger magnets at the top of the frame, with no base plate magnet.

Figure 4.22: Vertical post removed, showing unlocked magnet arrangement (copyright author)

Prior to performing the tests a spreadsheet was written in order to try and mimic the magnet design characteristics verses test criteria of positioning different sized magnets at different heights. The spreadsheet is shown in **Error! Reference source not found.**. The spreadsheet uses force equations to predict the result of positioning different strength magnets. It was derived as a tool to aid in the design of the underwater frame.

The first task was to position magnets and test the force required to dislodge the vertical post. The result was then entered into the spreadsheet and the data checked against the manufactures information. Once the spreadsheet was verified, runs could be conducted to ascertain the correct size and positioning of magnets for the full scale underwater frame design.



Baseplate 10mm thick test

Magnet	Datasheet force	Force in Newtons	Height from Bottom (m)	
ESPM125C (F2)	232.00 kg	2276 N	s1 =	1.520
EXPM100C (F3)	203.00 kg	1991 N	s2 =	1.020
EXPM75C (F4)	180.00 kg	1766 N	s3 =	0.820
EXPM75C (F5)	180.00 kg	1766 N	s4 =	0.620
Unused (F6)	0.00 kg	0 N	s5 =	0.420
			s6 =	0.000
			Length =	1.600

g = 9.81 m/s2
u = 0.150 m
p1 = 0.150 m
Pole Mass = 43.100 kg/m
Total Mass (FW) = 68.96 kg

Calculate
M[C] = 0 Nm
F1 = 391.76 kg
= 3843 N
= 3.84 kN

Baseplate 50mm thick test

Magnet	Datasheet force	Force in Newtons	Height from Bottom (m)	
ESPM125C (F2)	697.00 kg	6838 N	s1 =	1.520
EXPM100C (F3)	495.00 kg	4856 N	s2 =	1.020
EXPM75C (F4)	275.00 kg	2698 N	s3 =	0.820
EXPM75C (F5)	275.00 kg	2698 N	s4 =	0.620
Unused (F6)	0.00 kg	0 N	s5 =	0.420
			s6 =	0.000
			Length =	1.600

g = 9.81 m/s2
u = 0.150 m
p1 = 0.150 m
Pole Mass = 43.100 kg/m
Total Mass (FW) = 68.96 kg

Calculate
M[C] = 0 Nm
F1 = 926.32 kg
= 9087 N
= 9.09 kN

Figure 4.23: Analysis Spreadsheet

4.2.9 Results

The results were interesting and confirmed a few of the initial ideas regarding the magnet placement in the underwater frame.

The initial results were as follows, for 10mm baseplate and 50mm baseplate;

Table 4.2: Test results

Base thickness (mm)	Test result	Calculated result	Variance %
10	3.5kN	3.8kN	-8
50	8.3KN	9.1kN	-10

A series of runs showed that the actual test results were between 5% - 15% (av.10%) poorer than the factory test results. This was due to the metal being used for the vertical test piece being ordinary iron with some rust on its surface, hence affecting the air gap / magnet flux. This, in fact, is more likely to be closer to real underwater conditions than a gleaming shiny metal surface. Underwater conditions will involve the magnet having to lock against some corrosion, sand, etc. so the reduction of 10% was used for this analysis.

A series of runs was then conducted to calculate the best size, and arrangement of magnets for the locking system on the underwater frame. The results can be summarized as follows;

- A set of four vertically arranged 150mm OD magnets will provide a holding force of 2.2 metric tons
- One vertical magnet at the top of the post will provide a holding force of 0.27 metric tons
- Positioning magnets on the base of the post only adds <5% improvement to the vertical magnets
- Increasing the weight of the vertical post adds little to magnet lock ability

These results were based upon a vertical post length of 1m (3.2 ft). The actual frame will have a post length of 3.5m (12ft). If the longer post length is used then the results are;

- A set of four vertically arranged 150mm OD magnets will provide a holding force of 2.7 metric tons
- One vertical magnet at the top of the post will provide a holding force of 0.27 metric tons
- Positioning magnets on the base of the post only adds <5% improvement to the vertical magnets
- Increasing the weight of the vertical post adds little to magnet lock ability

Note: The test experiment with this rig up is actually the reverse of how it would look underwater, with the base magnet (Figure 5.4) being at the top.

In summary, the best arrangement for the full scale underwater frame would be two 150mm magnets set close together at the bottom of two overshot guide tubes (facing main tidal flows). This arrangement would resist a sideways force / moment of 1.5-1.7 metric tons. Please remember that the outer guide tubes of the underwater frame sit over the solid guideposts of the base structure, therefore there is considerable support available from internal rigid posts as well as the magnet locks. The magnet locks have the primary purpose of minimizing movement of the electrical power wet connect and reducing vibration. The structural steel of the guide tube over the guidepost will be the main resisting force to the tidal flow.

Reviewing Figures 5.8 and 5.9 the proposed positions of the magnets would be near the bottom of the guide tubes at position (2) in Fig 5.8. This would relate to position (5) in Fig 5.9.

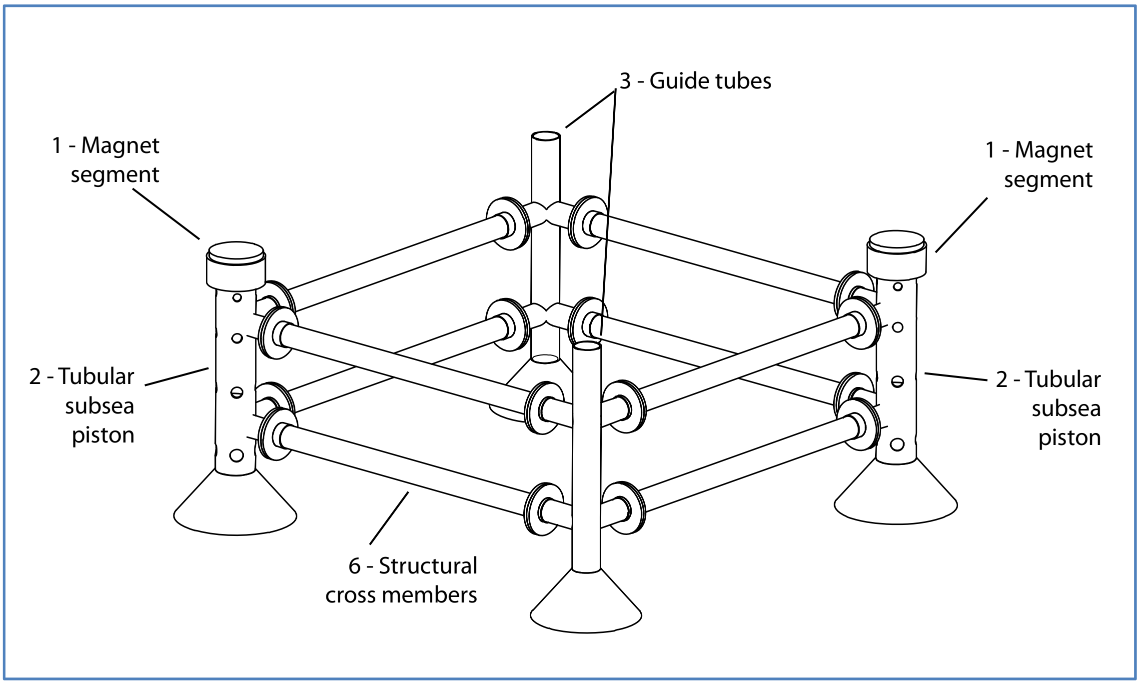


Figure 4.24: Schematic representation of frame structure

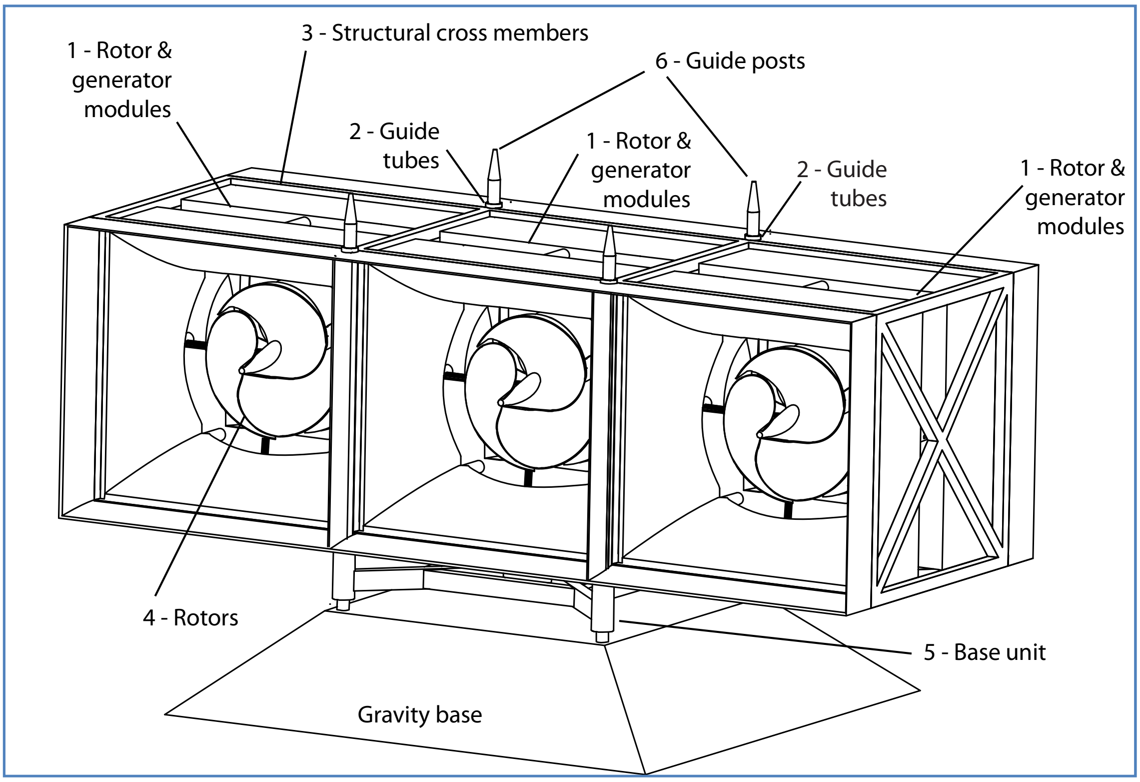


Figure 4.25: Perspective view of modular tidal energy system

4.3 Rotor Design Experimentation

After a review of technologies and manufacturer capabilities the primary options for rotor blade manufacture are:

- Rapid Prototyping: - for small test models and (complex) smaller prototypes.
- GRP: - for larger models it may be useful to use glass reinforced plastic however the cost moulds may be prohibitive for the largest sizes.
- Fabrication – larger scale simplified models will require construction using thin metal flashing welded or pinned to the central tubular frame. Complex blade may be impractical or too expensive using this method.

4.3.1 Analyse existing blade designs

Testing of three existing previous rotor designs was conducted in a water tank flow to ascertain the rotational speeds achieved at different rotor orientations.

4.3.1.1 Method

An array of pumps was used to create an even circulation of water around a 2.5 x 1.5 x 1.5m water tank. This was divided by a horizontal plane which created a stream approximately 300mm deep. A test point was chosen, through monitoring the flow with a flow meter, which had an average flow of around 0.5m/s.

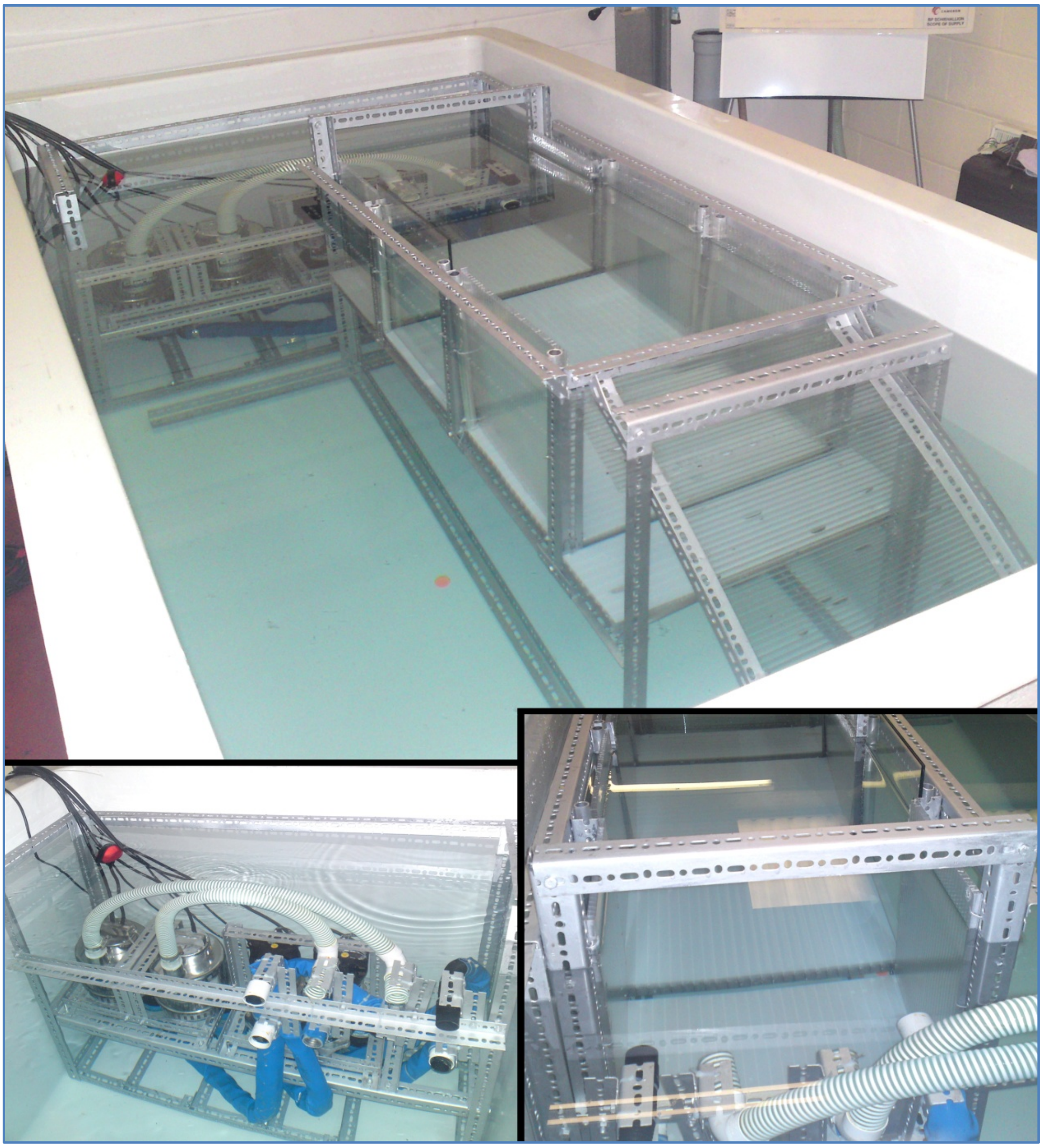
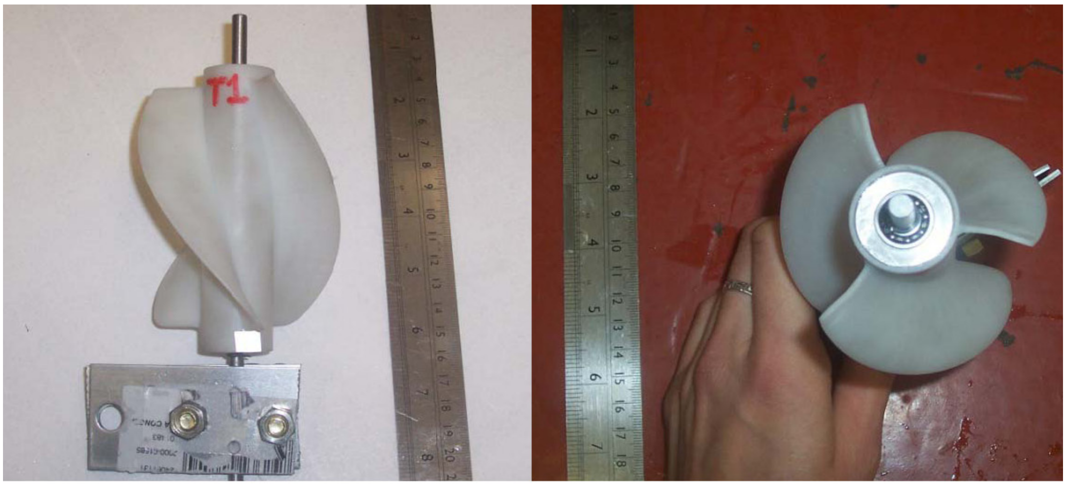
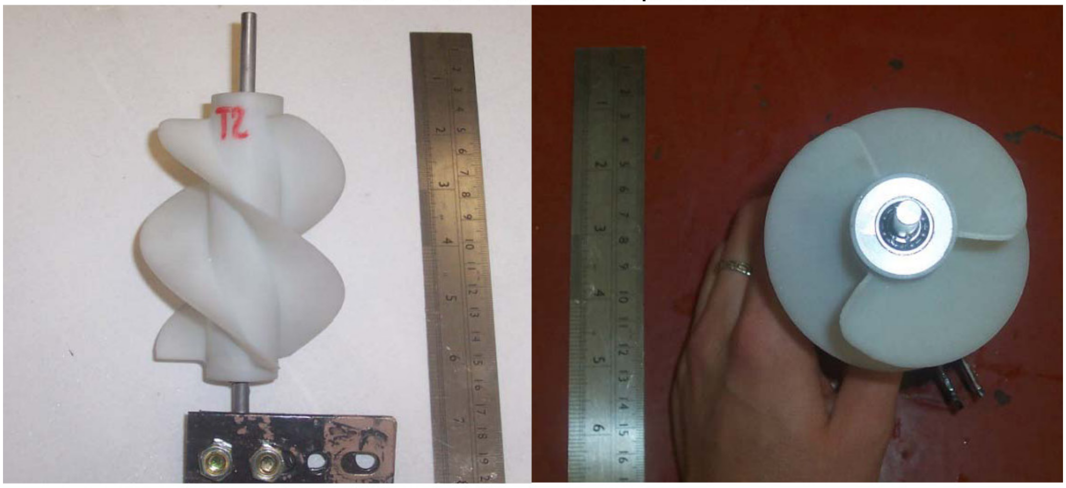


Figure 4.26: Test tank used for trials (copyright author)

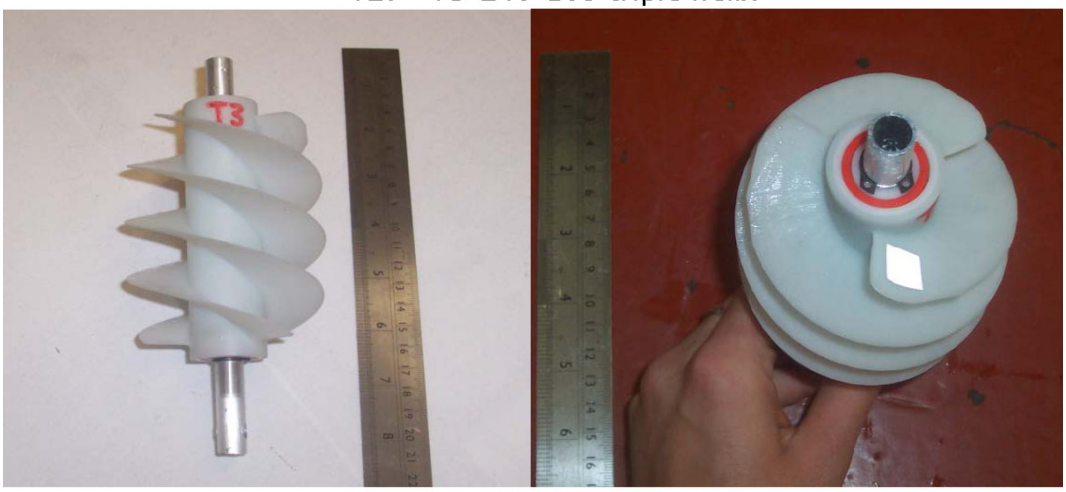
The three rotor shapes tested, T1 to T3, and are pictured below, with their part name/description:



T1:= TS-120-105 triple helix



T2:= TS-240-105 triple helix



T3:= TS-480-105 triple helix

Figure 4.27: Description of existing blades tested (copyright author)

A set of rpm readings was taken for different rotors clamped at the test point at different angles to the horizontal. The rotational speeds were measured using a tachometer.

Figure 4.28: Blade trials with 'T2' in vertical position and at a 45 degree angle (copyright author)

As well as taking a primary set of readings, observations were made regarding the effect of shielding parts of the blade and shaping the direction of the flow. One configuration is shown below.

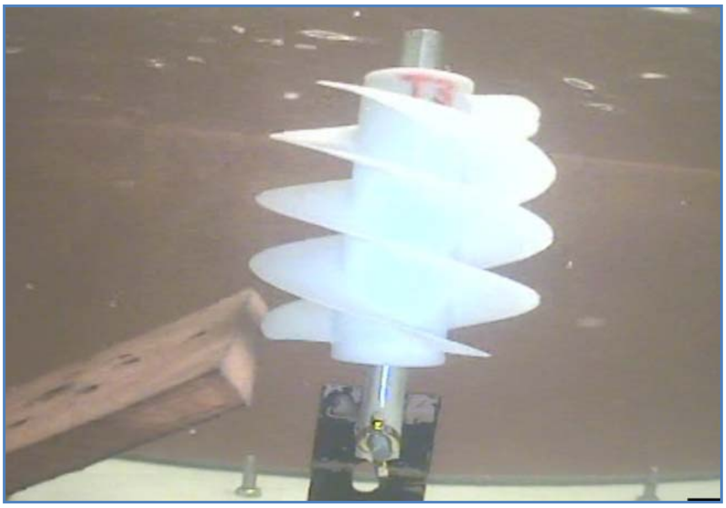


Figure 4.29: Blade trials, 'T3' with flow shaping (copyright author)

4.3.1.2 Results

Results from the trial are given in Table 4.3 below.

Table 4.3: Existing blade results

Rotor	Angle(o) up from horiz. facing flow	Rpm range Low	High	Average	Comments
T1 (TS-120-105)	0	52	60	56	(0)
	22.5			52	
	45			**30**	
	67.5			15	
	90			24	
	112.5			30	
	135			36	
	157.5			44	
	180			52	
T2 (TS-240-105)	0	160	180	170	
	22.5	120	140	130	
	45	90	100	95	
	67.5	58	60	59	
	90			0	(1)
	112.5	48	50	49	
	135	80	90	85	
	157.5	-	-		(2)
	180	-	-		
T3 (TS-480-105)	0	200	260	230	
	22.5	170	190	180	
	45	120	150	135	
	67.5	60	80	70	
	90			0	
	112.5			60	
	135	90	110	100	
	157.5	160	180	170	
	180			180	

Comments/observations:

(0) If no rpm range is given then the reading was taken as an average.

(1) T2 reaches a stationary point at about 80^{o}.

(2) T2 could not be extended beyond 135^{o} due to restrictions from the clamp.

A graph of rotor rotational speeds against rotor angle is given in below

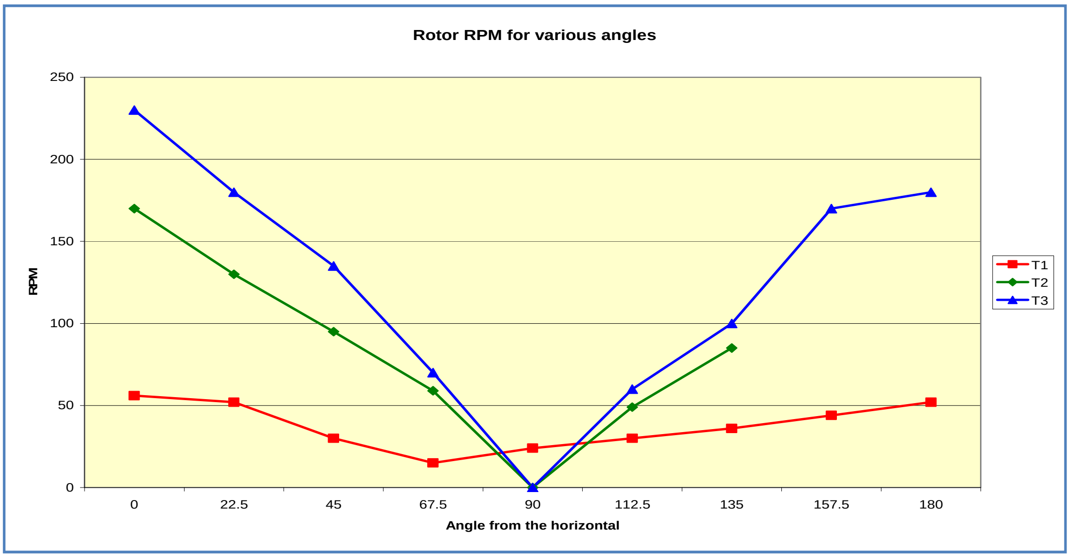


Figure 4.30: Graph of rotor rotational speeds

4.3.1.3 Conclusion

It can be seen from the results that the triple helix blades, T1 T2 and T3, gave varying rotational speeds in a water tank flow of about 0.5m/s. The tighter-angled blades of T3 (TS-480-105) were more suited to a horizontal orientation; T1 (TS-120-105) was the best performing rotor in a vertical orientation. The horizontally orientated T3 represents the best starting point for the new blade development, in horizontal axis turbines.

Further testing with various blade shields and flow shapers will be required, as is measurement of the torque produced.

Scale effects due to, for example, friction in the bearings or unsteadiness of the flow, are not taken to be significant in this case.

4.3.2 Blade Design

Following the initial blade tests, concepts for new designs were taken forward. The blades for the prototype and smaller models are the most costly component of the new design. Rapid Prototyping (RP) was used to produce the model blades by constructing a 3D CAD based version of the model from which a Stereo Lithography (STL) file submitted to a RP provider. Despite the advantages of speed and accuracy offered by RP modelling, the cost is prohibitive for larger scale blades and therefore to allow an affordable full scale model to be made, an alternative (non-RP) method of manufacture was procured. Producing the selected design at a smaller scale using both RP and non-RP methods did allow differences to be identified and compared. The aim was to be able to build a cost effective larger scale non-RP blade, which by definition may not be as optimised as an RP version, but still be able to extrapolate any performance difference from the smaller RP/non-RP comparison to predict what the performance of a properly manufacture large scale blade would be.

4.3.2.1 Option 1

A triple-start helical blade based on the earlier design with the following additional requirements:

- Thickened wall profile with 3-4 mm minimum tip width
- Larger OD central cavity approx 100mm+ to suit wider range of test generators
- Edge profiling to be made more aqua friendly

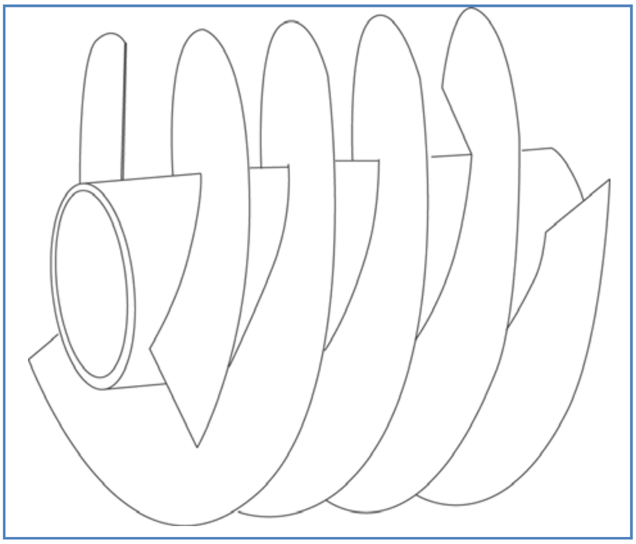


Figure 4.31: Modified triple start helix (copyright author)

The earlier design was a reasonably successful blade when operating in air and the above adaptations were designed to cope with the additional requirements expected in river or marine environments. Further work on the pitch of the blade is also required to cope with the much slower flow fluid speeds encountered in these environments. Blade tips and edges must also be adapted to minimise harm to aquatic life.

4.3.2.2 Option 2

Triple-start helical blade development with the addition of flow-through tapering slotted areas near base of first sections of blade with the intention of allowing more flow to remainder of blade length.

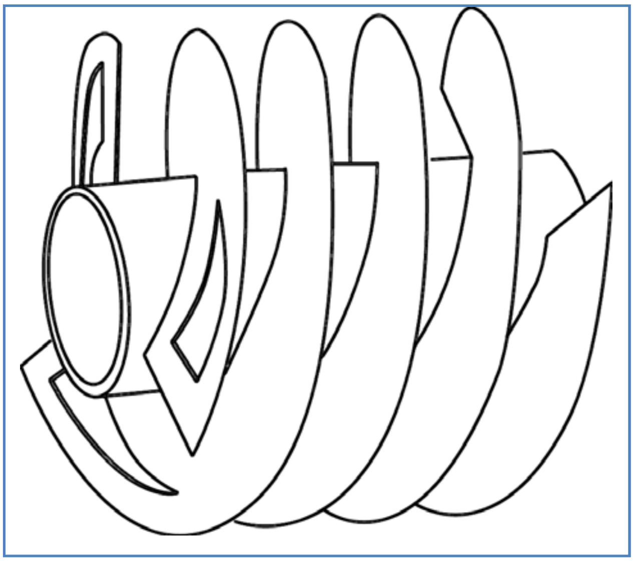


Figure 4.32: Triple start helix with flow-through option (copyright author)

Both the option of a single set of flow-through slots as well as multiple sets of flow-through slots were explored. There is also some future scope for looking at the relative position of each set of flow through slots on following blades; it may be advantageous to offset each set rotationally around the central axis. They amount of offset required may be dependant on flows speed and blade RPM.

4.3.2.3 Option 3

Simulated triple-start helical blade constructed from a series of stacked fan propellers as a basic option. The blades would be overlapped to maintain a smooth flow and mimic the continuous helix. This may prove to be a good low cost option, particularly in an area of very fast flow or high risk.

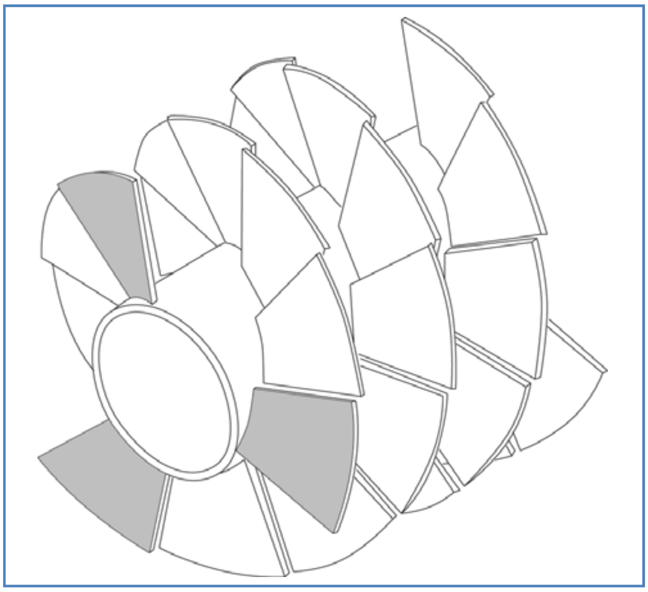


Figure 4.33: Multiple sets a triple start fan (copyright author)

4.3.2.4 Option 4

Triple start helical blade increasing in diameter along its length to form a cone shaped device. This cone shape presents a larger facing area of blade to the flow and minimises the internal volume of the blades central core cylinder. The increased blade area should aid performance both at start up and normal operation. The design also allows larger diameter generators to be rear mounted while still reducing the overall (un-bladed) core volume of the blade.

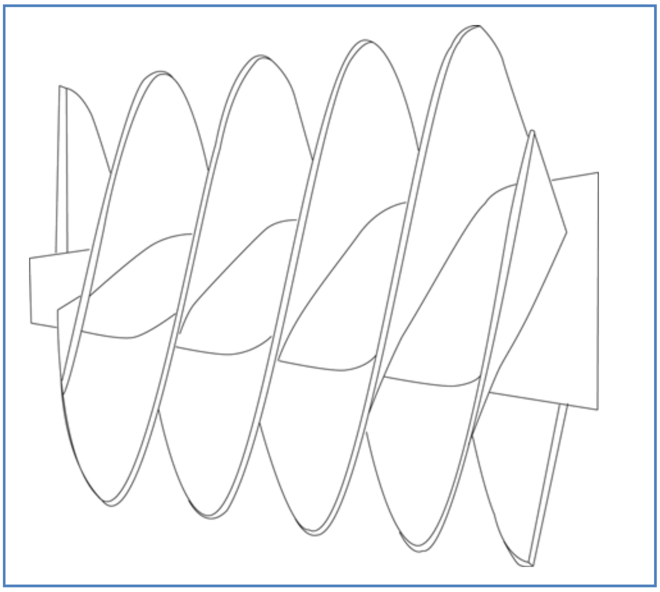


Figure 4.34: A tapered triple start helix forming a cone shape (copyright author)

4.3.2.5 Option 5

Triple start helical blade modified to produce a lift to drag cross over by use of a tightening blade profile along its length. The pitch of the helix decreases by a factor of 10 over its length. The blade is aimed at channelling the flow over the initial surfaces of the blades to produce a lift force; but it also designed to smoothly divert the flow along the blade length. This transitional flow will hopefully reduce back pressure and ensure maximum drag force is extracted from the flow by the rear of the blade.

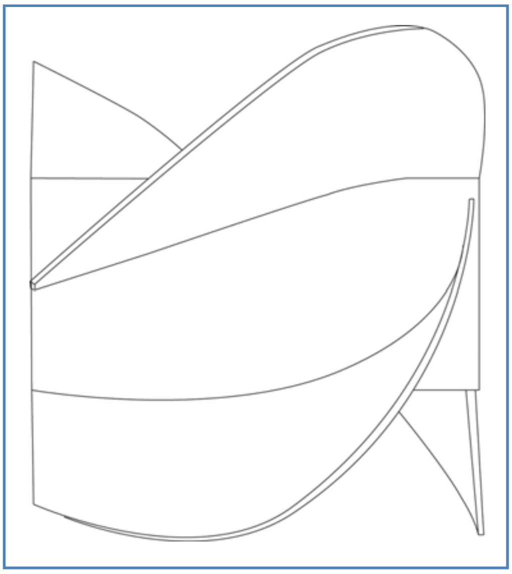


Figure 4.35: Triple start helix tightening along its length (copyright author)

4.3.3 Draw 3D models

Scale models of blade options 2, 3, 4 and 5 were constructed in a 3D CAD package (58) in preparation for flow analysis modelling. The models were used to choose the preferred option following flow analysis and the chosen option was optimised prior to being prepared for Rapid Prototyping.

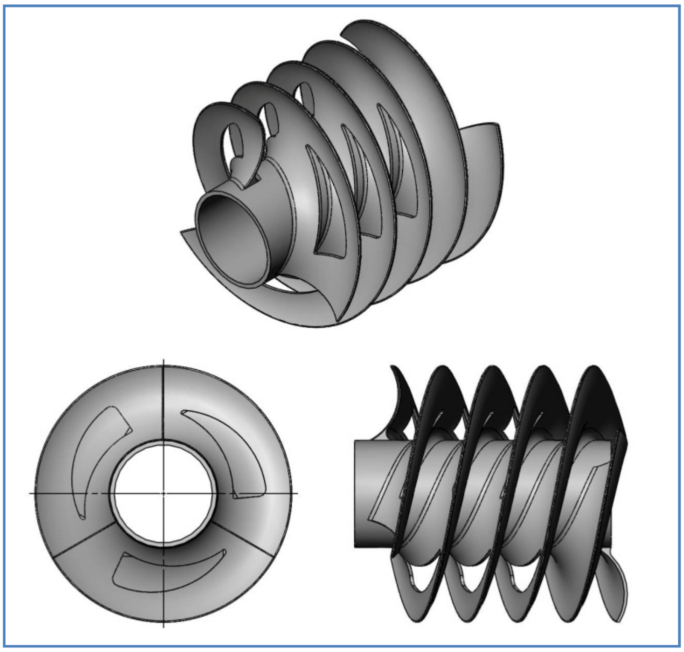


Figure 4.36: Option 2 –Flow-Through Triple helix (copyright author)

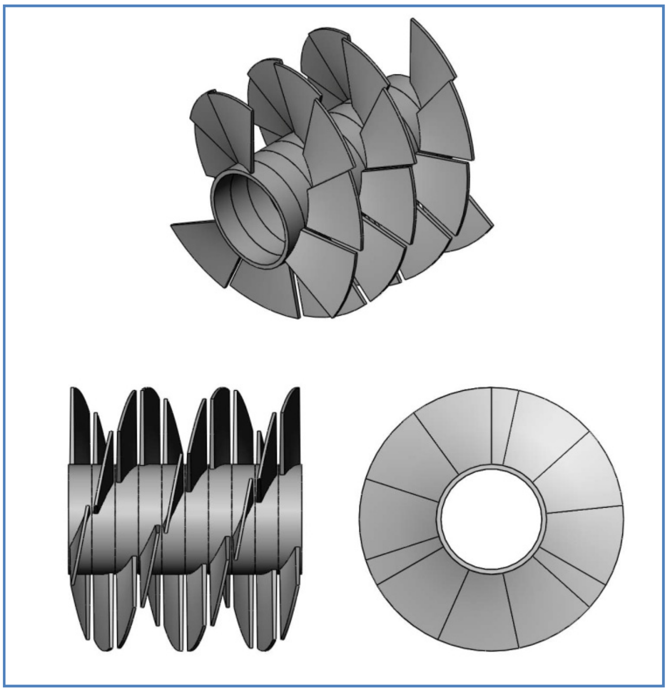


Figure 4.37: Option 3- Segmented Triple Helix (copyright author)

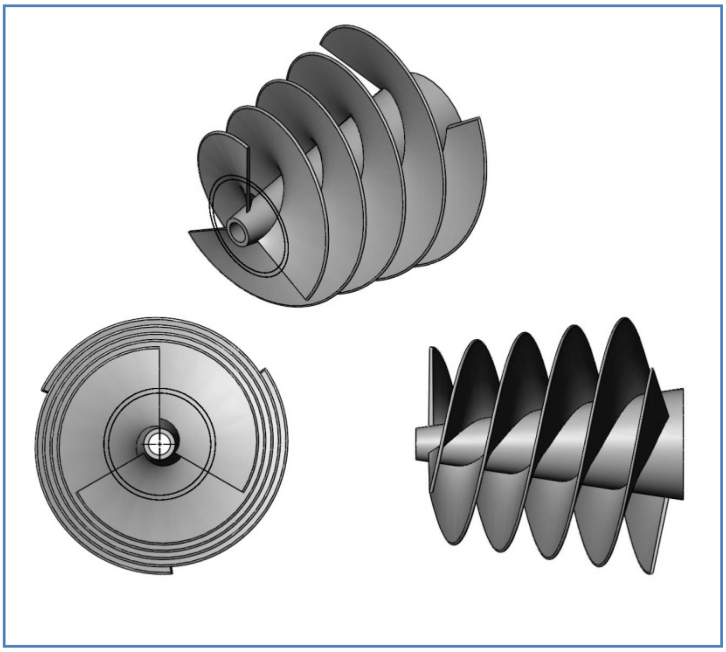


Figure 4.38: Option 4 – A tapered triple start helix forming a cone shape (copyright author)

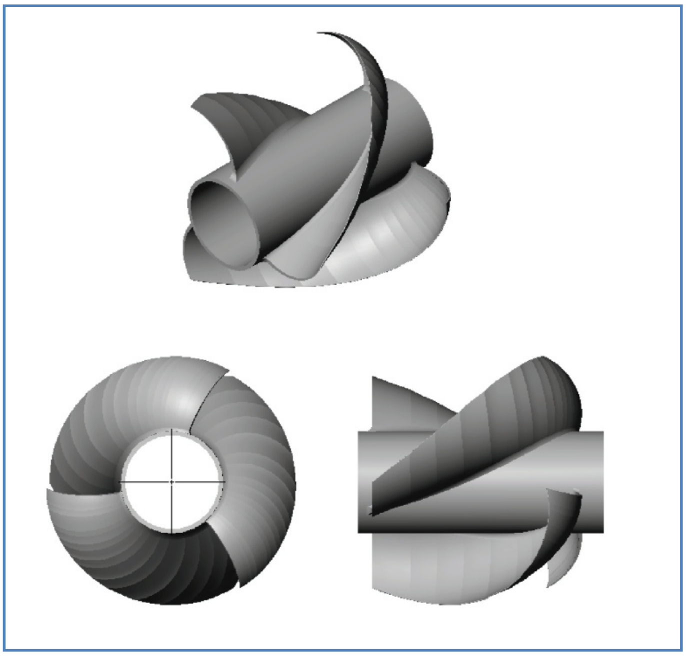


Figure 4.39: Option 5 – Triple start helix tightening along its length (copyright author)

4.3.4 Software analysis

Basic flow analysis, available with the software (58), was used to compare options 2, 3, 4 and 5 with a flow speed of 2m/s and various rotational velocities ranging from 0 to 60 radians per second.

It was determined that options 4 and 5 both appeared to have improved characteristics over the basic blade design. The cone profile of option 4 offers better pressure distribution but still appeared to show some back-pressure at start-up. Option 5 showed good pressure distribution and less apparent back-pressure at start-up but some low pressure zones where present at higher rotation speeds. Looking at both options, the decision was made to produce a hybrid of these two designs. This optimised design takes the triple start helix tightening along its length (as in option 5) and applies it to a central cone profile (as in option 4). The leading tips towards the front of the blades are therefore reduced in diameter relative to the rear of the blade. In order to deal with the low pressure problem that was previously seen at higher rotational velocities, the front tips are further tapered and smoothed to minimise flow disturbance in this area.

This resulted in the choice of a rotor design shown in Figure 4.40

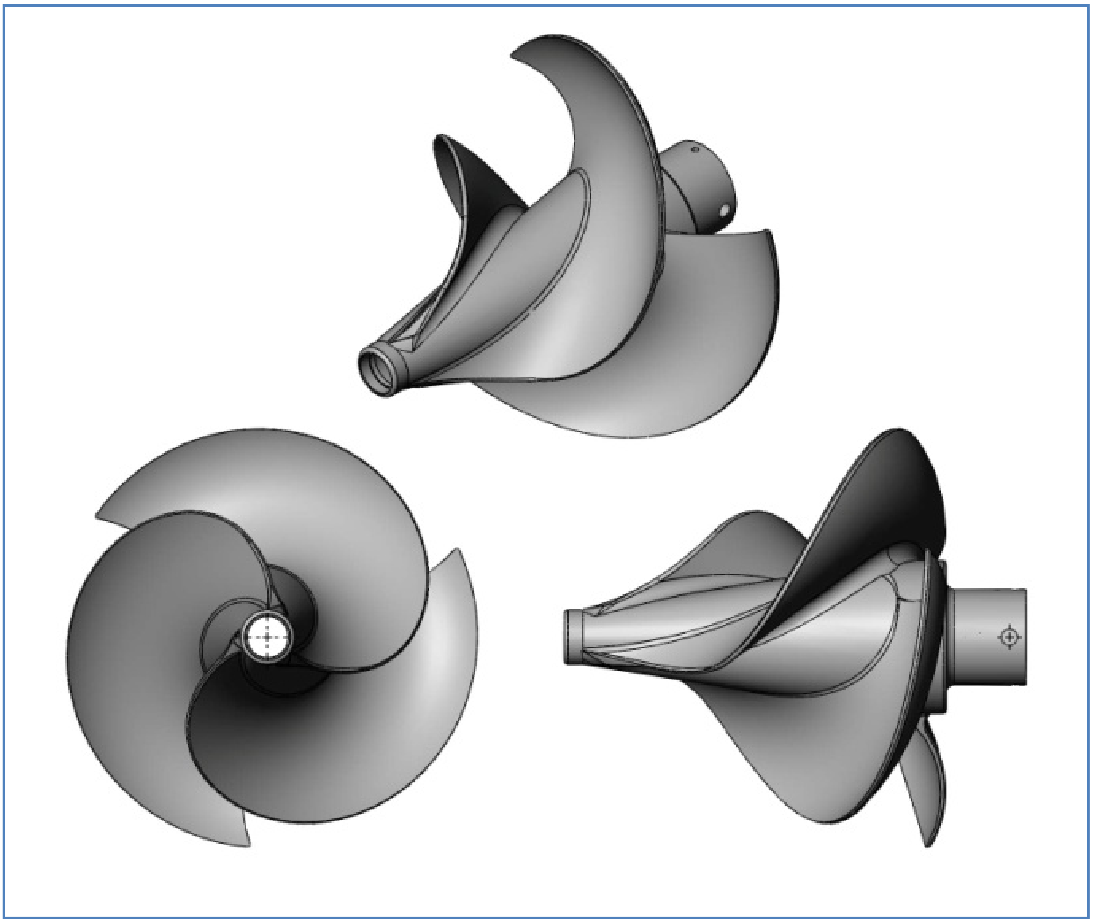


Figure 4.40: Chosen rotor design (copyright author)

Repeating the same analysis conditions showed an improved flow pattern which seemed more stable up to, and beyond, 36 Radians/second (~360 RPM). There was a good pressure distribution along the length of the blades at start-up and this again was maintained on the main driving sections of the blade at higher rotational velocities. Turbulence and potential for cavitation appeared greatly reduced on the frontal leading (smoothed) areas of the blade and back pressure appeared minimal below 60 Radians/second (~600 RPM)

4.3.5 Testing / Deployment / Monitoring

Following on from smaller scale tank tests of the blades driving dry generators, larger scale tow tank testing of the blade, bearings, frame and power control units were carried out using a 100 watt submersible generator . For the purposed of the tow test, the test frame was mounted on a suspended test rig attached to the tow tank gantry

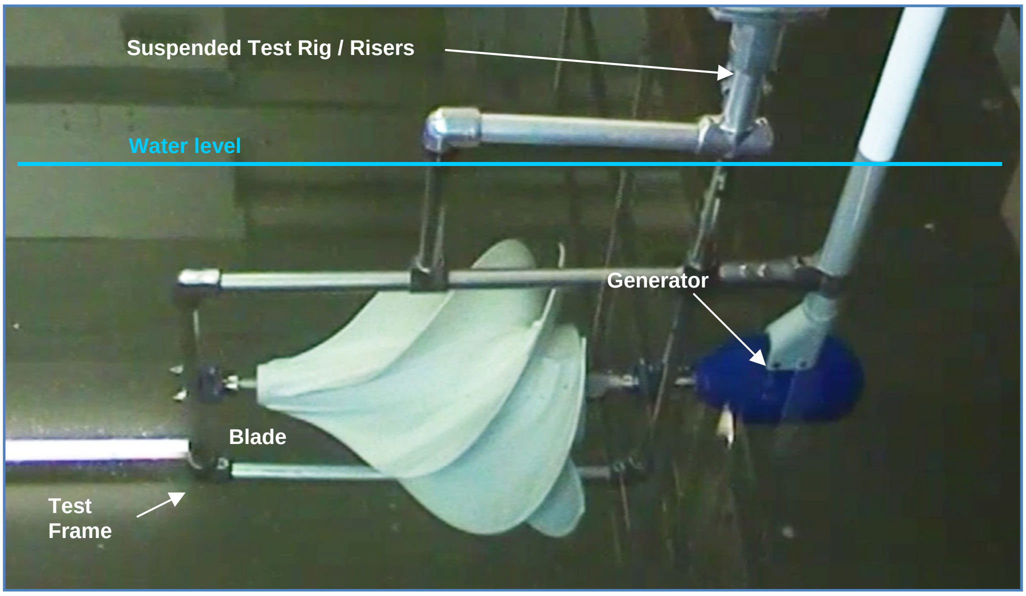


Figure 4.41: Testing rotor in tow tank (copyright author)

Further flow and deployment testing were carried out at the river site near Airlie where the flow was more varied and turbulent. In this case the frame was mounted between natural anchor points and crevices available on/in the river boulders. River levels were lower than expected due to this year's (2010) late thaw conditions in the upstream run-off area.

Figure 4.42: Testing rotor in river (copyright author)

4.3.6 Results

During the tow tests, the blade, frame, bearings and generator all performed well over a range of flow speeds and electrical loads; however restrictions caused by the suspended test rig meant that a wider range of flow speeds and load could not be tested. The set-up of the tow tank requires that the anchoring points for the suspended test rig be approximately 1.5 metres above the test frame. The bending moments experienced by the riser sections of the suspended test rig therefore limited the maximum flow speed and electrical load combination that could be achieved without risk of damage to the test rig.

While the test rig limited the extent of what could be achieved in these tests, the tests themselves did prove the concept of the overall rotor device as well as the functionality of the component parts.

A more robust test rig is required for further tow testing and this, in conjunction with an anchored device in a controlled water test location, should provide further verification of these results and extrapolated values.

The new design was deemed to be most successful and well suited for deployment into a three dimensional box structure, as defined by the underwater frame structure.

4.4 Design and test marinised generator options

A series of small generators were procured with the aim of investigating the options of “marinisation”. This is the placement inside a waterproof housing.

The following options were investigated;

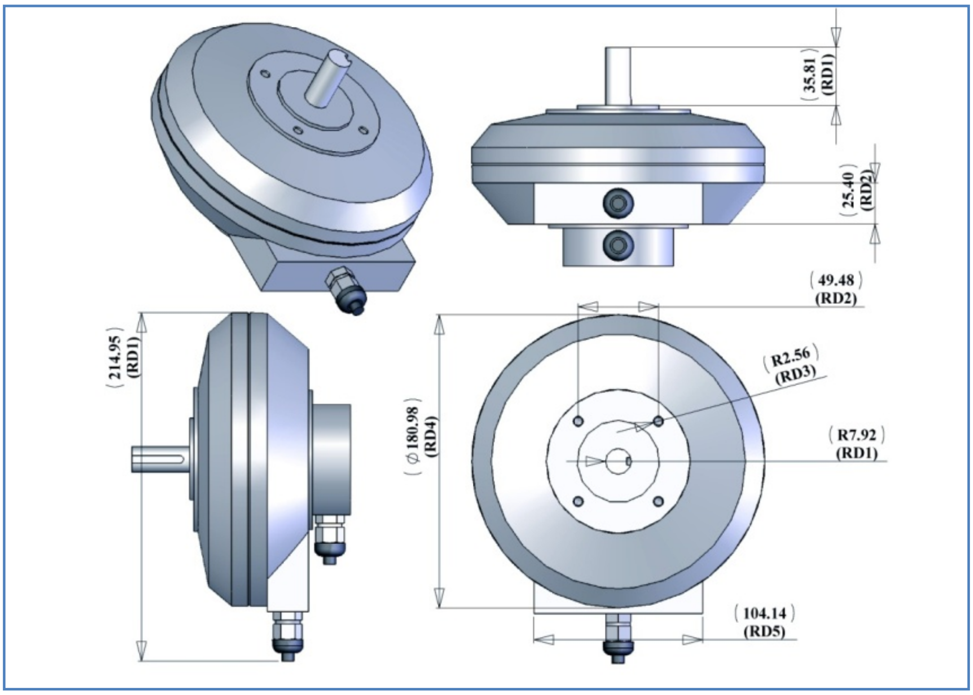


Figure 4.43: Option 1 - The Bodine Electric Company (59) 7 inch e-TORQ

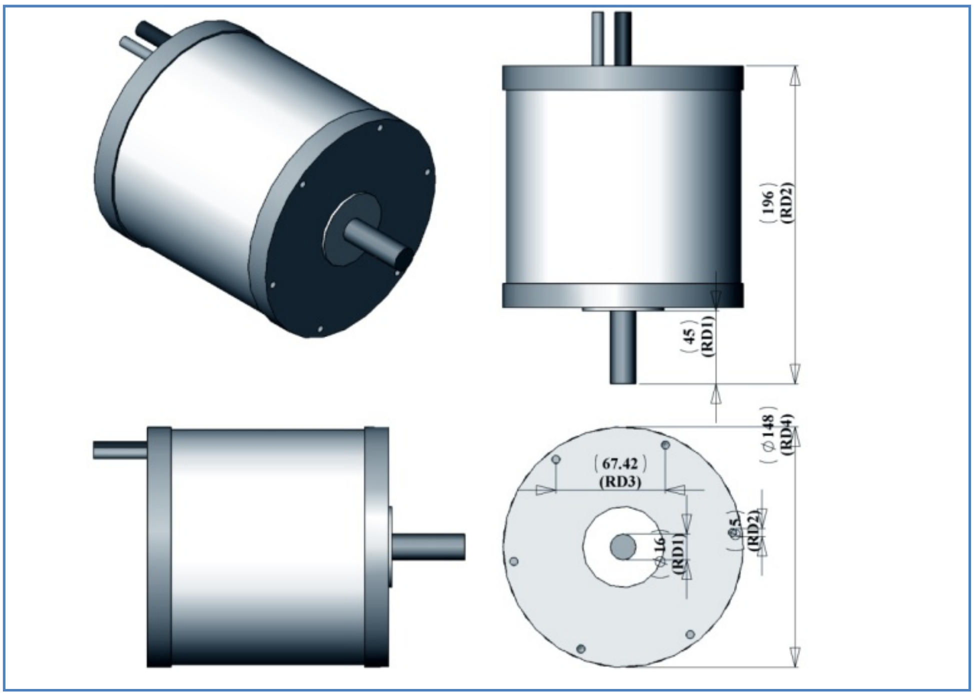


Figure 4.44: Option 2 - Alxion STK 145 2M Alternator (60)

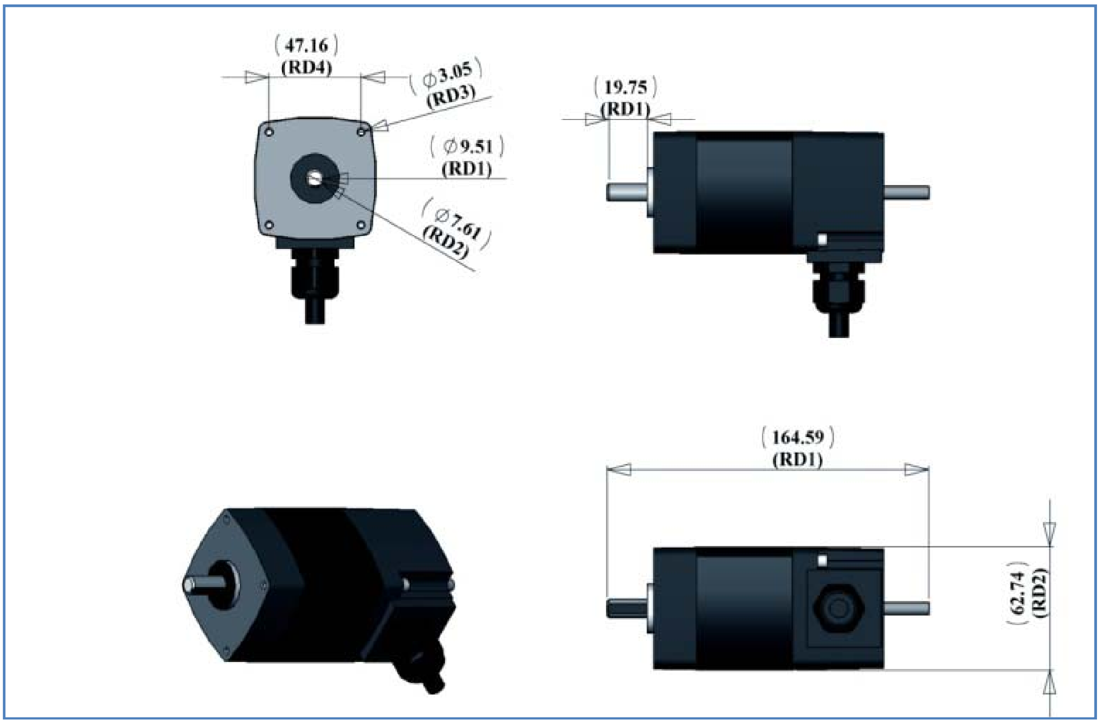


Figure 4.45: Option 3 (Test Model) – Bodine Electric Company (61) 22LB

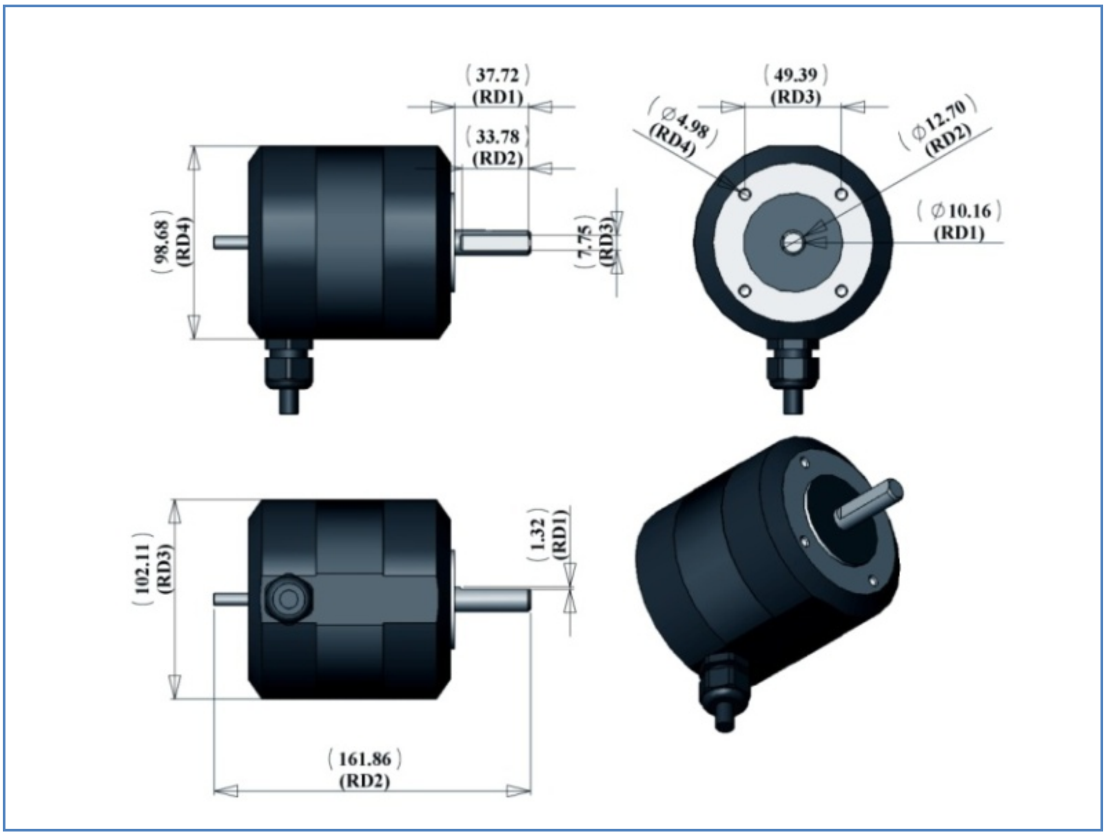


Figure 4.46: Option 4 (Test Model) - Bodine Electric Company (61) 34B

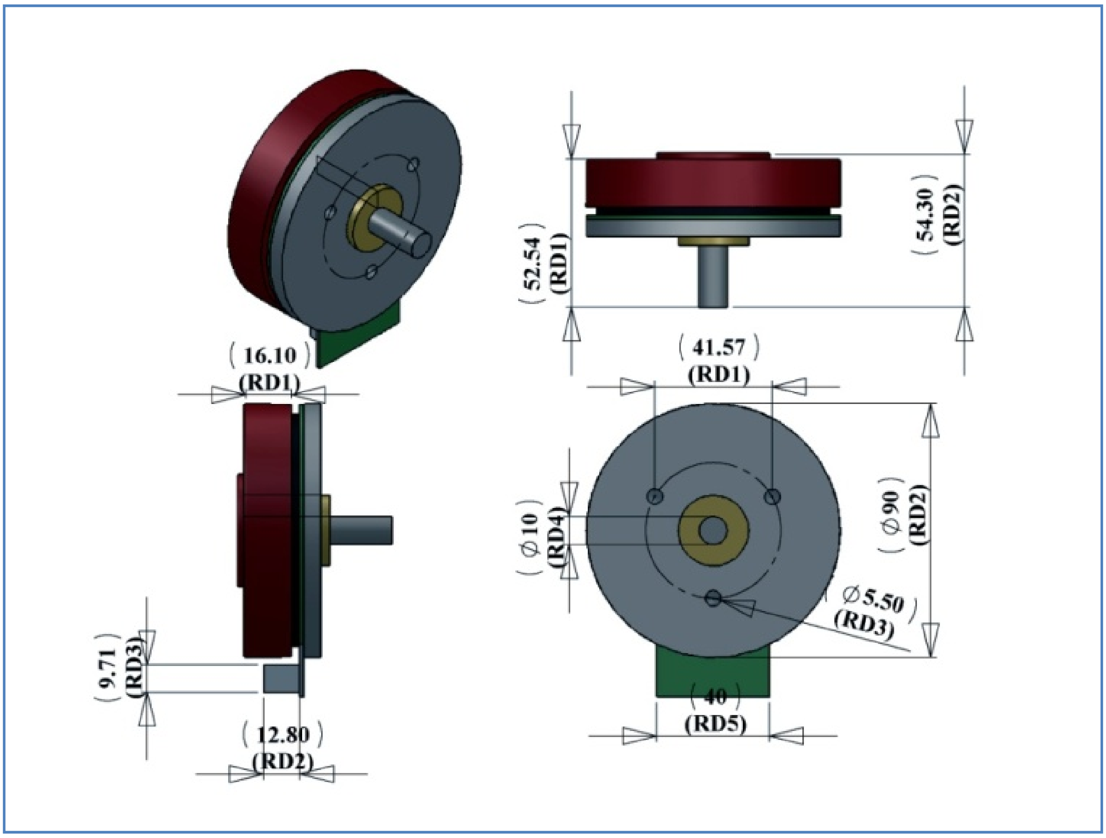


Figure 4.47: Option 5 – Maxon EC90 Flat (62) (Test model)

A generic design was to be used to house the generator being tested with the dimensions being altered as per the requirements of the generator. The housing was to be oil filled to resist and balance water ingress though pressure effects. The shaft of the generator exits through a pair of double sealed bearings separated by a small grease packed stuffing box. Electrical connections to the generator will pass though a compression sealed grommet.

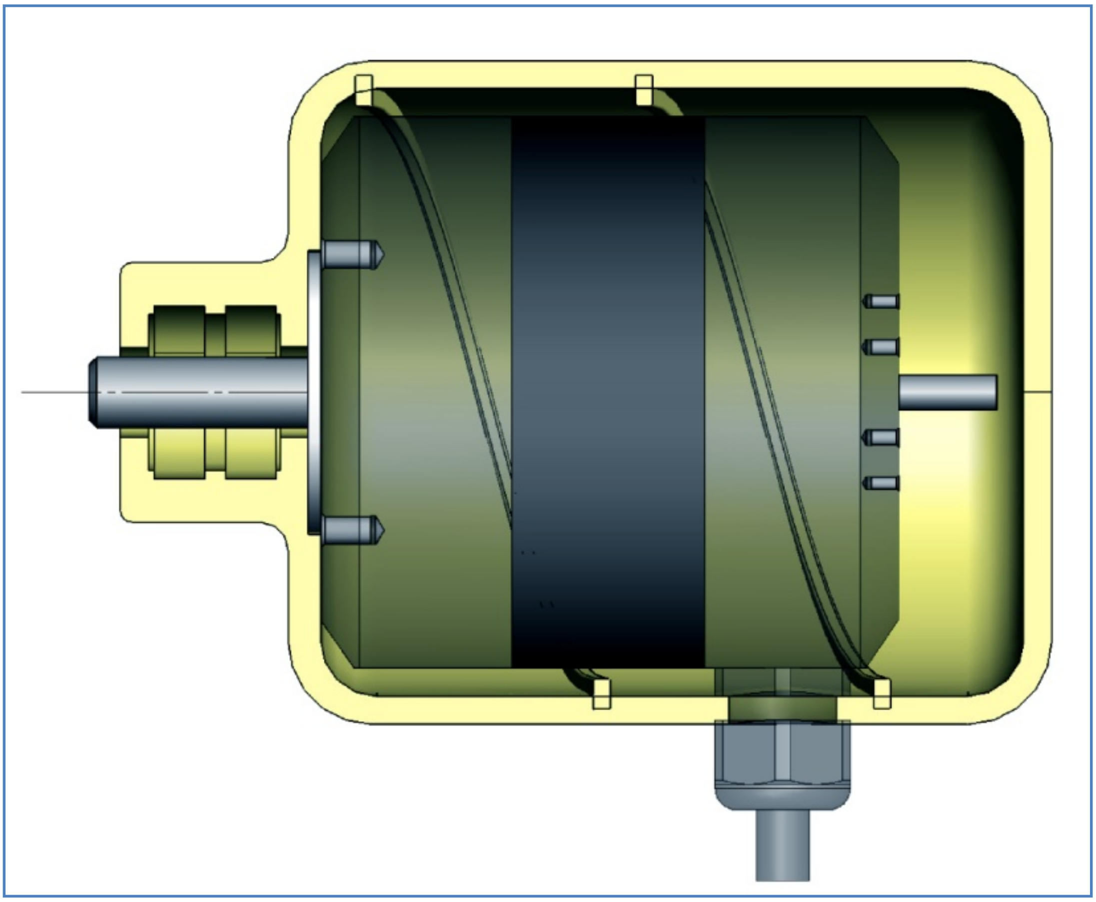


Figure 4.48: Housing example for the 34 B generator (copyright author)

Deep groove bearings with double seals are used in combination with a grease filled stuffing box to provide sealing integrity on the marinised generator during the testing and demonstration phases of the project. A commercial prototype will require the replacement of these bearings for sealed cassette typed pressure balanced bearings. This has to be discussed in conjunction with manufacturers with knowledge in the art.

The generator design selected for marinisation in the project was the Alxion STK 145 2M Alternator due the combination of the ease of sealing the compact deign inside a housing plus the performance of the generator.

The generic marinisation method was adapted to fit this choice and the design then finalised for fabrication as shown below.

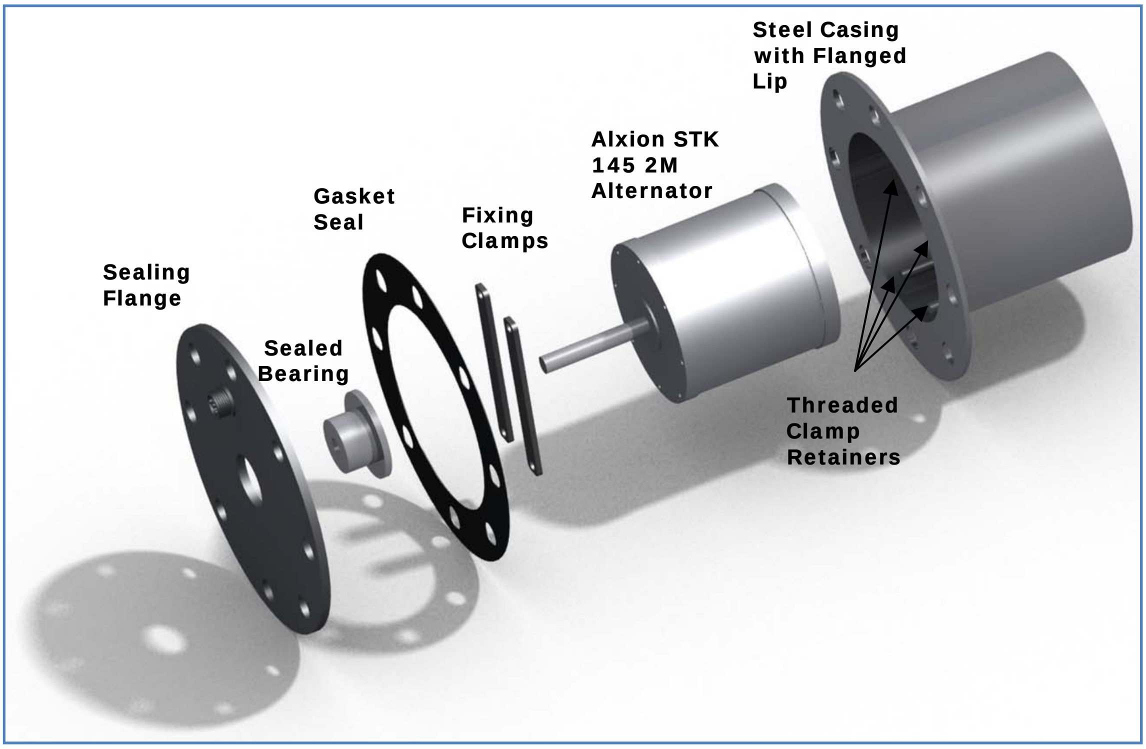


Figure 4.49: Generator marinisation design (copyright author)

The steel casing housing the generator was be oil filled to reduce pressure differentials on the gasket and bearing seals and therefore prevent water ingress to the generator area. The steel case is also of sufficient strength to protect the generator from impact forces that are to be expected. The gasket used was a standard API oilfield gasket, pressure rating of 150 psi or 10 bar. This would allow use in water depths of 75m, taking into account a safety factor on the shaft seals.

The marinised generator housing was constructed by the Galloway Group, Dundee.

Figure 4.50: Generator housing construction (copyright author)

The finished product is shown below. The system was successfully pressure tested to 100 psi. Further tests are required on the completed system.

Figure 4.51: Final product for testing, marinised generator (copyright author)

4.5 Fabrication

One of the deliverables of this research was to critically review existing tidal system costs, with a focus on installation / deployment. The same was conducted for Subsea Oil & Gas equipment. Where possible, capital and operational costs were sourced from industry. This proved to be difficult for the tidal sector as much information was deemed proprietary and confidential, especially regarding installation costs. However, some information was retrieved through literature surveys and telephone conversations. In summary, cost estimates for existing systems indicated a cost/power ratio of approximately £1million for 1 MegaWatt of power. It is unclear whether this included installation and project costs, which could quite easily add 50-100% to the above.

Costs from the main existing tidal prototype devices installed were reviewed and compared to quotes for building the full scale magnetically locked system. Discussions were held with various Fabrication companies regarding quotes for the new tidal system. Discussions were held with Subsea Oil & Gas equipment suppliers in order to determine which items of equipment were available at reduced cost (when not internal pressure rated).

The majority of UK developers of tidal systems are aiming for the megawatt sized machines. This proved to be out with the initial scope of this research, as the author had always aimed to develop tidal systems for the smaller market, under 100 kW power output. However, quotations for the new design were sought, either verbally or in writing.

Of interest, it was found that Fabricators involved in the NE Scotland oil and gas related industries, due to market forces, were happy to quote prices over three times the price (£6,000/metric tonne) of quotations received from non-oil industry related Fabricators (i.e. Agricultural related) of £2,000/metric tonne. Detailed discussions with Fabricators are required to achieve sensible quotations, and it was found that the more the Fabricators were engaged with (and interested in) the proposed technology then the quotations were correspondingly lower. This, of course, also relates to a Fabricator identifying that a mass market could be appearing and that a contract could be secured.

The project results and financial comparisons were compared and an economic analysis run on the new underwater frame system for use as a tidal energy converter deployment and locking device. Costs for wholesale electricity generation are used as a base line economic model.

4.6 Chapter Summary

The project secured a grant of £47,000 from Scottish Enterprise's Marine Energy Support Fund for a project to develop a novel Modular Locking System for a seabed-mounted tidal stream turbine. The award of the grant was based on research conducted on the potential of developing a lower cost deployment system for tidal energy converter devices. The funded project commenced in April 2008 and was scheduled for completion at the end of March 2009.

The deliverables of the research and funded project were met very successfully.

Throughout the funded project the advantages of prior research and literature review were proven advantageous, saving both time and money. The use of Rapid Prototyping and related Software modelling saved considerable effort and resources. The funded project came in considerably under budget on Capital Expenditure and was on budget regarding operational expenditure.

The results of the project were very successful and the author has now developed interesting intellectual property that should be commercially successful.

Next stage of the project and research is to build and test a new set of larger prototypes. Testing of the larger systems will be conducted from a vessel at sea, under typical ocean conditions. An application has been made to Scottish Enterprise to raise funding for the next stage of the project, and to link it to the deployment of a shallow water tidal turbine. Indications are that this funding will be made available for the new trials. Permission has been gratefully received form the RNLI Station at Broughty Ferry, near Dundee. The RNLI are extremely keen to progress the possible use of small scale tidal power, to offset the use of electricity at it's lifeboat stations.

Figure 4.52: New test site at RNLI Station near Dundee

5 Engineering and Cost Analysis

5.1 Introduction

This chapter introduces the analysis that has been conducted post feasibility work on the small scale prototypes. The analysis covers the following aspects of the design:

- Design integrity and weight
- Cost analysis
- Vessel requirements

The chapter includes a discussion on main summary points leading to the conclusions in Chapter 6.

5.2 Design integrity and weight

The next stage was to check the integrity requirements of the structure, make a selection of main structural material for the underwater frame housing and then check the final weight to ensure it was sensible and within realistic Safe Working Loads (SWL) of smaller inshore installation vessels (typical crane capacity of 20MT).

Continuing the philosophy of reviewing offshore oil and gas technology transfer the author decided to review the possible use of conventional downhole oilfield tubular. In the North Sea, the typical sizes are (described in oilfield units);

Table 5.1: Typical tubular materials used in well completions

Tubing OD (in)	4.5	5.5	7	9.625
Tubing ID (in)	3.958	4.892	6.366	8.535
Wall thickness (in)	0.271	0.304	0.317	0.545
Cross sectional area (in^2)	3.6	4.9	6.8	15
Grade psi	80,000	80,000	80,000	80,000
Tensile rating pipe walls (lbs)	288,000	392,000	544,000	1,200,000
Tensile rating pipe walls (tons)	131	178	247	545
Burst psi	7,780	7,740	8,160	7,930
Collapse psi	6,300	5,890	7,020	7,900
Weight (lbs) per foot	11.6	17	29	56

From this it can be seen that downhole tubulars have excellent tensile properties, which would make them very applicable to use in tidal flows. They are designed to handle very large loads, basically hanging from the wellhead in well completions. They would also offer adequate corrosion resistance for extended use in seawater, similar to their use downhole where the ‘A’ annulus is typically a seawater type brine.

To gain an estimation of weight, the above tubular sizes were used, in conjunction with an approximation of the length of tubular required to make up a single modular unit of the underwater frame.

The frame is assumed to be 12ft (3.7m) square. Not accounting for flanged connections the frame would consist of:

- Front piece
  - two x 12' x 7" guide tubes &
  - two x 12' x 5.5" cross members
- Back piece
  - two x 12' x 7" guide tubes &
  - two x 12' x 5.5" cross members
- Side piece
  - two x 5.5" cross members
- Side piece
  - two x 5.5" cross members

An estimation for the total length of tubing required is summarised in Table 5.2 below.

Table 5.2: Estimation of tubular lengths required for modular frame

Item	Amount	Unit length (ft)	Length (ft)
Front piece			
7" Guide tube	2	12	24
5.5" Cross members	2	12	24
Back piece			
7" Guide tube	2	12	24
5.5" Cross members	2	12	24
Side piece			
5.5" Cross members	2	12	24
Side piece			
5.5" Cross members	2	12	24
Summary			
7" Guide tube	**4**	12	**48**
5.5" Cross members	**8**	12	**96**

The estimation figure for the modular frame weight is summarised in Table 5.3 and is based upon the following information:

Weight of 7” tubular used in design is 29lb/ft.

Weight of 5” tubular used in design is 17lb/ft.

The design requires 16 flanges 6” API welded neck flanges, each set weighing 22lbs.

The design requires twin 30kW Alxion 400 STK4M generators weighing 128 lbs each.

The proposed rotor will be made from a GRP base and will be 10ft (3m) diameter. Due to the complex shape of the blade, the mass properties calculated by the SolidWorks modelling software (Figure 5.1) have been used in this estimation.

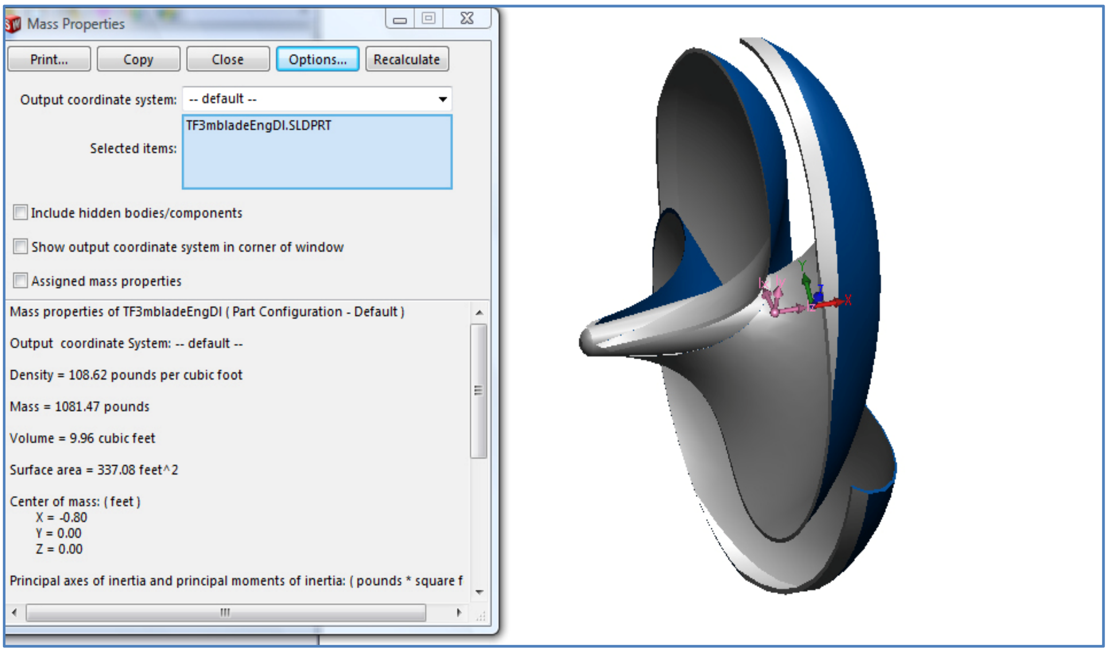


Figure 5.1: Mass properties output of blade from modelling software (58)

The estimation figure for the modular frame weight is summarised in Table 5.3 below.

Table 5.3: Weight estimation of modular frame and generation components

Item	Units	Unit weight	Weight
Tubular weight			
7” Guide tube	48 ft	29 lb/ft	1392 lbs
5.5” Cross members	96 ft	17 lb/ft	1632 lbs
Flange weight			
6” API welded neck flange sets	16 sets	22 lbs	352 lbs
Generator weight			
Alxion 400 STK4M	2	128 lbs	256 lbs
Rotor weight			
Triple blade cone	2	1081 lbs	2162 lbs
Summary			
Generation frame	n/a	n/a	**5794 lbs (2633kg)**

To summarise the approximate final weights; adding the structural framing, flanges, generators and rotors together gives a **total in-air weight of approximately 2.6 MT** (in air, for lifting purposes). In water, adding the commonly accepted simple buoyancy factor of 0.80 would mean the structure would weigh approximately 2.1 MT.

The base structure with the guideposts also needs calculated. The four guide posts would have to be 5.5” OD tubular, in order to fit inside the 7” guide funnels on the upper frame (ID = 6.366”). This would leave 0.433” gap either side of the guide post inside the guide funnel.

The Guideposts would be 12ft high.

Therefore, total length of 5.5” guideposts = 4 x 12 ft = 48 ft

Therefore, total length of 5.5” structural frame = 8 x 12 ft = 96 ft

Add 7” pipe for seabed stability (a “mudmat”) = 5 x 15 ft sections = 75 ft

Therefore total weight 5.5” tubular = 96ft x 17lbs/ft = 1632 lbs

Therefore weight of 7” tubular = 75ft x 20/lbs/ft = 2175 lbs

Therefore total approximate weight of base structure (without gravity base or ballast) = 1632 lbs + 2175 lbs = 3807 lbs or **1.7 MT**

Both these weights would be within the safe working limit (SWL) of a 20 MT lifting crane on a typical inshore construction vessel. Lifting 3 linked tidal rotor modules would be 2.8 X 3 = 9.4 MT, again it is within the safety factor for a 20 MT crane, and 'A' frame, at a reasonable SWL reach.

Now we have the weights of the seabed structures it is necessary to look at the loading the tidal forces would exert on the proposed modular structure.

5.3 Cost analysis

A cost analysis for any design is important, to ensure said design is sensible as far as future manufacture is concerned, but also that it provides a return on investment. The proposed modular tidal turbine design was costed up and the results were as follows;

Table 5.4: Cost analysis - Modular tidal rotor unit

Modular Tidal Rotor Unit; Outline Costs				
	Cost per Unit (£)	Unit Cost for	Number Required	Total Cost (£)
Tubular - 5.5"	40	per metre	100	4,000
Tubular -7 "	74	per metre	50	3,700
Flanges/bolts	25	each	32	800
EU Generators	4,000	each	2	8,000
Wet Connect	1,000	each	2	2,000
Cabling	30	per metre	10	300
Rotor/bearing assembly	3,500	each	2	7,000
Fabrication Cost	2,000	per MT	2.6	5,200
			Total	£31,000
			Add 15% Cont'	£35,600

Table 5.5: Cost analysis - Modular tidal rotor unit

Modular Tidal Base Unit; Outline Costs				
	Cost per Unit (£)	Unit Cost for	Number Required	Total Cost (£)
Tubular - 5.5"	40	per metre	50	2,000
Tubular -7 "	74	per metre	20	1,480
Flanges/bolts	25	each	24	600
EU Generators	4,000	each	0	-
Wet Connect	1,000	each	4	2,000
Cabling	30	per metre	10	300
Rotor/bearing assembly	3,500	each	0	7,000
Fabrication Cost	2,000	per MT	1.3	2,600
			Total	£10,980
			Add 15% Cont'	£12,627

The above costs have been gathered over a period of approximately 18 months, and are subject to variation. A 15% contingency has been added. The cost of Fabrication of £2,000 per metric ton equivalent was received from Afon Engineering, Swansea. The tubular prices were received from Shell UK, as typical stock prices for refurbished tubulars.

Current outline costs for new tubing, per metre, L80, 13 Chrome (ref Shell)

4.5" **£61.64 / m**

5.5" **£80.62 / m**

7" **£144.72 / m**

9 5/8" **£253.27 / m**

Again, considerable savings could be made if stock tubular were sourced from the oil companies. They are keen to reduce unused stocks, so an approach to purchase old tubulars would be viewed positively.

The above costs show that a complete 30kW modular tidal turbine unit could be manufactured for approximately £48,000. This would give a cost per kilowatt of approximately £1,600. However, this does not account for installation (& project management) costs for the system, which typically account for an additional 75-100% on top of supply costs (based on personal oil industry experience). This percentage is obviously variable because tidal exploitation will be so site specific, and the cost of marine power cables can be very high if the turbine is located too far from shore.

Before the full cost estimates are worked up, it will be interesting to compare with the costs per kilowatt of competing technologies. Typical industry estimates place these at;

Solar PV = £3000/kW

Onshore Wind = £1500 - £4000 / kW depending upon turbine size

Offshore Wind = £5000 - £10,000 / kW depending upon turbine size

Existing Tidal prototypes = £10,000 - £15,000 / kW

For the new tidal turbine, it is anticipated that a community or developer would pay approximately £100,000 for the proposed 30kW single tidal module. This places the cost of this new design directly in competition with existing solar and onshore wind systems. This would be a tremendous achievement, as tidal offers the big advantage of providing predictable power every 24 hours and hence project economics can be far better defined.

To review typical project economics for this system a payback was calculated. The price for electricity was based upon information received from Scottish Enterprise, see below;

The incentives to get companies to build alternative energy projects are known as renewables obligation certificates, or ROCs.
They are handed out to clean-energy providers for every unit of power — megawatt/hour (MW/hr) — that a wind farm or a tidal turbine might produce.

The ROCs can then be traded, typically with polluting companies such as coal-fired power stations which have to buy ROCs commensurate with the amount of carbon dioxide they emit. In recent years, ROCs have been traded in this secondary market at an average of around £47 a ROC (4.7p per kW/hr). — a significant incentive, especially if multiple ROCs are on offer for every MW/hr generated as the current forward price of electricity is around £40 for every MW/hr produced (4p per kW/hr).

Tidal will received a minimum of 3 ROCs, it is planned to extend this to 5 ROC's for Scotland.

Ref: Scottish Enterprise

Figure 5.2: Cost information on electricity prices (63)

Table 5.6 shows how payback figures were derived.

Table 5.6: Payback calculation

velocity m/sec	Max Power kW	Power @ 50% kW	Value @ 4p/kWHr over 24 hours (£)	Value @ 18p/kWHr over 24 hours (£)	Value @ 27.7p/kWHr over 24 hours (£)
1	2.46	1.23	1.18	5.13	34.10
2	19.682	9.84	9.45	41.04	**272.80**
3	66.42	33.21	31.88	138.28	**920.71**
4	157.44	78.72	75.57	328.28	**2,182.41**
5	307.50	153.75	147.60	641.17	4,262.53

The numbers highlighted in red were taken as an assumed example of the typical daily £cost output of a tidal turbine in flow stream from 2 to 4 m/sec (4-8 knots), over a 24 hour period. Obviously, there are many more tidal streams available at 2 m/sec rather than 4 m/sec. The data were calculated at three price scenarios for sold electricity. The 4p / kW hr is the base price for electricity into the grid. Obviously, at this price the tidal system cannot compete with conventional large scale power stations generating in bulk. The 18p / kW hour is the proposed price given for “green” electricity from large tidal generators, to include three Renewable Obligation Certificates (ROCs) (63). The 27.7p kW / hr was taken from the new government proposed ROCs for tidal, announced Oct 2010. The price would be contracted for 15+ years.

Taking the above table and converting it to an annual sum, gives;

Table 5.7: Payback calculation -annual sums

velocity m/sec	Max Power kW	Power @ 50% kW	Value @ 4p/kWHr	Value @ 18p/kWHr	Value @ 27.78p/kWHr
			over 365 days (£)	over 365 days (£)	over 365 days (£)
1	2.46	1.23	431	1,950	2,985
2	19.68	9.84	3,448	15,602	**23,877**
3	66.42	33.21	11,637	52,656	**80,585**
4	157.44	78.72	27,583	124,815	**191,016**
5	307.50	153.75	53,874	243,780	373,077

This shows that a single turbine would produce an electricity revenue of between £23,000-£191,000 per annum, depending upon site location. Obviously, sitting the turbine in a 4 m/sec flow will give far greater (and faster) financial return than 2 m/sec.

The payback times for the 30kW turbine in the different flow streams would be;

Based on 27.7p per kW/hr

2 m/sec = £100,000 / £23,877 = ~4.2 years payback

3 m/sec = £100,000 / £80.585 = ~1.2 years payback

4 m/sec = £100,000 / £191,016 = ~0.5 years payback

Based on 18.1p per kW/hr

2 m/sec = £100,000 / £15,602 = ~6.4 years payback

3 m/sec = £100,000 / £52,656 = ~1.9 years payback

4 m/sec = £100,000 / £124,815 = ~0.8 years payback

Based on 4p per kW/hr

2 m/sec = £100,000 / £3,448 = ~29 years payback

3 m/sec = £100,000 / £11,637 = ~8.6 years payback

4 m/sec = £100,000 / £27,583 = ~3.6 years payback

Reviewing these figures it is obvious that the new tidal system will only be attractive to investors if the electricity price is between 18-27.7p per kW/hr. The numbers highlighted in red would be an interesting payback number for investors, especially if tied to a 15+ year power sales contract.

The following simple spreadsheet gives an indication of the project economic / cashflow of a small community sided tide farm with 2 MW of installed power output (20 individual turbine modules).

Note that the turbines can be located together in blocks of three modules at a particular site, therefore only seven "hubs" would be required to be tied together on the seabed, making the installation simpler and more cost effective.

Community Scale Tidal Farm

Island Turbine Farm Cashflows

Assumptions Add data in red cell only

No of tidal turbines	20	Turbine Output MW	2.00	Installed Cost - £	£4,000,000
Pence per KWH	18.10	Price per KWH Escalation / per annum	0.03	OPEX Cost escalation per annum	0.03
Cost per Tidal Turbine	£100,000			PAYBACK YEARS	3.8
Daily Tidal Flow	16				

	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5	YEAR 6	YEAR 7	YEAR 8	YEAR 9	YEAR 10	
Profit After 28% Tax	£1,039,844	£1,081,839	£1,125,095	£1,169,648	£1,215,537	£1,262,803	£1,311,487	£1,361,632	£1,413,281	£1,466,479	£12,447,645
Profit Percentage	49%	50%	50%	51%	51%	52%	52%	52%	53%	53%	51%
Return on Investment multiplier	3.1			Total Profit	£12,447,645						
Tidal turbine MW	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
Annual Hours -	5,840	5,840	5,840	5,840	5,840	5,840	5,840	5,840	5,840	5,840	
Annual Output MW	11,680	11,680	11,680	11,680	11,680	11,680	11,680	11,680	11,680	11,680	
Income Pence/KWH	18.10	18.64	19.20	19.78	20.37	20.98	21.61	22.26	22.93	23.62	
Income £/ MWH escalated	181.00	186.43	192.02	197.78	203.72	209.83	216.12	222.61	229.29	236.16	

Figure 5.3: Community scale tidal farm economics

5.4 Vessel requirements

The correct use of installation vessels is going to be critical in the economic installation of tidal energy devices and so called “tide farms”. The use of offshore style Supply Boats, Crane Barges and jack up Rigs will not be economic for most in-shore or coastal tidal installations.

The use of multipurpose vessels such as the one illustrated below is the most sensible approach. This vessel is rated for coastal waters and can be fitted out with various sizes of cranes, A Frames and Moonpools. A new vessel such as this will cost around £450,000 new, but can be rented for £1,000 -£2,000 per day (depending on time requirements). Interestingly, it can be easily disassembled and transported by road, making it very mobile.

Deck Layout
Deck area: 85 m^2
Deck Rating: 7.5 tonne per m^2
Access Ramps: 15 tonne capacity
Winch: 5 tonne
Crane: Palfinger PK 23,500 MT ; 1570 kg@ 12m
Deck cargo: 28 tonnes
A Frame: 4 tonnes
Moonpool: 1200 mm

The flexibility of design and specification of the RT16 makes this vessel the perfect solution for customers engaged in marine civils, oil spill response, cable laying and harbour maintenance. For example, the 23.5tm crane has a lifting capability of 1,500kg at 12m and the triple hull RT16 provides up to 90m2 of working deck area, together with an impressive cargo capacity of 35 tonnes.

Figure 5.4: Meercat RT16 with crane (64)

Figure 5.5: Meercat RT16 in harbour cable laying mode (64)

The addition of an A frame will aid in the deployment of tidal units, as heavier loads can be hung from the frame. Typically, smaller workboats will have 4-10 MT A frames, such as shown below.

Figure 5.6: Oceanographic Vessel with 10MT A frame and large work area off stern (65)

The vessel shown above can be hired for £1,500 per day, with an additional £500 per day for air diving support, making this option very affordable for community style tidal installations.

For installing tidal devices the type of location will be critical in choice of vessel. As a starter, all sites will have fast tidal flows so the vessel will require the ability to attach itself to an anchor spread, so as not to be washed away while conducting operations. The vessel will need to be fitted with anchor winches so it can adjust tension on the anchors as the tide changes direction and force. A conventional 4 spread anchor pattern would suffice.

To install the proposed modular tidal device the following two main steps will be involved;

1. Install guidebase and associated cabling
2. Install and commission tidal turbines

To save time on site and also safety and complexity it would be proposed to split the job into two operations, perhaps split by several days or weeks. It is always more economic if prework can be completed first, before the main systems come to site. This allows for operational and equipment issues to be ironed out before the main phase of the operation.

5.5 Chapter summary

An outline engineering scope of work was performed and detailed during Chapter 5. A summary of findings is as follows:

1. The weight of a single tidal module would be 2.6 MT.
2. The weight of the tidal base structure would be 1.7 MT
3. Locked together weight would be ~ 4.3 MT
4. The turbine would output between 10 -78 kW in a 2 – 4 m/sec flow.
5. The generators can be matched to the kW output required. The windings can be altered to achieve the required supply voltages.
6. A single turbine would be economically viable at base electricity cost plus a minimum of three ROCs.
7. Triple turbines run on a single base structure would improve economics.
8. A community tide farm cashflow analysis of a 2MW installation of 20 single turbines provides for an attractive return on investment.
9. The use of low cost inshore workboats are essential in achieving economics.
10. The testing conducted as part of this project was inconclusive and further work is required.

6 Discussion, Conclusions and Further Work

6.1 Introduction to chapter

This final chapter will present a discussion and the conclusions of this research. Included in Discussions is a brief synopsis of original contributions to the subject matter. The aims and objectives of the research, as outlined in Chapter 1, are reviewed and examined with reference to the research and development work carried out in previous chapters. Suggestions for additional work are made. Some concluding remarks are added.

6.2 Discussion

This EngD submission covers a project submission to the Robert Gordon University Aberdeen. This part time project has been ongoing for 5 years and started with the award of a patent in 2005.

The main aim of the EngD project was to transfer elements of technology from existing subsea installation procedures that are used in the oil and gas industry. The outcome was to develop a concept for a low-cost modular solution for exploiting tidal energy, which also provided a sensible return on investment. The technology would be applicable to communities, in the UK and overseas.

When assessing any research project deliverables, a question always arises regarding the contribution of new knowledge made by the researcher and his/her work. This EngD project has several original aspects to it, all of which are derived from the work conducted. The following is a list of original contribution aspects;

- Award of patent GB 2400632
- Design of novel underwater locking and underater modular frame system
- Design and early test of innovative rotor concept
- Design and early test of new modular tidal energy prototype
- Filing of two new patents as a result of the work

- Proving up that small scale tidal systems can be made economically viable if an alternative approach is made to the build and installation cost.

The results of the project were very successful and the author has now developed interesting intellectual property that should be commercially successful. Project partners are being actively sought to work on next stage prototype developments.

6.3 Conclusions

The project commenced with setting out a set of deliverables. The following conclusions are matched to the original deliverables, namely:

- **Produce a literature search and brief review of the emerging tidal energy market, and related business opportunity.** This literature search proved that the emerging tidal market is very exciting and does offer an alternative option for renewable energy development. Of particular interest was the fact that tidal resources could offer coastal communities a very sustainable energy source. This resource would be available to many communities worldwide.

- **Critically review tidal technology deployment activities and compare oil & gas installation techniques to several tidal technology installation techniques.** A comprehensive review showed that numerous options for installation technology and methodologies were being tried by the emerging tidal developers, but are proving to be at high cost. Interestingly, no developer was using the tried and testing conventional subsea oil and gas installation tools and techniques.

- **Critically review existing subsea oil and gas technology and attempt to derive a lower cost system for use in tidal devices.** Both subsea architecture design and subsea well technologies were critically analysed and it was shown that it was possible to cross over aspects of subsea oil and gas technologies to the tidal industry. Of particular interest was subsea well technology. There were several aspects of this which could easily be transferred to the tidal industry. The main aspects were related to subsea wellhead and subsea tree technology, which if slightly redesigned could be applied to the tidal industry

- **Produce a concept for a simple non-hydraulic locking device, using magnetic force as opposed to hydraulic force.** The author derived this concept while looking for an alternative to hydraulic and mechanical locks. Hydraulic locks are commonly used in the subsea industry to seal in pressure, but this would not be required in the tidal industry. Conventional magnet or electromagnet technology would not be applicable but the new range of electrically excited permanent magnets were of interest.

- **Build scaled prototypes of a magnetically operated lock, and test these under different conditions.** Sets of magnets were tested under laboratory conditions and under flow conditions (river and seawater). The magnet technology worked well and it was proved up that an arrangement of larger magnets could be used in a full scale tidal prototype to aid in locking modular components of the tidal rotor together. This new design is now Patent Pending.

- **Build scaled prototypes of a new style of rotor, and test / analyse these under different conditions.** A new design of rotor was introduced, following computer and rapid prototyping modelling work. In order to prove the functionality of the design and illustrate its modular features, a series of scaled prototypes of the new tidal system were constructed. These have been subjected to various component tests and tow tests of the various assemblies. A simplification of the underwater frame design and locking system type enabled significant capital savings compared to other tidal device developers. The fame design is modular and purposely designed to be simple to fabricate and assemble.

Fabrication effectively involves cutting and welding flanges to tubulars, then bolting them together. The whole system becomes an easily transportable 'kit', and can be built on site by local labour. This helps create local employment in coastal communities.

- **Analyse the design from an economics perspective, and prove if the system was viable for coastal communities.** Various economic analysis were run on the proposed system and it was proved that the system could be made economically viable if the tidal industry received the Renewable Obligation Certificates. An alternative is of course that the tidal system is just installed to provide electricity to remote communities in the third world, and not as a return on Investment option.

6.4 Suggestions for further work

This research has brought forward many innovations and potentially interesting new avenues for additional research and development. The following is a summary of two main areas of further work that is required;

The first is to complete the detailed mathematical modelling on the design innovations that have come forward as a result of this research. Included here is the modelling of the new rotor design under various loads and flow regimes, as well as the detailed numerical modelling of the numerous forces that will be exerted on the modular tidal system using a range of real tidal site flow data.

The second is to progress larger scale prototype work in both the laboratory and at sea. The work will involve collaboration between a fabrication company and a local community that are interested in a tidal project. A promise of a test site has already been given from the RNLI, based near Dundee. The Isle of Eigg are showing considerable interest in a community linked small scale tidal array

Additional funding will be required to achieve the above, and the author is now interested in putting together a consortia of fabrication companies, academia and also some small coastal communities to progress the work. Scottish Enterprise are very interested in this opportunity and have indicated that 33% funding can be made available for the next stages in this interesting project.

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8 Appendices

Appendix one – Patent applications

This appendix contains Patent Application and Certificate details for Subsea Energy Generation by the author along with filing receipts and UK Patent Specification details for a Subsea Energy Magnetic Locking System Apparatus and a Subsea Energy Production Apparatus.

Appendix two – Project Risk Register

This appendix contains an extract from a typical risk register used during the project, in this case, the Magnetic Locking System (MLS) risk register.

Appendix three – Eclipse magnet force curves

This appendix contains dimensional and performance information on the eclipse magnets used during the construction and testing of the magnetic locking system phases of the project.

Appendix four – Marine Corrosion and material selection for subsea equipment

This appendix discusses the requirements and solutions relating to the different types of marine corrosion problems associated with subsea equipment.

Appendix One – Patent applications

APPENDIX ONE

Patent Application & Certificate - Subsea Energy Generation

The present invention relates to an apparatus for generating energy from flowing water. The invention is primarily, although not exclusively, intended for subsea use; and is particularly suited for use in the offshore oil and gas exploration and production industries. Particular embodiments of the invention may be used to generate electricity; however, alternative energy may be generated.

There are numerous different devices and systems for generating energy from flowing water; for example, wave power systems, tidal power systems, hydroelectric generators, and the like. However, these suffer from a number of disadvantages.

Common wave and tidal barrage systems both typically require a number of generating units to be installed in order to provide sufficient power to be commercially useful. This can lead to unsightly installations and unwanted environmental impact. Further, it is often necessary to construct large, heavy structures to hold generating systems in place against fast current flow. It is often difficult to deploy and install generating systems, particularly in deep or fast-flowing water; for this reason the majority of practical systems are often limited to installation at less than 50 metres in depth. This in turn leads to further problems as the relatively shallow location of the generators can result either in the generators obstructing other use of the water, or even protruding from the surface of the water, and so being unsightly.

An additional problem with certain electricity generating systems is the need to create dams or tidal barrages to obtain sufficient water flow to allow for economical generation of electricity. Clearly such systems have an additional environmental impact beyond that of simply installing the generators themselves.

It is among the objects of embodiments of the present invention to obviate or alleviate, at least in part, certain of the disadvantages of prior art energy generating devices.

One potential user of energy generated by subsea systems is the offshore oil and gas exploration and production industry. Drilling rigs and similar structures require an energy supply to assist in powering the operation of subsea equipment. Further, downhole tools as used in the drilling / completion industry may also require an energy supply for their operation. At present this energy supply is provided by conventional fossil-fuel electricity generators located on the drilling rig; such generators must be regularly supplied with fuel. It would be more convenient to provide electricity generated locally which does not require a fuel supply; such as that generated from water power. It would further be beneficial to generate energy used downhole at the subsea well itself.

Furthermore, the offshore oil and gas industry often faces the relatively high cost of abandoning or decommissioning exhausted wells and wellheads.

Embodiments of the present invention allow such wells and wellheads to be used as locations (anchors) for equipment to generate energy; this is particularly advantageous when combined with an existing distribution network, such as the pipelines which will already be present near a well and which may thus be used to distribute generated energy.

These and other objects of the invention are achieved in part in certain embodiments of the invention by the use of a modular generator system which is arranged to engage with what is generally known as a wellhead guidebase assembly located (anchored) in a subsea location. Wellhead guidebase assemblies are generally cemented in place to the top of a well bore, and hence provide a convenient anchor point for attachment of tools and the like. The assembly may typically be used for the attachment of 'Christmas trees', which are structures used during oil and gas production operations to allow control of fluid flow from a well, and to provide means whereby downhole tools and the like may be attached to the well. Wellhead guidebase assemblies are generally of a standard form, as will be described, and so provide a convenient means for attaching a generator system and apparatus of the present invention.

According to a first aspect of the present invention, there is provided an apparatus for generating energy from flowing water, the apparatus comprising a turbine rotor portion for being driven by flowing water, the turbine rotor portion being operably connected to an energy generator portion; and a support portion connected to one of the turbine rotor portion and the energy generator portion; wherein the support portion is adapted to be engaged with a portion of a subsea wellhead guidebase assembly so as to retain and anchor the apparatus in position.

At least two of said turbine rotor, generator and support portions may be releasably connected to one another, such that said two of said portions may be deployed or retrieved separately from an underwater location. Thus, the present invention allows for a modular construction of the apparatus, such that, for example, the support portion may be deployed in a subsea location first, followed by separate deployment of the generator and turbine portions. This allows for the apparatus to be deployed using smaller, less powerful means than prior art systems, so making it less costly to deploy. For example, the apparatus may be deployed by means of a drilling industry running tool (typically used to deploy or 'run in' downhole tools and the like), or by means of cables or the like running from surface. The modular nature of the apparatus also allows for relatively straightforward replacement or retrieval of separate portions for maintenance, as well as the substitution of variant portions for others, for example to adapt the apparatus to different subsea conditions. Of course, despite the modular nature of the apparatus, the complete apparatus may be deployed as a single unit, rather than modularly, if desired.

References herein to 'subsea' , 'seabed' and the like will be understood by the skilled person to include other underwater locations, such as lakebeds, riverbeds, and the like, including coastal locations such as a foreshore.

Preferably the generator portion is an electrical generator portion; the apparatus may conveniently be used to generate electricity from water movement. However, alternative forms of energy may be generated if desired; in particular a hydraulic generator may be used, or the apparatus may include a device for separating hydrogen from water which may be powered directly from water movement or indirectly via an electricity generator. The generation of hydrogen may be particularly convenient where the hydrogen is able to be transferred along existing pipelines such as those leading from oil and gas wells. Suitable electrical, hydraulic, or hydrogen generators are known, and may be readily used by the skilled person.

Preferably all three of the turbine rotor, generator and support portions are releasably connected together; in a preferred arrangement, the turbine portion is connected to the generator portion, and the generator portion is connected to the support portion. Preferably the apparatus comprises connectors, for releasably connecting the portions together and for connecting the support portion to a subsea wellhead guidebase assembly. The connectors may be hydraulic connectors; alternatively or in addition mechanical connectors may be used. Suitable connectors will be known to those of skill in the art.

A typical guidebase assembly includes a number of upwardly extending members; the support portion may comprise members arranged to engage with such upwardly extending members; the members may be in the form of openings located on a supporting frame of the support portion. Wellhead guidebase assemblies are also generally of a standardised form, which allows the present invention and in particular the support portion thereof to be produced in a corresponding standard form which will be suitable for engaging with such guidebase assemblies. In use, the support portion may engage with an existing guidebase assembly previously mounted on the sea floor or to the head of a drill bore. This allows the present invention, in certain embodiments, to be retrofitted to an existing guidebase assembly, which may be of particular benefit for the use of the invention in providing electricity to downhole tools and similar devices, or to drilling rigs and platforms.

Alternatively, the apparatus may further comprise a welihead guidebase assembly for engaging with the support portion. In this case, the guidebase assembly (and optionally the support portion) may be deployed first of all, by for example drilling or piling and cementing the guidebase assembly into a suitable seabed location, with the remaining portions being deployed subsequently. It will be appreciated that this may require more work than retrofitting the apparatus to an existing guidebase assembly, but may be the preferred option in the event that suitably-located guidebase assemblies do not exist in the desired location. In still further embodiments, the apparatus may comprise one or more vertically oriented members for engaging with the support portion; these members are preferably of the same size and arrangement as the members provided on a conventional guidebase assembly. Conveniently four of these members are provided, arranged in the corners of a quadrilateral. The members may be comprised in the support portion, or may be separate from the support portion. Two and four post wellhead assemblies will be known to those of skill in the art, and either form may be used in the present invention.

As afore-described the support portion is adapted to engage with a guidebase assembly, or with one or more vertically oriented members thereof. Preferably one or both of the remaining portions are also adapted to engage with a guidebase assembly, or with said members. This provides a convenient means whereby the various portions may be aligned and engaged during deployment.

The support portion may further comprise a ballast to assist in retaining the apparatus on the seabed. The ballast may comprise a concrete weight or the like.

The apparatus may still further comprise additional portions for interposing between the generator portion and the turbine portion. The additional portions may include spacer portions, for raising the effective height of the turbine portion to allow for variations in location of water flow and local conditions; or may include additional turbine portions, for improving the area over which water flow is intercepted. In further embodiments of the invention, the additional portions may comprise buoyancy members, such as buoyancy chambers, for adjusting the buoyancy of the apparatus or of parts thereof.

The turbine portion may include a turbine rotor of any suitable form, and may be selected depending on the expected conditions where the apparatus is to be deployed. The person skilled in the art of energy generation will be aware of suitable forms of rotor which may be used. For example, helical vertical rotors, or multiple-bladed horizontal rotors may be used, as may numerous alternative forms. In certain embodiments of the invention, the apparatus may be provided with a plurality of interchangeable turbine portions, to allow selection of an appropriate form.

The generator portion may include a generator of any suitable form; again the skilled person will be aware of numerous suitable types of generator. Examples of suitable electrical generators include permanent magnet alternators, and induction generators. Alternatively, hydraulic generators or hydrogen generators may be used. Again, the generator may be selected depending on expected conditions in the location where the apparatus is to be deployed.

Preferably the apparatus further comprises means for distributing generated energy; preferably the device is for distributing generated electricity. This may conveniently take the form of a conducting device leading from the apparatus. In certain embodiments, the conducting device may communicate with a manifold for communicating with a plurality of similar apparatuses; the manifold allows electricity from multiple apparatuses to be combined and transmitted onwardly. Alternatively, or in addition, the conducting device may communicate with an offshore drilling platform; or with an electricity storage device for example capacitors or batteries; or with an onshore electricity distribution network. The apparatus may further comprise a transformer. Where the apparatus generates energy that is not electricity, the apparatus may comprise an alternative appropriate form of energy distribution means; for example, hydrogen pipelines, storage containers, or the like.

According to a further aspect of the present invention, there is provided an apparatus for generating energy from flowing water, the apparatus comprising a turbine rotor portion for being driven by flowing water and for connecting to an energy generator portion; and a support portion for connecting to one of the turbine rotor portion and the energy generator portion; wherein at least two of said portions are adapted to be releasably connected to one another, such that said two of said portions may be deployed or retrieved separately from an underwater location, and wherein the support portion is adapted to be engaged with a portion of a subsea wellhead guidebase assembly so as to retain and anchor the apparatus in position.

According to a further aspect of the present invention, there is provided a system for generating energy from flowing water according to claim.

According to a yet further aspect of the present invention, there is provided a method of deploying the apparatus for generating energy according to the first aspect of the invention, the method comprising the steps of

> deploying the support portion on the seabed;
> deploying the generating portion on the support portion, and releasably connecting the generating portion thereto;
> and
> deploying the turbine rotor portion on the generating portion, and releasably connecting the generating portion thereto.

The deployment preferably takes place from surface, and may be effected by means of cables, running tools or the like.

The method may further comprise the step of deploying the guidebase assembly and securing the assembly to the seabed prior to deploying the support portion, although it may be that the support portion is instead deployed to engage with an existing guidebase assembly. The generator portion and turbine rotor portions may also be deployed so as to engage with a portion of a guidebase assembly; in alternative embodiments, the apparatus may engage with a portion of a Christmas tree which is itself engaged with a guidebase assembly.

The various portions are preferably connected by means of hydraulic and/or mechanical connectors.

The method may yet further comprise the step of connecting the apparatus to energy conducting means.

These and other aspects of the present invention will now be described by way of example only and with reference to the accompanying Figures, in which:

1/3

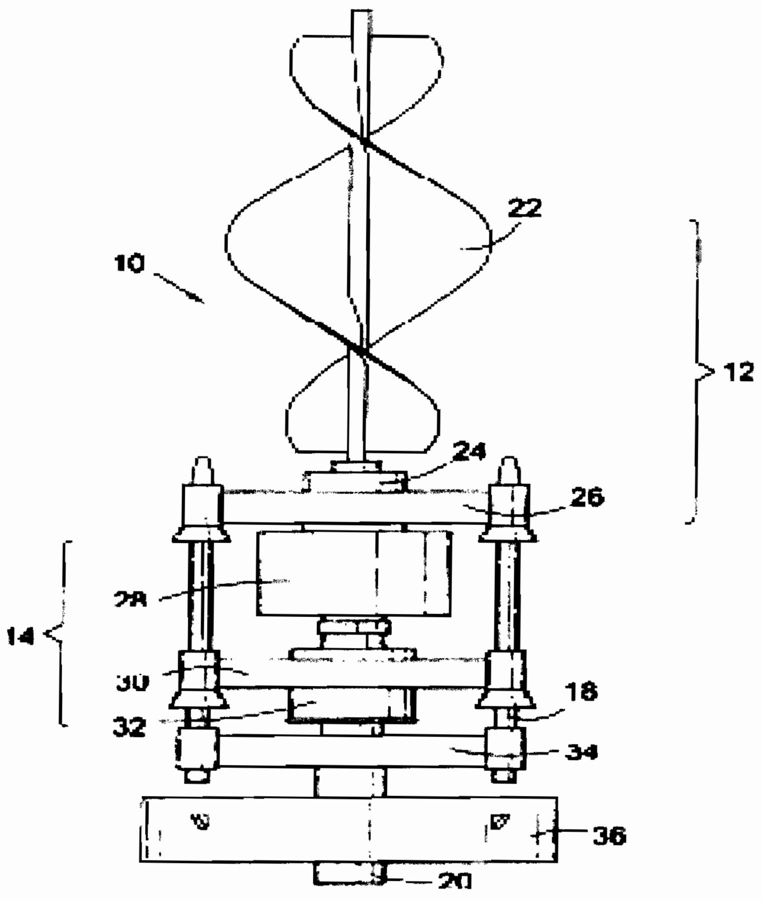

Fig. 1

Figure 1 shows a side view of an apparatus for generating energy in accordance with an embodiment of the present invention;

2/3

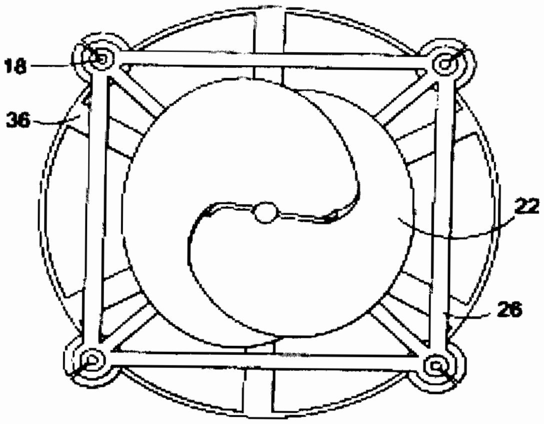

Fig. 2

Figure 2 shows a top view of the apparatus of Figure 1; and

3/3

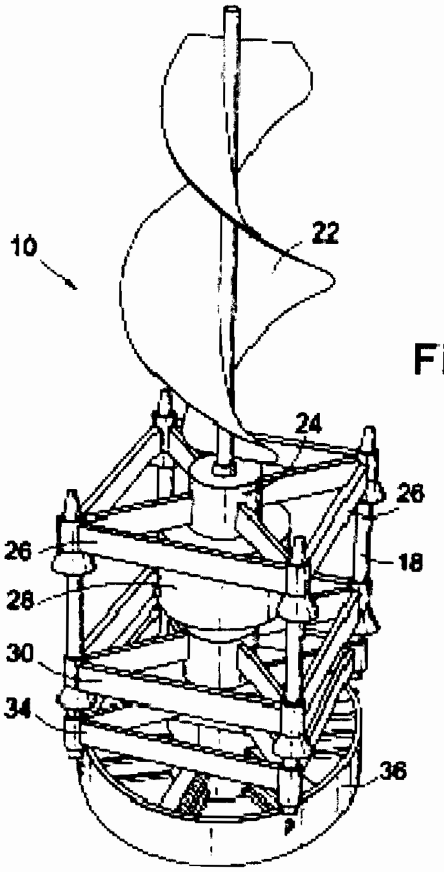

Fig. 3

Figure 3 shows a perspective view of the apparatus of Figure 1.

Referring to the Figures, *these* show an apparatus 10 for generating energy from flowing water in accordance with an embodiment of the present invention. In this example, the apparatus generates electricity from flowing water, although it will be apparent to the skilled person that alternative forms of energy may be generated using the present invention. The apparatus 10 includes three distinct portions a turbine rotor portion 12, an electrical generator portion 14, and a support portion.

Also shown in the Figures is a wellhead guidebase assembly 18/34, which in this example comprises four vertically-extending guideposts which are attached to the sea floor by virtue of being anchored 36 to a subsea well head 20. The design of guidebase assemblies and their anchoring to well heads is well-known in the oil and gas industry, and will not be described in detail here.

The turbine rotor module 12 includes a helical rotor blade 22 having at its base a hydraulic connector 24 of known design, and a square steel frame 26 which includes corner openings arranged to allow the frame 26 to engage with the guideposts of the guidebase assembly 18. The hydraulic connector 24 includes integral bearings (not shown) which allow the rotor 22 to turn, and is also used to allow the turbine rotor module 12 to releasably connect to the electrical generator module 14. In certain embodiments of the invention, the hydraulic connectors may be replaced with mechanical connectors.

The electrical generator module 14 includes a generator 28 which is driven by rotation of the rotor 22, a further square steel frame 30 for engaging with the guidebase assembly 18, and a further hydraulic connector 22. The square steel frame 30 comprises an upper and a lower square portion connected by upwardly extending corner opening posts; in effect this makes the frame 30 resemble two single frames connected by the posts and this frame comprises the support portion.

The further connector 32 allows the generator module 14 to connect to a wellhead base 36. The further connector 32 hydraulically locks onto the well head 20, which is of known design (typically an 18 3/4 inch housing) and includes a profile to which the connector attaches. The frame and base 36 cooperate with the well head 20, and by this means are connected to the electrical generator module 14.

Deployment of the apparatus proceeds as follows. Firstly the wellhead guidebase assembly 18 is deployed in an appropriate sea floor location. The guidebase assembly may be deployed using conventional oil and gas industry devices, and may be attached to the sea floor by means of a conductor pipe drilled and cemented or piled into position, with the well head 20 being hydraulically locked into this conductor by use of a hydraulic set packer device or similar. Alternatively, and preferably a previously-deployed guidebase assembly may be utilised, for example an assembly forming part of an oil or gas well.

The generator module 14 and associated support frame is then lowered over the guidebase assembly 18. The module 14 is lowered from the surface, and the frame 30 is run over the cables, which extend through the corner openings of the frame 30. These corner openings are received on the guidebase assembly to align the module 14 in the correct position.

The hydraulic connector 32 is operated (for example, from an umbilical to surface, or by interface with a remotely operated vehicle (ROV), or by divers) to connect the modules together. The generator 28 may be connected to an export cable, transformer, capacitor, or battery arrangement (not shown). This may be by any convenient connector arrangement, and may be operated for example, by a ROV or by divers.

Finally, the turbine rotor module 12 is lowered on the cables and connected in the same manner. The apparatus 10 is then ready to generate electricity.

It will be noted that the present invention allows for a modular deployment of the apparatus; this is simpler than deploying a complete structure at once. Equally, retrieval of the apparatus or individual modules may proceed in a similar manner, with the hydraulic connectors 24, 32 being disengaged remotely or locally.

The modular nature of the apparatus also allows for a deal of flexibility in its use. The form of the rotor blade 22 used will depend on the current velocity and depth; the style may range from a helical type blade to a multi-bladed horizontal propeller type blade system. Due to the modular nature of the apparatus, it is possible to stack multiple vertical blades together or to raise the position of the blades by means or a 'riser system' to allow optimum location in a current.

The generator type may be a permanent magnet alternator or an induction generator. Depending on the type used, a hydrostatic housing may be included to protect the generator. A gearing system may be included to increase rotation rate from the rotor to the generator. Alternatively, the apparatus may be used to generate non electrical forms of energy; for example, using a hydraulic generator or using a hydrogen generator to split water into hydrogen and oxygen. Suitable energy export devices will of course be necessary, and will be readily apparent to the skilled parson; for example, gas export pipelines or the like.

Further, an array of individual apparatuses may be connected together at a central manifold. An electrical power cable may connect the manifold to the appropriate end user (onshore grid, storage batteries, transformer, drilling rig, and so forth). The manifold may contain a transformer to increase voltage for export over long distances.

The apparatus may generally be installed at any location with sufficient water velocity to drive the rotor. Typically this would be at flow rates above 2 metres / second. It is expected that a suitable array of devices may be used to produce from 0.1 to 2 megawatts of electricity. The environmental impact will be limited, and since the devices may be located entirely subsea, there will be no visual impact from land. Further, with suitable depth, there will also be no or limited disruption to surface currents or shipping movements.

Claims

1 An apparatus for generating energy from flowing water, the apparatus comprising a turbine rotor portion for being driven by flowing water, the turbine rotor portion being operably connected to an energy generator portion; and a support portion connected to one of the turbine rotor portion and the energy generator portion; wherein the support portion is adapted to be engaged with a portion of a subsea wellhead guidebase assembly so as to retain and anchor the apparatus in position.

2. An apparatus according to claim 1, wherein the support portion comprises a plurality of members arranged to engage with a plurality of upwardly extending members of the guidebase assembly.

3. An apparatus according to claim 2, wherein said members of the support portion are in the form of openings located on a supporting frame of the support portion.

4. An apparatus according to any preceding claim, wherein at least one of the generator portion and the turbine portion are also adapted to be engaged with a portion of said guidebase assembly.

5. An apparatus according to any preceding claim, wherein at least two of said turbine rotor, generator and support portions are releasably connected to one another, such that said two of said portions may be deployed or retrieved separately from an underwater location.

6. An apparatus according to claim 5, wherein all three of the turbine rotor, generator and support portions are releasably connected together.

7. An apparatus according to claim 6, wherein the turbine portion is connected to the generator portion, and the generator portion is connected to the support portion.

8. An apparatus according to claim 5 or claim 6, further comprising connectors for releasably connecting the portions together and for connecting the support portion to a subsea wellhead guidebase assembly.

9. An apparatus according to any preceding claim, further comprising a subsea wellhead guidebase assembly for engaging with the support portion.

10. An apparatus according to any of claims 1 to 8, further comprising at least one vertically oriented member for engaging with the support portion.

11. An apparatus according to claim 10, wherein four said vertically oriented members are provided, arranged in the corners of a quadrilateral.

12. An apparatus according to any preceding claim, wherein the support portion includes a ballast to assist in retaining the apparatus on the seabed.

13. An apparatus for generating energy from flowing water, the apparatus

comprising a turbine rotor portion for being driven by flowing water and for connecting to an energy generator portion; and a support portion for connecting to one of the turbine rotor portion and the energy generator portion; wherein at least two of said portions are adapted to be releasably connected to one another, such that said two of said portions may be deployed or retrieved separately from an underwater location, and wherein the support portion is adapted to be engaged with a portion of a subsea wellhead guidebase assembly so as to retain and anchor the apparatus in position.

14. An apparatus according to any preceding claim, wherein the generator portion is an electrical generator portion.

15. An apparatus according to any preceding claim, further comprising additional portions for interposing between the generator portion and the turbine portion.

16 An apparatus according to claim 15, wherein the additional portions comprise spacer portions for raising the effective height of the turbine portion.

17. An apparatus according to claim 15, wherein the additional portions comprise buoyancy members.

18. An apparatus according to any preceding claim, wherein the turbine portion comprises a helical vertical rotor.

19. An apparatus according to any preceding claim, further comprising means for distributing the generated energy.

20. A system for generating energy from flowing water, the system comprising: a plurality of apparatuses, each apparatus comprising a turbine rotor portion for being driven by flowing water, the turbine rotor portion being operably connected to an energy generator portion; and a support portion connected to one of the turbine rotor portion and the energy generator portion; each said support portion being adapted to be engaged with a portion of a respective wellhead guidebase assembly so as to retain and anchor the apparatuses in position; and a manifold for collecting and onwardly distributing energy generated by the apparatuses; wherein each apparatus is in communication with the manifold to allow transmission of generated energy.

21. A system according to claim 20 for generating energy from flowing water, wherein at least two of said turbine rotor, energy generator, and support portions are releasably connected to one another, such that said two of said portions may be deployed or retrieved separately from an underwater location.

22. A method of deploying the apparatus of claim 1, the method comprising the steps of:

deploying the support portion on the seabed;
deploying the generating portion on the support portion, and releasably connecting the generating portion thereto;
and

deploying the turbine rotor portion on the generating portion, and releasably connecting the generating portion thereto.

23. A method according to claim 22, wherein the support portion is deployed so as to anchor and engage with a portion of a guidebase assembly secured to the seabed.
24. A method according to claim 22, further comprising the step of deploying a guidebase assembly and securing the assembly to the seabed prior to deploying the support25. A method according to claim 22, wherein the support portion is deployed so as to anchor and engage with a portion of a Christmas tree which is itself engaged with a guidebase assembly secured to the seabed.
26. An apparatus for generating energy from flowing water as described herein and with reference to Figs. 1 to 3.

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Your Ref. : Subsea Energy PA03

Date : 09–Dec–2009

PATENT APPLICATION NUMBER 0921513.8

We have received your request for grant of a patent and recorded its details as follows :

Filing Date*	:	09–Dec–2009	
Earliest Priority Date	:		
Applicant(s)/contact point	:	Anthony Thomas Morse, John Queenan	
Application Fee Paid	:	No	Must be paid by 09–Dec–2010
Description (number of pages)	:	5	
	:		
Claims (number of pages)	:	2	
Drawings(number of pages)	:	5	
Abstract (number of pages)	:	1	
Statement of inventorship (Form 7)	:	No	
Request for search (Form 9A)	:	No	Must be submitted by 09–Dec–2010
Request for examination (Form 10)	:	No	
Priority documents	:	None	
Other attachments received	:		

Please quote the application number in the heading whenever you contact us about this application.

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* This filing date is provisional. We may have to change it if we find during preliminary examination that the application does not satisfy section 15(1) of the Patents Act 1977 or if we re–date the application to the date when we get any later filed documents.

UK Patent Specification

Subsea Energy Magnetic Locking System Apparatus

A. T. Morse & J. Queenan

Abstract

Subsea Energy Magnetic Locking System Apparatus

The present invention relates to a remotely operated underwater magnetic locking and holding system. It primary use will be in the marine renewables, subsea oil and gas, oceanographic, and hydro power industries.

This invention relates to a subsea or underwater deployed, seabed mounted magnetic locking system that can be activated or deactivated remotely. Activation of the system is either by electrical pulse or pneumatic pulse. It is not operated using conventional electromagnetism.

An apparatus which includes a seabed mounted base structure onto which an underwater frame structure is locked into place using electrically or pneumatically excited permanent magnetic technology. The frame structure is comprised of a set of magnet modules and subsea landing pistons arranged in such a way to allow more simple connection in an underwater environment.

Figure 6 to accompany abstract.

Title: Subsea Energy Magnetic Locking System Apparatus

Field of invention

The present invention relates to a remotely operated underwater magnetic locking and holding system apparatus that can be used to connect components together either permanently or temporarily. It primary use will be in the marine renewables, subsea oil and gas, oceanographic, and hydro power industries.

Background

Conventional underwater locking systems are known.

Conventional subsea locking systems are designed to lock and secure various devices to the seabed. Typically, these devices operate either mechanically or hydraulically.

This invention relates to a subsea or underwater deployed, seabed mounted externally excited permanent magnetic locking system apparatus that can be activated or deactivated remotely. Activation of the system is either by electrical pulse or pneumatic pulse, as opposed to the use conventional electromagnetic technology. The main components of the apparatus are the underwater frame structure and the underwater base structure.

Statement of invention

The present inventors have appreciated that conventional subsea and underwater locking devices have shortcomings. The present invention has been devised in light of this appreciation. The present invention provides modular flexibility in order to deploy different modules onto the seabed or underwater structures, and permanently or temporarily lock these structures and modules into place. A subsea landing piston is included in the apparatus, to allow for slow make up of frame and base components as they are being connected underwater.

According to a first aspect of the present invention, there is provided a seabed or underwater magnetic locking system operable as at least an electrically or pneumatically energised unit, the apparatus comprising:

> a first arrangement of a magnetic locking device incorporated into an underwater landing frame structure: and,
>
> a second arrangement of modular electrical power connectors linked to the magnetic locking device, either internally to, or externally arranged around the magnets.

a third arrangement termed the subsea landing piston, which allows for a slow connection speed when the landing frame is lowered to the sea bed or river bed base structure.

a fourth arrangement whereby one of the first, second and third arrangements can be configured into an underwater landing frame structure for deployment.

a fifth arrangement whereby the fourth arrangement would lock on to a base structure.

Advantages

The present invention simplifies the technology required for the connection of underwater structures together.

The present invention allows for a lower cost installation vessel to be used for the operation.

The present invention allows for a vessel of opportunity to be utilised for the subsea or underwater connection operation.

The present invention allows the magnetic locking system to be used by diver and, or Remotely Operated Vehicle (ROV).

The configuration of the components in segments or modules allows for the apparatus to be deployed and, or, removed in stages. The main components are the underwater landing frame structure and the underwater base structure.

The present invention allows for multiple magnetic locking devices to be deployed together in one underwater landing frame structure. Either single or multiple magnets may be used in one magnetic connector.

The configuration of the components allows for the site to be completely decommissioned, leaving no infrastructure in place.

The apparatus will be modular in nature and besides the primary function of locking two mechanical components together, it will also have the ability to allow simple removal and repositioning of the following;

Electrical power cables, connectors and umbilicals
Hydraulic power cables, connectors and umbilicals
Signal and fibre-optic cables
Chemical lines and umbilicals
Underwater mechanical tools
Underwater Remotely Operated Vehicle tooling
Underwater sensors
Underwater cameras
Underwater explosives and cutting tools

Introduction to drawings

An example of the invention will now be described solely by way of referring to the accompanying drawings in which:

- figure 1 shows a first perspective of the underwater frame structure;
- figure 2 is a perspective representation of the underwater base unit;
- figure 3 is a side view representation of figure 1;
- figure 4 is a side view representation of figure 2;
- figure 5 is a perspective representation of the underwater frame structure deployment tool;
- figure 6 is a perspective representation of the complete frame and base system with magnetic locking system included;
- figure 7 is a perspective representation of an underwater power connector incorporated into the magnetic locking connector;
- figure 8 is a side cut-away view of an underwater power connector incorporated into the magnetic locking connector.

Detailed description

Figure 1 shows the fully constructed underwater landing frame structure. It is comprised of a series of individual magnet segments 1 which are attached to the top of a tubular subsea piston structure 2. The subsea piston structure allows for the underwater landing frame to slow its descent as it is lowered over the corresponding metal plate on the underwater base structure 4.

Incorporated in the underwater landing frame structure are also guide tubes 3, and structural cross members 6. The underwater frame structure may be arranged in other ways, according to the requirements of the system being deployed. For example, a variety of flanged and metal plate orientations may be used. Materials used may include non-metallic components, such as fibreglass, carbon fibre materials and Kevlar materials.

There may be a single magnet module to lock the frame or structure in place, or a multiple of magnet modules utilised in a single frame.

Figure 2 shows the fully constructed underwater base unit. This structure may be constructed from tubular and, or box steel members. Steel plate structural members may also be included. Materials used will also vary according to the use required.

Incorporated in the underwater base unit are four vertical posts. These posts will either function as guide posts 5 for the upper frame structure or magnetic lock plates 4 to match the upper magnets 1 in the upper frame structure.

The underwater base unit, as in figure 2, would be attached to a suitable gravity structure. The underwater base unit and gravity structure would then be deployed to the seabed. The fully constructed apparatus will be placed such that it can act as a base unit for deploying the underwater frame structure onto.

Once in position on the seabed there would be the option of attaching one, or several, guidewires to the underwater base structure. Each guidewire would attach to the top of guidepost 5. The guidewire attachments are of known design. The top of the guidewires would then be attached to the vessel or fixed surface structure being used for the deployment operation. Depending upon the site conditions there may be the option of not using the guidewire method.

Once the underwater base structure was secure and the guidewires attached then the underwater frame structure would be deployed. The guidewires are positioned inside guide tubes 3.

Figure 5 shows an example of a running tool to be used on top of the underwater frame structure. This running tool has magnets 7 for locking on to the top of the underwater frame magnets, and guide funnels for 8 for placing over the guide tubes 3, and associated guidewires. It also makes the connection between the control umbilical, used to operate the magnets.

The running tool would be magnetically locked to the top on the underwater frame structure and the whole assembly run to the sea or river bed, using the guidewires to assist in accurate deployment to the base structure.

The running tool would be lowered using a suitable cable from the surface vessel. Lifting points 9, of various known designs, are attached to the running tool. Attached to this cable would be the control umbilical for the magnets.

As the underwater frame structure reaches the base unit, the guide tubes and subsea piston tube will commence running down over posts 4 and 5. The magnet lock plate on the top of post 4 will immediately slow down the underwater frame structure as water will be forced out of the holes in the subsea piston structure 2, due to the piston effect of the magnet lock plate moving up the inside of the subsea piston 2. The holes in 2 can be sized according to the landing speed required. The subsea piston structure is acting like a motion compensation device at this point.

An option with the magnet module 1 in the underwater frame structure will be to incorporate an electrical power wet connect feature. This can be made integral to the magnet module, or attached to the side of the magnet module. Figures 7 and 8 indicate different views of this option. The electrical wet connectors are indicated as 10 and 11. Besides electrical power connectors other connectors of known design could be used, for example fibre optic signal cables.

Once the underwater frame structure is located on the base structure then the magnets would be energised by using either an electric pulse or by a pneumatic pressure pulse. Several magnets would be controlled from one power or pneumatic source. Magnets can be energised at different set electrical voltages, or different pneumatic pressures.

Following confirmation that the underwater frame structure was locked onto the underwater base structure (by using an overpull) the magnets in the running tool would be unlocked. The running tool would then be retrieved to surface, followed by retrieving the guidewires by known methods.

The fully constructed segmented apparatus and associated equipment, as shown in figure 6, can be parametrically scaled, as required.

Drawings

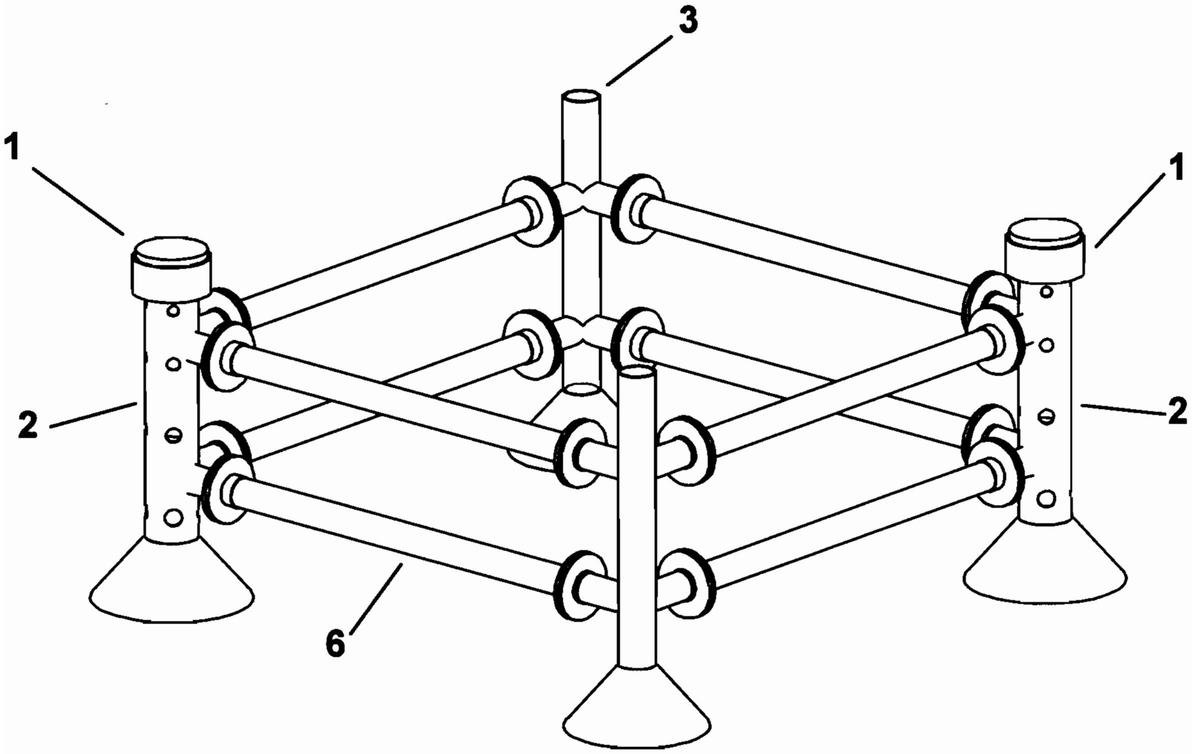

FIGURE 1

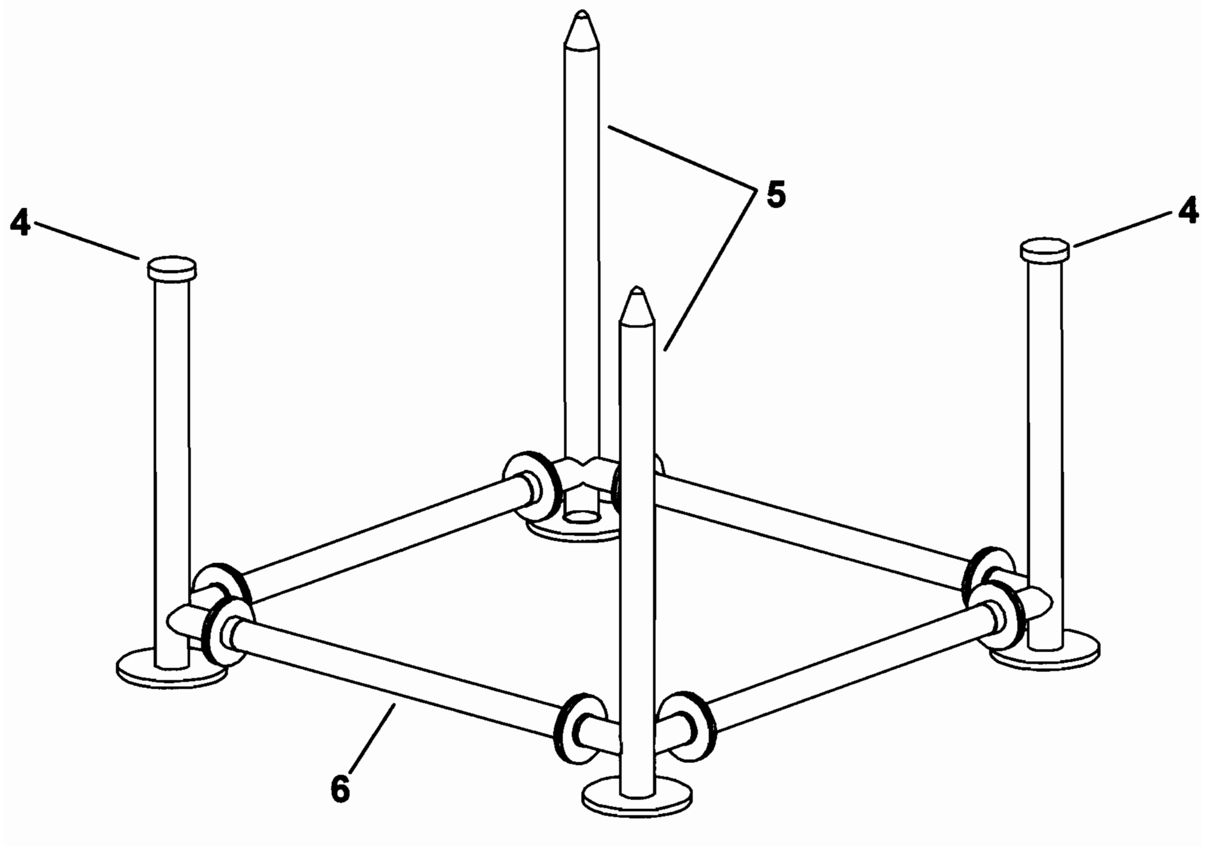

FIGURE 2

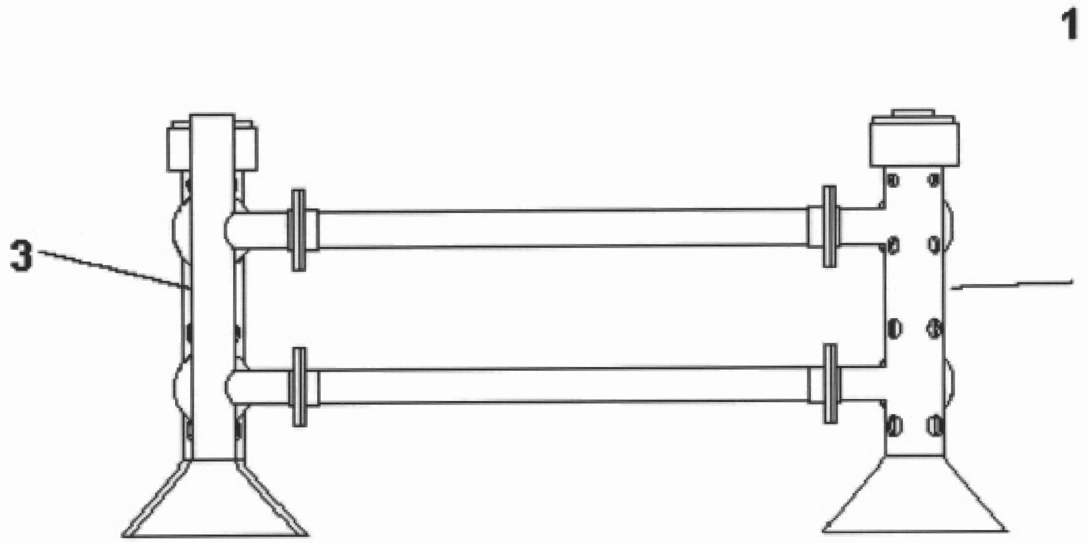

FIGURE 3

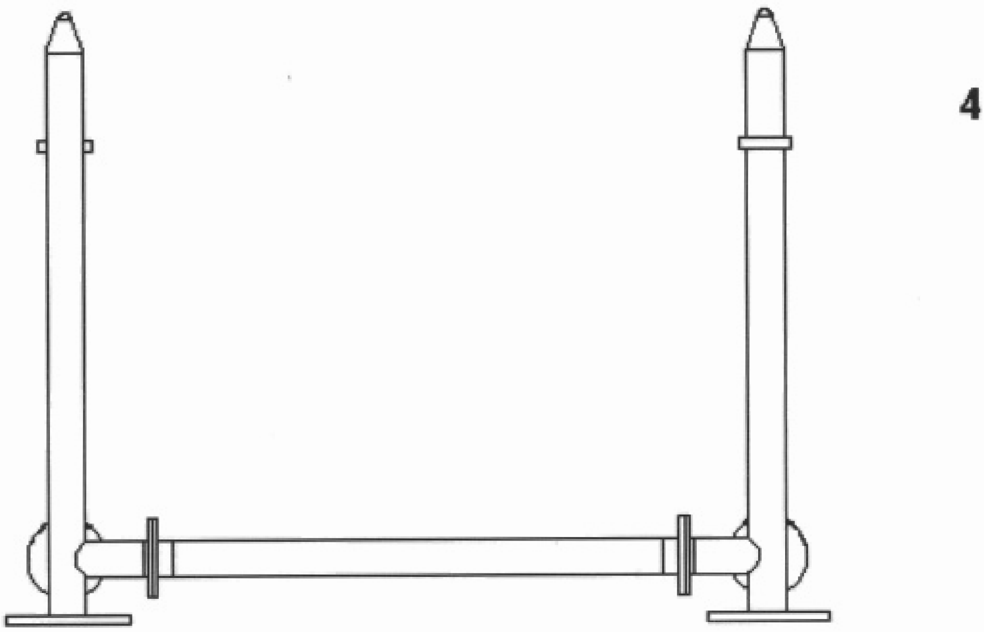

FIGURE 4

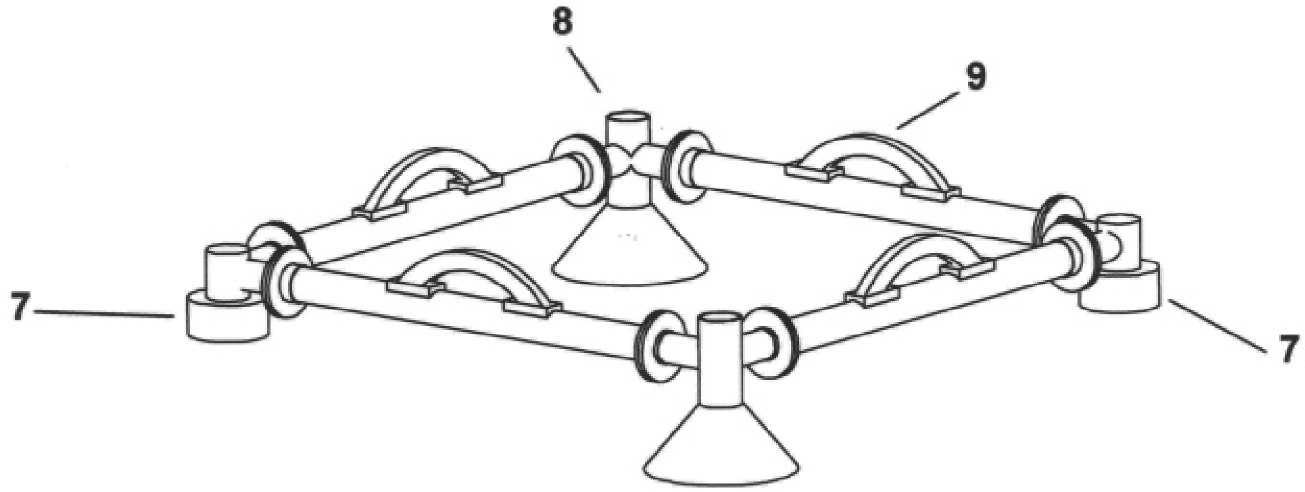

FIGURE 5

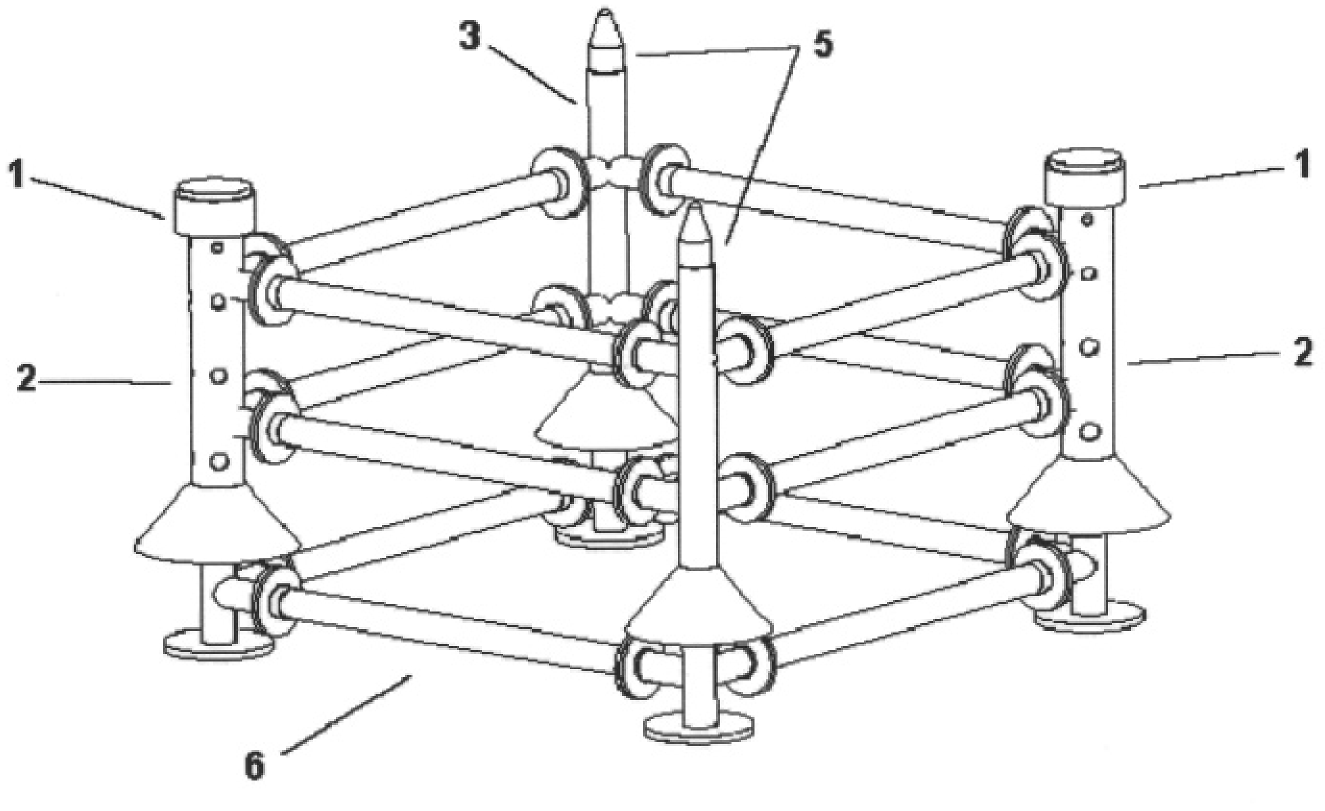

FIGURE 6

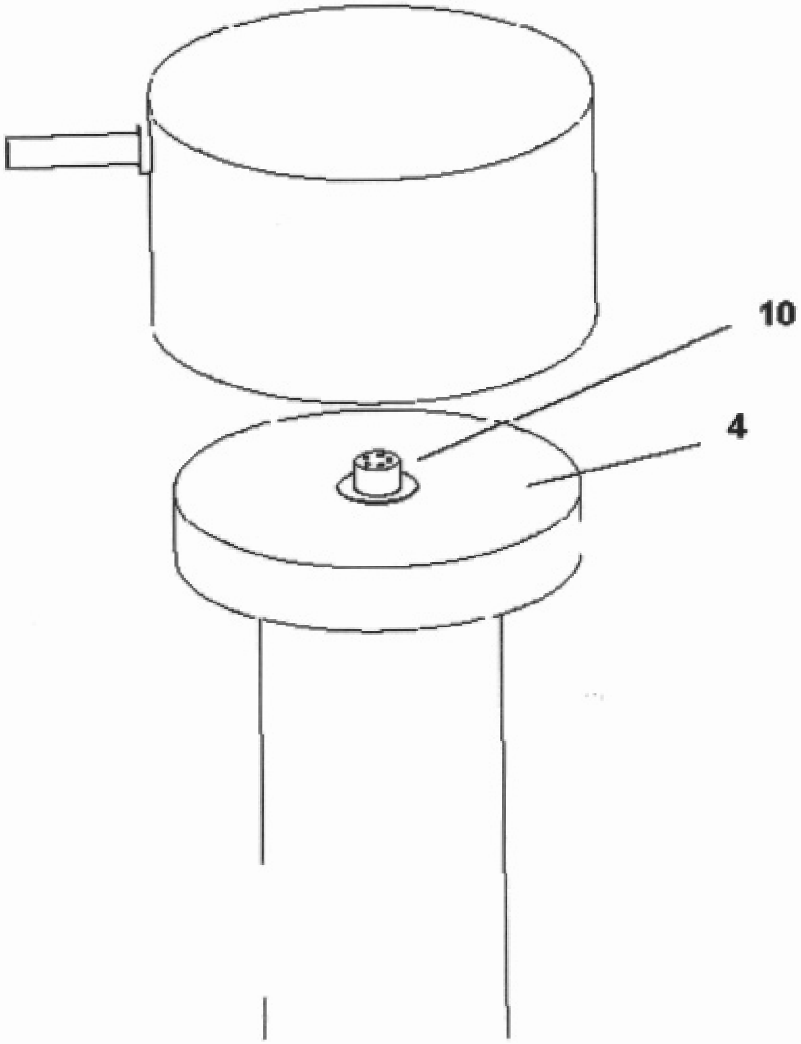

FIGURE 7

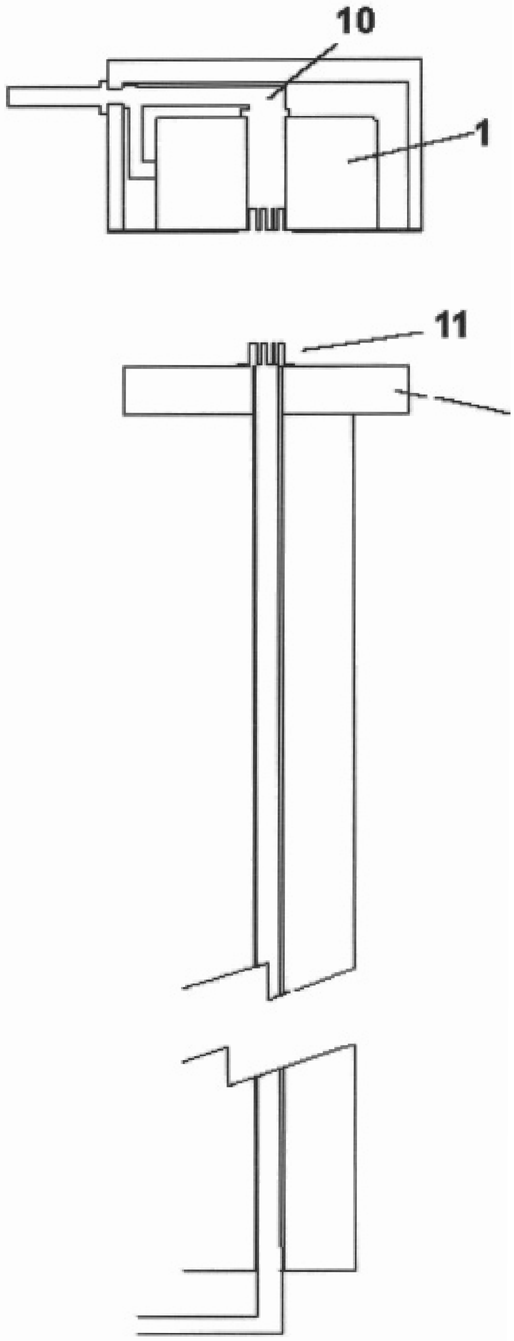

FIGURE 8

Claims

1. A modular subsea or underwater deployed, electrically or pneumatically excited permanent magnet locking system apparatus that can be used to connect components together either permanently or temporarily.

2. An apparatus, according to claim 1, that is comprised of a frame structure and base structure.

3. An apparatus, according to claim 1, that can be constructed of numerous sizes and material specifications, and can be parametrically scaled.

4. An apparatus, according to claim 1, that can be activated or deactivated remotely.

5. An apparatus, according to claim 1, that can be activated or deactivated by either electrical pulse or pneumatic pulse.

6. An apparatus, according to claim 1, that can be integrated with underwater mateable electrical power and, or signal cables.

7. An apparatus, according to claim 6, that can be integrated with underwater mateable hydraulic power and, or signal cables.

8. An apparatus, according to claim 6, that can be integrated with underwater mechanical, diver or Remotely Operated Vehicle tooling.

9. An apparatus, according to claim 2, that can include a manual over ride device for emergency locking or unlocking.

10. An apparatus, according to claim 2, that can be independently deployed and, or, retrieved.

11. An apparatus, according to claim 2, that has all magnetic modules and components mounted within an underwater frame structure.

12. An apparatus, according to claim 11, whereby the frame structure might hold components of wave or tidal rotors, equipment, and / or generators.

13. An apparatus, according to claim 11, whereby the frame structure might hold components of subsea oil and gas equipment.

14. An apparatus, according to claim 11, whereby the frame structure might hold components of river hydro rotors, equipment and, or / generators.

15. An apparatus, according to claim 11, whereby the frame structure will lock onto a base structure of specific design.

16. An apparatus according to claim 1, in which the apparatus can be fitted to, and deployed from a non-specific vessel of opportunity.

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AMENDMENT

Your Ref. : Subsea Energy PA04 Date : 01–Feb–2010

PATENT APPLICATION NUMBER 1001122.9

We have received your request for grant of a patent and recorded its details as follows :

Filing Date*	: 25–Jan–2010	
Earliest Priority Date	:	
Applicant(s)/contact point	: Anthony Thomas Morse, John Queenan	
Application Fee Paid	: No	Must be paid by 25–Jan–2011
Description (number of pages)	: 5	
	:	
Claims (number of pages)	: 2	
Drawings(number of pages)	: 7	
Abstract (number of pages)	: 1	
Statement of inventorship (Form 7)	: No	
Request for search (Form 9A)	: No	Must be submitted by 25–Jan–2011
Request for examination (Form 10)	: No	
Priority documents	: None	
Other attachments received	: Advantages & Introduction to drawings included in description	

Please quote the application number in the heading whenever you contact us about this application.

If you have any queries about the accuracy of this receipt please phone the Document Reception Manager on +44 (0) 1633 814570. For all other queries, please phone our Central Enquiry Unit on 08459 500 505 if you are calling from the UK, or +44 1633 813930 if you are calling from outside the UK. Or email enquiries@ipo.gov.uk.

* This filing date is provisional. We may have to change it if we find during preliminary examination that the application does not satisfy section 15(1) of the Patents Act 1977 or if we re–date the application to the date when we get any later filed documents.

UK Patent Specification

Subsea Energy Production Apparatus

A. T. Morse & J. Queenan

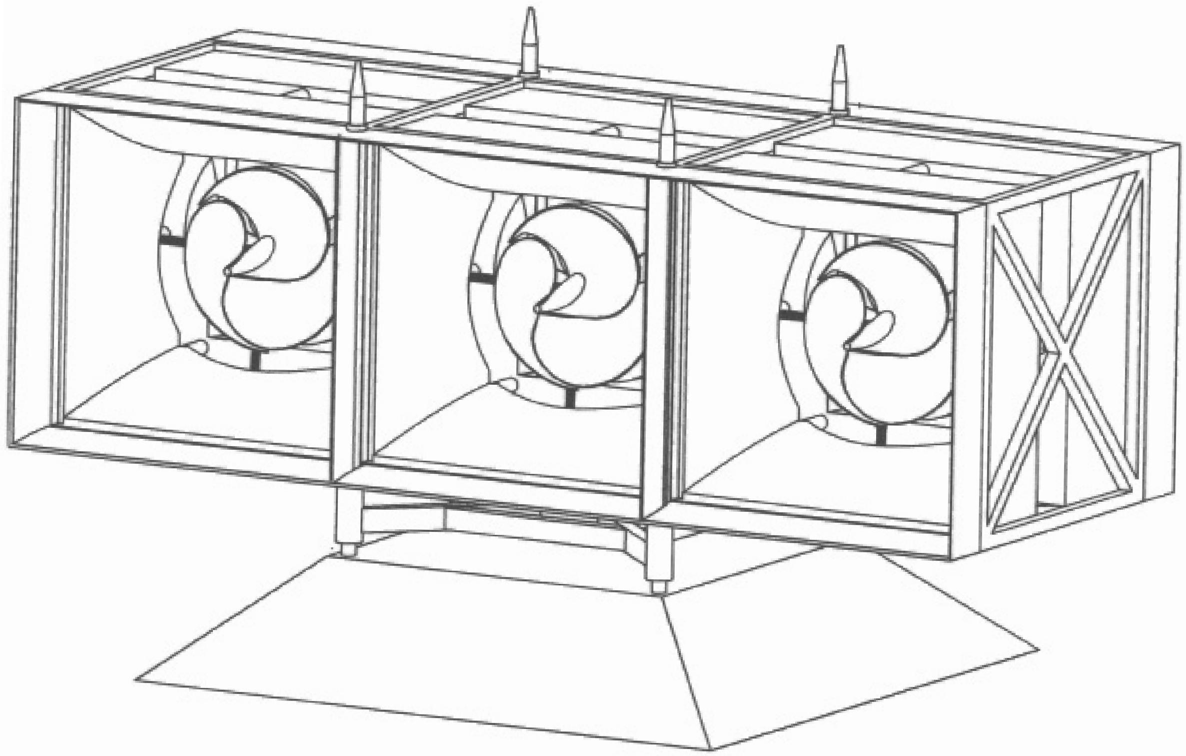
Abstract

Subsea Energy Production Apparatus

This invention relates to a modular subsea energy production apparatus that is deployed underwater. It can be sea bed or river bed mounted and generates electricity from the kinetic energy in flowing water. Its primary use will be in the marine renewables, subsea oil and gas, oceanographic and hydro power industries.

An apparatus which includes a sea bed or river bed mounted base structure onto which an underwater frame structure is locked into place. The frame structure can typically include a twin set of rotors and generators linked together by a shaft, gearbox and, or a set of flexible shafts. A power cable is used to export electricity.

Figure 3 to accompany abstract.



Title: Subsea Energy Production Apparatus

Field of invention

The present invention relates to a subsea energy production apparatus that converts kinetic energy from flowing water into electrical energy. This can be tidal and ocean currents, or river flows. Its primary use will be in the marine renewables, subsea oil and gas, oceanographic, and hydro power industries.

Background

Conventional underwater kinetic energy extraction systems are known.

Conventional horizontal axis systems are designed to extract energy from flowing water (either river, tidal flows or ocean currents) by using propeller type rotor blades. The rotor, or turbine, blade is directly attached via a solid shaft to either an electrical or hydraulic generator. This present invention describes a new type of rotor design and an improved way of linking several rotors and generators together, by using flexible shaft technology.

This apparatus uses information and technology descriptions from existing UK patent, number GB2400632, filed 16th April 2004. This Patent was filed by one of the inventors named in this application.

Statement of invention

The present inventors have appreciated that conventional horizontal axis devices have shortcomings, especially with regard to the rotor design and also the method of connection rotor to generator. The present invention has been devised in light of this appreciation. The present invention provides modular flexibility in order to deploy different modules onto the seabed or underwater structures, and permanently or temporarily lock these structures and modules into place.

According to a first aspect of the present invention, there is provided a seabed or underwater kinetic energy conversion system operable as at least an electricity production system, the apparatus comprising:

> a first arrangement of a single, or set of horizontal axis rotors of a new design incorporated into an underwater landing frame structure: and,
>
> a second arrangement of modular generator units that can be independently connected to the rotor structure.

a third arrangement whereby a plurality of rotor frame structures and generators may be connected together with flexible shaft technology.

a fourth arrangement whereby one of the first, second and third arrangements can be configured into an underwater structure for deployment.

a fifth arrangement whereby the fourth arrangement would lock on to a base structure.

Advantages

The present invention simplifies the technology required for the extraction of kinetic energy from flowing water.

The present invention allows for a lower cost installation vessel to be used for the operation.

The present invention allows for a vessel of opportunity to be utilised for the subsea or underwater deployment operation.

The present invention allows the system to be deployed by diver and, or Remotely Operated Vehicle (ROV).

The configuration of the components in segments or modules allows for the apparatus to be deployed and, or, removed in stages. The main components are the underwater landing frame structures (holding the rotors and generators), and the underwater base structure.

The present invention allows for multiple modules to be deployed together onto one underwater base structure. Either single or multiple rotors may be used in one landing frame structure.

The configuration of the components allows for the site to be completely decommissioned, leaving no infrastructure in place.

The apparatus will be modular in nature and besides the primary function of converting the kinetic energy in flowing water to electrical energy, it will also have the ability to allow simple connection, removal and repositioning of the following;

Electrical power cables, connectors and umbilicals
Hydraulic power cables, connectors and umbilicals
Signal and fibre-optic cables
Underwater mechanical tools
Underwater Remotely Operated Vehicle tooling
Underwater sensors
Underwater cameras

Introduction to drawings

An example of the invention will now be described solely by way of referring to the accompanying drawings in which:

- figure 1 shows a front view of the underwater frame structure with triple sets of twin rotors and generators incorporated, mounted on a base system ;
- figure 2 is a side view representation of figure 1;
- figure 3 is a perspective representation of the apparatus;
- figure 4 is a front view representation of the rotor blade design;
- figure 5 is a side view representation of the rotor blade design;
- figure 6 is a rear view of the rotor blade design;
- figure 7 is a perspective representation of the rotor design ;
- figure 8 is a front view of the underwater frame structure with the option of two sets of twin rotors and generators incorporated between the rotor modules and connected with flexible shafts, all mounted on a base system;
- figure 9 is a front view of the underwater frame structure with the option of three sets of twin rotors and generators incorporated above the rotor modules and connected with flexible shafts, all mounted on a base system;
- figure 10 is a side view representation of figure 9;

Detailed description

Figure 1 shows an example of the fully constructed apparatus. It is comprised of a series of individual rotor and generator modules 1, which are connected together as three sets as in this example. Single or Multiple modules, 1, may be linked together, depending upon site conditions and power generation requirements.

Incorporated in the individual modules also guide tubes 2, and structural cross members 3. The underwater frame structure may be arranged in other ways, according to the requirements of the system being deployed. For example, a variety of flanged and metal plate orientations may be used. Materials used may include non-metallic components, such as fibreglass, carbon fibre materials and Kevlar materials.

There may be a single rotor in a module for uni-directional flow such as in a river, or a multiple of rotors and generators utilised in a single frame, such as in a tidal environment.

Figure 1 also shows a fully constructed triple module on an underwater base unit. This base structure may be constructed from tubular and, or box steel members. Steel plate structural members may also be included. Materials used will also vary according to the use required.

Incorporated in the underwater base unit are four vertical guideposts, 6. These posts will either function as guide posts for the upper modules or as segments. This design helps minimise the risk of marine strike injury through the reduction of leading edges on the blade.

Figure 5 also depicts how the rear surfaces of the rotor flow capture segments are curved over to face the incoming flow, 9. This curved portion, or segment wing tip, can be of varying thickness and variable angle of attack to the oncoming water flow. An option would be to make this part of the flow capture segment a pressure adjustable system, to maximise flow capture under variable water speeds.

Figure 8 shows a front view of two underwater rotor / generator modules linked to a third housing containing a dedicated generator pack, 11. This option allows for a larger generator to be used, by driving it with two rotors as opposed to a single rotor. The generator, 11, would be connected to the rotors by utilising a solid rotating shaft or a flexible rotating shaft. An integral gearbox option could be used on the ends of either type of shaft, or the gearbox or gear head may be part of the generator module.

Figure 9 shows a front view of three underwater rotor / generator modules linked to a fourth module containing a dedicated generator pack, 12. This option allows for a larger generator to be used, by driving it with three rotors as opposed to a single or dual rotors. The generator, 12, would be connected to the rotors by utilising a solid rotating shaft or a flexible rotating shaft. An integral gearbox option could be used on the ends of either type of shaft, or the gearbox or gear head may be part of the generator module.

Figure 10 shows a side view of Figure 9. The generators, 13, are attached to the twin blade rotors by using a set of twin solid or flexible steel shafts. An integral gearbox option could be used on the ends of either type of shaft, or the gearbox or gear head may be part of the generator module. An option would be to make this generator part, 13, of the system retrievable, without the need to remove each of the underwater rotor / generator modules.

The fully constructed segmented apparatus and associated equipment, as shown in figure 3, can be parametrically scaled, as required.

The fully constructed segmented apparatus and associated equipment, as shown in figure 3, can be also attached to a floating structure such as a boat or dedicated barge.

The fully constructed segmented apparatus and associated equipment, as shown in figure 3, can be attached to a rigid structure such as a bridge span or the pillars of a bridge.

The fully constructed segmented apparatus and associated equipment, as shown in figure 3, can be covered with a protection mesh to prevent ingress of debris or underwater organisms such as fish.

locations where power cables and locking mechanisms may be incorporated.

The underwater base unit, 4, as in figure 1, would be attached to a suitable gravity structure, commonly made from concrete or steel. This may also contain ballast. The underwater base unit and gravity structure would then be deployed to the seabed. The fully constructed apparatus will be placed such that it can act as a base unit for deploying the rotor / generator modules onto.

Once in position on the seabed there would be the option of attaching one, or several, guidewires to the underwater base structure, to aid in deployment operations. Each guidewire would attach to the top of guidepost 6. The guidewire attachments are of known design. The top of the guidewires would then be attached to the vessel or fixed surface structure being used for the deployment operation. Depending upon the site conditions there may be the option of not using the guidewire method.

Once the underwater base structure was secure and the guidewires attached then the underwater rotor / generator modules would be deployed. Running tools and cables of known design would be used.

Figure 2 shows a side view on one of the underwater rotor / generator modules on the base structure. The twin rotors are shown, 4, with a set of individual generators, 7, directly attached to the rear of each rotor blade arrangement. Internal to each module will be a set of deflector plates, 8, the purpose of these will be to help direct the water flow directly onto the rotor or turbine blades. The deflector plates may, or may not, have side openings in them to allow for the egress of water after it has passed over the rotor blades. The deflector plates may, or may not, extend beyond the structural cross members, 3, of each individual module. The deflector plates may, or may not, be pressure flexible and therefore capable of automatically adjusting themselves to the velocity of the water flow, in order to influence the rotational speed of the rotor blade

Figure 3 shows a perspective view of Figure 1. It shows how multiple underwater rotor / generator modules can be linked together, in this case it depicts three modules. The modules can be linked horizontally or vertically, or a combination of both. Single modules are also possible.

Figures 4 to 7 depict the new rotor blade / turbine blade design. Figure 5 shows a side view of the rotor blade. The design addresses the shortcomings of traditional propeller type rotor designs. Figure 5 shows the elongated nose of the rotor extending outwards into an angled set of individual flow capture segments. Three, or more flow capture segments, 4, can be linked together on the central cone to form the complete rotor blade system. The central cone taper angle can be modified to suit underwater flow conditions and power output requirements. Each segment is shaped to maximise flow across the whole surface area of the rotor blade. The elongated nose reduces abrupt back pressure effects and aids deflection of the flow towards the outer diameter of the flow capture

Drawings

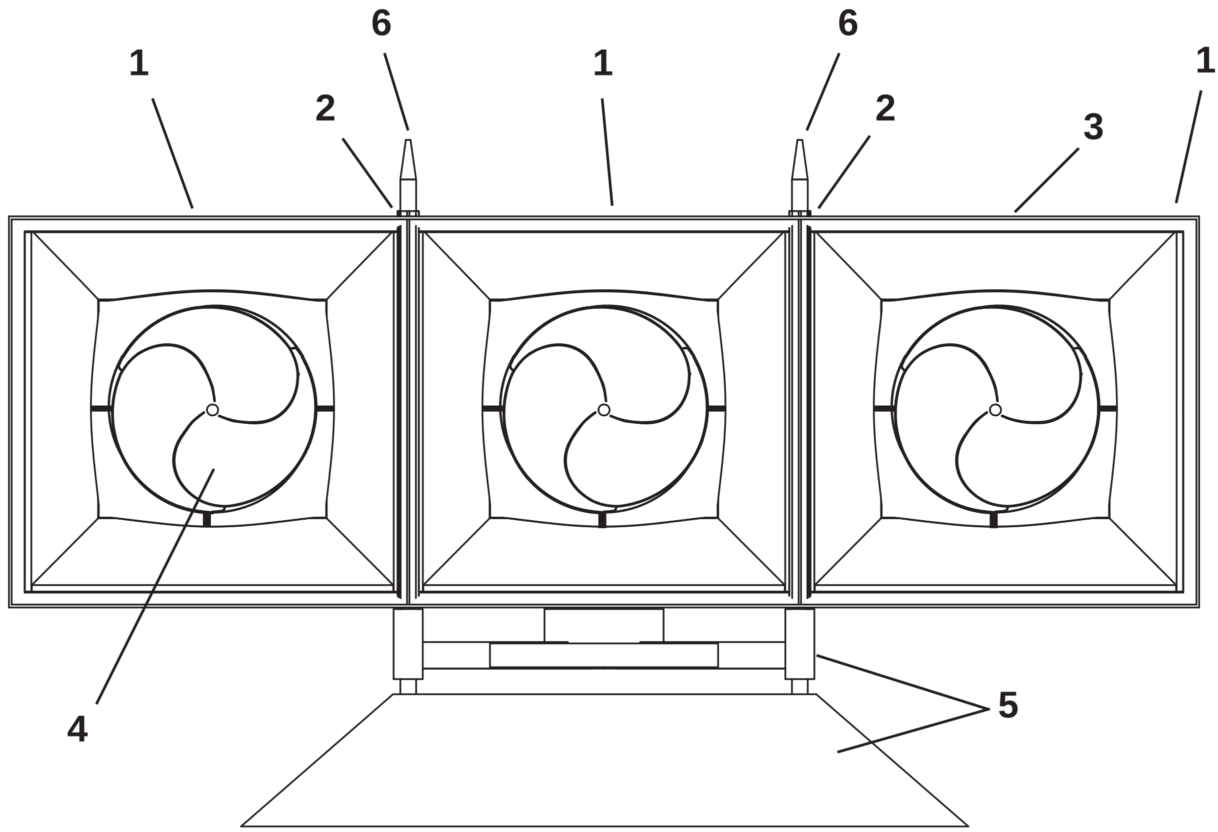


FIGURE 1

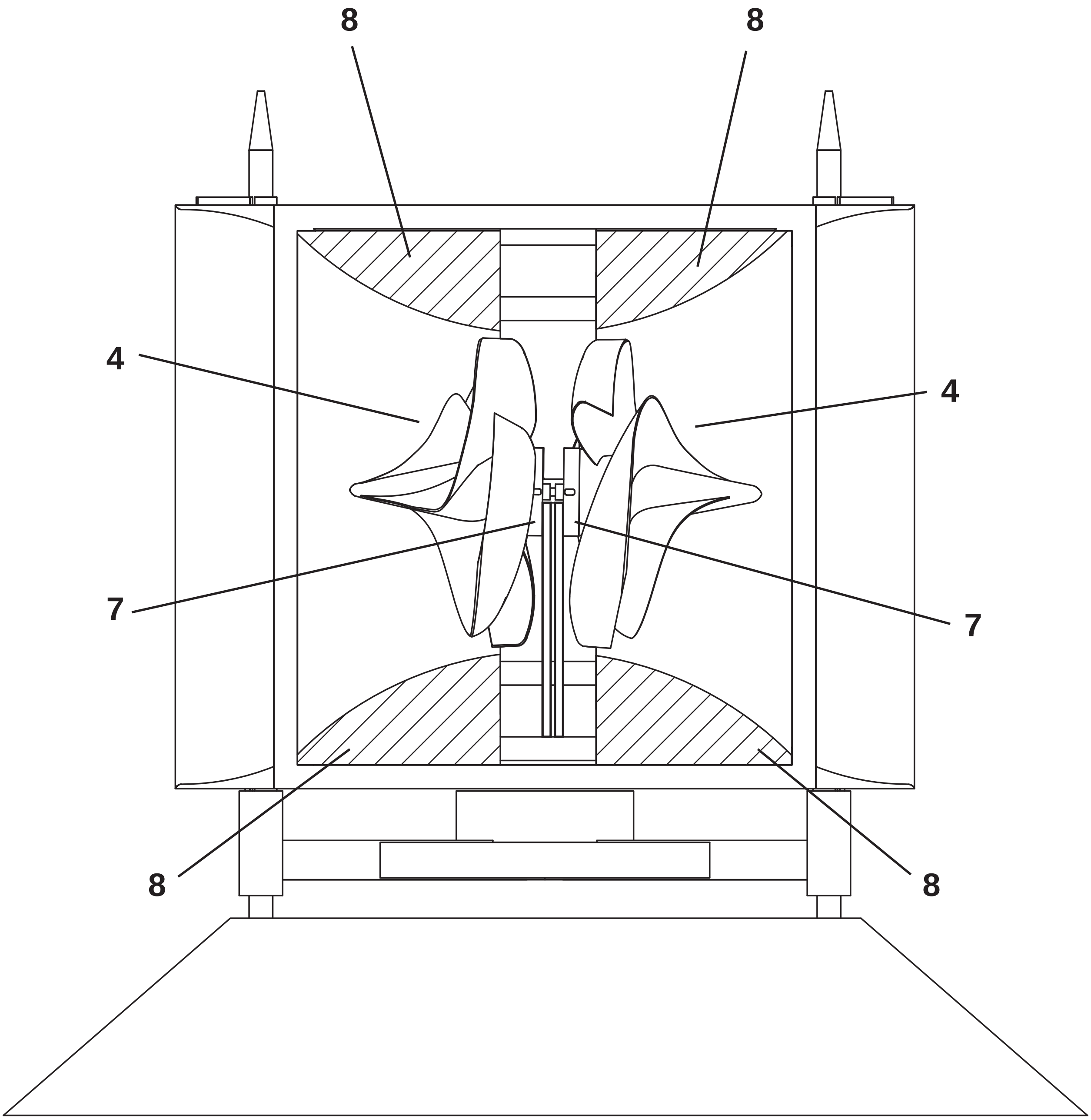


FIGURE 2

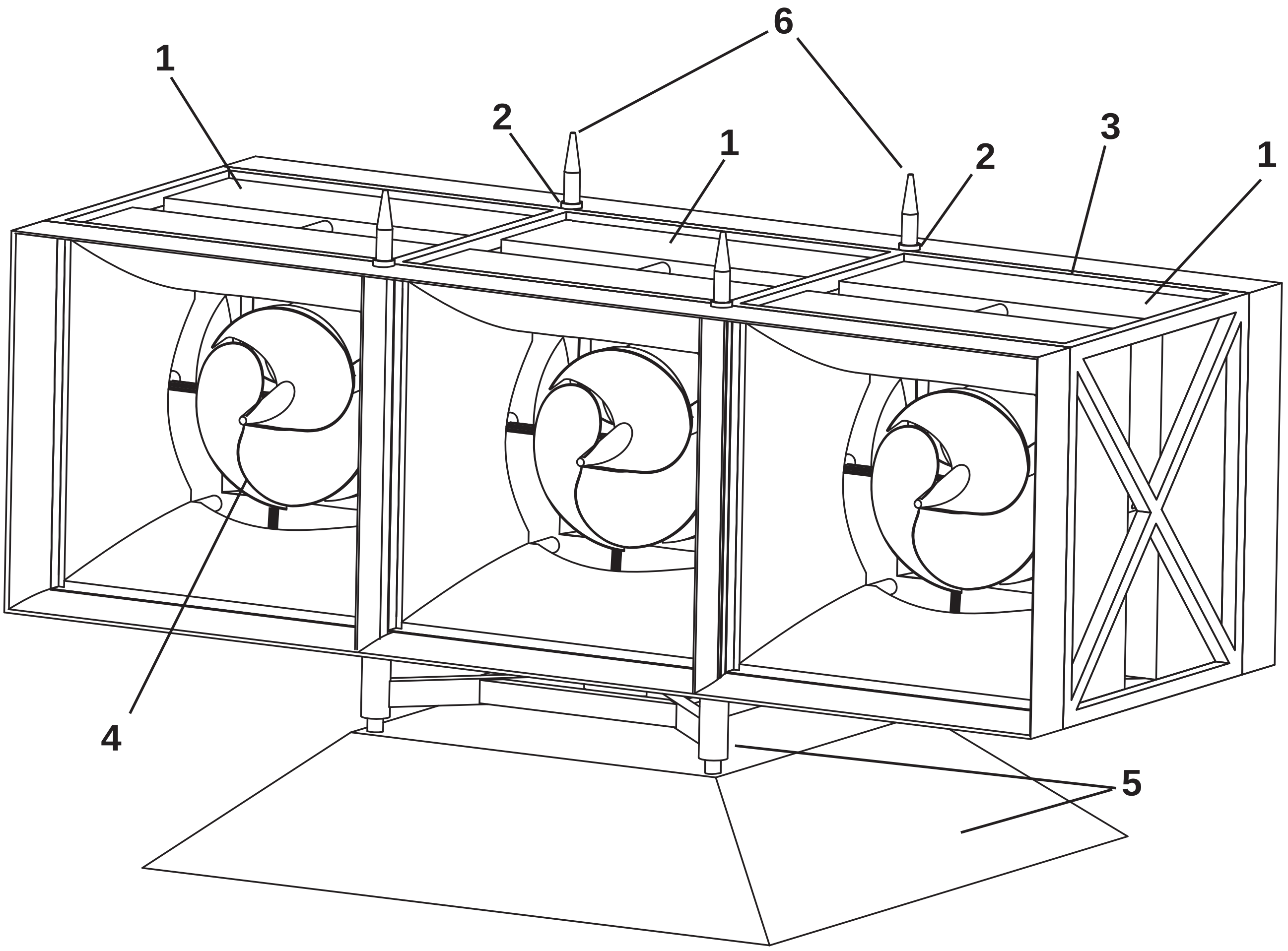


FIGURE 3

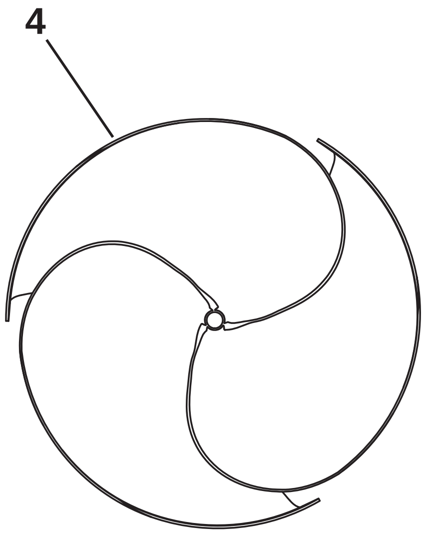


FIGURE 4

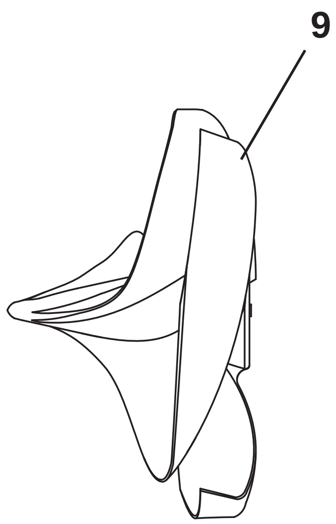


FIGURE 5

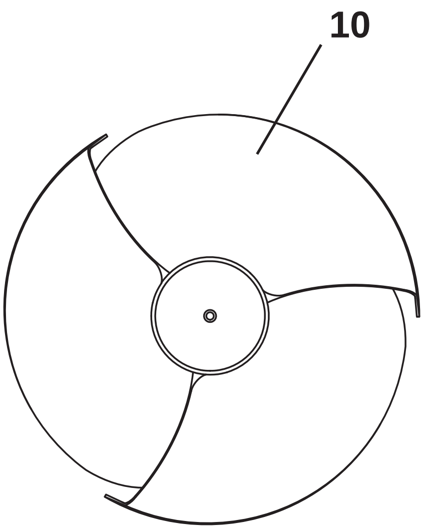


FIGURE 6

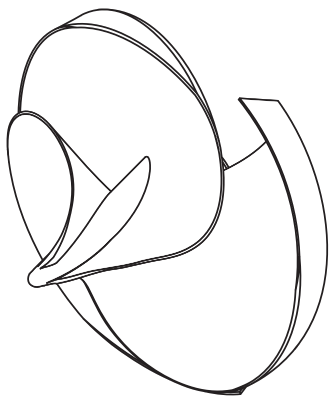


FIGURE 7

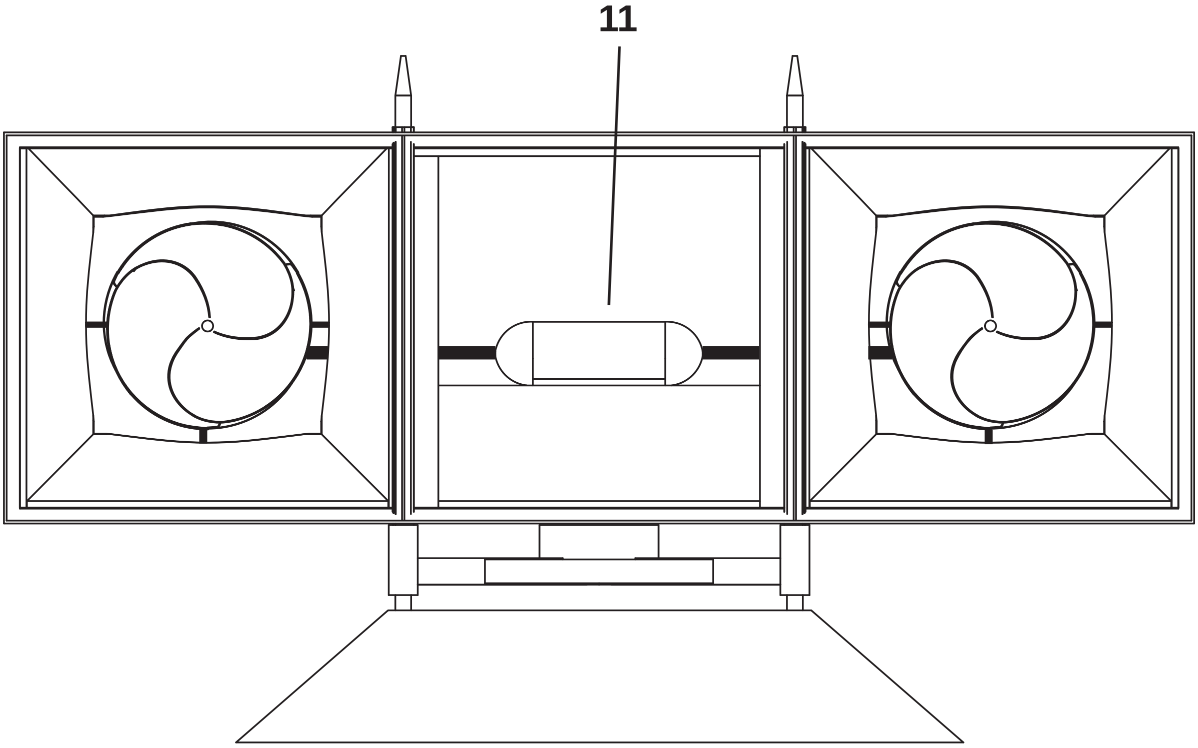


FIGURE 8

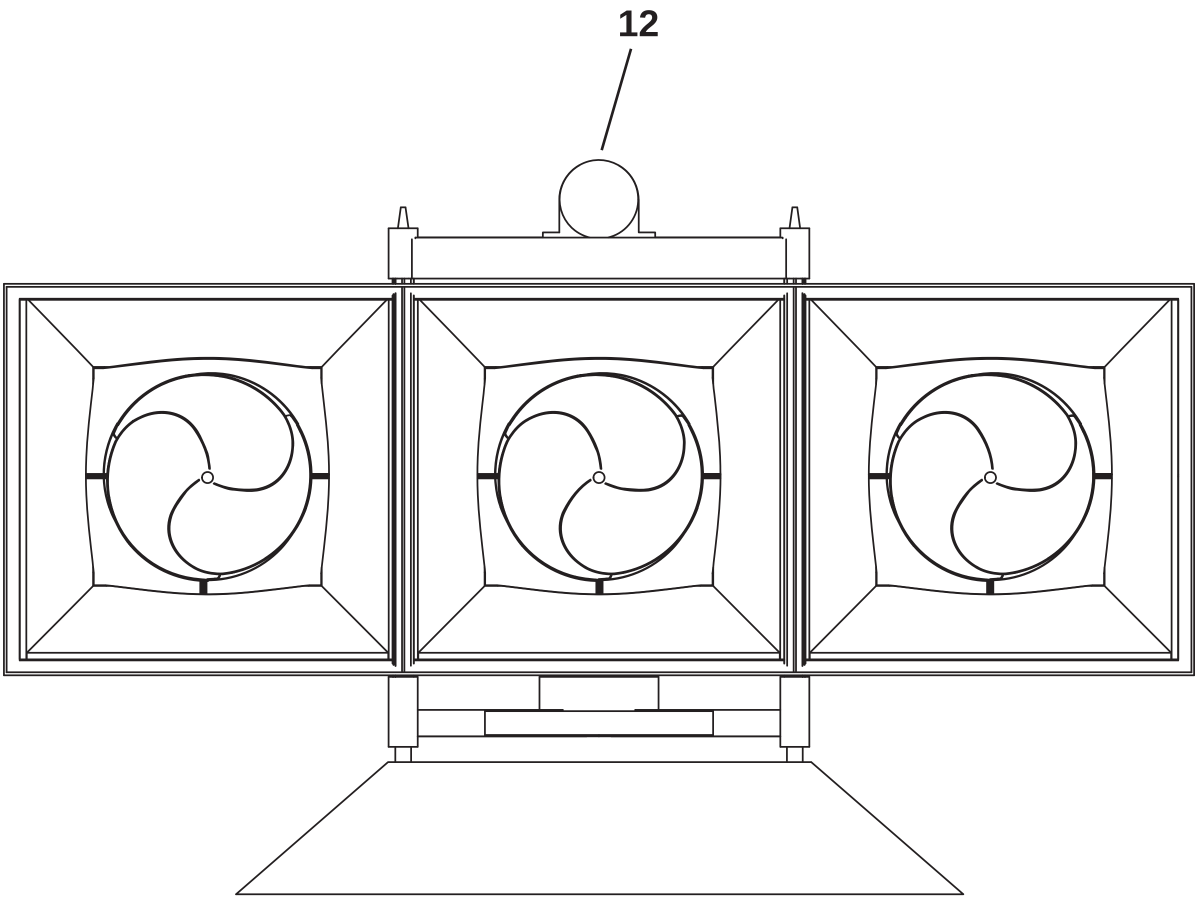


FIGURE 9

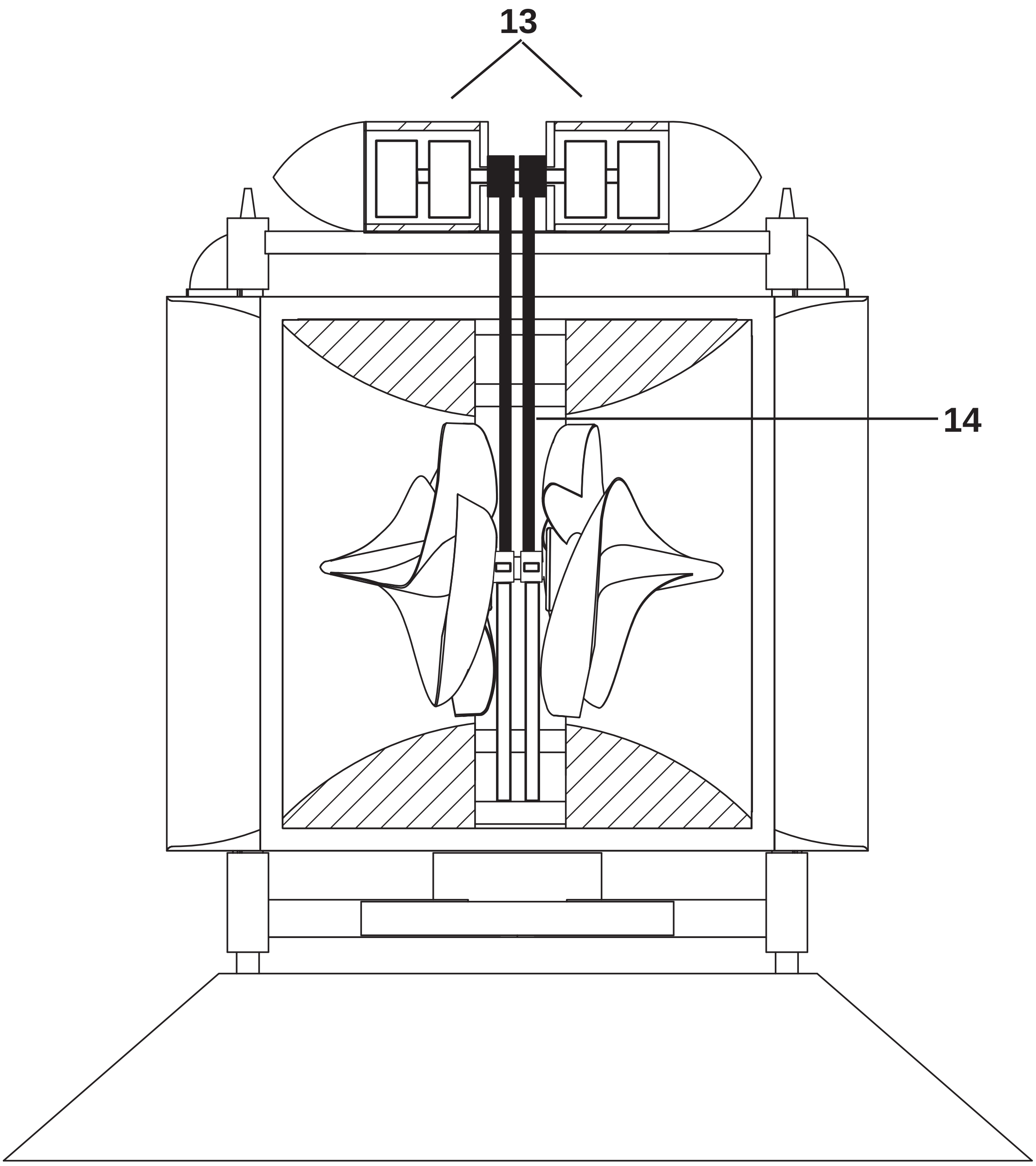


FIGURE 10

Claims

1. A subsea or underwater deployed rotor blade apparatus that is comprised of a central cone onto which a series of curved flow capture segments are attached. The elongated nose of the cone reduces abrupt back pressure effects and thus aids the deflection of water to the rear surfaces of the blade.

2. An apparatus, according to claim 1, that can be constructed of numerous sizes and material specifications, and can be parametrically scaled.

3. A subsea or underwater deployed rotor blade apparatus that produces minimal flow disturbance immediately behind the blade.

4. An apparatus, according to claim 1, whereby two rotor blades may be mounted back to back.

5. A subsea or underwater deployed rotor blade apparatus that has the rear surfaces of the flow capture segments curved over to face the direction of flow.

6. An apparatus, according to claim 4, whereby the curved portions may be of varying thickness and varying angle of attack to the direction of flow.

7. A subsea or underwater deployed rotor blade apparatus, according to claim 6, whereby the leading edges of the curved portions of the flow capture segments help minimise the risk of injury to underwater organisms.

8. A subsea or underwater deployed rotor blade apparatus that can be connected to additional blades or generators by using a flexible steel shaft.

9. An apparatus, according to claim 8, that may have gear boxes attached to one or more ends of the flexible shafts.

10. An apparatus, according to claim 8, whereby multiple flexible shafts are connected from individual rotors to one generator.

11. An apparatus, according to claim 8, whereby the generator may be detachable from the flexible shaft.

12. An apparatus, according to claim 8, whereby the generator may be located out of the water environment, but remain connected to the underwater rotor by using a flexible shaft.

13. A subsea or underwater deployed rotor blade apparatus that has flow capture segments and curved leading edges of a diameter that locates inside a set of deflector plates. The deflector plates are attached to structural members, the whole making up a modular

unit that can be deployed and positioned on a gravity base structure.

14. An apparatus, according to claim 13, whereby the position of the deflector plates are varied by the velocity of water as the flow speed increases or decreases.

15. An apparatus, according to claim 13, that may be comprised of a single module of rotors and generators, or may be comprised on a multiple of modules that are linked horizontally, vertically or diagonally.

16. An apparatus, according to claim 13, whereby the individual modules might hold a combination of underwater rotors, generators and flexible shafts.

17. An apparatus, according to claim 13, whereby the individual modules might hold a single underwater rotor, a twin underwater rotor or a generator.

18. An apparatus according to claim 1, in which the apparatus can be fitted to, and deployed from a non-specific vessel of opportunity.

Appendix Two – Project Risk Register

MESF Project - Modular Locking System
Project Risk Register - Revision 3.0

Item	Threat and Issues	Cause	Risk - Consequence	Control
1.0	**Management & Interface Threats**			
1.1	Project fails to meet objectives laid out by management team.	Insufficient priority given to achieving company objectives.	Project does not proceed and commercial potential is not realised. Future project funding is jeopardised.	Ensure necessary time and resources are allocated to enable project to proceed as planned.
1.2	Insufficient cashflow available for project.	Necessary income to company is curtailed or delayed. Company overheads increase significantly.	Project proceeds slower than scheduled or is halted pending necessary income.	Ensure adequate financial provisions made to cover basic needs of project.
1.3	Disruption to project by external business factors.	Organisational, legal, accounting or tax procedures.	Key personnel unavailable to work on project. Delay to project while disruption eliminated.	Maintain communication with legal / financial advisors.
2.0	**Project Schedule Threats**			
2.1	Schedule slippage due to personnel or company factors.	Illness; personal circumstances; other unforeseen circumstances; business demands; communication problems. Lack of back-up cover due to high involvement from small team.	Delay to project or project proceeds using back-up personnel, with potential loss of information or consistency.	Ensure good communication within company. Balance workload in project schedule and allow periods to recover any lost time.
2.2	Schedule slippage due to equipment.	Lead times; repair or replacement of failed equipment.	Delay to project.	Scope suppliers early to allow ample time for pre-ordering. Log any failure and eliminate the cause prior to proceeding.
2.3	Schedule slippage due to third parties.	Inadequate estimates of time required by third parties.	Delay to project.	Maintain good communication with third parties.

Item	Threat and Issues	Cause	Risk - Consequence	Control
		Insufficient notice provided to third parties. Misunderstanding of requirements. Incompatibility between company technology and third party technology. Unsatisfactory standard of work.	Increased cost to project, if billed by time.	Use known or recommended service companies where possible. Test compatibility prior to scheduled work where possible.
2.4	Schedule slippage due to weather.	Unpredictable or un-seasonal conditions..	Installation date delayed until conditions more clement.	Ensure operations are planned to allow continuation at earliest possible opportunity.
3.0	**Design Threats**			
3.1	Original project becomes technically unfeasible.	Insufficient consideration given to possible design outcomes.	Radical redesign or termination of project.	Regular review of design and adherence to good design procedures.
3.1.1	Magnetic switching unfeasible.	Sufficient power unavailable (electrically actuated) or electrical isolation fails. Pneumatic supply fails to supply air at depth, or pneumatic isolation fails.	Redesign required.	Maintain contingency design option. Test electrical/pneumatic components at early opportunity. Consult with suppliers for technical advice.
3.1.2	Frame design unfeasible.	Structural complexity too great.	Prototype can't be built within time and budget.	Regular review of design.
3.1.3	Installation unfeasible.	Proposed installation method unreliable. Equipment too large or heavy.	Prototype can't be installed in real environment and is therefore not fully tested.	Regular review of design and methods. Use of lighter materials (eg Al) to reduce weight of structure.
3.2	Volume of materials is greater than budgeted.	Inaccurate initial design estimates.	Increased cost to project.	Confirm estimates in Feasibility Review to allow for adjustments

Item	Threat and Issues	Cause	Risk - Consequence	Control
		Stress analysis indicates that greater structural strength required.		if necessary.
3.3	Final prototype performs differently to scale model(s).	Scale effects.	Inaccurate design and performance predictions.	Consider scale effects in design process. Apply appropriate scaling for dynamic similarity.
3.3.1	Exact scaled dimensions of components not available.	Availability of parts.	Inaccurate design and performance predictions.	Work towards best compromise between consistency of materials and accurate scaled dimensioning. Apply compensations where required.
3.4	Software models do not replicate real-life conditions/performance.	Limitation of simulation functionality.	Limited usefulness of simulation results for predictions.	Revise software models iteratively.
3.5	Corrosion of materials under test.	Failure of anti-corrosion methods. Exacerbation due to mixed metals used together in structure.	Damage to components / prototype.	Test anti-corrosion methods prior to installation. Use mixed metals only if sacrificial anodes protect important parts of structure. Regular inspection of equipment under test.
3.6	Prototype damaged prior to locking due to impact of surfaces when landing frame.	Failure of soft-landing mechanism.	Damage to prototype and questions raised over viability of full-scale installation.	Design build and test soft-landing mechanism separately, prior to installation.
3.7	Design is incompatible with use of guidewires on guideposts.	Frame and magnet design requirements interfere with guidepost function.	Unfeasible or impractical design.	Use separate posts for guidewires and magnet locking.
3.8	Electrical hazards: - short circuits - loss of electrical isolation - insufficient power supply available on site	Inadequate attention given to electrical safety and necessary precautions.	Injury to personnel. Damage to equipment.	Undergo rigorous electrical safety checks prior to testing, using a qualified expert where appropriate. Use equipment with BS certification.

Item	Threat and Issues	Cause	Risk - Consequence	Control
				Follow clear procedures for usage of electrical equipment. Design to use a portable power supply that is sufficient for duration of locking/unlocking operation planned. Acquire and carry a back-up power supply. In situations where electrical hazards cannot be controlled satisfactorily, use pneumatic SPMs to model electrical SPMs.
3.9	Pneumatic SPMs do not replicate performance of Electrical SPMs.	Varying strength characteristics of different SPM ranges.	Inaccurate performance predictions, in particular early failure of model.	Test a control pair of electrical and pneumatic SPMs to ascertain performance differences. Apply correction to results or add extra pneumatic SPM locking forces if necessary to match electrical SPMs.
3.10	Design confidentiality breached.	Third parties disclose details of project or design to others.	Design is copied and ultimately Subsea Energy loses market share.	Ensure that Confidentiality Agreements are signed with third parties and limit information provided to what is necessary in relation to their function.
3.11	Patent covering similar concept comes into force.	Prior art.	Radical redesign required; or transfer of design to new application.	Conduct regular patent searches and seek legal counsel.
3.12	Patent application rejected.	Design deemed to be insufficiently novel.	Project proceeds to commerciality with increased risk of concept being copied, or of legal challenge from competitor.	Conduct survey of any similar IP. Seek legal counsel to ensure patent application reflects novelty of design.

Item	Threat and Issues	Cause	Risk - Consequence	Control
4.0	**Equipment/Supply Threats**			
4.1	Cost of materials / components and/or services rises significantly within project period.	Global demand. Volatile market prices. Supplier control.	Increased cost to project. Alternative materials/components used which may compromise original design and introduce delay.	Source materials/components early in schedule and check a variety of suppliers incl. non-industrial sources. Avoid over-reliance on single suppliers. Use workshop for small machining and assembly tasks.
4.2	Specification of materials / components unable to be provided by suppliers.	Non-standard specification included in design. Limited supplier capacity/flexibility/ know-how.	Alternative materials/components used which may compromise original design. Redesign causing delay to schedule.	Maintain simple low-cost design. Scope suppliers early in schedule.
4.3	Shortage of essential materials / components.	Demand exceeding supply, locally and/or globally.	Delay to project schedule. Alternative materials/components used which may compromise original design.	Conduct regular checks on component availability. Maintain good communication with suppliers.
4.4.	Service companies unavailable.	Inadequate notice provided for securing services. Change of priorities for service companies that have indicated their availability.	Delay to project schedule. Quality of service compromised.	Maintain good communication with service companies. Draw up official contracts for services?
4.5	Test facilities unavailable for required period.	Inadequate notice provided for securing facilities. Increased cost of facility hire.	Testing is conducted using inferior facilities or further afield. Delay to project schedule. Increased cost to project.	Research facilities and make preliminary bookings early in schedule.
4.6	Damage to equipment.	Accident; shearing; fatigue; burn-out; demagnetisation.	Increased cost to project.	Consult with suppliers and comply with safety instructions.

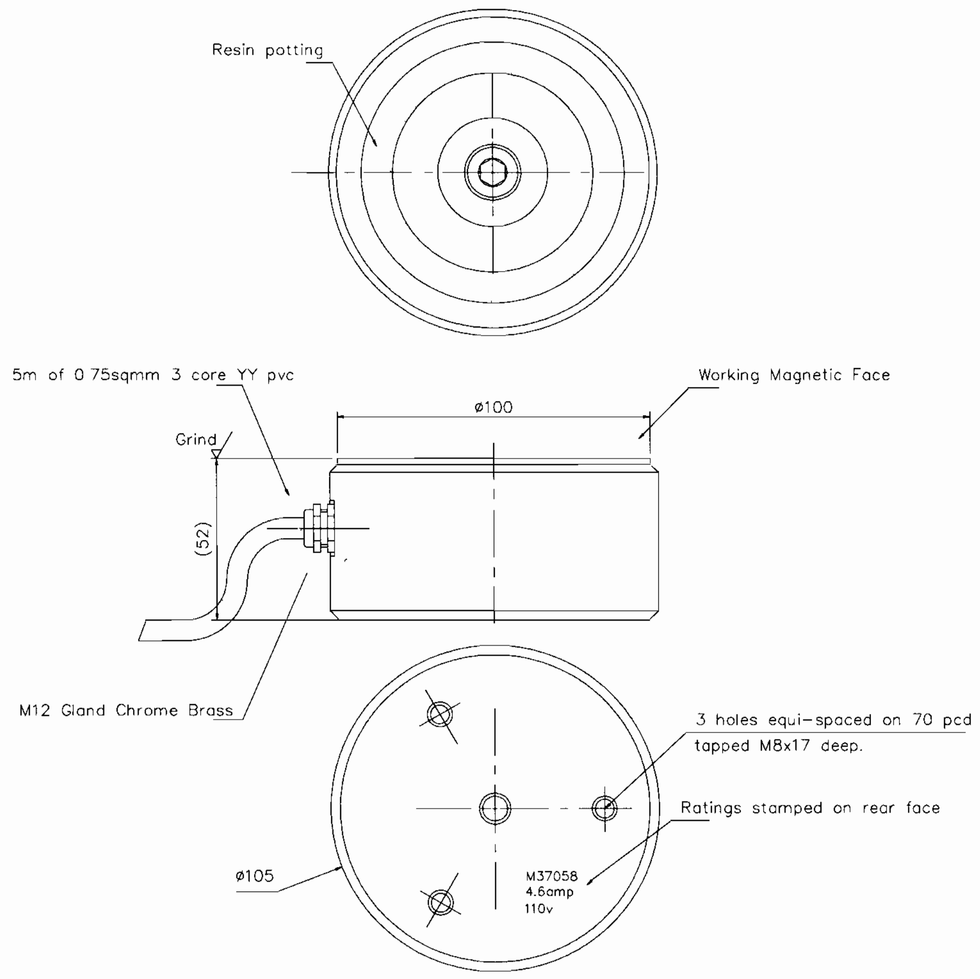
Item	Threat and Issues	Cause	Risk - Consequence	Control
			Delay to project schedule.	Apply simulations to model where possible. Apply appropriate factors of safety eg for electrical supply and mechanical strength.
4.7	Equipment fails to function to specification.	Data logger failure. Magnet power failure. Isolation failure.	Test data not available. Redesign necessary. Increased cost and delay.	Test components prior to installation.
5.0	**Operational Threats**			
5.0.5	Hazards encountered during construction and sub-assembly work conducted in workshop.	Use of sharp tools and electric machines. Ordinary hazards occurring in workshop environment.	Injury or death. Damage to equipment.	See Risk Control Sheet 1A
5.1	Suitable open-environment (tidal/river) test locations unavailable or inaccessible.	Restrictions to site access. Restricted permissions. Procedures require extensive use of equipment or manpower in order to be carried out safely.	Full scope of testing is not conducted. Testing situation creates higher level of risk to be managed.	Establish range of site options early in project. Ensure necessary permissions are clarified. Consult with third parties providing installation services.
5.2	Equipment gets washed away/misappropriated during open-environment testing.	Equipment inadequately secured.	Increased cost to project. Delay to project schedule.	Secure guidebase with sufficiently large gravity base (or alternative) and test before extended deployment. Deploy in secure areas and monitor closely at first and regularly thereafter. Consider installing CCTV.

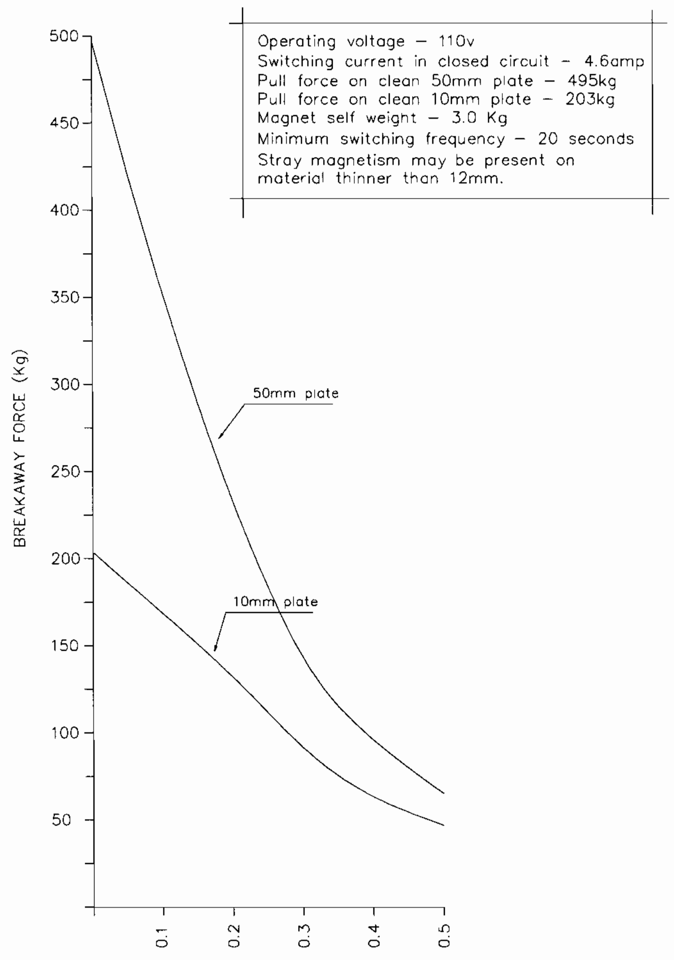
Item	Threat and Issues	Cause	Risk - Consequence	Control
				Insure equipment against theft/mooring failure.
5.3	Tidal forces (real or simulated) insufficient to test models.	Test facilities and locations that are practical and affordable do not offer sufficiently high flow speeds High speed flow produces undesirable side effects (eg excessive stresses or vibrations) and must therefore be limited.	Models not tested to 100% of requirements.	Clarify available facilities and seek high-velocity test sites. Mitigate side effects.
5.4	Installation difficulties resulting in possible damage to equipment or personal injury.	Changing tides, powerful currents, waves, rough water. Inexperience with equipment and procedures.	Damage to equipment. Delay to schedule.	See Risk Control Sheet 1B.
5.5	Difficulties with removal operation resulting in possible damage to equipment or personal injury.	As for installation, plus: magnets fail to switch; equipment seizes up; reverse of soft-landing causes swabbing effect taking time to be overcome.	As above.	See Risk Control Sheet 1B2.
5.6	Powerful magnets requiring careful handling.	Powerful switchable permanent magnets in variable states.	Crushing injury due to sudden movements of magnetic parts. Damage to equipment caused by sudden movements of magnetic parts. Loss of electronic data due to electromagnetic fields.	See Risk Control Sheet 1C.
5.7	Environmental considerations raised.	Unforeseen environmental implications	Work cannot be carried out as planned.	Assess environmental implications continually, starting from design preview stage.
5.8	Health and Safety considerations raised.	Unforeseen Health and Safety implications	Work cannot be carried out as planned.	Assess health and safety implications continually, starting from design preview stage.
5.9	Cost/market analysis not	Market uncertainty/volatility.	Project may proceed to	Establish cost envelopes and

Item	Threat and Issues	Cause	Risk - Consequence	Control
	possible.	Information withheld or expensive to acquire.	commerciality with increased risk due to market uncertainties.	monitor market trends and predictions from various sources.
5.10	Commercial analysis not possible.	Information withheld due to commercial sensitivity or otherwise unavailable.	Full commercial implications of project not known.	Use range of direct and indirect information sources.

Appendix 3 – Eclipse magnet force curves

JOB No.	NO. OF ASSEMBLIES	QTY. PER ASSEMBLY	MATERIAL:–	FINISH:–	ISSUE	DATE	AMMENDMENT	AUTH
			BDMS	Paint Bright Red	1			





Graph of performance/induced air gap

ECLIPSE MAGNETICS APPLIED MAGNETIC SYSTEMS	TITLE:– Assembly Drawing Dia 100mm espm	SCALE	SHEET No. OF SHEETS
DIMENSIONS IN MILLIMETRES UNLESS OTHERWISE STATED	DRAWN KN / CHECK / DATE 23-10-03	GENERAL TOL. LIN. ±	DRG.No. M37058 -4c