STINGRAY TIDAL STREAM ENERGY DEVICE – PHASE 2

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Contractor

The Engineering Business Ltd

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EXECUTIVE SUMMARY

Introduction

The Stingray project is the latest phase in the tidal stream energy programme established by The Engineering Business Ltd (EB). Stingray is a system, developed and patented by The Engineering Business Limited (EB), to extract useable electricity from tidal currents. It differs from other proposed devices in that it utilises an oscillating motion rather than rotation to capture the energy from the flowing water. The programme started in 1997 with the Active Water Column Generator (AWCG), which subsequently developed into the Stingray concept. A technical and commercial feasibility study (Phase 1) in 2001 led to Phase 2 – the design, build, installation and operation of the Stingray demonstrator in Yell Sound in 2002. Phase 2 was extended into 2003 to consider various aspects of the technology in more detail.

The key component of Stingray is the wing-like hydroplane. It is attached to a seabed-mounted supporting frame by a pivoted arm. As tidal currents pass over the hydroplane, lift and drag forces cause the hydroplane to lift. Hydraulically powered cylinders are used to alter the hydroplane angle such that its apparent angle of attack, relative to the oncoming current, is maintained at its optimum angle. As the current lifts the hydroplane, this causes the arm to lift, actuating hydraulic cylinders at the arm / frame pivot. The cylinders turn a hydraulic motor that, in turn, drives an electric generator. When the hydroplane (and arm) reach their upper limit, the hydroplane angle is reversed such that the arm is driven down, and the cycle repeated.

The research programmes have been part-funded by the DTI through a Smart award for the early AWCG work and the New and Renewable Energy programme for the Stingray project.

Project Aims and Objectives

The project objective was to evaluate the technical and economic potential of the Stingray concept by designing and building a demonstration 150kW generator and testing it in a suitable tidal stream.

To achieve this objective, a number of activities were undertaken, including:

- The design and construction of a working Stingray
- The design of the installation and maintenance methodology for Stingray
- The site selection and acquisition, including assessing tidal flows, seabed geotechnical conditions, the environmental impact of Stingray and the requirements associated with obtaining permits and consents
- The infrastructure requirements and power generation characteristics of the Stingray generator
- The economics of supplying electricity to consumers using Stingray generators

Summary of Methodology Adopted

In 2002 EB embarked on a very ambitious programme to design, build and operate a full-scale Stingray tidal stream demonstrator. Design started in January 2002, with Stingray leaving the Tyne for the Shetland Islands in mid-July. Reassembly, deployment trials and alongside static testing was undertaken at Sullom Voe before installation and operation in September 2002. In parallel with the design and production activities, a demonstrator site was selected, marine survey undertaken, environmental appraisal produced, and all necessary consents, licences and leases obtained.

Results from the time-limited marine operations undertaken in September 2002 indicated that significant power is available, with 250kW peak powers observed in a 3 knot current for a single sweep. Repeatable power cycles were achieved with peak power levels of 145kW and average power of 40-50kW in a 3.5 knot current. Future control strategy development to optimise the cycle times will improve the energy collection and conversion.

Extensive and comprehensive economic modelling illustrated that Stingray technology could generate electricity at a price of between 5p and 10p per kWh within a foreseeable and achievable timescale.

Conclusions and Recommendations

The overall aim of the project was to evaluate the technical and economic potential of the Stingray concept by designing and building a demonstration 150kW generator and testing it in a suitable tidal stream.

Just nine months after award of the DTI grant, EB safely installed and operated the first-ever full-size tidal stream generator. This, in itself, was an outstanding achievement. It was built on the successful completion of the wide-ranging activities undertaken. Each of these activities resulted in significant areas of development, including:

- Obtaining preliminary, and encouraging, power generation performance data.
- Validation of the mathematical modelling that was undertaken.
- Realisation of an efficient and cost-effective deployment / recovery system.
- Negotiation of the permitting / consents process for installation of Stingray, moorings for the deployment system, a subsea cable and onshore facilities.
- Appraisal of the environmental impact of tidal stream power generators, including obtaining acoustic monitoring data and information on cetacean behaviour.
- Understanding the limitations / deficiencies of conventional seabed surveys in a strong tidal environment, and determination of methods of improving on them.
- Development of marine operations / safety requirements in a very harsh environment, including implementation of the HSE CDM regulations in an industry to which they are only just being applied.
- Raising the public and industry profile of marine renewables in general, and tidal stream in particular.

Although the final operation period was shorter than all had hoped for, good information was obtained on power generation. This indicated:

- Significant power is clearly available with 250 kW peak powers seen in a 3 knot current for a single sweep.
- Repeatable power cycles were achieved with peak power levels of 145kW and average power of 40 to 50kW in a 3.5 knot current.
- Faster cycle times required for higher levels of power generation were not achievable due to limitations in the actuation system.

- All powers quoted are hydraulic – they take no account of the losses in conversion to electricity. The drive output powers require further investigation.

Further development work undertaken by EB has identified that significantly more power could be generated by modifications to the control strategy adopted for Stingray.

The Phase 2 operations have demonstrated the Stingray proof of concept – power can be generated from the oscillation of hydroplanes driven by moving water. Reasonable power generation levels have been recorded, and improvements to the system, particularly the control strategies and cycle times, should result in demonstrable improvements.

There is strong evidence that Stingray has the potential to be commercially viable both within the domestic UK electricity market and in alternative markets.

EB proposes to return Stingray to Shetland in 2003 for a third phase of the project. This would complete the validation of the mathematical models, further develop the control strategies and produce uninterrupted power cycles. Following this, EB is planning the development of a 5MW Stingray farm.

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1 INTRODUCTION

1.1 The Stingray Project

The Stingray project is the latest phase in the tidal stream energy programme established by The Engineering Business Ltd (EB). The programme started in 1997 with the Active Water Column Generator (AWCG), which subsequently developed into the Stingray concept. A technical and commercial feasibility study (Phase 1) in 2001 led to Phase 2 – the design, build, installation and operation of the Stingray demonstrator in Yell Sound in 2002. Phase 2 was extended into 2003 to consider various aspects of the technology in more detail.

The research programmes have been part-funded by the DTI through a Smart award for the early AWCG work and the New and Renewable Energy programme for the Stingray project.

This report presents an overview of the work undertaken during the Phase 2 project and summarises the results obtained.

The Phase 1 work was reported by The Engineering Business (2002). That report provides the background to the project development.

1.2 The Stingray Principle

Stingray is a system designed to extract useable electricity from tidal currents. It differs from other proposed devices in that it utilises an oscillating motion rather than rotation to capture the energy from the tidal flow.

The key component of Stingray is the wing-like hydroplane. This is attached to a supporting frame by a moveable arm. The supporting frame is seabed mounted. As tidal currents pass over the hydroplane, lift and drag forces cause the hydroplane to lift. Hydraulically powered cylinders are used to alter the hydroplane angle such that its apparent angle of attack, relative to the oncoming current, is maintained at its optimum angle. As the current lifts the hydroplane, this causes the arm to lift, actuating hydraulic cylinders at the arm / frame junction. The high-pressure oil developed by the cylinders turns a hydraulic motor that, in turn, drives an electric generator. When the hydroplane (and arm) reach their upper limit, the hydroplane angle is reversed such that the arm is driven down, and the cycle repeated.

Although, for the Phase 2 demonstrator, generation has only been undertaken on the flood tide, simple mechanisms have been investigated to allow the hydroplane/arm unit to be repositioned and thus operate on both tides. A suitable system would be incorporated into future, commercial, machines.

1.3 The Stingray Vision

The clear vision is to develop Stingray technology so that it will generate predictable and commercially attractive power with minimum impact on the environment. Farms of Stingray machines are envisaged, typically providing a generating capacity in the range 20MW to 100MW. The technology will make a small but significant impact on UK electricity generation, going some way towards achieving the goal of a sustainable low carbon economy, and offer the prospect of developing a world-class UK industry creating jobs, wealth and export potential.

Although electricity generation for the domestic UK market is the primary aim, the Stingray technology may have other commercially attractive markets in meeting growing global requirements for both renewable energy and potable water.

1.4 Background to Phase 2

The background to the project, and the potential for exploiting tidal stream energy, is covered in detail in the 2002 ETSU report. In summary, EB won a DTI Smart award in 1998 to investigate the feasibility of the AWCG. Considerations of the practical difficulties involved in operating a "surface-piercing" device, as well as the opportunity for simplifying the engineering led to EB developing the seabed mounted Stingray principle as an alternative embodiment of the concept.

In August 2001 EB was awarded funding by the DTI, under the New and Renewable Energy programme, to carry out the Stingray Phase 1 project. This was a review of the technical and commercial viability of the Stingray concept. From this study, EB concluded that a concept had been developed that appeared to be technically robust and commercially viable. Continued feasibility studies would provide answers to some remaining questions. However, adequate feasibility studies would take a significant time, and any results could not be taken as conclusive until validated by a realistic, comprehensive demonstration project. Any delay in the installation and operation of a viable demonstrator would prevent it benefiting from the current window of opportunity for the development of tidal stream generation in the UK and possible international export. It was therefore recommended that the design, manufacture, installation, operation and decommissioning of a full-scale demonstrator Stingray would be the most effective route of progressing the technology.

These conclusions were presented to the DTI in November 2001. Their agreement with the conclusions led to the award, in January 2002, of the Phase 2 project.

1.5 Phase 2 Objectives and Plan

In 2002 EB embarked on a very ambitious programme to design, build and operate a "full-scale" prototype. Design started in January, with Stingray leaving the Tyne for the Shetlands in mid-July. Reassembly, deployment trials and alongside static testing was undertaken at Sullom Voe before installation and operation in September 2002. Details of this programme are presented in subsequent sections of this report.

The overall aim of the project was to fully evaluate the technical and economic potential of the Stingray concept by designing and building a demonstration 150kW generator and testing it in a suitable tidal stream. To achieve this aim, EB proposed the fast-track Phase 2 project that saw the working Stingray generator installed off the Shetland Islands within 9 months of the grant approval being awarded. This was to allow certain aspects of both the technology and its practical application to be studied in depth. Table 1 indicates the areas identified, and where they are covered in this report.

Activity	Section of this report
The design and construction of a working Stingray	3, 4
The site investigation including monitoring tidal flows, seabed geotechnical review and the problems associated with obtaining permits and permissions	2
The design of the installation and maintenance methodology for Stingray	4
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The economics of supplying electricity to consumers using Stingray generators	9
Problems and costs associated with decommissioning Stingray	5

Table 1: Phase 2 Activity Objectives

1.6 Project Timeline

Having presented the Phase 1 results to the DTI in November 2001, the grant for Phase 2 of the project was awarded on 10th January 2002. Work started immediately to develop the Stingray concept into a detailed design, developing a cost-effective, safe and viable deployment system, locating a suitable site for the demonstrator and acquiring all the necessary consents, permits and licences to operate.

A site survey was undertaken in February 2002, including the deployment of a current meter that was recovered in April 2002.

As different phases of the design reached completion, production (fabrication, painting and assembly) started, with the first order being placed in April 2002. The first components arrived at the Amec Howdon Supply Base on the River Tyne at the start of June 2002. An open-day and launch was held on the Tyne later in June, with the Energy Minister formally 'launching' Stingray. Further testing of components and the deployment system was completed in early July, followed by the dissassembly and sea-fastening for the transit to Shetland.

Stingray left the Tyne on July 17th 2002, aboard the barge Harry McGill. Arrival in Sullom Voe on the 20th July was followed by a period of reassembly and commissioning at the Construction Jetty. During this period the seafastenings holding Stingray to the barge were removed and the component parts unloaded to the Construction Jetty. Limitations on available craneage in Shetland resulted in Stingray having to be reassembled over the water, while suspended from the lift beams installed on the barge.

The barge moorings were laid on site at the end of July. An initial move to site in August was ended before deployment to allow a reappraisal of the deployment procedures. In early September deployment trials and still-water testing were performed while alongside the Construction Jetty. Poor weather prevented the final mobilisation to site until 13th September 2002. An intense period of operation and testing was then undertaken, with recovery of Stingray on 25th September. This is described in greater detail in later sections.

Once recovered, the major Stingray items were put into winter storage in Shetland. Poor weather delayed demobilisation of the barge until November 2002.

The results were presented to the DTI at a meeting in December 2002, after which it was agreed to undertake an extension to the project to investigate a number of technology and theoretical developments.

2 SURVEY, ENVIRONMENT AND CONSENTS

2.1 Site Selection

Site location was determined by a number of factors, as indicated in Table 2:

Hydrographic / metocean	Water depth, current velocity, current direction, current profile and wave regime
Physical	Foundation and cable route conditions
Environmental	Designated environmentally sensitive areas and other users (fishing, aquaculture, military, etc)
Other factors	Accessibility, in terms of travel time and costs; local port facilities for use in connection with installation/decommissioning; local stakeholder interests in terms of support of local official bodies and other stakeholders; applicable consents and leases

Table 2: Site Selection Parameters

The site selection process comprises a combination of Desk Top Study, Environmental Appraisal, Consultation, Current Modelling and Survey.

2.2 Desk Study

This was undertaken as part of the Phase 1 project and was reported by The Engineering Business (2002).

The Desk Top Study was undertaken by EB with input from SEtech (Geotechnical Engineers) Ltd. As part of this study, a shortlist of ten potential Stingray demonstrator sites were assessed against defined selection criteria (based on the parameters identified in Table 2). The preferred site identified by this review was Yell Sound on Shetland (Figure 1).

Figure 1: The Site (Photo courtesy Kieren Murray)

Yell Sound has a strong, predictable tidal regime in water depths that are suitable for the demonstrator. Preliminary assessment of foundation conditions suggested the probability of bedrock at the seabed. Although a number of environmentally sensitive sites border Yell Sound, they were not assessed to be prohibitive to the project. Other seabed use was minimal in the immediate area of interest. Strong support for, and interest in, the project was encountered at local (Shetland and NE England) and national (Scotland and UK) level.

2.3 Current Modelling

A 3D current model of Yell Sound was commissioned from the Robert Gordon University in Aberdeen. The objective of this study was to predict the most suitable sites in which to install the Stingray generator. This prediction was based primarily on tidal energy considerations, but it also took account of other constraints.

A computational grid was developed, which used a low density grid (150 m) in the far field and a high density grid (90 m) in the narrow channels around the principal area of interest. This is the region where the fastest and most complicated currents occur and where the best sites for locating a tidal current energy generator were predicted. The hydrodynamic model was validated against data from Hydrographic Office tidal diamonds and a BP survey of tidal currents. A good correlation was achieved between these data sets. Within the targeted area, the fastest predicted spring current was approximately 2.7m/s (5.4 kts).

The predictions were based on available data. As such, the data sets produced can only be assumed to be as accurate as the validation data sources.

The model, in conjunction with the Desk Study and Environmental Scoping Report / Consultee Responses, was used to identify specific target locations within Yell Sound for the seabed and shoreline surveys.

2.4 Survey and Seabed Conditions

A survey (Figure 2) was undertaken to determine whether the tidal resource in the proposed location was adequate for power generation and to enable the safe and economic design of foundations, installation methods and operational integrity of the structure. To achieve this, site specific information was required on:

- Hydrographic elements – bathymetry (water depth and slopes) using echo-sounder and current regime using seabed / vessel-mounted current meters (Figure 3 and Figure 4).
- Seabed conditions - side-scan sonar (Figure 5), sub-bottom profiling (Figure 6) and magnetometer to assess soil type, variability and obstructions.
- Environmental / benthic aspects – sub-littoral drop-down video to provide data to assess potential environmental impacts.
- Shoreline – walk-over environmental (littoral) and cable-route / geotechnical surveys.

Initial geophysical and hydrographic surveys were carried out simultaneously on the 23rd February 2002, but the data acquired was considered to be outside acceptable quality limits as a result of the rough sea state. The work was therefore repeated in the areas concerned on 25th February 2002. ADCP 'transect' measurements were taken at the same time as the main survey, with an additional temporary set of bottom mounted measurements over 5 hours on the 28th of February 2002 prior to the full 30 day static site deployment on the 1st March 2002. The survey data is summarised below.

Figure 2: The survey vessel, MV Hegrie

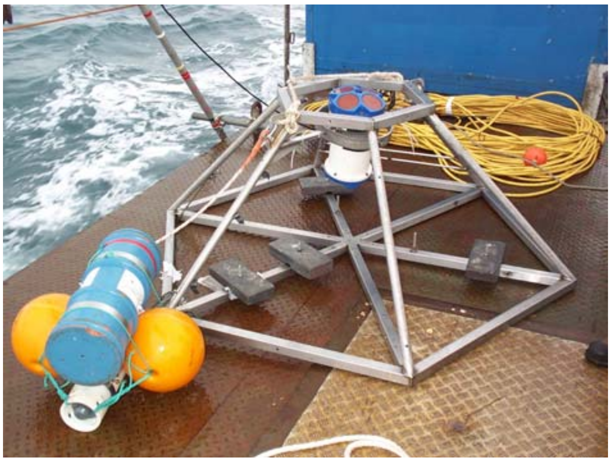

Figure 3: The ADCP and seabed frame

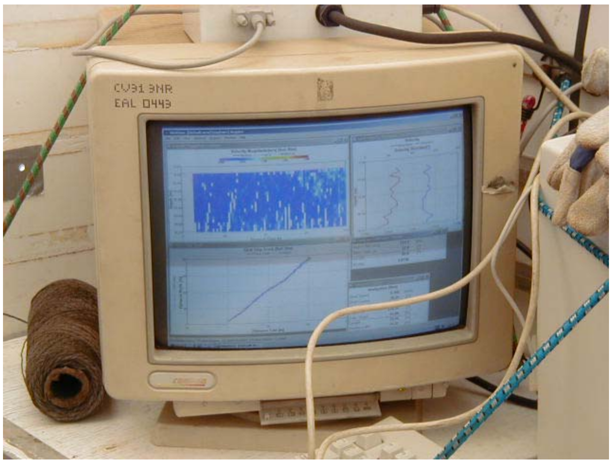

Figure 4: Vessel-mounted ADCP data acquisition

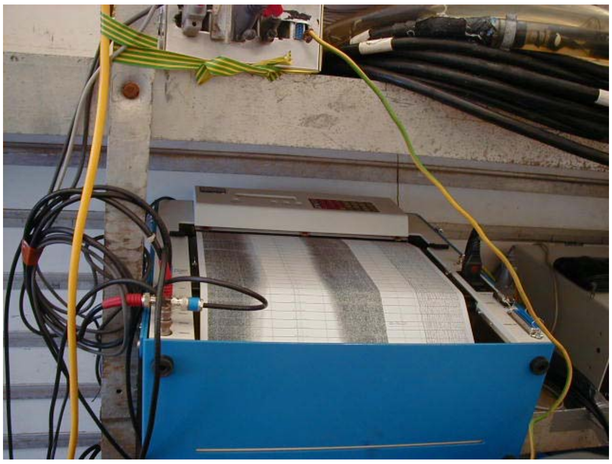

Figure 5: Sidescan Sonar data acquisition

Figure 6: Sub-bottom profiling – the 'boomer'

Within the survey area seabed levels varied between 7.8m and 55.3m below Chart Datum. The seabed fell away steeply at a gradient of approximately 1:10 from the shore in a westerly direction until a depth of 30m below Chart Datum was reached, whereupon the seabed gradient reduced to approximately 1:20, dipping toward 50m below Chart Datum. In the south-east of the site a promontory occurred, originating from the headland on the Yell shore.

The seabed characteristics varied considerably across the survey area ranging from exposed rock to areas of sandwaves and gravel dunes. Unfortunately sediments were only visually confirmed in a few areas by camera at slack water due to high tidal currents and encroaching weather. Certain targets located by sonar were interpreted as possible boulders 1.1-2.7m high. However, only 5 were identified throughout the survey area.

It was apparent from the isopachyte model of sediment thickness above rockhead that several regions exist where bedrock is exposed or occurs within 0.5m of the surface. Regions of thicker superficial material are found over the south and west of the site. Maximum sediment thickness, of approximately 10m, occur at the eastern extents of the survey area. It must be noted that this seismic reflection method has a vertical resolution of 0.3 metres. Therefore, it is possible that areas of slight sediment cover were not visible on the seismic records due to insufficient thickness.

The current magnitude identified during the survey ranged from a minimum of 0.2m/s to a maximum of 1.6m/s. The predominant direction of the flow was approximately NW/SE. The ADCP was deployed for the static measurements at 1°10.237629'W, 60°29.841420'N (WGS84)for a period of 30 days. The data sets from the ADCP were analysed by RGU using a number of techniques. These included tidal ellipse and velocity components, velocity depth profile, frequency analysis, parametric analysis, exceedence and occurrence. The results were used to determine the maximum significant current vector, predominant tidal harmonics and amplitude, and an impression of the power available.

The current is essentially bi-directional, running from the NW to the SE and reversing on the ebb tide. The current is generally more energetic during the flood tide, when the NW-SE velocity component exceeds 2.3m/s at 13m above the seabed (approximating to the mid-sweep of Stingray). During the neap tides, the depth profile follows the 1/7th power law profile for turbulent fluid flow. There is a slight deviation from this profile for the spring tide, in that the velocity gradient is less, and consequently, the bulk flow velocity is achieved further up the water column. In general there is a broad band of energetic flow within the operational span of Stingray. Quantitative frequency analysis did not prove useful as it is necessary to have data over a significantly longer time-scale. Qualitatively, there are significant contributions from the lunar month and diurnal harmonics in addition to the usual lunar fortnight (Mf) and semi-diurnal (M2) harmonics. These additional harmonics prevented a good match with the parametric modelling, which considered only the M2 and Mf harmonics. The exceedence data demonstrated that there was not a significant proportion of the current in excess of 2.25m/s. The occurrence data indicated that the modal velocity band is between 1.0 and 1.25m/s.

The sublittoral video survey took place on 28th February in the Yell-Bigga channel in conditions of strong currents and winds. Grab samples were deemed inappropriate since there was a lack of significant seabed sediments, and therefore a dropdown / towed video array was used instead (Figure 7). Video footage was collected at the site. This was recorded to digital format and time-stamped against the GPS position. The videos were analysed as a whole and by freezing the footage at intervals, allowing a detailed description of the biotopes present to be made (Figure 8).

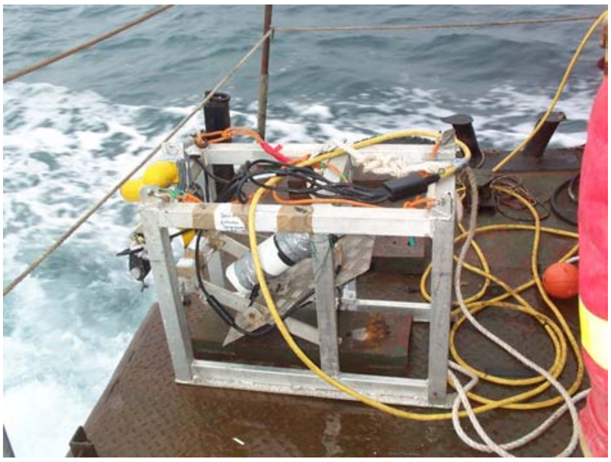

Figure 7: The camera and camera housing

Figure 8: Still from video drop 4 showing MCR.Flu.SerHy

The seabed at the proposed location does not support a well developed infaunal benthos since sedimentary fauna is limited due to the thin and highly mobile nature of the sediment. The epibenthic fauna is adapted to the high-energy tide swept environment. In the main, species present included hydroids and bryozoans, typically found in tide swept boulder and cobble habitats which contained pockets of collected coarse and clean sandy sediment. The biotopes and species present in the sublittoral surveys are common with recorded distributions throughout the UK, and typical of tide swept areas. No species of conservation concern were identified.

An initial littoral shoreline survey was undertaken on 26th February. The survey covered approximately 1km of coastline from the harbour at Ulsta northwards. This survey showed that the littoral biotopes and species present are common in the region and, indeed, throughout the British isles with recorded distributions throughout the UK. With the exception of otter, there are no species of conservation importance or protected benthic species in the vicinity of the proposed works. It was noted that the lower littoral (extreme lower shore) was noted as containing a healthy kelp zone which would be the preferred foraging habitat of the otter. These were not seen on the video sublittoral surveys since this zone does not extend out very far due to the steeply shelving nature of the shoreline.

A second shoreline survey was undertaken on behalf of EB by the Shetland Biological Records Centre on 11th July 2002, before any marine or land operations took place. This formed part of the site consent requirements. This covered the same stretch of coastline as the February survey. It categorised the shoreline as comprising cliff vegetation (on cliff faces beyond the reach of sheep), maritime grassland (1-10m back from the cliffs, generally narrower where the cliffs were higher) and acid grassland (inland from the maritime grassland). Of ornithological interest, five species of breeding birds (Fulmar, Great Skua, Skylark, Rock Pipit and Shetland Wren) and two feeding species (Black Guillemots and Shags) were noted. Sea mammals observed included Common Seal and Otter.

Walk-over shoreline surveys were undertaken by EB in February and July 2002 to identify the potential cable route and location for any onshore facilities.

2.5 Stingray Location and Orientation

As a result of the site selection activities (particularly the current modelling and survey), it was decided to install Stingray at the ADCP location. Interpretation of the ADCP data indicated that the prevailing direction of the high velocity currents within the flood tide is towards the SE, in the range 130-135 degrees (Figure 9). It was therefore decided that Stingray should be installed on an alignment of 133 degrees (magnetic). It was anticipated that this location would have a slope of approximately 2.5° along the fore-aft and port-starboard axes. Seabed conditions were anticipated to comprise up to 1.5m of sand / gravel over bedrock.

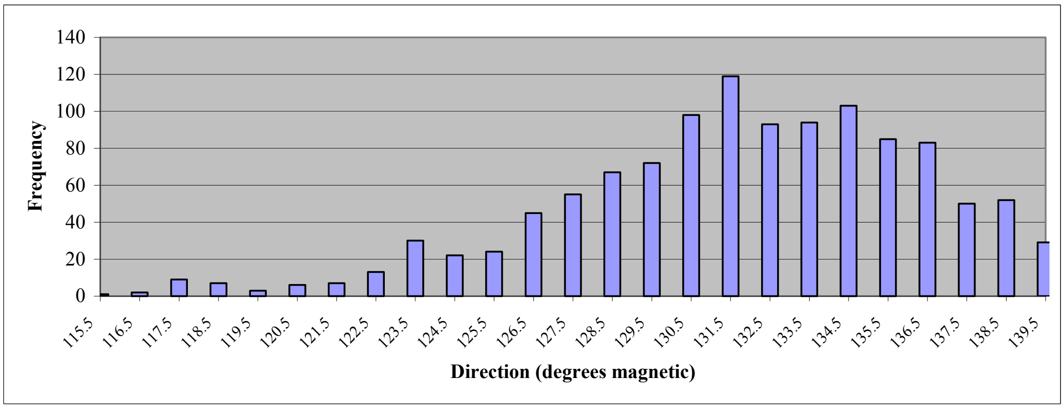

Figure 9: Prevailing Current Directions Recorded by Survey ADCP

2.6 Environmental Appraisal

Under the existing legislation, there is not a requirement for a formal Environmental Impact Assessment for this project. However, EB believe that it is essential that a responsible attitude to site selection and stakeholder consultation is taken and an Environmental Scoping Report, Environmental Appraisal and Benthic Survey were therefore commissioned. EB appointed Entec UK Ltd to undertake the Environmental Scoping and Appraisal study. The principal conclusions on significant impacts from the Environmental Appraisal are reproduced in Section 2.6.3.

The project required environmental supporting information to accompany the various permit applications required, particularly as Yell Sound is a candidate SAC for otters.

2.6.1 Environmental Impact Assessment

Environmental Impact Assessment (EIA) is the process by which information about the environmental effects of a project is collected, evaluated and presented in a form that provides a basis for consultation and enables decision-makers to take account of these effects when determining whether or not a project should proceed. The process also includes environmental monitoring and other work that is carried out following any decision to allow the development to proceed (eg monitoring carried out during the installation phase, or after decommissioning).

EB appointed environmental consultants, Entec UK Ltd, to undertake the environmental appraisal. The appraisal process commenced with a Scoping Report in 2001. This identified the legislative framework within which the appraisal must be performed. Since devolution, legislation and statutory consultation requirements have also, to some extent, been devolved to the regional executives. For the Stingray demonstrator project, all environmental appraisal aspects are, therefore, within the Scottish context.

The Scoping Report identified the existing environment, and its interaction with the project, in terms of:

- Planning context
- Flora and fauna
- Noise and vibration
- Hydrography, sediments and coastal changes
- Fisheries and aquaculture
- Navigation and other uses of the sea
- Archaeology

Having identified these aspects, and considered the project within the requirements of the applicable legislation, Entec suggested that a formal EIA was not required (largely due to the size, location and duration of the demonstrator project). This was discussed at a meeting in December 2001, attended by EB, Entec, the Scottish Executive (Development Department, SEDD, and Environment and Rural Affairs Department, SEERAD), Scottish Natural Heritage (SNH) and the Crown Estate. It was deemed at this meeting that an EIA would only be required if, in SNHs opinion, the benthic survey identified species of conservation interest. It is anticipated that, in a commercial situation, an EIA would be required.

2.6.2 Consultation

The Environmental Scoping Report was issued to recognised organisations (statutory consultees and other stakeholders) for comment in November 2001. The consultees comprise:

- Local Community Councils (Delting and Yell)
- Statutory consultees (Crown Estate, Scottish Environment Protection Agency, Scottish Executive Development Department [CPA consents], Scottish Executive Environment and Rural Affairs Department [FEPA licence and fisheries], Scottish Executive Energy Division, Shetland Islands Council [Transport and Environment, Marine Operations, Development – Planning Permission and Works Licence], Scottish Natural Heritage)
- Fishery organisations (Shetland Fish Producers Association, Shetland Fishermans Association, Shetland Salmon Farmers Association, Shetland Shellfish Growers Association, Shetland Shellfish Management Organisation)
- Other stakeholders (RSPB, Scottish Coastal Forum, Sea Mammals Research Unit, Shetland Sea Mammal Group, United Kingdom Hydrographic Office, Sullom Voe Oil Terminal Advisory Group, Scottish and Southern Energy, BP, Shell, Ministry of Defence, BT, British Geological Survey)

Consultee responses were obtained and suggested that there were no objections to the development of the project. The success of the project depended not only on resolving the technical and environmental problems, but also required the willing assistance of bodies and people that have a direct or indirect interest in the location of the test site. EB focused on Yell Sound as its preferred site for the demonstrator. Preliminary site assessment and stakeholder consultation encountered exceptional interest and support from the local Council, fishermen and industrial interests.

2.6.3 Conclusions from Entec Environmental Appraisal

The Environmental Appraisal, undertaken by Entec, was based around the Scoping Report, plus consultee responses, and provided the necessary environmental information to satisfy the requirements of all relevant authorities involved in permitting the project. It reviews the significant impacts that applied to the Stingray project during the construction (installation and decommissioning) and operation phases. These are summarised below.

Key:	Type	Probability	Policy importance	Magnitude	Significance
	- = negative	Certain	I = inter-national	Quantified and duration	Level and rationale
	+ = positive	Likely	N = national (UK)	Major	High
				Medium	
	?=unknown	Unlikely	R = regional	Minor	Low
			C = county	None	
	0 = none		D = district		Not significant
			L = local/parish		
			<L = less than local/parish		

Main issues during construction

Environmental effect	Type of effect	Probability of effect occurring	Policy importance/ sensitivity	Magnitude of effect	Significance:	
					Level	Rationale
Construction *Effects on tides and currents*	-ve	Unlikely	L	Minor	Not significant	None anticipated
Construction *Effects on sedimentation*	-	Unlikely	L	Minor	Not significant	Only localised disturbance due to placement of Stingray, effects minimal due to high energy environment.
Construction *Effects on sublittoral (seabed) benthos*	-ve	Certain	L	Medium but short term. Reversible	Not significant	Loss of benthic community due to footprint of gravity base but area of habitat removed insignificant. Area relatively species poor due to high tide energy, and no species of conservation concern will be lost. Effects reversible once Stingray removed. Recovery expected within few months.
Construction *Effects on littoral (shore) benthos*	-ve	Likely	L	Medium but short term. Reversible	Not significant	Exact location of cable unknown. Potential for loss or damage to littoral benthic community due to placement of cable, depending on location. However, no species of conservation concern will be lost. Effects reversible once Stingray removed. Recovery expected within few months.
Construction *Effects on protected*	-ve	Unlikely	L	Major	Low	Potential for disturbance of otter holts in littoral zone of

Environmental effect	Type of effect	Probability of effect occurring	Policy importance/ sensitivity	Magnitude of effect	Significance:	
					Level	Rationale
species- otter						Yell, and potential disturbance to foraging otters during installation of cable. Survey should take place prior to installation to avoid impacts occurring.
Construction *Effects on species of conservation concern- common seal*	-	Unlikely	L	Major	Low	Common seal use Bigga for haul out and moulting and pupping in May-July and subsequent 3-6 week lactation (nursing). Small possibility that some individuals may use Yell coast for pupping, therefore potential disturbance to nursing seals and young during installation of cable (dependent on location) Checks should take place prior to installation to avoid impacts occurring.
Construction *Effects on breeding seabirds*	-ve	Unlikely	L	Medium	Low	Coast of Yell contains many breeding seabird colonies. Potential for disturbance is reduced due to distance of unit and barge offshore. No large colonies recorded in area therefore probability of disturbance during shore installation works is low. However, nests and young are protected and therefore checks should take place prior to installation to avoid impacts occurring.
Construction *Noise effects on marine mammals*	-ve	Likely	L	Medium	Low	Studies have shown that mammals will avoid areas of excessive noise, and become habituated to constant regular noise. Barge generator noise reduced through use of acoustic hoods.

Main issues during operation

Environmental effect	Type of effect	Probability of effect occurring	Policy importance/ sensitivity	Magnitude of effect	Significance	
					level	rationale
Operation *Effects on sublittoral (seabed) benthos*	-ve	Unlikely	L	Minor Reversible	Not significant	Possible further loss of benthic community due to maintenance works requiring lifting and repositioning of unit. However, area of habitat removed insignificant and no species of conservation concern will be lost. Effects reversible once Stingray removed. Recovery expected within few months.
Operation *Effects on protected species- otter*	-ve	Unlikely	L	Medium but short term	Not significant	Potential disturbance to otters if maintenance activities require

Environmental effect	Type of effect	Probability of effect occurring	Policy importance/ sensitivity	Magnitude of effect	Significance	
					level	rationale
						repositioning of cable. Survey prior to installation should identify any holts in the vicinity and positioning will take this into account.
Operation *Effects on species of conservation concern-common seal*	-ve	Unlikely	L	Medium but short term	Low	Potential to disturb pupping common seal if present on Yell shore during maintenance works in September if requiring shore works to cable. Checks should take place prior to installation.
Operation *Effects on diving seabirds*	-ve	Unlikely	L	Minor/ Medium	Low	Depth of unit will be below diving depth of most birds. Potential risk to some deep diving specie such as gannet, but given size of Stingray not considered to be significant issue.
Operation *Noise effects on marine mammals*	-ve	Unlikely	L	Medium	Low	Operational noise levels are not anticipated to be add to the existing high background noise levels resulting from the heavy freighters and other vessels.

2.6.4 Environmental Monitoring

In addition to the pre-operations surveys, environmental monitoring was also undertaken during the operations period.

An inspection of the Stingray foundation beams was made on 8th September, before the trial deployment, to identify what, if any, marine growth had occurred whilst in the relatively still waters alongside the Construction Jetty. A test patch was scraped clean before deployment (Figure 10) and re-inspected three days later on recovery (Figure 11). As indicated below, a small quantity of green algae, possibly Blidingia or Enteromorpha, had colonised the steel surface. However, these organisms are unlikely to thrive in the deeper water, higher current environment at the site.

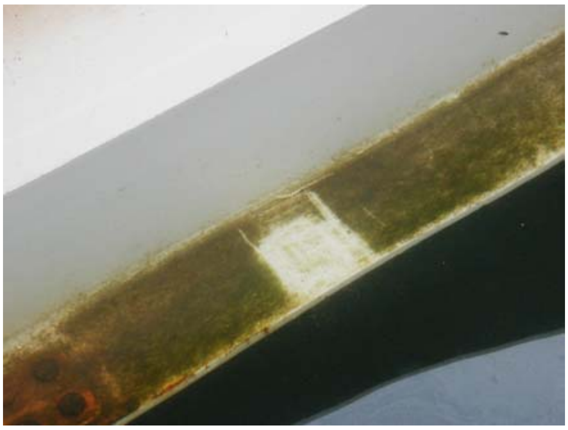

Figure 10: Green algae on beam surface before deployment – note square test area where algae wiped off by hand

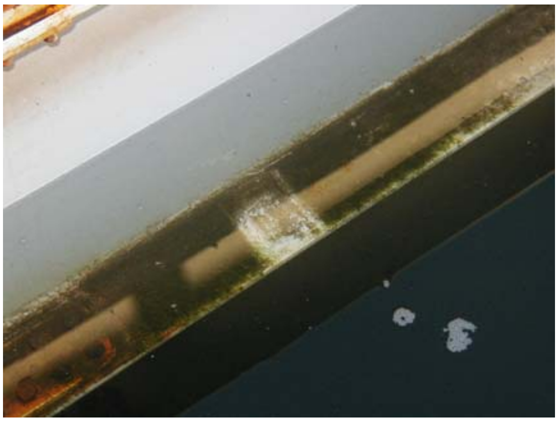

Figure 11: Minor further growth noted on recovery

Acoustic monitoring of Stingray was undertaken on Friday 20th September. This was undertaken using a Magrec HP30 general purpose hydrophone. Data was recorded from the Harry McGill, above Stingray, during periods of activity and non-operation (to provide background readings). Background readings from the shore had been obtained in August. This data was later analysed in terms of frequency, duration and signal power level. An example of a spectogram recorded whilst Stingray was operating in 25 second power cycles is illustrated in Figure 12.

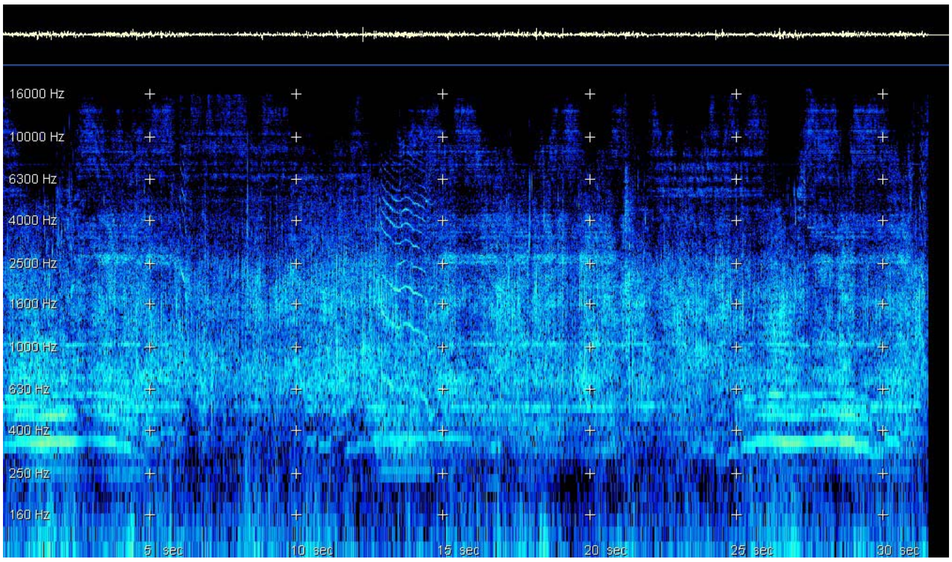

Figure 12: Spectogram of 25 second Stingray cycle

Although not part of the Stingray programme, third party monitoring of cetaceans was undertaken in Yell Sound during the operation period. This comprised cetacean watches undertaken by members of the Shetland Sea Mammal Group, chance sightings recorded by vessels and land-based observers and a programme of acoustic monitoring funded by Highlands and Islands Enterprise.

The preliminary output from this work suggests that there was no indication of reduced or increased activity around Stingray and that, as would be expected, high current areas (such as Stingrays location) are generally transit areas rather than feeding or breeding sites. However, this data, even when combined with the historical records that exist for cetaceans in Yell Sound, only represents the development of baseline data. Significantly more work is required before any behavioural conclusions can be drawn.

2.7 Consents Process

2.7.1 Permissions required

For a commercial tidal stream development in Scotland, consents could be required under:

- The Electricity Act 1989 and Electricity Works (EIA) (Scotland) Regulations 2000– administered by the Energy Division of the Scottish Executive. However, this only applies to developments exceeding 1MW (s36) or involving overhead cables (s37) and does not, therefore, apply to the Yell Sound site.
- The Food and Environmental Protection Act 1985 - Part II - Deposits in the Sea (FEPA) – administered by Fisheries Research Services (FRS) division of the Scottish Executive Environment and Rural Affairs Department (SEERAD).

- Section 34 of the Coast Protection Act 1949 (a CPA consent) - s.34 of the CPA applies to areas below high water mark of ordinary spring tides (HWMOST), which are not excluded from the definitions of sea and seashore detailed in Schedule 4 to the Act. In the case of Yell Sound, the development would not fall within the excluded area, so a CPA consent would be required. This is administered by the Transport Division of the Scottish Executive Development Department.

In the case of the Yell Sound site, a works licence was also required from Shetland Islands Council, which has control over development in the coastal area around Shetland and is the harbour authority for the water around Sullom Voe. Although the offshore installation of the Stingray generator does not fall within the control of the normal land-based planning system, there was the possibility of associated land-based activities during the construction phase which required planning permission from Shetland Islands Council. A seabed lease for the Stingray generator and cable route was also required from the Crown Estate.

3 DESIGN

On the technical front, EB had to develop Stingray's hydroplane design, drive train, control system, support structure and its seabed mounting. In addition EB had to develop a launch and recovery system capable of safely and economically deploying the 180 tonne device in moving water. These represented a large number of first of kind systems to be developed, tested and proved in an extremely limited timescale.

The design was performed in-house, with parallel activities of mathematical modelling, mechanical design, design of the hydro-electric control circuits and development of the deployment system. These aspects are elaborated on in subsequent sections.

3.1 Mathematical and Physical Modelling

As part of Phase 1 of the C80 Stingray project, and reported by The Engineering Business (2002), a mathematical modelling exercise was undertaken to allow investigation of various machine parameters. The aims of this exercise were to:

1. Gain more accurate estimates of the power output of the machine.
2. Investigate the sensitivity of generator performance to variation in basic machine parameters.
3. Optimise operation of the machine for different tidal flow conditions.
4. Develop the hydraulic and electrical transmission configurations and their detailed implementation.
5. Begin development of machine control strategies.

The results of the study fed into the machine design in Phase 2 of the programme and formed the basis for further modelling work.

The model was constructed in block diagram format using the Simulink™ software package from MathWorks. This software is commonly used in the simulation of dynamic, electronic and mechanical systems. The model was developed to combine all of the mechanical, hydraulic and electrical elements of the machine in to one. By combining all of the elements involved in the conversion of tidal flow to electrical power in this way, the model provided a powerful tool for the investigation of system level effects of design parameter changes.

At the heart of the mathematical model is a differential equation representing the dynamics of the arm/hydroplane structure. This uses the net torque acting on the structure to calculate its resulting motion. The outputs then feed back in to other parts of the model to calculate cylinder displacements, flows, pressures, damping effects and so forth. The motion of the hydroplanes on the arm pivot are calculated in a similar fashion.

Control strategies for the machine can be implemented using fed back outputs from the model, with implementation of sensing and actuating devices as necessary.

Tabulated data on hydrodynamic characteristics is used to calculate the hydroplane forces and moments for given angles of attack and tidal flow velocities. The collection and validation of this data is carried out in separate exercises.

A top-level view of the basic model structure is shown in Figure 13.

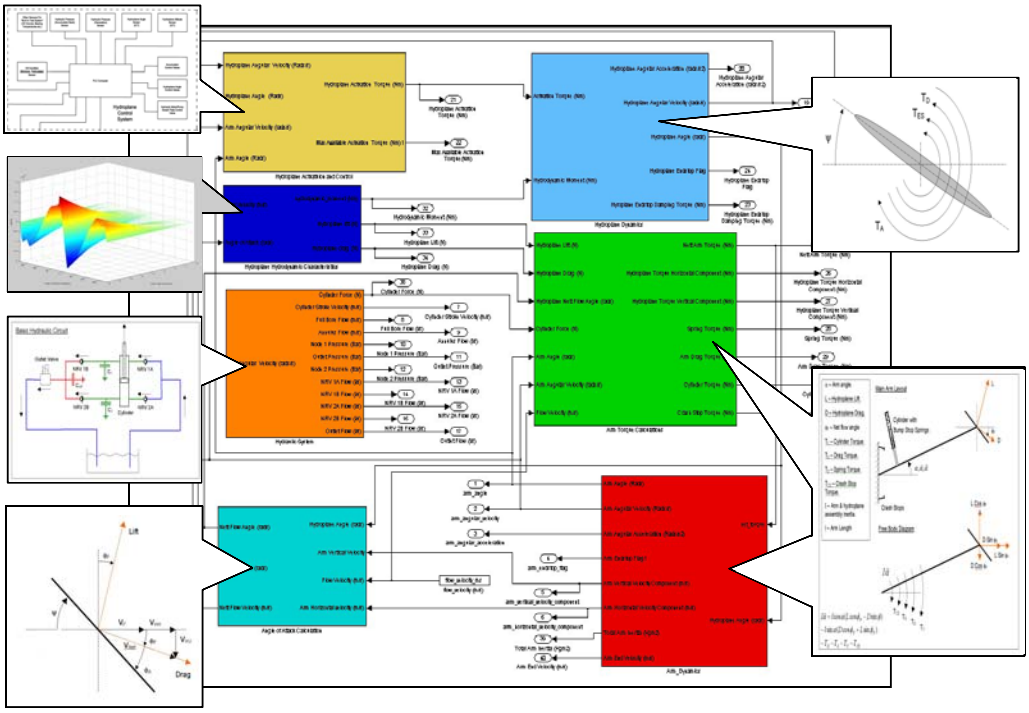

Figure 13: Top-level view of mathematical model

The program of work undertaken in Phase 1 established a range of model configurations for the Stingray concept which were subsequently used to investigate a range of areas:

- Baseline machine performance – the nominal machine characteristics were established.
- Effects of parameter variations – key machine parameters were varied and their influence on machine performance identified.
- Control strategy development – this was identified as an area of particular significance. A number of control strategies were evolved and the direction for further work established.
- Transmission system development – the hydraulic transmission system was investigated and developed in conjunction with the control system operating strategy to maximise machine power output.
- Scaling effects – a brief study into the effects of scaling up the machine was carried out and an approximate rule established.

These results were used to develop the specification of the demonstrator machine , undertake parametric cost modelling studies looking at the overall economic effects of parameter variations and aid with ongoing control system development work. Once the Phase 2 demonstrator machine had been installed and its performance established, acquired data was used to validate the model. This further increased the value of the mathematical model for the continuing development of the Stingray concept.

3.2 Mechanical Design

The general arrangement of Stingray is shown in Figure 14, below.

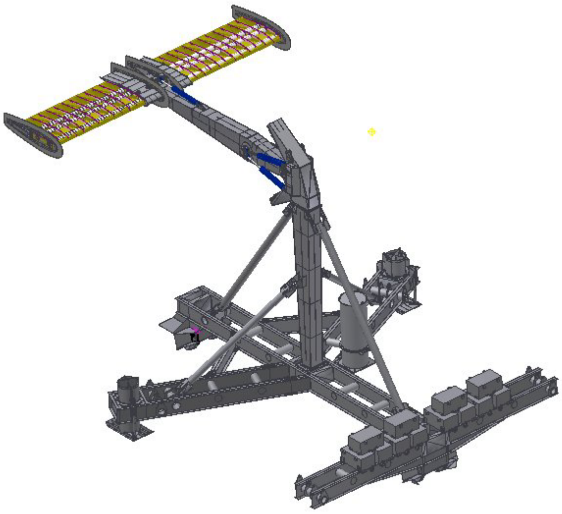

Figure 14: Stingray Mechanical General Arrangement

Key specification parameters are defined in Table 3.

Maximum height	23.6 m with hydroplanes in highest position
Maximum width	15.5m
Arm length	11m
Arm operating angle	+/- 35 degrees
Hydroplane actuation angle	Relative to arm +/- 90 degrees
Rated power	150kW at 3 knots and above

Table 3: Stingray Specification

Material selections were made using EB's in house knowledge of building subsea machines. The timescale of the project and cost limitations also had a large influence on specification. For example a commercial machine designed to be in the water for many years would have a greater number of stainless steel components to resist corrosion and allow for easy maintenance over its lifetime. However a compromise with cost had to made in this project and in many places painted steel parts could be used at a fraction of the equivalent stainless steel cost.

Due to the size of the machine the design allowed for the machine to be broken down easily into key parts for transportation by barge and re-assembly on site.

3.2.1 Hydroplanes

The principal hydroplane features are indicated in Table 4.

General	Single pair mounted on trailing arm
Profile	NACA 0015
Size	3m chord, 7.05m per side. Total width approximately 15.5 m (1.3m gap between hydroplanes for pivot, cylinder mount etc)

Table 4: Hydroplane Features

Preliminary designs had been for a twin hydroplane machine. During the design process this was simplified to a single hydroplane design to ease manufacture and reduce cost. Parametric modelling of performance and cost had shown that a single hydroplane could be configured such that it had similar overall performance to that of the optimised twin hydroplane machine developed in the Phase 1 study.

Each hydroplane was built up out of six one meter wide GRP sections, fitted onto a steel hydroplane-root substructure. The steel structure carried the lift forces generated across the hydroplane to the arm. The choice of using sectional hydroplanes over a single large construction was made to allow for the possibility to repair local damage by swapping a single section and to provide the ability, if required, to begin tests with a shorter hydroplane and build up to full width when initial results had been obtained.

Different methods of surface coatings were considered for the hydroplanes. Conventional anti-fouling paints were investigated and also copper nickel based coatings. Environmental issues meant that biocide based anti-fouling coatings were not preferable, while copper nickel based coatings would be expensive over short time periods. The choice of GRP construction for the hydroplane sections meant that a smooth gel-coat finish could be achieved and, with expected low water temperatures and high water currents, it was decided that the degree of marine fouling over the expected time scale could be tolerated.

3.2.2 Yawing

The direction of the tidal flow from which energy was to be captured was not unidirectional. A complete change in direction occurred when the tide turns, along with minor variations of direction within this. Yawing is the ability of the hydroplane assembly to rotate so the arm is parallel to the flow of the tidal stream. Several methods of yawing were considered.

After investigations of possible yaw mechanism it was decided to opt for a fixed head machine. The project objective was to prove the oscillating hydroplane concept. If this could be demonstrated to work in one direction of tidal flow, it could be safely assumed that, if the head was to yaw, the hydroplanes would perform in the other direction. Removal of a yawing mechanism had several advantages for this project, in that cost savings could be made and a reduction in complexity resulted in potential time savings.

3.2.3 Pod assembly

The pod is a sealed pressure vessel that houses the subsea electrical equipment, main generator/pump assembly and auxiliary hydraulic pump and associated components.

For a longterm, commercial system the pod would be constructed from stainless steel. However, for this project the cost was prohibitive and therefore mild steel was chosen. This led to more care being taken to ensure sealing faces are well greased to prevent them being damaged by rust. On a commercial machine this would not be acceptable but, as noted previously, compromises between cost and performance must be made.

3.2.4 Ballast and Ground Anchors

Stingray was not physically fixed to the seabed. It was designed to stay in position through a gravity base system utilising a combination of weight and earth anchors. Ballast weights were added to the machine to bring the total weight up to the calculated required value. This design was based on the findings of the site survey and desk study of geotechnical conditions.

3.3 Stingray Hydraulic Design

3.3.1 Hydraulic Circuit Overview

The motion of Stingrays power arm drives four hydraulic cylinders, acting in pairs, pumping oil to a hydraulic motor. As the hydroplane rises and falls oil is pushed in different directions across the hydraulic motor causing it to turn one way and then the other. The hydraulic motor is directly coupled to the main electric generator. The induced pressure on either side of the hydraulic motor is electrically monitored. This provides feedback on how efficiently electricity is being produced.

3.3.2 Hydraulic Auxiliary Functions

The hydraulic auxiliary functions were driven by an electric motor driving three hydraulic pumps (located in the pod). Each pump performed a separate task. The system pressure pump delivered the hydraulic pressure and flow that ultimately drove the hydroplane actuation cylinder (hydroplane angle) and the levelling foot. The boost pump ensured that oil flowed through the system to keep the circuit topped up and to circulate oil through the cooler to provide system cooling. The accumulator charge pump ensured the high pressure accumulators remained charged to their required pressure. The accumulators provided a reserve of potential hydraulic power that could be called upon during high speed operations such as reversal of hydroplane angle at end of stroke.

The motor was designed to run continuously even though the amount of auxiliary power available would not be required continuously. This project also required a diesel generator running constantly to power the auxiliary motor. A commercial machine would self generate this power (or, since grid connected, import the required energy) as and when required with a fairly small average consumed power overall. Tests carried out during the project would indicate how much power would actually be required to operate the machine.

3.3.3 Hydroplane angle control

To enable optimum performance of the generated power throughout a machine cycle the angle of the hydroplane needed rapid but controllable adjustment. The angle of the hydroplane was to be controlled by the movement of a single hydraulic cylinder coupled to a linkage system. The position of the hydroplane was monitored from the hydroplane cylinder transducer. Controlled motion was achieved by use of a large hydraulic proportional control valve governing oil flows to the hydroplane cylinder. This valve was controlled by a varying electrical signal and allowed the angle of the hydroplane to be programmed to be at certain values throughout the power arm cycle.

Should the proportional control of the hydroplane fail, a second backup function could be used to drive the hydroplane. This function (known as ‘direct injection’) could slowly move the hydroplane at a fixed speed until a desired safe angle is achieved.

3.3.4 Foot Cylinder Control

As the seabed was unlikely to be perfectly flat, one of the feet that stabilises Stingray was adjustable. This allowed some levelling adjustment to be made after deployment.

3.3.5 Other Hydraulic Parts

Filters were required for each of the three systems pumps. The target cleanliness of the system oil is NAS 6.

Two pre-charge accumulators offer an additional power source to aid the main system requirements, while a third provides additional oil to aid the boost circuit.

In order to be able to stop the power arm from moving when in service, an electronically operated ball valve was mounted between the driving cylinders and the hydraulic motor. When closed, this valve only allowed the arm to move down until it was fixed in the lowest possible position. This was considered to be a safe ‘park’ position to allow for a safe recovery. This valve was fail safe and, should power be lost to the control system, batteries installed subsea would automatically close this valve.

The valve tank housed a series of hydraulic control valves, hydraulic sensors and associated electronics to process the required input and output signals.

The hydraulic cylinders are integral to the operation of Stingray. The cylinders chosen were designed to withstand the effects of being submerged in sea water, as well as having long life seals to cope with the constant reciprocating movement of the hydroplane arm. Discussions with the cylinder manufacturers led to two alternative coatings being used on the main cylinder rods. After completion of the project the condition of the two coatings would be carefully inspected to show the best choice for a future machine.

3.4 Stingray Electrical

The electrical system is split into two main parts: a surface control system and subsea system, linked by an umbilical bundle. The main control and monitoring functions of the subsea system included pod monitoring, pod control, valve tank monitoring, valve tank control and surveillance.

The main surface control system features were a Programmable Logic Control (PLC) system and remote input and output circuitry.

All control and monitoring of the system was carried out via a PLC unit. A graphical user interface running on a personal computer (PC) was used to display machine status and allow control over machine functions. This PC also logged and processed all the results and test data. The PLC unit runs a highly reliable control program that continually looks after the machine even if the PC used to run the graphical interface is switched off or crashes. All machine controls could be operated via the computer keyboard and mouse but it is the PLC that would actually generate the electrical signals that operate machine functions and look after the safe running of the system. This is an industry standard for control system architecture with a proven history of reliability. Hardwired emergency stops were located in key places that could override all the electronic control and shut the system down in an emergency.

3.4.1 Power Train Components and Theory of Operation

The machine was sized for a nominal average power of 150kW in a current of 3 knots or more. It was anticipated that peak powers would be observed for short times during the power cycle and therefore key components had to be sized for these peaks.

The power from the Stingray machine was designed to be generated in a varying way. The power would not be constant (as it would be if from a conventional engine driven generator), therefore the variable speed drives were required to condition this power to a useable format.

The drives require a permanent connection to a mains electrical supply. Ideally this would be a grid connection but, for this project, a diesel generator was to be used. This generator would also run the auxiliary motor and provide power for the Stingray deployment system. The drives selected for this project could run from a generator or a grid connection. When running from a generator any power generated from Stingray would be diverted to the load bank and dissipated as heat. When connected to the grid any power captured by Stingray could (dependant on satisfying Electricity Regulations) be regenerated back into the grid.

As well as taking power from the main motor the drives would also supply power and drive the motor. This bi-directional power flow would be required for some of the planned tests. It allowed the arm to be accelerated from rest and up to a required speed quicker than if the tidal flow alone was causing the movement. These ‘assisted’ accelerations demonstrated, on the mathematical models, a net overall increase in energy capture.

3.4.2 Umbilical Bundle

An umbilical bundle comprising three separate cables was designed to connect the subsea and surface electrical systems. This comprised two power cables, one for the main generated power (4 core 150mm2) and a second (4 core 25mm2) to run the auxiliary hydraulic motor. A third cable was used for the control and monitoring functions.

The power cables were industry standard steel wire armoured cables. These cables, selected after discussions with Scottish and Southern Electricity submarine cable department, being readily available and relatively low cost, are suited to the short-term nature of this installation.

The control cable is a specialist cable designed for applications such as this project and of the type used by EB in the past. It is made up from copper power conductors, signal cables and fibre optic cores. The fibre optics could be used for communications if Stingray was controlled from shore.