dti

STINGRAY TIDAL STREAM ENERGY DEVICE - PHASE 3

CONTRACT NUMBER: T/06/00230/00/00

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dti

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T/06/00230/00/REP
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Contractor

The Engineering Business Ltd

The work described in this report was carried out under contract as part of the DTI Technology Programme: New and Renewable Energy, which is managed by Future Energy Solutions. The views and judgements expressed in this report are those of the contractor and do not necessarily reflect those of the DTI or Future Energy Solutions.

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EXECUTIVE SUMMARY

Since 1997, The Engineering Business Ltd (EB) has been developing tidal stream generation technology. In 2002 EB designed, built and installed the worlds first full-scale tidal stream generator, the 150kW Stingray demonstrator. The Stingray concept is that the energy within tidal currents can be harnessed through oscillating hydroplanes. A full description of the concept and technology is presented in the Phase 1 and Phase 2 reports. Stingray was reinstalled in Yell Sound in the Shetland Islands between July and September 2003 for Phase 3 of the project. This report presents an overview of this phase of the project, the results obtained and outlines the implications of those results on the potential for commercial electricity generation.

The fundamental objective of the project was to demonstrate that electricity could be generated at a potentially commercially viable unit energy cost utilising Stingray technology. In addition to this, a number of measurable targets for the Phase 3 operations were agreed with the DTI.

The aim of the marine operations was to undertake a series of tests, at slack water and on the flood tide, to reconfirm basic machine characteristics, develop the control strategy and demonstrate performance and power collection through periods of continuous operation.

A summary of the main test work findings is as follows:

- Basic machine characteristics were found to be in good agreement with previous test work.
- Power cycle development enabled significant gains to be made on the levels achieved in 2002, with further gains clearly available. Control through the cycle still remains the key issue particularly as regards the introduction of the high hydroplane actuation flows required for faster cycle times.
- Actuation power consumption was higher than expected at the cycle times achieved although much of the reason for this lies in poor control and significant efficiency gains should be realisable once this area is improved.
- Overall power generation was demonstrated on several occasions as cumulative energy collection through the course of a tide. A continuous operation period over 14 tides was also attempted – the levels of power collected would have been in excess of target values but machine downtime due to minor failures prevented operation on some of the tides.
- Useful data on the interaction of Stingray with the tidal regime was acquired and analysed.
- A decommissioning survey and environmental review have identified that Stingray has had no identifiable impact on the seabed environment during its two operating seasons.
- The cost modelling indicates a future unit energy cost of 6.7p/kWh at the stage when 100MW of Stingray capacity has been installed.

Although compliance with the targets set by the DTI was at a lower level than would have been hoped, the broader aims were met in the majority of cases. There is evidence to suggest that the technology is capable of full compliance with all targets that remain relevant.

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Appendices

1 INTRODUCTION

1.1 The Stingray Project

The Stingray project is the culmination of 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 150kW Stingray demonstrator in Yell Sound in the Shetland Islands in 2002.

The results of the test work carried out with this prototype machine during the summer of 2002 showed that the concept had considerable potential. However, there were a number of areas that required further development, test work and analysis in order to move the technology on from engineering concept to a commercially viable system. To this end, a program of work was set in place to carry out further test work with a modified version of the demonstrator in the summer of 2003 (Phase 3). This report provides an overview of Phase 3 and presents the results arising from this work.

The Phase 1 work was reported on in 2002 (T/06/00211/00/REP, DTI URN 02/1400, 2002), with the Phase 2 work reported on in 2003 (T/06/00218/00/REP, DTI URN 03/1433, 2003). Those reports provide 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 uses an oscillating motion rather than rotation to capture the energy from the tidal flow.

The key component of Stingray is the wing-like hydroplane (Figure 1). 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 the 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.

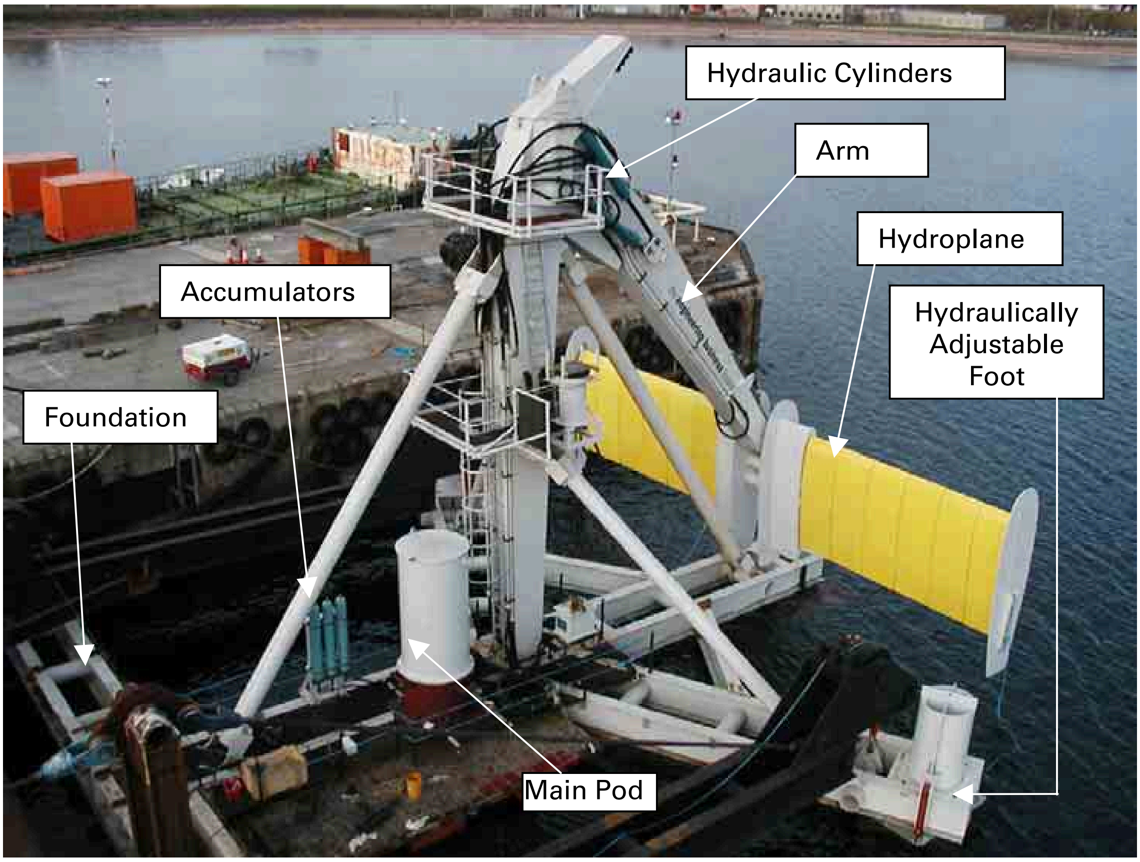

Figure 1 – Stingray General Arrangement

1.3 Phase 3 Objectives and Targets

1.3.1 Project Objectives

The key objective of Phase 3 was defined as being "to demonstrate that electricity can be generated at a potentially commercially viable unit energy cost". To meet this objective, the proposal identified the need to demonstrate:

- The technology can be fully developed to exploit the resource effectively
- Sites exist where the technology can be effectively operated
- The electricity produced is acceptable to the grid

To this end, four tasks were identified:

- Produce a repeatable, optimised power cycle
- Demonstrate the flow/machine interaction mechanism
- Collect more and varied data points for full validation of existing model
- Demonstrate that it is technically and economically viable to connect to the grid

1.3.2 Project Targets

Following discussion with the DTI, EB proposed a number of measurable targets for the Phase 3 operations. These were intended as targets against which progression of the project could be measured. However, they were not intended, individually or collectively, to represent the only measure of the success, or otherwise, of the project. The Phase 3 project targets were as follows:

i) The time average of the mean power produced over an operating cycle is to be greater than half the value of measured instantaneous peak power (based on a data logging frequency of approximately 10 measurements per second).

ii) Automatic control of the machine to allow continuous operation over a 10 minute period with cycle times not greater than:

23 secs. @ 1.25 m/s average tidal speed measured at the machine

21 secs. @ 1.5 m/s average tidal speed measured at the machine

20 secs. @ 1.75 m/s average tidal speed measured at the machine

19 secs. @ 2.00 m/s average tidal speed measured at the machine

iii) Continuous operation using automatic control for at least 3 hours per 12.5 hour tidal cycle on at least one occasion.

iv) The average hydraulic power measured at the motor over a 30 minute period of continuous operation to be:

45 kW @ 1.5 m/s average tidal speed measured at the machine

60 kW @ 1.75 m/s average tidal speed measured at the machine

75 kW @ 2.0 m/s average tidal speed measured at the machine

v) The total energy collected (measured in terms of hydraulic pressure and flow at the motor) over a 14 tide cycle period of operation to be 2600kWh.

vi) The total energy collected (measured in terms of hydraulic pressure and flow at the motor) over a 56 tide cycle period of operation to be 10,000kWh.

vii) The total energy collected (measured in terms of input to the load bank) over a 56 tide cycle period of operation to be 8,000kWh.

viii) Current velocity upstream and downstream of the machine measured continuously and simultaneously for at least 15 minutes with the machine operating at steady cycle times of 23, 21, 19 seconds.

ix) Drive power conversion efficiency to be measured/calculated for a range of input powers and waveforms that represent the output from the Stingray generator.

x) Post-decommissioning site survey demonstrates no significant environmental impact.

These targets are reviewed in light of the operational experience in Section 14.

1.4 Project Activities

To fulfil these requirements, a number of activities were undertaken, with the broad aim of reinstalling the 150kW Stingray, obtaining more operational data for analysis, and undertaking certain site / resource related studies. These comprised:

- Design
- Manufacture and Assembly
- Marine Operations (Installation, Operations, Monitoring and Removal)
- Investigations and Analysis
- Site and Resource Appraisal
- Project Management and Reporting

1.5 Project Timeline

To enable continuity, certain time-critical elements of design and procurement were undertaken in the closing stages of the Phase 2 project. Phase 3 activities started in May 2003. The barge, having been mobilised at Burntisland, arrived in Shetland on 13th June. Site Acceptance Tests were carried out in Lerwick on 6th July, before the marine spread was moved to Sullom Voe on 7th July for final commissioning. Installation occurred on 27th July, with marine operations commencing immediately. Stingray was finally recovered on 17th September, having operated for 53 days on location and worked 41 tides. Initial decommissioning of Stingray started in Lerwick, with components being stored in Lerwick, Burntisland and at EBs workshop. Having been returned to its pre-charter condition, the barge was demobilised on 17th November 2003. Analysis of the data, along with development studies relating to the tidal resource, site locations, grid connection, the second generation Stingray concept and cost model refinement were undertaken in late 2003 / early 2004. As part of the consent requirements, a post-decommissioning seabed survey was undertaken in 2004.

2 DESIGN AND PRODUCTION

2.1 Design

Reviews of the general Stingray design and Launch and Recovery System were carried out following completion of the Phase 2 operations. These enabled areas of possible optimisation and improvement to be identified for further assessment. Redesign started in early 2003, with a number of modelling, desk study and design activities. The control system was a particular focus of this work. Purchase Orders were issued and, on receipt, the components were tested prior to assembly.

Once a suitable operating barge had been selected, various design tasks had to be undertaken prior to its arrival. These included a barge stability check and longitudinal strength assessment performed by naval architect's prior to charter. Both investigations revealed that there were no problems with the barge. As the barge was delivered as an empty floating platform without any equipment onboard, the first step following stability check was to design a comprehensive deck layout with key equipment positions. This was followed by calculations and new drawings being prepared for the redesign of the handling system to be installed on the barge. In addition, a slack-rope management system to be used when Stingray was in operation was designed.

2.2 Mathematical Modelling

The mathematical model is central to the progression of the Stingray project. As well as being the key development tool, permitting design changes to be assessed without the need for model or full-scale testing, it is also, critically, the source for estimates of power capture used in the economic modelling. It was therefore critical that the model was developed to fully represent the Stingray system, and for its output to be validated by the full-scale testing of the demonstrator.

The Phase 2 model used a basic representation of the hydroplane and main arm structures. New software allowed a more complete representation to be implemented, including full representation of the hydroplane and main cylinder linkages, along with all of the dynamic coupling effects.

The parameter file, defining the values used for key characteristics in the mathematical model, was reviewed in line with the test results from on site testing.

An accurate representation of the hydroplane control counterbalance valve and Direction Control Valve (DCV) was required in the mathematical model to combine with other hydraulic elements in the revised circuit. The elements of valve performance important to the model were identified then an outline model constructed. This was tested for a range of inputs and outputs and compared against anticipated performance. The hydroplane counterbalance and DCV models were then combined with the existing hydroplane hydraulics and the basic operation of the actuation circuit tested.

All the revised mechanical electrical and hydraulic elements were combined in the top-level model. Initial simulations were then run, and the structure reviewed to ensure performance was as anticipated. Initial tuning was performed to maximise power output with the existing control structure. The revised model was then run through a directly equivalent cycle to the test cycle and the results analysed.

The control system IO, and essential elements of the existing control software, were modelled in Simulink format. This enabled the revised and validated mathematical model to investigate improvements to control of arm and hydroplane to maximise power output. Initial effort concentrated on sinusoidal cycle but was developed to look at alternative cycles. The control sensitivity to alternative arrangements of hydroplane hydraulics was investigated.

One of the mathematical modelling activities was the development of a Simulink model for the variable speed drive (VSD) system. The foundations of this were performed externally using Mathworks as consultants but with considerable liaison with EB to ensure the model was well understood and that the modelling work focused on the areas of importance to EB.

2.3 Component Reviews

The performance of a number of specific components used during the Phase 2 operations was reviewed, identifying their strengths and weaknesses. After this, possible changes for Phase 3 testing were investigated. These included:

Control system hardware - specifically whether a closed loop controller in the hardware on the hydroplane control valve would be beneficial and how could control from the mathematical model be directly interfaced with the current control system.

Hydroplane actuation hydraulic circuit - specifically methods of improving stability, enabling faster response/pressure build up and controlling over-running load. From this review, it was clear that the load sensing circuits in the hydroplane hydraulics were not operating as intended. The necessary elements of the circuit were assembled in the workshop and a series of tests conducted to establish the reasons behind this. This review also identified a number of possible options for changes in the hydraulic circuit that could improve stability and control. It was therefore necessary to identify the complete list of components to cover all options highlighted in the review, as well as establishing their costs and lead times. The design activity necessary to support any layout changes was identified.

Actuation linkage – This is the mechanical linkahe that converts the linear motion of the hydraulic actuation cylinder to the required rotational movement of the hydroplane to control the hydroplane angle. It was determined, after Phase 2, that the side link components of this linkage required upgrading for Phase 3 operations. The linkage material was changed to RQT 701 and some side stiffening was also required. The design of these aspects was undertaken. RQT 701 is a specialist high-strength steel produced by Corus. It is designated RQT to indicate the technology used in its production – Roller Quenched and Tempered, whilst the 701 denotes the grade, related to the minimum yield stress (690N/mm2).

Reservoir - The reservoir expansion capacity on Stingray in Phase 2 was insufficient to cope with the volume changes in the circuit due to charging and discharging of the accumulators. There were also issues with the transducer system used to monitor the oil level. The system was re-designed for return to site.

Main transmission pod - Specific issues considered included whether the current motor orientation was acceptable, adequacy of the main seal and cable penetrations, whether there could be benefits from positively pressurising the pod and what benefits a separate electrical pod could offer. The pod penetrations used in Phase 2 were identified as a weak point in the environmental sealing of the pod pressure vessel. The existing penetration design was replaced with water blocked connectors to be installed through the pod wall, leading to a field termination of the cables in an oil filled junction box external to the pod. These items required specified design work undertaken to support their installation. As part of preparation of the Stingray machine for Phase 3, the implementation of the pod hydraulic circuit also required some revision.

Instrumentation pod - The possibility was raised of using a separate electrical pod to package the elements of the control and instrumentation electronics that had to be housed sub-sea. To determine whether this was appropriate, a review was undertaken of all sub-sea electronic elements (including instrumentation) and their environmental and packaging space requirements. Based on this review, it was determined that the electrical subsea equipment for Stingray Phase 3 should be housed in a separate instrumentation pod.

Hydroplane - During Phase 2 testing the hydroplane endplates were observed dishing concavely around the bolt patterns which secured them to the hydroplane tube ends. A support tube on the endplate fabrications was designed to limit this dishing effect.

Access - As part of the Stingray operational review it was identified that access around the machine could be improved. A review of existing walkways and platforms was undertaken to identify and implement changes as necessary. It was also necessary to identify and implement access to additional area of the machine such as the valve tank and main post bolts. Once this was completed, an outline design was prepared for the intermediate upper access platform to allow working access to main arm head fixings (beneath arm) and valve tank, now located on the underside of the arm. Access platforms were also designed for the adjustable feet, and additional grating and handrails positioned to permit access to the liftpoints closest the barge.

2.4 Commissioning plans

Commissioning documents were prepared to review and test the electrical and hydraulic transmission system and hydroplane control system elements with the aim of ensuring all systems were fully functional and ready for transport from Newcastle to site and ready for deployment.

All of the instrumentation installed on Stingray had to be adequately commissioned and calibrated before the start of test work to ensure the quality of the recorded data. To this end a commissioning document for all of the instrumentation sensors and systems was written, covering calibrations and commissioning to be conducted in Newcastle (Factory Acceptance Tests - FAT) and those to be conducted in Shetland.

2.5 Instrumentation

Instrumentation on the Stingray machine was reviewed in detail following operations in 2002 and a significant number of additional sensors were introduced to provide more detailed information on the machine performance and its interaction with the tidal stream. Table 1 provides a summary of the key measurement sensors. Data acquisition from the instrumentation was generally at a frequency of around 15Hz.

Sensor	Purpose	Accuracy / Resolution	Location
Pressure Sensors: Trafag (UK) Ltd	At all areas in the hydraulic circuits, allowing accurate measurement of loading, hydraulic power and losses through the circuits.	Range: 0 to 400 bar Accuracy: ±0.3%	On all major hydraulic circuits
Current Measurement: One 1500kHz Sontek Argonaut MD Two 1000kHz Sontek Acoustic Doppler Profilers (ADP)	Used to monitor the tidal flow at and around the Stingray installation site.	24-40m profiling range (ADP) Velocity range: ± 6m/s (MD) ± 10m/s (ADP) Resolution: 0.1 cm/s Accuracy: ± 1% of measured velocity ± 0.5cm/s Up to 100 range cells (ADP)	Argonaut MD mounted on Stingray upstream (with reference to flood tide) of the hydroplane at approximately mid-sweep level. The two ADPs were mounted on the seabed approximately 70m upstream and 50m downstream of Stingray.
Hydroplane Load Cell: Dual shear plane load cell pin from Dynamic Load Monitoring Ltd.	The main pin connecting the hydroplane to the main arm was instrumented, allowing direct measurement of the hydroplane lift and drag loads.	200 tonne range ± 1% FS	Main hydroplane pivot pin
Cameras: RF Concepts Ltd.	Several cameras were positioned around Stingray	Submersible to 50m 30m Visual range	Inside pod, on hydraulically adjustable foot

Sensor	Purpose	Accuracy / Resolution	Location
CC70C-50	and inside the main pod to allow visual monitoring.	using IR	and on main arm
Strain Gauges: Dynamic Load Monitoring Ltd.	Key elements in the hydroplane structure were instrumented with strain gauges to monitor how the loads within the hydroplane were distributed.	4-20mA output	Hydroplane tube structure, foundation beams, main arm
Relative flow angle meter Built in-house by EB	This is a flap meter, which is intended to measure the incoming flow direction relative to the hydroplane, taking in to account all of the machine motions.	Measures 360° rotation	Starboard hydroplane end-plate
Hydroplane Accelerometer Monitran	An accelerometer was mounted on the outside endplate of the hydroplane to monitor vertical vibrations in the hydroplane structure.	± 2g 100mV/g	Starboard hydroplane end-plate
Hydroplane dP sensor RPD Electronics Ltd	A pressure sensor was installed to measure the differential pressure between the top and bottom surfaces. This was with the intention of measuring the increase in the differential	± 150mB ± 0.25% FS	Towards the trailing edge of one of the hydroplane sections

Sensor	Purpose	Accuracy / Resolution	Location
	pressure that will arise when the hydroplane begins to stall and separation of the flow on one side of the structure is present.		
In cylinder transducers: Micropulse linear displacement transducer from Balluff Multiswitch Precision Switching	Transducers measuring the length of the hydroplane actuation and main transmission cylinders provide the necessary information to determine the position and motions of the machine.	Repeatability (resolution + hysteresis) = 0.3mV Sample rate = 2 kHz	The hydroplane actuation cylinder and 2 of the 4 main transmission cylinders
Motor Speed Encoder: British Encoder Products Co.	The motor speed encoder measures the speed of the transmission system	Series 260 low-profile (30mm) Incremental, 1024ppr (pulses per revolution) 10mm hollow shaft, accuracy (cycle to cycle): +/- 0.017degrees.	Electric motor

Table 1: Stingray Instrumentation

2.6 Production

The rebuild / reassembly of Stingray was undertaken at four sites - EBs workshop on Tyneside, Briggs Marine Contractors Burntisland base and Lerwick / Sullom Voe in the Shetland Islands. Activities included mobilisation / modification of the barge, assembly of Stingray and commissioning / testing.

To enable the operations required for the 2003 Stingray Phase 3 programme, a number of modifications and improvements to the Stingray arrangement were required. These modifications and improvements focussed on the following areas.

Main Pod

The redesign of the main, boost and auxiliary hydraulic circuit was fabricated and assembled, along with the mounting of all hydraulic valves in manifolds and the elimination of as much hard piping and compression fittings as possible. A new manifold was welded into the pod base to eliminate use of excessive BSP fittings and T- pieces. This enabled simpler fitting of hoses via the use of SAE flanges and adjustment of manually controlled valves without removal of the pod lid.

The pod was also subject to a mechanical reconfiguration and rebuild, in part to improve access and handling improvements. These comprised the inclusion of pod lid guides and hose / harness protection around framework; tapped holes in bottom flange for bolts to guide lid onto face; a clean up of housing flanges; removal of original manifolds and fitting of replacement manifolds; and removal of stub pipes as appropriate.

Electrical

The original main electrical motor was inspected and refurbished in preparation for the Phase 3 operations. This involved the cleaning and repairing of the stator, cleaning of all component parts, dynamically balancing the rotor, fitting of new bearings and testing. The auxiliary and blower motors were also subjected to the same refurbishment regime. A new electric motor was also procured as a spare. The newly designed additional junction boxes were assembled and installed.

Generator

An electrical & mechanical overhaul of the generator was carried out to ensure that all components were operating correctly and in a safe manner. The fire extinguishing system was also fully checked out by the supplier prior to shipment from the EB workshop.

Drive system

Based on the experience obtained in Phase 2, the drive cabin was subject to a review of its hardware and operation. Based on this, changes were implemented, including the re-wiring of the load bank, improved cable transits and addition of extra instrumentation.

Instrumentation

Additional instrumentation including power measurement and main hydraulic circuit monitoring was procured and installed. In conjunction with the specification and purchase of the instrumentation, the brackets for mounting them on the machine were designed and built. A separate, discrete stainless steel junction box was also designed and manufactured for the distribution of harnesses servicing the instrumentation on the main structure.

The instrumentation pod pressure vessel, including faceplate was manufactured (Figures 2 and 3) and then subject to a pressure test prior to delivery. The pressure test involved the pod being subjected to an internal pressure of 56.25 bar and external pressure of 37.50 bar.

The internal mounting frame for the instrumentation pod was fabricated. This frame housed the PLC rack and associated I/O equipment, all of which was ordered in conjunction with the frame design. The main power and instrumentation harnesses that interconnect the pod, valve tanks and the various instruments on Stingray were installed, as were the custom-built main pod and umbilical termination penetrator cables.

The seabed frames for the two ADCPs were manufactured (Figure 4).

Figure 2: Instrumentation Pod during assembly

Figure 3: Instrumentation Pod and Junction Box in position on Stingray

Figure 4: ADCP Frame

Figure 5: Reservoir

<u>Control</u>

The existing software and control strategy was modified, with an alternative strategy developed in parallel.

<u>Hydraulics</u>

The auxiliary hydraulic circuit instrumentation was procured and installed. The valve tank that housed the counterbalance, flow control and directional control valves was relocated from the base to the arm, to minimise hose lengths between the valve and actuator. The foot cylinders (including pressure sensors) and counterbalance valves were assembled.

The hydraulic reservoir was redesigned and rebuilt to increase the volume of hydraulic oil stored (Figure 5). The reservoir expansion capacity on the Phase 2 machine was insufficient to cope with the volume changes in the circuit due to charging and discharging of the accumulators. This involved fitting an additional bellows unit so increasing the capacity of the reservoir and the design and purchase of a new oil level sensor to cater for the increase.

Safety

New walkways and platforms for Stingray were designed and manufactured. These were identified as being required, following an internal review, to improve access around the machine and to increase safety for personnel during operations.

2.7 Factory Acceptance Tests (FATs)

The purpose of the factory acceptance test (FAT) was:

- To demonstrate that the equipment to be shipped operated "as designed"
- To demonstrate that the equipment was safe in operation
- To demonstrate that the equipment fulfilled the technical requirements of the programme.
- To provide information on the main transmission characteristics and efficiencies.

Each FAT set-up followed the test sequences identified in the pre-prepared FAT documents and functional test specifications.

The main transmission hydraulic and electrical circuit test set-up was intended to allow a functional test for all of the hydraulic and electrical elements in the main transmission circuit (Figure 6). It also allowed commissioning of the power measurement instrumentation and some initial measurement of the transmission system efficiencies for steady state and transient cases. An electric driven HPU unit with variable displacement pump was hired and connected to the main hydraulic circuit at the pod wall where the main transmission cylinder hoses would normally be connected. This HPU represented the effects of the tide, hydroplane and main arm during the FAT. It had a pressure compensated override which could be set to provide the appropriate level of torque for a particular case. The flow for a given case would dictated by the speed setting of the Stingray drive motor system, within the limits of what the HPU could provide.

Specific FAT software (SCADA and PLC, Figure 7) was written by EB to enable this element of the FAT to be undertaken. Performance of the FAT was monitored using a combination of an oscilloscope and power harmonic analyser.

Figure 6: Pod contents (main motor at base, auxiliary motor at top), with hired in HPU in background

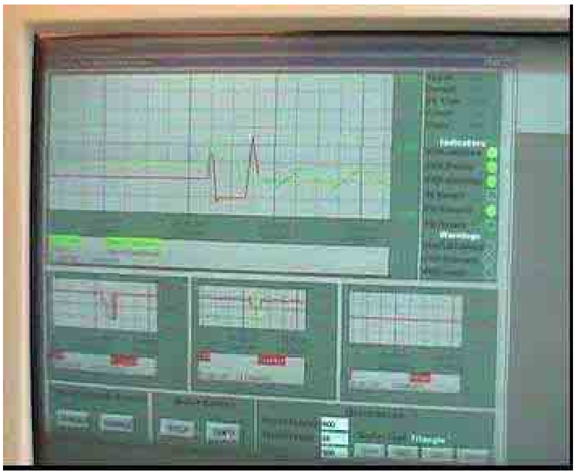

Figure 7: FAT test software

Another test sequence examined the basic functionality of the pod auxiliary circuits (boost circuits, accumulator switching, load sensing logic valve switching, etc) with the intention of confirming the correct valve function, pressures and flow rates and to test the accumulator operation. These tests required the complete pod auxiliary hydraulic circuit to be supplied by the auxiliary pump set-up and reservoir assembly. Accumulators were connected to the circuit but the valve tank was not connected.

Further tests checked the port and starboard adjustable foot circuits. In addition to the equipment used in the previous test phases, one set of foot cylinders & counterbalance valves was also required. These were switched between the port and starboard pod connections as required. The next phase of testing was for the valve tank counterbalance / hydroplane circuit, allowing for various modifications to tune circuit stability. Additional auxiliary circuit tests that required load sense signals from the valve tank were also carried out at this point. Additional equipment introduced in this phase included the valve tank circuit. The final phase of testing was for the flow rate related aspects of hydroplane control, including switching in of the additional hydraulic supply from accumulators and measurement of the rate of flow associated with different proportional valve driver card settings.

In addition to the main FAT activities, the modified subsea pod was subject to a specific FAT. This investigated the mechanical, hydraulic, control, electrical, instrumentation and system functions.

Mechanical items covered included the main and auxiliary motor / pump couplings, a pod vacuum test, function tests of the reservoir, pod lid guide, pod frame lowering system and torque checks of the main and auxiliary motors mounting / bellhousing, and hydraulic connections.

Hydraulic items covered included, amongst other tests, flow rate check tests of main motor and pumps (boost, auxiliary and accumulator) covered by supplier FATs; function checks of valves, the foot cylinder circuits, boost and actuation accumulators and the hydroplane actuation circuit; and reservoir volume adequacy.

Control and electrical tests included function tests of the emergency stop for the drive system, the main motor, encoder, auxiliary motor, drive speed control, solenoid, and the emergency ball valve; a check of the proportional valve driver card set-up; drive control tuning and experimentation; brake chopper function / set-up; main motor ventilation fan test, and current meter connections.

Instrumentation tests included calibration and functional checks of power measuring equipment, pressure transducers and reservoir transducers. In addition, a number of sensors were tested against their specifications and the circuit wiring verified. These included pod humidity and temperature, pod leakage / water level sensors, motorised ball valve status indication, main motor temperature, auxiliary motor temperature, oil temperature and filter clogging indicators.

System testing included in the pod FAT comprised component efficiencies when steady state (conversion efficiency and power flows in the system for steady state running of the hydraulic motor at various speeds and torques) and transient (as above but for transient cases), as well as actuation cylinder extension / retraction rates.

2.8 Stingray P3 Barge Mobilisation

The EMS6 barge arrived in Burntisland and went on charter from 15th May 2003 (Figure 8). A full barge survey was undertaken by EB on its arrival. The barge conversion was undertaken between 18th May and 11th June, when the barge left Burntisland, arriving in Lerwick on 13th June.

The existing handling system was overhauled, checking, and where necessary replacing, all components form the Phase 2 operations and manufacturing and fitting new components specific to the requirements of the EMS6 (Figure 9). The new barge was found to have solid bars fitted around the edges, which clashed with the position of certain parts of the handling system. These were removed and the area prepared prior to mounting of the handling system fabrications. On completion of this preparatory workscope, work commenced on the different aspects of the conversion including general deck strengthening and fittings, handling system installation and Stingray and barge operational equipment.

The general deck strengthening and fittings included new base mounts, mooring winches with appropriate fairleads and snatch blocks, and a deck generator (with transformer) to power lights, barge domestics and other deck equipment. A mobile deck crane was installed on the barge with appropriate crane mats for travelling along the deck. Pump sets for filling and emptying ballast compartments were installed. Access gangways from the barge to Stingray were designed, manufactured and fitted to the barge.

The handling system installation included the manufacture and fitting of new strand jack mounts, the new slack-rope management system and two sets of steering winches for maintaining Stingray alignment during launch and recovery. The handling system was fully assembled on the barge prior to departure for Lerwick.

Facilities essential for the operation of Stingray included the manufacture of container mounts for the drive and control containers. The generator and workshop containers were fitted to the barge, along with a new mess container with cooking and changing facilities. A full suite of safety equipment was installed onboard prior to departure, including lifejackets, VHF radio equipment, inflatable life rafts and survival suits.

Loose equipment such as strand jacks, hydraulic oil, pod-access fabrication, etc were all adequately sea fastened for the barges journey to Lerwick (Figures 10 and 11).

Figure 8: Barge upon delivery

Figure 9: Major components MPI'd

Figure 10: Crane seafastened for journey

Figure 11: Barge leaving Burntisland

2.9 Shetland Reassembly

The main structural elements of Stingray had been stored in Shetland since the Phase 2 demobilisation (Figure 12). Preparation of the Stingray components in Shetland started in May, using a combination of EB and local labour. This included fabrication of new walkways, minor structural repairs and the Magnetic Particle Inspection (MPI) and repair, where necessary, of all critical welds. Coupled with this was the repair and rebuild of the hydroplane, including fitting of instrumentation and electrical harnesses.

Planning for the Shetland reassembly identified a number of build strategies, dependant on the craneage used. Following analysis of the options it was decide to re-assemble Stingray on shore, in two discrete parts, (base/central column/bracing members and arm/hydroplane), using the largest Shetland-based crane (as used for Phase 2) and then hiring in a 350 tonne crane from the mainland for the lifting of the two heavy parts on to the barge. Although the large crane represented a significant cost to the project, this strategy had the advantage of allowing building of Stingray to be completed onshore in parallel with the mobilisation of the barge and installation system.

The barge and Briggs crew arrived in Shetland on 13th June. A team of mechanical and electrical engineers began the task of mobilising the barge and completing the on-shore build of Stingray prior to the lift. On completion of these on-shore activities Stingray was loaded onto the barge on the 26th June (Figures 13 to 17).

On the barge the electrical work included running the cables between the generator, drives and control cabins; completing wiring modifications to the I-Pod; modifications to the drive cabin and application software; installation in the control cabin of the computer network and dSPACE system hardware; make-up and connection at barge end of the umbilical bundle; fitting a new breaker to the generator; and completion of the barge electrics.

Figure 12: Stingray prior to reassembly

Figure 13: Preparing base section for lift

Figure 14: Base section loading onto

Figure 15: Arm/hydroplane section lift

barge *onto barge*

Figure 16: Bolting of arm to column

Figure 17: Stingray loaded onto barge

Mechanical work on the barge included the installation of the strandjack system, including running the strand and lift wires and their connection to Stingray. In conjunction with the installation of the strandjacks, a strand wire tensioning system was installed on the barge. This comprised a series of goalposts welded down both sides of the barge in line with the strand and lift wires and towers forward of the strandjacks. The tensioning system operated by maintaining a constant tension in the lift wires when Stingray was deployed to the seabed. The system operated passively with a tensioning weight, fitted inside the towers, attached via a system of pulleys directly to the Stingray lift wires at the strand termination blocks.

With Stingray secured to the barge via the launch and recovery system, the instrumentation pod, electrical junction box, hydraulic hoses, electrical harness and instrumentation were installed on the machine

The safe operating procedures for the strandjacks were verified with the assistance of an engineer from the supplier. On completion of this, the launch and recovery system was subjected to a load test prior to the barges departure from Lerwick. This was carried out on the 6th July in the presence of an independent third party surveyor.

A static load test was carried out with the system being subjected to the addition of 95 tonne of ballast on Stingray, so increasing the total load to approximately 170 tonnes. During this test Stingray was suspended from the lift beams using four 30 tonne strops, doubled up to give a total load capacity of 240 tonnes. The strops were attached to Stingray by four 55 tonne proof weight shackles, with no weight on the lifting wires

The static load test was completed to the satisfaction of the surveyor and this was followed by a test where the weight was transferred from the strops to the lifting wires. Stingray was then raised by 1m. A test of the emergency stop system was then undertaken, by cutting the power to the strandjacks whilst lifting. At this point the fixed collets engaged automatically and the moving collets remained engaged. Finally, the lowering system was tested to return Stingray to its original position.

The entire system was examined before, during and after the tests. No distortion was noted at any point. In his report, the surveyor noted that "all parts, components and control systems worked without fault during the tests and none of the tests had to be repeated. I am therefore satisfied that the Lifting and Recovery System operated as designed". Once the test on the installation system had been completed, all equipment was seafastened for the transit to Sullom Voe for a final assembly and slack water testing. This included removal of all ballast blocks prior to departure.

The barge, with Stingray loaded on the lift beams, was towed from Lerwick to Sullom Voe by the Forth Drummer tug on 7th July. The greater water depth at the Construction Jetty at Sullom Voe (compared with Lerwick) meant that it was, as in 2002, to be the site of final commissioning and deployment tests before moving Stingray to its site in the Yell-Bigga channel. Deployment tests were to be undertaken as part of the commissioning / Site Acceptance Test procedure, but also to ensure all EB and barge personnel were sufficiently experienced and confident in the installation process before moving to the harsher environment on station at the Stingray site.

Final assembly included terminating the main power and umbilical cables, filling the reservoir with oil, terminating the main and auxiliary motor cables in the drive, installing a new power meter on the main motor cables, completion of hosing and harnesses, installing the safety nets and non-slip pads, running the hydraulic hoses for the foot cylinder and bleeding air from the main hydraulic lines on the cylinders. Preparation for the deployment trials required the ballast blocks to be loaded back onto the Stingray base. The Stingray assembly was completed on 12th July and commissioning of the system commenced. This included running the auxiliary motor, moving the hydroplane through its full arc, moving the feet, energising the hydroplane logic control stack, commissioning the instrumentation and sensors, lockdown valve, computer network, dSPACE and drive system.

Following this initial period of commissioning a series of full deployment trials were undertaken, lowering the machine to the seabed in approximately 10m water depth (Figure 18). These were carried out on the 15th, 20th, 21st and 22nd July. With the machine deployed, commissioning tests on the arm and hydroplane control systems were conducted by driving the machine against still water (Figure 19). These allowed trial operations of the arm and hydroplane, commissioning of the main motor, control system modification and implementation, PLC operation verification, drive system operation, dSPACE set up, and software modifications.

Once these commissioning tests had been satisfactorily completed, Stingray was ready for mobilisation to the main test site in the Bigga-Yell channel. All of the tests for which analysis is reported were carried out at this site. A planned move on the 24th July was postponed due to a forecast of unsuitable weather, which continued through the next day, with Stingray finally moving to site on the 26th July.

Figure 18: Stingray at Sullom Voe

Figure 19: Main arm transmission system testing

3 MARINE OPERATIONS SUMMARY

Stingray was located in Yell Sound, Shetland, in the channel between the islands of Yell and Bigga, in approximately 30m water depth. For the purposes of the demonstration project, Stingray was deployed to the seabed by a strand-jack system from the pontoon barge EMS6. The barge, on an anchored mooring, remained on station to house the control systems and provide a working platform for the test crew. This negated the requirement for procurement and installation of a subsea and onshore cable.

Installation of Stingray took place on 27th July 2003 and test operations were undertaken until 17th September 2003. On completion of operations, Stingray was recovered to the surface and returned to Lerwick for decommissioning.

3.1 Installation

In parallel with the manufacture / assembly tasks, the marine spread had been mobilised to Shetland and a certified mooring system installed at the test location in the Yell-Bigga channel.

On the 26th July the barge left Sullom Voe to be towed to its moorings in the Yell-Bigga channel by the tug the Forth Drummer. With the assistance of a local multi-cat vessel, the Voe Venture, the barge was safely positioned on its moorings with no problems being encountered (Figure 20). The forecast for the 27th August was encouraging for deployment, indicating the wind to be Westerly 5-12 knots (Force 2-4), backing South South Easterly. The total significant wave and swell heights were predicted as 0.1 to 0.5m, with a maximum of 0.8m, within Yell Sound.

Following final commissioning checks, safety briefings and pre-launch checks, Stingray was deployed to the seabed on 27th July. Installation started at 14:00 (Figure 21) and Stingray touched down at 20:00 in approximately 30m water depth.

Figure 20: Stingray on moorings

Figure 21: Stingray during launch

3.2 Operations

Control system development was seen as the key area requiring improvement at the end of 2002 testing in order to achieve the full machine potential. Because of its importance, two different tools were used to address the problem.

- PLC control system – This is the same hardware and basic software as used in 2002. It uses standard industrial Programmable Logic Controller (PLC) technology to implement closed loop control for both the hydroplane position and the arm torque or speed.
- dSPACE – This advanced control technology was introduced to address the integration of the two basic, but interrelated, control loops that comprised the PLC solution, which was believed to be a possible limiting factor to improving the machine cycle. It works by characterising the machine hardware through a system identification approach and using this characterisation to implement a controller that takes account of all of the system characteristics. Once the machine is characterised, the control algorithms are developed and tested against a mathematical model before being applied to the machine.

Both approaches address control of the hydroplane / arm unit and the drive system. More details on the control strategies are presented in Section 7.

3.2.1 Test Definition

Testwork was undertaken on the flood tide and at slack water, depending on the test requirements and objectives. The overall aims of the testing programme was to confirm previously defined machine characteristics, progress control development (using two distinct strategies), and measure generation performance. The limited time available resulted in the test work being almost entirely focussed around development of the machine power cycle. Table 2 below summarises the areas covered, the objectives and rationale behind the tests, details of the tests and the instrumentation used to acquire the key parameters.

Test Area	Objective	Specific Tests	Key Parameters
Machine static characteristics	Confirm basic performance assumptions - by looking at the static loads in the main transmission and actuation systems it is possible to gain a measure of the net gravity/buoyancy load on the structure and compare this with the values estimated during the design process.	Static arm gravity load Static hydroplane gravity load	Main transmission pressure transducers Hydroplane actuation system pressure transducers Arm and hydroplane angular position Tide speed (Ensure slack water)
Added mass verification tests	Confirm basic performance assumptions - by	Arm impulse acceleration tests	Main transmission pressure transducers

Test Area	Objective	Specific Tests	Key Parameters
	providing an impulsive load on the hydroplane and arm assembly from the transmission, and measuring the subsequent level of acceleration, it is possible to calculate the total mass/inertia of the assembly and compare this with the assumptions used in previous analyses.		transducers Hydroplane actuation system pressure transducers Arm and hydroplane angular position, velocity & acceleration Tide speed (Ensure slack water)
Hydroplane hydrodynamic performance check	Confirm basic performance assumptions - if the hydroplane is held at a range of fixed angles to the incoming flow with the arm stationary, the loads generated in the transmission and actuation systems can be used to derive static performance coefficients for the hydroplane which can then be verified against previously assumed values.	Steady state lift measurements	Main transmission pressure transducers Hydroplane actuation system pressure transducers Arm and hydroplane angular position, velocity & acceleration Tide speed
PLC hydroplane control tuning	Optimisation of hydroplane control - basic tuning of the hydroplane position control is required before any attempt to put the machine through the desired range	Hydroplane PID tuning tests for: • Position control • Constant relative angle control • Angle of attack	Hydroplane actuation system pressure transducers Hydroplane angular position & control error

Test Area	Objective	Specific Tests	Key Parameters
	of cycles.	control	
PLC torque control cycle development – With angle of attack and relative angle control	Development of machine cycle control & power output. This is the core work of the programme, putting the machine through a range of cycles and modifying the cycle form and control algorithm to continually improve the levels of power generated by the machine.	Extensive range of tests aimed at development of torque control software, algorithm development and subsequent tuning – all with the aim of maximising power output. Simultaneous upstream & downstream flow measurement	All main transmission and auxiliary system sensors. Upstream & downstream ADCP units
dSPACE hydroplane and arm identification testing	Development of hydroplane control and machine cycle control. This alternative control strategy requires a plant identification process to be carried out – the response of the plant to set inputs is measured. The knowledge of this response can then be used to derive a bespoke controller for that system.	Hydroplane system identification tests Arm system identification tests	Hydroplane actuation system pressure transducers Hydroplane angular position & control error
dSPACE controller testing	Development of hydroplane control and machine cycle control. Testing of the dSPACE controller follows the same aim as testing of the main controller – ie to put the machine through a range of	Controller verification tests Subsequent cycle tuning to maximise power output	All main transmission and auxiliary system sensors

Test Area	Objective	Specific Tests	Key Parameters
	cycles and modify the cycle form to optimise the power output at a given tide speed.		
Accumulator firing trials	Development of hydroplane control to allow faster (higher power) cycle times to be achieved. Accumulator firing forms part of the overall cycle development and optimisation – in particular it allows faster cycle times to be approached via more rapid hydroplane actuation. Investigate the power consumed by charging the accumulators to assess their net benefit.	Various tests carried out in conjunction with both PLC and dSPACE controller development	All main transmission and auxiliary system sensors
Continuous operation period	Demonstration of energy collection over an extended time period - one of the key aims of the programme was to look at energy collection over longer periods of time (rather than just individual cycles).	Machine running continuously under PLC control	All main transmission and auxiliary system sensors

Table 2: Phase 3 Test Definition

3.2.2 *Test Record*

The daily operation of Stingray followed strict operating and test procedures, following a defined test regime. However, the nature of development trials such as this was that variations from a planned progression could be taken if advantageous effects were noted. Multiple data inputs were logged simultaneously, hence one operating sequence could fulfil the requirements of a number of tests. A shift system was operated, enabling parallel development routes to be followed each day.

For some of the control development, particularly the dSPACE system identification testing, work could be undertaken at slack water as well as during the tidal flow periods.

A typical tidal operating shift would commence with a team briefing / shift handover for the test team and the marine crew. This would outline the previous shifts operations, define the work to be undertaken and outlining any other issues (marine operations, data logging, safety, housekeeping, etc). Once complete, the barge-mounted generator would be started to provide basic power to the control cabin and for the hydroplane control. A systems check of the PCs, including the PLC / SCADA and data logging units, would follow. Power would then be switched on to the drive and pod, and a check would be made that all communication systems between the barge and Stingray were operational and the tide speed monitored. When the tide speed reached approximately 1m/s, a pre-start check of all monitoring instrumentation would also be made, to ensure nothing untoward had occurred since the previous shift. The lockdown valve would then be opened (this ensures that, when not in use, the hydroplane is held in its 'parked' position near the seabed). The pod auxiliary motor would then be started to provide the service hydraulic pressure. Operations could then commence.

The machine would be operated through the PLC / SCADA control screens (Figures 22 to 27). This could be operated in a number of modes, ranging from manual control of the arm and hydroplane to semi and fully automatic power generation, depending on the specific objective for the test.

Figure 22: Control Cabin

Figure 23: Top-level Control Screen

Figure 24: Main SCADA screen for PLC control (automatic mode)

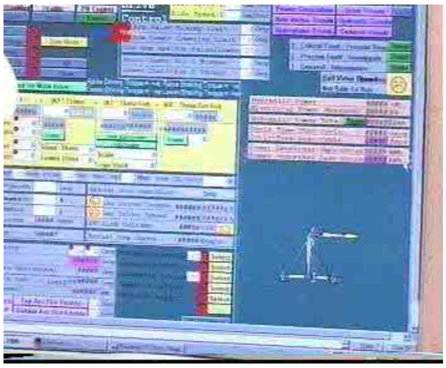

Figure 25: Detail of SCADA screen

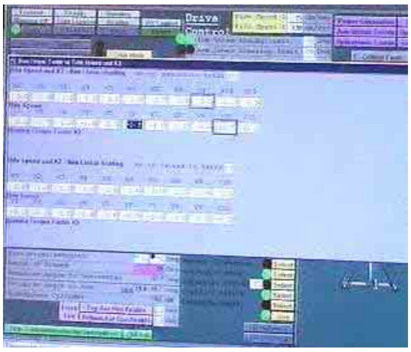

Figure 26: Control variable set-up screen

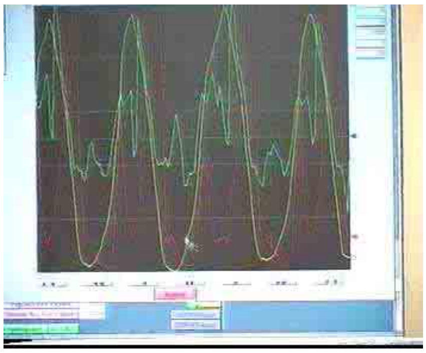

Figure 27: Trend screen for logged data

Whilst Stingray was operational, all data from the instrumentation mounted on Stingray and in the control cabin would be logged. Some instruments, such as the ADCPs, would also be logged when Stingray was not operating, to supplement the databases. On completion of the shift, the hydroplane would be parked in the down position, the auxiliary motor would be switched off and the lockdown valve engaged. The pod and generator would then be powered down until the arrival of the next shift.

A summary of the marine operations is given below:

Date	Activity
July 26th	Move to moorings
July 27th	Deploy
July 27th – 29th	Operate
July 29th	Recover
July 29th – August 1st	Maintenance
August 2nd	Deployment following adverse weather conditions
August 2nd – 8th	Operate; reattachment of disconnected lift wire
August 8th	Recovery following slippage of electrical/hydraulic motor coupling
August 8th – 11th	Maintenance
August 11th	Deployment of Stingray and seabed ADCP
August 11th – 18th	Operate
August 12th	Repositioned (2m lift)
August 18th	Recovery following low hydraulic pressure warning
August 18th – 30th	Maintenance and delay due to adverse weather
August 31st	Deployment, slight repositioning
August 31st – September 4th	Operate; installation of forward ADCP frame on seabed
September 4th	Recover for maintenance following compression fitting failure
September 5th	Deploy
September 6th – September 8th	Operate
September 8th	Recover, maintain and deploy
September 9th – September 14th	Operate; low oil-level alarm on 14th
September 15th	Recover, maintain and deploy
September 15th – September 17th	Operate; malfunction of oil monitoring equipment on 17th
September 17th	Recover
September 18th – 19th	Maintenance
September 20th	Transit Lerwick

Table 3: Marine Operations

3.3 Demobilisation

Following the barges arrival in Lerwick the demobilisation commenced on the 21st September. Due to the lifting capacity limit on available craneage on the island, the dismantling of Stingray had to be carried out in a series of smaller lifts, rather than in the two large lifts undertaken during the mobilisation.

The main focus of the demobilisation was on the strip down and removal of Stingray from the barge and the inspection of the constituent parts on the quayside. To this end, the first task was to remove all electrical and hydraulic equipment from Stingray prior to its disassembly. This included all harnesses, hoses, the main and instrumentation pods, reservoir, accumulator bank, umbilical termination and junction boxes from the main structure. The work during this phase was hindered by extremely high winds (45-50 knots) and driving rain that restricted the use of the crane and limited personnel activities from the man basket.

Once all the "loose" equipment had been removed from Stingray, it was dismantled piece by piece. This involved removing the arm/hydroplane section first, followed by the main central tower and support tubes. Once these items had all been disconnected and removed the lifting off of the main structural items commenced. These activities took place in continuing very unfavourable weather conditions, winds up to Force 8 and driving rain, which severely limited the use of craneage at certain times.

Following this procedure Stingray was dismantled, with the last section being removed from the barge on 27th September. In conjunction with the removal of Stingray from the barge, a number of support activities were carried out, including demobilisation of the control cabin and storage on land of all items too large to transport back to Newcastle by road.

The weather did nor calm down sufficiently until the 12th October, when the support vessel MV Cameron was able to return to the site to recover the moorings and ADCP frame. The vessel then returned to Lerwick to offload these onto the barge for transport to Burntisland. However, as with the operations of the MV Cameron, the towage of the barge back to Burntisland was delayed by the bad weather in Shetland and the rest of the North of Scotland. Thus the MV Cameron, the barge and the tug did not depart Lerwick until the 16th October. The transit to Burntisland was uneventful, with the MV Cameron arriving on the 18th October and the barge and tug on the 19th October. On their arrival, both the MV Cameron and tug were no longer on charter to EB.

Demobilisation of the barge commenced on the 20th October. All project equipment was removed from the barge and returned to the EB workshop for storage and investigations. The equipment returned included the main pod, instrumentation pod, valve tank, junction boxes, hydraulic cylinders, strandjack system, generator, drives cabin and workshop. The handling system items were stored at Briggs Marine yard in Burntisland.

Once all the installed equipment was removed from the barge it had to be returned to its original pre-charter condition prior to delivery back to the owners. This included the grinding down flush of any deck welds, repair of damaged paintwork, reinstatement of permanent structures, inspection of ballast tanks and repair of internal coating as required. The demobilisation of the barge was completed on the 5th November. The tug to tow the barge to its homeport of Delfzjil, The Netherlands, arrived in Burntisland on Tuesday 11th November. After a short period of waiting on weather the barge departed on the 13th November and arrived at it's home port on the 17th November. This was the end of the charter of the barge and of all marine operations for Phase 3 of the Stingray Project.

4 STAKEHOLDERS AND THE ENVIRONMENT

4.1 Consents

All statutory consents were obtained for the installation and operation of Stingray. As part of this process, an Environmental Appraisal was produced and widespread stakeholder consultation undertaken. The consents obtained were:

Consent	Issuing Body / Details	Reference
Food and Environmental Protection Act 1985 - Part II - Deposits in the Sea (FEPA) Licence	SEERAD FRS Marine Lab This licence is required for the protection of the marine environment and to prevent interference with legitimate uses of the sea.	FKB/Z168 1832
Coast Protection Act (1949) Part II (CPA) Consent	SE Development Department, Transport Division Responsible for the maintenance of navigational safety	2SPC/1/10(24) and PVC/4/10(1)
Harbour Works Licence	SIC Coastal Zone Management Controls development in the coastal area round Shetland and acts as the harbour authority for the water around Sullom Voe.	2002/032/NC
Onshore Planning Permission	SIC Infrastructure Services Required in respect of an onshore cabin, grid connector and substation.	PL2002\304\PCD
Seabed Lease	The Crown Estate Acts as a landowner for the seabed rather than as a regulator.	SH-48-5

Table 4: Stingray Consents

In addition, Notices to Mariners were issued through SIC Marine Operations and UKHO.

Permissions were not required under Section 36 of the Electricity Act 1989, The Electricity (Applications for Consent) Regulations 1990 (SI 1990 No. 455) and the associated Electricity Works (Environmental Impact Assessment) (Scotland) Regulations 2000 (SSI 2000, No 320). This is due to the generating capacity of the unit (150 kW) being below the appropriate threshold (permission is required for electricity generation proposals over 50 MW, or 1 MW for hydro plant).

Furthermore, consent was not needed from Scottish Natural Heritage (SNH) regarding potentially damaging activities within a SSSI since the works wouldl take place outside the Yell Sound SSSI. However, SNH were consulted for the CPA consent, FEPA licence and Harbour Works Licence.

Since the trial was scheduled to take place close to Yell Sound Coast cSAC, which extends to the low water mark around many of the islands, and close to the Sullom Voe pSAC, an Appropriate Assessment could be requested by SNH under the Conservation Regulations. Regulation 48 of The Conservation (Natural Habitats &c.) Regulations S.I. 1994:2716 (as amended) states than an Appropriate Assessment must be undertaken in respect of any plan or project which:

a) either alone or in combination with other plans or projects would be likely to have a significant effect on a European Site, and

b) is not directly connected with the management of the site for nature conservation.

An assessment was made of the likelihood of any significant effect, and an Appropriate Assessment was deemed unnecessary.

4.2 Pre-installation Surveys

A number of surveys were undertaken as part of the Environmental Appraisal stage. These were:

Hydrographic and geophysical surveys

Hydrographic and geophysical surveys covered an area some 2000 metres in length, bounded on either side by the Isle of Bigga and the Isle of Yell.

The pre-construction hydrographic and geophysical survey showed that sediment characteristics in the Yell – Bigga channel vary to some degree across the area surveyed, ranging from exposed rock to areas of sandwaves and gravel dunes. The surveyed seabed levels varied between 7.8 metres and 55.34 metres below chart datum (CD), and the bed falls away steeply at a gradient of approximately 1:10 from the shore in a westerly direction until a depth of 30m below CD is reached, whereupon the seabed gradient reduces to approximately 1:20, dipping toward 50 metres below CD. In the south east of the site lies a promontory that originates from the headland on Yell shore. Stingray was installed on the northern flank of this promontory.

Seismic reflection surveys confirmed that there are several regions where bedrock is exposed or within 0.5 metres of the surface. Regions of thicker superficial material can be found over the south and west of the site. Maximum sediment thickness, of approximately 10 metres, can be found at the eastern extents of the survey area. Sediment depth at the Stingray location is approximately 0.4-1.6m, although locally is absent or present as just a veneer. It was found that there is very little sediment near to the proposed unit location since tidal currents are strong and currents effectively scour the area of significant amounts of sediment.

Littoral Benthos (shore) survey

Shoreline wildlife and littoral surveys covered a stretch of coastline one kilometre north from Ulsta harbour.

A pre-construction shore survey was undertaken on the 26 February 2002. The survey covered approximately one kilometre of coastline north from the harbour at Ulsta. The main biotopes and features were identified using the Marine Nature Conservation Review (MNCR) marine biotope dictionary (Version 97.06). Supplementary data were obtained from earlier surveys conducted for the MNCR in 1987.

The pre-construction littoral survey showed that species abundance and diversity was typical of this type of habitat. No species of importance to nature conservation were found. The cSAC is designated for its otter and seal population, but no individuals of either species were observed. The littoral zone is noted for its area of kelp, but this is not extensive between the trial site and shore and may therefore contribute to the absence of otter from survey data.

Baseline data were obtained from the Shetland Biological Records Centre covering the spatial and seasonal distribution of seabirds, seaduck and sea mammals in southern Yell Sound.

A pre-installation survey of wildlife interests along the stretch of coastline running northwest for approximately one kilometre from Ulsta at the southern end of Yell was conducted on the 11 July 2002. Three main habitats were identified: cliff vegetation, maritime grassland and acid grassland. The former occurs on cliff faces outwith the reach of sheep. A narrow band of maritime grassland extended between one and ten metres back from the cliff edge, generally being narrower where the cliffs are higher. Inland from this lies acid grassland.

Breeding bird species noted include fulmar (*Fulmarus glacialis*), great skua (*Stercorarius skua*), skylark (*Alauda arvensis*), rock pipit (*Anthus petrosus*), shetland wren (*Troglodytes troglodytes zetlandicus*. Black guillemots (*Cepphus grylle*) and shags (*Phalacrocorax aristotelis*) were also recorded feeding offshore, but in low numbers (<10).

Two common seals (*Phoca vitulina*) were noted feeding offshore, no young seals were found along the shore. Several signs indicating otter activity were found, but no active holts or individuals were noted.

<u>Sublittoral Benthos (video) survey</u>

The pre-construction survey took place on 28 February 2002 in the Yell - Bigga channel in conditions of strong currents and winds. Grab samples were deemed inappropriate since there was a lack of seabed sediments, and therefore a dropdown / towed video array was used.

The seabed at the proposed location does not support a well-developed infaunal benthos since sedimentary fauna is limited due to the highly mobile nature of the sediment. The epibenthic fauna is adapted to a high-energy tide swept environment. In the main, species present included hydroids and bryozoans, typically found in tideswept boulder and cobble habitats which contain pockets of collected coarse and clean (sandy) sediment.

Video data of the survey was recorded to digital format, time stamped against GPS position. The videos were analyzed as a whole and by freezing the footage at intervals, and allowing a detailed description of the biotopes present to be made. Biotopes were identified in accordance with MNCR definitions.

4.3 Environmental monitoring

Acoustics

Preliminary acoustic monitoring of the Stingray device was undertaken on the 20 September 2002 to provide an initial assessment of potential impacts. These data supplemented shoreline measurements taken during August.

A general-purpose hydrophone was suspended from a vessel located above Stingray. Recordings were taken during periods of device operation (at 25 second cycles) and non-operation to provide background readings for comparison, using a general purpose hydrophone with a recording bandwidth of 200 Hz – 15 kHz.

Acoustic data was collected from the shoreline south east of Stingray, the Ulsta terminal breakwater and from the construction barge itself.

Further acoustic recordings of Stingray were taken during the Phase 3 operations in 2003.

Marine Growth

An inspection of the Stingray foundation beams was made on 8 September 2002, before the Phase 2 trial deployment, to assess marine growth whilst moored in the relatively still waters alongside the Construction Jetty. A test patch was scraped clean before deployment and re-inspected three days later upon recovery. A small quantity of green algae had colonised the steel surface of the device, thought to be Blidingia or Enteromorpha.

Although antifoul coatings had been investigated for Stingray, it was decided that the hydroplane gel-coat and the high-energy environment would restrict marine growth during the trials to a tolerable level. Inspections conducted during the 2003 Phase 3 trials revealed no indication of any marine growth over the two month period when the device was located within the high energy tidal currents of the Yell – Bigga channel (Figure 28). However, it is recognised that marine growth will have to be allowed for and controlled in longer duration projects.

Figure 28: Image of main post taken to determine levels of marine growth during September 2003

Cetacean Monitoring

Cetacean activity surveys were conducted at both the site of Stingray and construction barge, and a comparison site in Hamna Voe.

The harbour porpoise (*Phocoena phocoena*) is the commonest cetacean found in coastal waters around Shetland. It's abundance, behaviour and distribution make it an ideal candidate for monitoring the effects and impacts of maritime engineering projects on this group of marine mammals. The species is listed on Annex IIa and IVa of the EC habitats Directive and Schedule 5 of the Wildlife and Countryside Act 1981 (as amended).

Although not part of the Stingray programme, third party monitoring of cetaceans continued during the operational periods in 2002 and 2003. During both years, data were recorded at the trial site and at a site for comparison in Hamna Voe. Reports were made by independent consultants to the Highlands and Islands Enterprise, Shetland Islands Council, The Crown Estate, and the Engineering Business Ltd.

The monitoring programme comprised cetacean watches undertaken by members of the Shetland Sea Mammal Group, chance sightings recorded by vessels, land-based observers, and periods of acoustic monitoring using porpoise detector hydrophones (PODs) in 2002. In 2003, PODs were used in conjunction with a number of Porpoise Alerting Devices (PADs) to assess their effectiveness in keeping porpoises away from the Stingray site. Details of the deployment of instrumentation are given in the respective sections below.

The programme did not collect baseline data prior to installation of Stingray and the conclusions drawn should be interpreted with this caveat in mind; however, data collection did occur in the first year after Stingray had been demobilised, and these provide an indication of baseline conditions.

The 2002 season

During 2002, PODs were deployed at three locations in proximity to the Stingray site in Yell Sound. The layout was designed to monitor the distribution and abundance of cetaceans during the installation, operation and retrieval of Stingray during it's first season, but the scale of the 2002 survey alone was not considered sufficient to monitor specifically the effects of Stingray or other human activities on porpoise behaviour. Further data were therefore collected in the following year.

Harbour porpoise frequented all three sites during the initial deployment of Stringray in 2002 at different levels of intensity. This may have reflected the habitat use available at each. Porpoises were recorded moving with the main tidal stream in the Sound. Fisher (2002) suggested that individuals moved between Voes (bays) during periods of slack water at the maximum height of the tide. Once in the Voes they would feed and rest, sometimes over a complete tidal cycle.

The number and duration of porpoise encounters were assessed from the recorded sounds. Silent periods greater than 10 minutes were considered to delineate consecutive encounters. In October, when the frequency of encounter increased markedly, encounter duration averaged 7 minutes in the main tidal channel, and 127 minutes in Hamna Voe.

Encounters of short duration generally denoted porpoises transiting between Voes. Visual observations indicated that these movements were made by small groups of two to three animals. Observations at Hamna Voe, where encounters were of much longer duration, indicated much larger groups of 10 to 40 individuals.

Visual surveys for porpoise activity were carried out at all sites during August and September. In general it was found that visual observations could not be reliably matched with data from the PODs, but there was no suggestion from either data source of an adverse effect of Stingray on the distribution and behaviour of porpoise in proximity to the installation.

The 2003 season

In 2003, acoustic monitoring involved the assessment of a porpoise-alerting device (PAD) on the distribution and activity of harbour porpoise during the Stingray trial. This was achieved by the use of porpoise detectors (PODs) at two sites in Yell Sound. The PAD is a device that produces sound to alert porpoises to its presence. The sound it produces is beyond the normal hearing range of other marine mammals (seals and otters) in the area.

To monitor the impact of Stingray, one POD (Figure 29) and one PAD (Figure 30) were mounted from the Stingray barge. A second POD was deployed on the sea bed approximately 200m north of the site. Due to the high velocity tidal stream, suspended sediment in the water column, and acoustic interference from shipping in the vicinity (including echo-sounders of the local ferries, the barge's tugs and other vessels), the assessment faced considerable technological challenges that were overcome.

Figure 29: Barge POD, with data cable and lead to remote acoustic sensor (in foreground). Photo courtesy P. Fisher.

Figure 30: A self-contained experimental PAD. Photo courtesy of P. Fisher.

As a comparison, two PODs (fixed demersally, approximately 250m apart) and a PAD were deployed nearby in Hamna Voe. Hamna Voe is a significantly lower energy site noted for high porpoise activity. Its sheltered nature may make it more attractive to them.

Harbour porpoise activity was observed and recorded at both locations between August and October 2003. The maximum duration of encounters was 310 minutes at Hamna Voe compared to 8 minutes at the Stingray trial site.

Visual observations confirm the knowledge that the Hamna Voe site was preferred by harbour porpoise: 240 individuals were counted in three weeks during October although 92% of these were recorded in the final week. By comparison, only 20 individuals were observed at the trial site over nine days between August and September. All observations at the trial site indicated that individuals were on passage while at the control site, observations indicated that individuals were participating in a range of activities including feeding and resting.

Although the Stingray trial site and Hamna Voe are not truly comparable marine environments, the study showed that porpoise activity continued through Yell Sound during the trial period. The 2003 work indicates that echo-sounders from marine traffic (including local ferries and the barge's tug) may be of more significance to porpoise distribution and behaviour than Stingray itself.

Shoreline

A repeat survey of wildlife interests along the stretch of coastline running north-west for approximately one kilometre from Ulsta at the southern end of Yell was conducted on the 17th June, 2003 to compare with the pre-construction survey carried out in July 2002. The results of the second survey showed that there was no notable change in the flora from the previous survey.

Breeding bird species noted included curlew (*Numenius arquata*), skylark, rock pipit, Shetland wren, and wheatear (*Oenanthe oenanthe*). Feeding species included the black guillemot, and there was no evidence of disturbance or displacement of bird species resulting from the trial.

Of the sea mammals (seals and otters), only one seal, a grey seal (*Halichoerus grypus*) was observed. There were signs of otter (*Lutra lutra*) activity along the coastline and it is likely that they use the whole coastline for foraging. Again, there was no indication of displacement or disturbance resulting from the Stingray trial.

Tidal Currents

An Acoustic Doppler Current Profiler (ADCP) was deployed on Stingray during operations, with seabed mounted ADCPs installed for some of the trial duration. This work is outlined in Section 10.

4.4 Post-decommissioning Surveys

Hydrography and Geophysics

Hydrographic and geophysical surveys following comparable methodology to those undertaken prior to Stingray deployment were conducted during May 2004.

Figure 31 shows a projection of the Yell-Bigga Channel developed from multibeam bathymetry data. Figure 32 shows an example of a sidescan sonar data mosaic. Identifiable features are the rock outcropping (35 metres to 38 metres water depth, near the top of the image) and large (10 metres peak to peak) sand waves (near vertical lines in the lower half of the image marking the sand wave crests). Dark and light stripes are due to the direction of the survey lines.

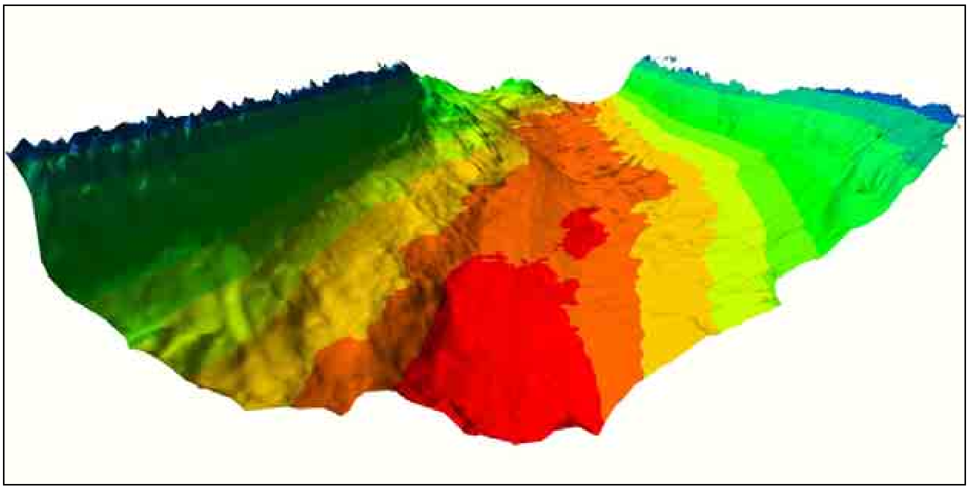

Figure 31: Digital terrain model of Yell-Bigga channel looking north

Note: Bigga to left hand side of image, Yell to right hand side

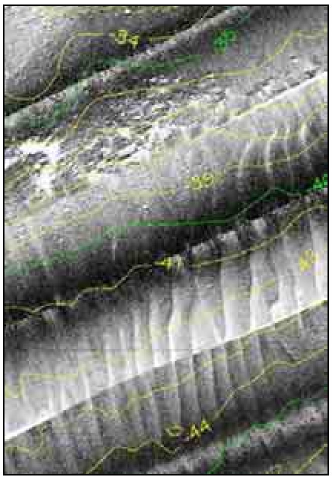

Figure 32: Sidescan data mosaic section

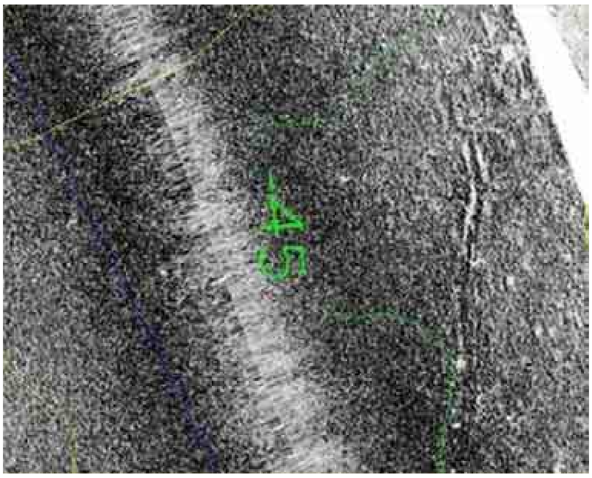

Figure 33: The seabed scar

Note: vertical line to right hand side of image represents scar

Results revealed virtually identical data to that of the original surveys, with areas of outcropping rock and sediment cover. However, a seabed scar some 62 metres in length is apparent from the side scan sonar (Figure 33). This is thought to result from one of the construction barge anchors.

<u>Sublittoral Benthos</u>

Whilst pre-installation Sublittoral surveys were taken at several points throughout the Yell-Bigga Channel; post-decommissioning surveys only targeted areas of Stingray activity.

The survey took place on 19 and 20 May 2004, in the Yell - Bigga channel in conditions of strong tidal currents but calm sea state. Methodology followed that of the pre-deployment benthic surveys. As before, main biotopes and features were identified using the MNCR marine biotope definitions.

Biotopes recorded appeared established and undisturbed and the video footage captured illustrated the hostile nature of the environment in respect of the accelerated tidal streams and consequent natural scouring of coarse sediment (Figures 34 and 35).

Figure 34: Mixed kelp (MIR.XKScrR) biotope.

Figure 35: A mosaic of two biotopes (MIR.LhypGz.Pk and ECR.AlcC)

The only anthropogenic items identified during this survey were a short length of rope and a small (less than 20cm long)

<u>Shoreline</u>

The shoreline survey of wildlife interests along the stretch of coastline running north-west for approximately one kilometre from Ulsta at the southern end of Yell was repeated on the 23rd October 2003.

With the exception of seasonal variation, the three main habitats identified in the baseline and operational phases remained unchanged. Of the bird species, shag (*Phalacrocorax aristotelis*), turnstone (*Arenaria interpres*), curlew, snipe (*Gallinago gallinago*), black guillemot, skylark, rock pipit, shetland wren, and twite (*Carduelis flavirostris*) were observed, and the area appears to be important for feeding black guillemots with 25 individuals counted. Other species seen flying through area included long-tailed duck (*Clangula hyemalis*), herring gull (*Larus argentatus*), great black-backed gull (*L. marinus*), starling (*Sturnus vulgaris*), hooded crow (*Corvus cornix*) and raven (*C. corax*). Of the mammal species, only one common seal (*Phoca vitulina*) was observed. Evidence of otter activity continued to be widespread along the shoreline, but no individuals were observed suggesting that the Stingray trials were not having an effect on the otter population.

4.5 <u>Environmental Impact</u>

On completion of the project, Entec UK Ltd, the authors of the original Environmental Appraisal report, were commissioned to review it in light of the findings of the operational monitoring and post-decommissioning survey. This review concluded that the Stingray operation had resulted in no significant adverse environmental impacts. This report has been submitted to the Consenting authorities.

5 TEST RESULTS - MACHINE CHARACTERISTICS & SENSOR PERFORMANCE

Due to the limited time available on site, basic testing of machine characteristics was kept to a minimum, with a few tests designed to verify key machine parameters. An indication of sensor performance is also assessed here.

5.1 Static Loading

Objective: To confirm basic performance assumptions

5.1.1 Arm

The static gravity load of the arm was checked by holding the arm horizontal in slack water conditions and measuring the pressures required in the transmission system to maintain this position.

The average arm torque across this steady state period was –269.6 kNm. This is equivalent to a mass of 2.7 Tonnes acting at the end of the 10-metre arm. This value is higher than the 1.4 Tonnes estimated from 2002 test data, however there have been a number of changes in the machine specification and the test procedure used which contribute towards this difference.

In air, the weight of the hydroplane / arm unit is in excess of 20 tonnes. This testing therefore demonstrates that the arm has a slight submerged weight, as it was designed to have, which agrees reasonably with pre-test expectations.

5.1.2 Hydroplane

Examination of the hydroplane torque for the same period as used in the arm static load test gives an indication of the contribution due to net buoyancy and gravity effects on the hydroplane structure. The average torque through this period is around 2.5kNm. In 2002 testing this torque was estimated to be 5 to 6 kNm. Although this difference seems large at first it is not that surprising given the generally very low level of torque ('Full scale' hydroplane torque is around 200kNm for 250 bar maximum pressure) and the poor accuracy of the sensors used in last years testing.

In a torsional sense, the hydroplane can therefore essentially be considered to be neutrally buoyant, as expected. The impact of this slight non-neutral buoyancy can easily be designed out for future phases, and is discussed further in Section 6.

5.2 Added Mass

Objective: To confirm basic performance assumptions

Testing in 2002 indicated that the added mass associated with the motion of the arm and hydroplane assembly matched well with the predicted values, based on hydroplane projected area in the direction of acceleration. It was also found that the added mass varied as expected when the hydroplane position was changed to manipulate this projected area. There were some limitations in the 2002 data due to the low frequency of data logging, resulting in low levels of confidence for these transient tests. Further brief experiments were carried out in the early part of 2003 testing to reinforce confidence in our understanding of this.

With the hydroplane at zero degrees to the arm, presenting the maximum area in the direction of acceleration, the arm was driven through a series of acceleration impulses via the transmission. The torque applied by the transmission is calculated using the pressure sensor measurements at the main arm cylinders and the resultant acceleration can be used to determine the inertia of the whole assembly. The calculation is quite sensitive to the period over which the data is selected – It needs to be as brief as possible to try and prevent steady state drag effects from establishing and artificially inflating the figure but if it is too short the data quality will be poor. A period of 1 to 1.5 seconds is considered reasonable for most of the test cases. Table 5 below lists the calculated values as averaged over 14 cases for both of these periods.

Data period (s)	Average Inertia (kgm^2)
1	12.2×10^6
1.5	18.6×10^6

Table 5

Given that the predicted value for the assembly inertia was $13.4 \times 10^6 kgm^2$, the values obtained match well and lend further weight to the use of the projected area theory.

5.3 Hydroplane Hydrodynamic Performance

Objective: To confirm basic performance assumptions

Significant data was collected on the basic hydrodynamic performance of the hydroplane during 2002. This demonstrated good correlation between the anticipated lift, drag and pitching moment coefficients and the actual hydroplane performance measured on site. Some of this testing was briefly repeated at the start of the present test program to ensure that the relationship was still as anticipated. Figure 36 shows the relationship for the hydroplane lift coefficient and angle of attack.

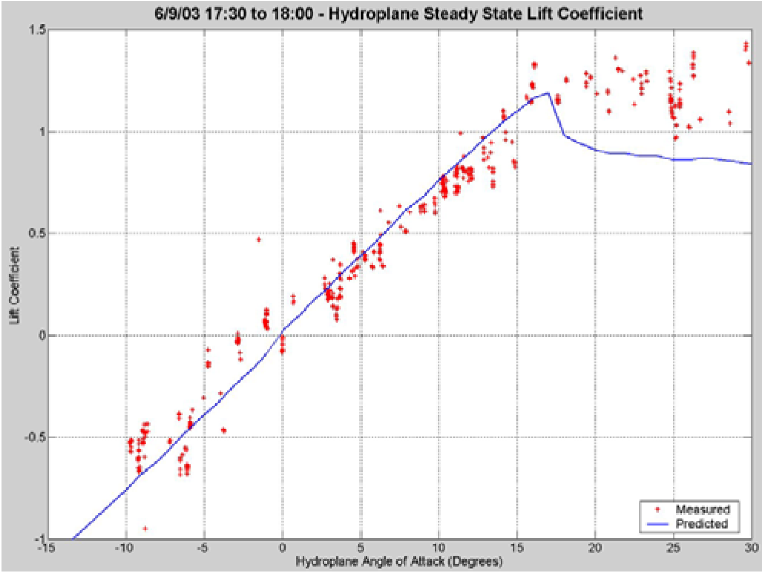

Figure 36

The relationship displayed in Figure 36 is almost identical to that recorded in 2002, confirming previous observations, and increasing confidence in the integrity of the readings.

6 TEST RESULTS - OVERVIEW POWER CYCLE ANALYSIS

Analysis carried out on the power cycles achieved on site has been carried out at two levels. Firstly a 'top level' summary analysis for the cycles achieved across a range of operating conditions on site was conducted. This did not look at the detail of particular cycles; rather it was used to pick out the headline numbers for the cycles achieved.

Following this detailed analysis of the actual cycle characteristics for a selected range of cases was carried out. The emphasis here is on examining the details of the cycle such as the hydroplane control and angle of attack and relating this to the details of the form and magnitude of the power produced.

This overview is a 'top level' analysis of what cycles have actually been achieved during the operation of the machine.

The range of data analysed in the top-level review is taken from a section of the continuous operation period, with all operating tides from 10th to 14th September as well as two tides from 1st September. The 3D bar chart in Figure 37 shows the distribution of the cycles achieved during this period. Note that averaged values near the fringes may be less robust due to the small sample range.

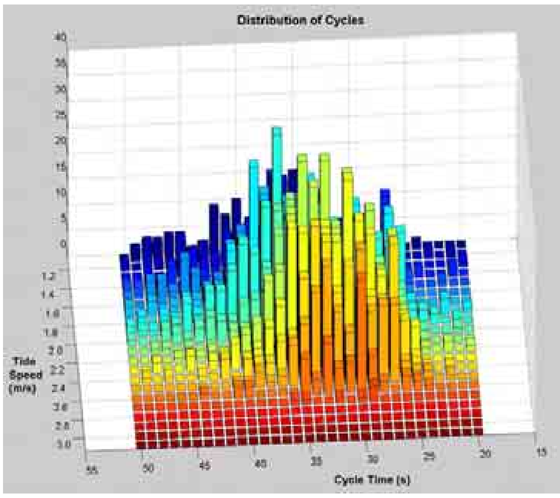

Figure 37

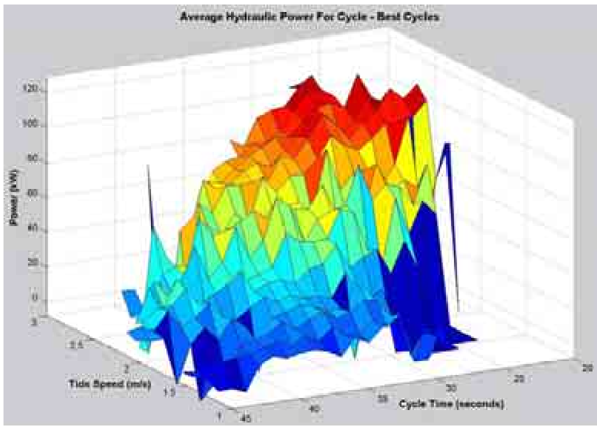

Figure 38

Figure 38 shows the picture that emerges from the above analysis. The figure is a surface representation of the best hydraulic power averaged across a single cycle from all cycles analysed within the specified range of cycle times and tide speeds. Examination of the Figure demonstrates that the power increases with increasing tide speed and decreasing cycle time as would be expected.

Whilst Figure 38 gives a reasonable view of the range of cycles achieved it is difficult to read off specific values. Figure 39 shows the power produced against cycle time for some specific tide speeds in a more readable format.

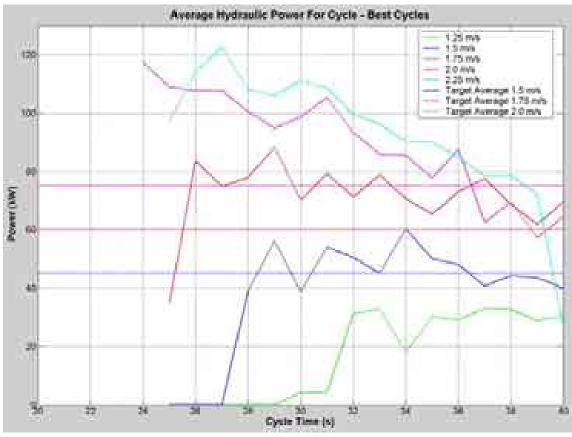

Figure 39

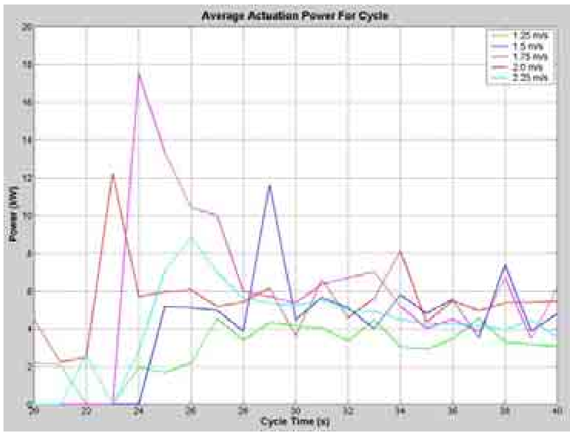

Figure 40

Powers can be read more easily from this graph, giving peak values in excess of 120kW. Also shown on the figure are the DTI target levels for power generation at three current speeds of 1.5m/s 1.75m/s and 2m/s (Note that the targets were for ½ hour averages rather than single cycles as shown). It can be seen that the average power levels for the tide speeds exceed the target levels specified at several cycle times, significantly so for the two higher tide speed targets – this increase in performance against targets is not entirely surprising given that the targets increase linearly against tide speed whereas the available power increases with the cube. What is particularly encouraging is that the quoted powers have been achieved at significantly longer cycle times than originally envisaged, suggesting that once the intended cycle times are achieved, the generated power will exceed the target levels by a considerable margin.

One important element in the assessment of the power cycles achieved is the amount of power consumed in actuation of the hydroplane through the cycle. This is quoted in terms of hydraulic power at the actuation cylinder in order to give a representative view of the power requirements without the inefficiencies of the actuation circuit, which could benefit considerably from optimisation. Figure 40 shows the actuation power consumed across the same range of cycle times and tide speeds as the output power in Figure 39. Note that the power is averaged over all valid cycles rather than picked out to match the individual best cycles displayed in Figure 39 – this is because the actuation power measurement has quite a lot of variation due to its relatively low level and it is difficult to pick out trends without averaging over a reasonable range of cycles.

Points to note from Figure 40 are as that the levels of power consumption were generally low (less than 20kW for a typical cycle) and that the actuation power requirement rises steeply for faster cycle times where good levels of power were achieved (the 1.75 and 2.0 m/s cases). This is in line with the anticipated characteristics.

The averages shown across all of the data analysed in section have been calculated, however they give an unduly pessimistic picture since they cover all periods of operation, including substantial lengths of time when the system will not have been in any sort of state of optimisation. Picking out specific periods of running where the machine was running at steady cycles in a reasonably developed state gives a more representative picture of the consistency of the power cycles achieved. Particular periods of interest are given in Table 6.

Period of Operation				Current Speed (m/s)		Mean Hydraulic Power (kW)	
Date	Start	Stop	Duration (Minutes)	Average	Range	Average Measured	DTI Average Target
1st Sept	12:12	12:22	10	2.00	2.18 to 1.84	85.3	-
1st Sept	11:58	12:28	30	2.00	2.29 to 1.67	85.4	75
1st Sept	23:31	23:41	10	1.75	1.60 to 2.10	73.4	-
1st Sept	10:36	11:06	30	1.75	2.02 to 1.57	59.7	60
13th Sept	12:08	12:18	10	1.50	1.20 to 1.62	42.1	-
1st Sept	10:07	10:37	30	1.50	1.23 to 1.68	39.0	45

Table 6

As can be seen from the range of current speeds encountered in the periods of running presented, it is not possible to extract data for long periods of running where the current remains absolutely constant - it is not the nature of the flow regime to provide a particularly stable current speed. Interestingly almost all of the most productive periods of operation were on 1st September – part of the reason for this is that this was the period when running with the accumulators was tested for sustained periods. Against the specific DTI target for ½ hour of running, the 2m/s current speed case exceeds the target comfortably, the 1.75m/s just meets the target (If rounded to 2 significant figures) and the 1.5m/s target falls short by 6kW (13%). This change in performance against the targets is not surprising given the fact the target increases linearly whereas the power change is non-linear as observed previously.

In general, for the cycles achieved, the power produced in the part of the cycle where the arm was moving from top to bottom (down-stroke) was better than for the up-stroke. There are a number of contributory factors to this asymmetry:

- The weight of the arm assembly contributes to the power generated on the down-stroke and detracts from it on the upstroke. The arm torque involved is about 27kNm, which equates to 337Nm at the motor. (To put this in perspective, the average torque through a down-stroke at 2m/s tide speed is 1500Nm).
- The flow requirements for turn around of the hydroplane at the top of its stroke are much lower in this direction (the rod side of the cylinder is being filled with high pressure oil rather than the full bore side). Hence, the actuation system could maintain higher hydroplane speeds and hence faster 'half-cycle' times in this direction before running out of flow.
- The control of the hydroplane angle of attack through the down-stroke was perceived to be generally more accurate. This will be due at least in part to the lower flow requirements of the actuation turn around.

It should be possible by looking at the power produced on the down-stroke only to gain an indication of what power might be available over a full cycle if the up-stroke was maintained at the same level of control and stroke time. Obviously the additional power due to gravity effects would not be available since anything gained here will always be balanced by a loss on the up-stroke, however the gains due to the faster half-cycle and more accurate control should be realisable in both directions. Figure 41 shows the spread of powers achieved and Figure 42 gives the data in a more readable format against specific tide speeds.

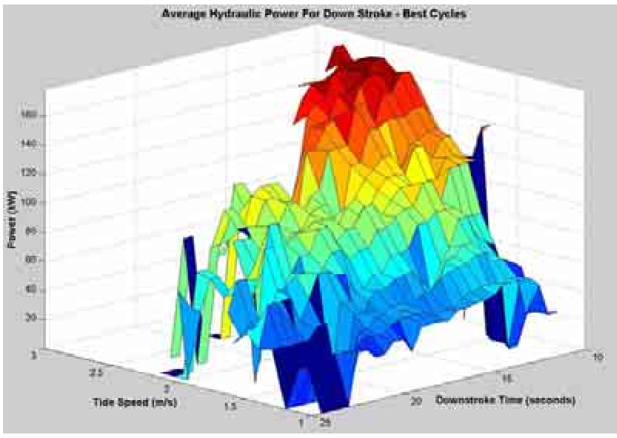

Figure 41

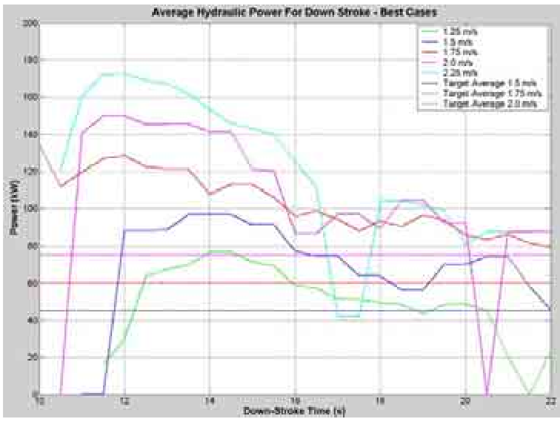

Figure 42

As the data given in Figure 41 and Figure 42 demonstrates, the improvement in average power generated is considerable if only the down-strokes are considered, with a maximum average power in the region of 170kW. However, an adjustment to compensate for the gravity torque is required to give a true indication of the full cycle gains available. This adjustment is carried out in Table 7 – Since the power produced is directly proportional to the motor torque, in each case the half cycle power is reduced with reference to the ratio of the gravity torque component (337Nm) to the average torque through the particular down-stroke (In the range of 910 to 1640Nm). The table also lists equivalent full cycle time for the down-strokes rather than half cycle time so a direct comparison can be made with the actual full cycles achieved.

Tide Speed (m/s)	Full Cycle		Half Cycle		Gravity Torque % of Cycle Mean	Half Cycle Power (Gravity Adjusted) (kW)
	Power (kW)	Cycle Time (s)	Power (kW)	Equivalent Cycle Time (s)		
1.25	32.9	33	76.8	28	37.0	48.4
1.50	60.2	29	96.9	28	27.8	70.0
1.75	88.4	29	134.3	20	23.0	103.4
2.00	117.5	24	149.7	23	22.2	116.5
2.25	122.7	27	172.6	23	20.5	137.2

Table 7

In cases where the equivalent cycle time from the half-cycle significantly exceeds the full cycle time for a given tide speed there are clearly considerable gains in power. Clearly further reductions in cycle time through improved control and actuation capabilities will yield higher powers still.

Table 8 gives a summary of the results extracted from the 'top level' analysis of the power cycles achieved on site at some key tidal current speeds.

Tide Speed (m/s)	Best Cycle		Best Down-stroke (Gravity adjusted)		Longer Time-scale Power Averages	
	Cycle Time (s)	Average Power (kW)	Cycle Time (s)	Average Power (kW)	10 Min (kW)	½ Hour (kW)
1.5	29	60.2	28	70.0	42.1	39.0
1.75	29	88.4	20	103.2	73.4	59.7
2.0	24	117.5	23	116.7	85.3	85.4

Table 8

Based on this information and the preceding analysis the following conclusions can be drawn:

- Best power cycles – Average hydraulic power across the best cycles achieved reached encouraging levels, with a maximum of 117.5kW in a 2.0m/s current. Note that the cycle times achieved are generally longer than originally envisaged and this is what is primarily responsible for limiting the power output (original estimates for the cycle time necessary to achieve 150kW were in the region of 18 to 19 seconds). Whilst this is disappointing in certain respects, significant encouragement should be taken from the fact that the maximum power figure was attained at a slower cycle time than would have been previously expected for this level of generation. It follows from this that, once the faster cycle times are attained, the power generated is likely to exceed expectations.
- Half Cycles – In general, higher average powers were found for down-stroke cycles, even when the beneficial effects of gravity in this direction were discounted. This was particularly noticeable where faster equivalent cycle times were achieved.
- Average over ½ hour periods of running – The faster cycle times required for the power levels achieved in the best cycle and half-cycles were not sustained for long periods due to a lack of development time. However, the ½ hour averages are still at encouraging levels, exceeding DTI targets in some cases.
- Actuation power levels – Actuation power as measured at the cylinder was generally low, in the range of 3 to 8kW, rising to a maximum of around 20kW for the faster cycles.

In general the performance characteristics for the cycles achieved are reasonably close to expectations and show good prospects for improvement.

7 TEST RESULTS - DETAILED POWER CYCLE ANALYSIS

Objective: Development of hydroplane control to allow faster (higher power) cycle times to be achieved.

In the previous section basic cycle analysis on the levels of power produced was described. What follows here is a more detailed look at particularly promising cycles with the aim of understanding their characteristics and establishing what improvements may be possible and what the most appropriate development route may be to achieve these improvements.

Control system development was seen as the key area requiring improvement at the end of 2002 testing in order to achieve the full machine potential. Because of its importance, two different tools were used to address the problem.

- PLC control system – This is the same hardware and basic software as used in 2002. It uses standard industrial Programmable Logic Controller (PLC) technology to implement closed loop control for both the hydroplane position and the arm torque or speed.
- dSPACE – This advanced control technology was brought in to try to ensure any limitations in the PLC approach did not present a barrier to improving the machine cycle. It works by characterising the machine hardware through a system identification approach and using this characterisation to implement a controller that takes account of all of the system characteristics.

Both approaches address control of the hydroplane / arm unit and the drive system.

7.1 Torque Control (PLC)

Objective: Optimisation of hydroplane control and development of machine cycle control and power output.

The bulk of test work carried out was done with the machine fully under PLC control.

The basic methodology of the torque control approach used in PLC testing was developed from the simple 'manual cycle' philosophy used in some of the 2002 test work. This used speed control of the main Stingray arm with a zero speed demand and a motor electrical current limit. The control system would try to prevent the arm from moving under the action of the flow on the hydroplane up until the point at which the required torque resulted in the electrical current limit being exceeded. After this point the arm would move against the fixed torque corresponding to this current limit, doing work and hence extracting energy from the flow. The key benefit of this approach over the sinusoidal speed control cycles developed was that it was tolerant of poor hydroplane control and would not consume power if the control were not quite right.

In reality this was a crude method of achieving a basic form of torque control, allowing only one fixed torque level to be specified in each direction via the motor current limit. By switching the transmission variable speed drive system from speed in to torque control it was possible to vary the torque set-point in a more flexible manner through different points in the cycle.

A system was set up for calculation of this torque set-point that allowed tuning of the set-point 'T_{SP}' using the following formula:

$$T_{SP} = k_1 + k_2\theta + k_3\dot{\theta} + k_4\ddot{\theta}$$

Here ' ' is the main arm angle. Hence the set-point was determined by an offset coefficient 'k_1' a position dependant coefficient 'k_2' a speed dependant coefficient 'k_3' and an acceleration dependant coefficient 'k_4'. In reality the position and acceleration coefficients tended to be set to zero for most of the more successful cycles. Tuning centred mainly on the 'k_1' and 'k_3' factors. Later developments included variation of the offset coefficient 'k_1' at different points in the cycle and introduction of tidal speed dependant maps for the 'k_3' factor.

A representative range of the cycles achieved using this approach is examined below. Table 9 summarises the key details for all of the cases used in the analysis. A description of the key features for each of the cycles follows along with a general summary for all.

Date	Start Time	End Time	Tide Speed m/s (x component)	Average Power (kW)		Peak Power (kW)	
				Hydraulic	Electrical	Hydraulic	Electrical
13/9/03	10:04:51	10:05:21	2.56	111.8	98.5	375.1	332.4
13/9/03	11:06:17	11:06:55	1.98	66.5	60.2	334.4	295.1
13/9/03	11:36:40	11:37:57	1.70	51.1	46.0	317.6	281.9
13/9/03	22:48:02	22:48:43	1.97	57.4	51.3	327.6	288.3
1/9/03	10:19:14	10:19:54	1.44	35.4	35.9	166.1	156.6
1/9/03	10:50:07	10:50:40	1.76	72.7	71.6	312.3	316.0
1/9/03	12:07:33	12:08:00	2.14	105.9	100.7	353.4	322.8

Table 9

The tests clearly demonstrate that it is the combination of angle of attack control with an appropriate level of torque extraction, allowing a reasonably fast cycle to be developed, which is necessary to establish optimum levels of power generation. One without the other will not deliver the right results.

Due to the short development time available re-tuning of the torque parameters to try to achieve this balance was frequent. Although a reasonably stable set of parameters was established towards the end of operations further optimisation of this approach should be feasible. All torque settings have been logged and it should be possible to build up a picture of what combinations yielded the best cycles – this has not been done within the time-scale of the present analysis exercise.

Another development of the torque set-point calculation pioneered on site was to use the known state of the machine to calculate what level of torque should be available and then extract a percentage of this torque depending on the stage in the cycle. At a given instant the tide speed and machine motion are known and can be used to estimate the overall torque on the arm due to generated lift and drag as well as added mass & other effects. If the cycle is just starting it might be appropriate to take a low percentage of this torque via the transmission so that the bulk of the torque is accelerating the stingray arm. Once the desired arm speed has been reached, around the middle of the cycle the transmission would be set to extract 100% of the estimated torque, maintaining the arm at a constant speed. In the final stages of the cycle the transmission torque demand would be ramped up to over 100% of the estimated available torque giving a net torque which acts to decelerate the arm. This was implemented but tuning time was limited and the results were not as good as for the more basic set-point calculation. However, given time, it should be possible to use such an approach to good effect and this should be considered in future developments.

Hydroplane control achieved through the machine cycles with relative angle control and angle of attack control using this approach was reasonable, although there is a tendency to under and over-shoot, resulting in poor energy efficiency. Introduction of accumulators, whilst overcoming the flow limitations which held back cycle speeds, generally resulted in much poorer control.

The Variable Speed Drive (VSD) software incorporates its own torque and speed control algorithms – it is separately configured to operate with either a speed or torque input set-point with 'crisis' limits as appropriate. The PLC controller works with the drive controller by generating the set-point and passing it on to the drive. The majority of development was done with the system working to a torque set-point.

Through all of the torque control cycles examined there are some common observations that can be made.

- Good angle of attack control coincides with the highest level of power generation. Big improvements on the cycle and overall power are clearly available if the angle of attack is manipulated correctly
- The effects of stall on the cycle can be seen where the hydroplane moves significantly outside its stall limits. In most cases it has a negative effect on the cycle however it can be used constructively at points in the cycle – see separate section.
- Good power cycles are a combination of appropriate angle of attack manipulation (may include stall at beneficial points) and a sufficient level of torque extraction to remove power from the system whilst still allowing the machine to build up speed. Hence establishing the transmission torque set-point for different condition and stages in the cycle is critical.
- Actuation power consumption during the tests will be higher than is necessary because of the poor level hydroplane control resulting in frequent adjustments and recoveries from stalled conditions
- There is clearly much scope for cycle improvement, which is encouraging given that the existing cycles can produce significant levels of power.

7.2 Speed Control (dSPACE)

Objective: Development of hydroplane control, machine cycle control and power output via alternative control approach.

In addition to the PLC control development, a separate program was pursued in parallel. It was recognised that the PLC control approach might run in to limitations so, as a backup, a system identification approach using dSPACE software and hardware was also developed. In basic terms, system identification works by examining the response of the hardware to a variety of signal inputs then simplifying the hardware down to a basic 'transfer function' relating the control input to the response output. This transfer function can then be used to design a controller which should achieve the desired output for a given input very accurately, taking in to account all of the characteristics of the machine.

Note that the time available for dSPACE development on site was limited. Basic controllers were established for position control of the hydroplane and speed control of the main arm but these did not include any allowance for the effects of tide speed, coupling effects between the arm and hydroplane dynamics and firing of the accumulators. Significant further identification work would be required to implement controllers that fully compensated for all of these effects. The absence of accumulators in the cycle also limits the cycle times that can be achieved as will be apparent for the dSPACE cases examined.

Note also that all of the dSPACE work as carried out on tide cycles with lower peak speeds hence demonstration of its ultimate potential for power generation against the PLC performance was limited by this.

The dSPACE controller implemented for hydroplane control was position based as for the PLC case. Work concentrated on angle of attack control – no relative angle tests were carried out. The level of accuracy achieved was excellent within the flow limitations of the actuation system. The introduction of the accumulators resulted in the same controllability problems as for the PLC case as no specific tests were done to characterise the system with the accumulators included.

For control of the arm, the dSPACE system concentrated on using a sinusoidal speed demand in a similar manner to the 2002 PLC development. In reality, the drive system was set in torque control when the dSPACE characterisation and development was carried out although the actual set-point sent by the dSPACE system was a speed demand (effectively operating the drive in crisis mode). The speed control achieved with this approach was reasonable given the amount of development time available although it did exhibit a small time lag and was not designed to cope with coupling effects from hydroplane dynamics.

Some general comments on dSPACE progress can be made:

- The Angle of attack control achieved is very promising. There was a small amount of overshoot but the controller was capable of holding the angle at a relatively stable level through the machine sweep.
- The cycle times achieved were quite slow as it was necessary to avoid pushing the system beyond its hydraulic limitations and the accumulators, which are

designed to overcome these limitations, were not brought in to the identification work. Note that the cycle time problem becomes more of an issue at lower tide speeds – it takes a greater range of hydroplane motion to achieve angle of attack control with the sinusoidal cycle in a current of 1.5m/s than it does in 2m/s. If higher tide speeds had been available in testing then faster cycle times would have been achieved.

- The cycle is not symmetrical in that the down stroke happens over a shorter period of time than the upstroke (38 second total cycle time with a 17s down-stroke and 21s up-stroke) – the sinusoidal demand was modified to achieve this since the system is physically capable of sustaining a faster down-stroke due to the lower actuation flow requirements.
- Power curve on down stroke – This shows very good form with a 'fat' curve coinciding with the stable angle of attack control through the sweep.
- Power on upstroke – this is much lower primarily due to gravity effects which are very significant for the low tide speeds examined

If development of the existing approach to hydroplane actuation and control is identified as the most advantageous route forward from both a technical and economic standpoint, further development of dSPACE control shows significant potential in improving the machine performance.

7.3 Accumulator Firing

The hydroplane actuation system uses an auxiliary pump unit that supplies a limited flow of oil at pressures of up to 280 Bar. In order to achieve faster cycle times and higher powers it is momentarily necessary to provide higher levels of flow than delivered by this unit. For this purpose there is an additional circuit of accumulators which are charged by a separate pump unit driven in tandem to the main auxiliary pump by the same electric motor. This allows accumulators to be charged up to a pre-set level of pressure at times when demand on the electric motor is low. This additional store of high pressure oil is then switched in to the main actuation circuit when higher levels of flow are required.

The key area in the cycle where this additional flow is required is at the reversal of the hydroplane, particularly from down-stroke to up-stroke where it is the larger full bore area of the actuation cylinder which must be filled. Hence initial use of the accumulators concentrated on bringing in this additional oil supply for set periods as the hydroplane was approaching the end of its stroke. Figure 43 shows two cycles achieved in a 2m/s current, one with and one without firing of the accumulators.

As can be seen the accumulator firing has a marked impact on the cycle time (and hence power produced). The highest powers recorded for individual cycles were attained in cases where the accumulators were used. Despite this, only a limited amount of test work was carried out with this approach, mainly because the abrupt nature of the additional oil delivery resulted in control and hardware difficulties – running without the accumulators gave more consistent and reliable performance.

For future development the manner in which oil is supplied for these high flow periods will need to be reviewed. It is possible that a system of the existing type could be used, particularly if more effort was put in to the control of switching the accumulator supply in and out (perhaps with dSPACE system identification). However the actuation system as it exists is high on power consumption and this may also have some bearing on future development decisions.

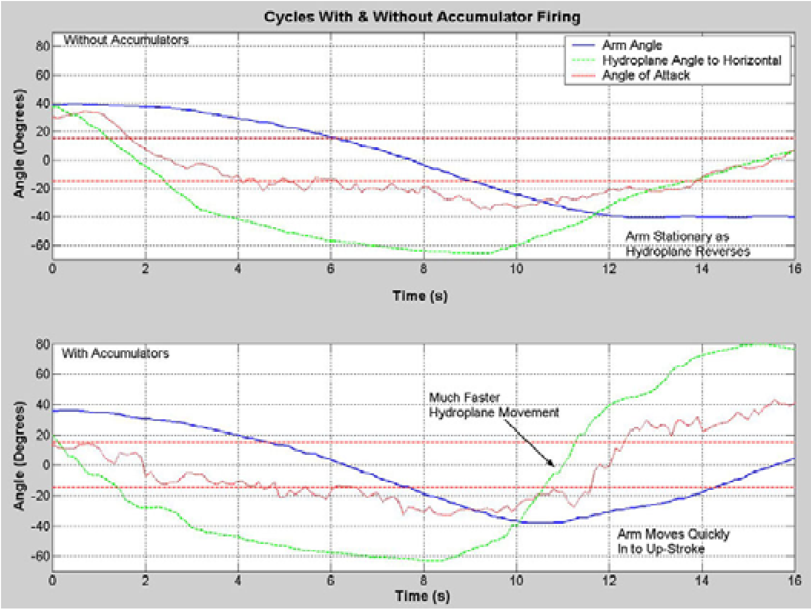

Figure 43

7.4 Fixed relative angle cycles & the effects of stall

One point noted during the 2002 testing program was that hydroplane stall could have beneficial effects if it occurred at the right stage in the machine cycle. If the arm is in the upper section of its sweep moving downwards or in the lower section moving upwards then any drag forces generated will act to assist in the direction of motion. The effect of these drag forces is greatest when the arm is furthest away from the horizontal plane since this is when the induced moment is at its highest.

It has already been seen in some of the cycles examined so far that stall can be beneficial. The following cycles set out to specifically exploit this characteristic in conjunction with the investigation of a more straightforward method of controlling the hydroplane – the so-called 'relative angle' cycle. The idea of this cycle is that the hydroplane is held at a fixed angle to the horizontal through the up-stroke and down-stroke. The angle should be large enough to induce significant stall at the start of the stroke, which acts as the main driving force to start the motion of the arm. Once the arm is moving there will be an additional velocity component due to the motion of the arm, which changes the direction of the flow relative to the hydroplane and acts to reduce the angle of attack at the hydroplane. If the arm is allowed to gain sufficient speed then the angle of attack should move in to the main lift generating region (Less that 15-20°) and lift should become the dominant force for the rest of the cycle.

A limited amount of testing was carried out to investigate this approach at low current speeds (around 90 minutes of testing at tide speeds from 0.8 to 1.7m/s). Figure 44 and Figure 45 show the type of cycles achieved and Table 10 summarises the key outputs.

Date	Start Time	End Time	Tide Speed m/s (x component)	Average Power (kW)		Peak Power (kW)	
				Hydraulic	Electrical	Hydraulic	Electrical
12/9/03	8:22:10	8:23:40	1.68	*27.4	*26.2	*108.5	*85.0
12/9/03	8:26:05	8:26:47	1.64	32.7	31.2	136.9	114.5

Table 10

* Not including stalled section from 1405s to 1420s

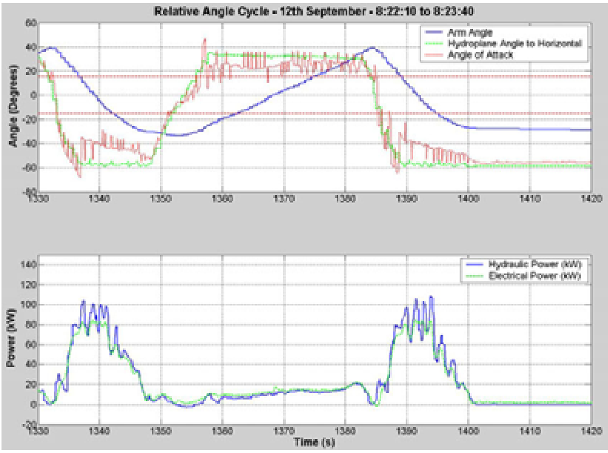

Figure 44

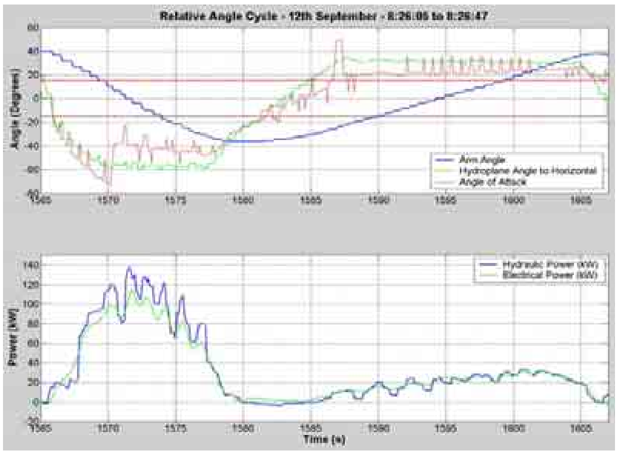

Figure 45

Note that the arm position update is a little slow for this data which results in quite a noisy angle of attack signal but the key points are still apparent. Comments are as follows:

- The basic principle appears to work in that large amounts of stall are present at the start of the cycle and this moves closer towards lift once the arm is moving sufficiently fast. However the cycles achieved are far from refined and the target region for angle of attack of 15 to 20° is never attained. This is reflected in the comparatively low levels of power generated.
- The actual control of the relative angle is quite good once the hydroplane turn around has been achieved suggesting that minor tuning of the target angle should be able to yield good angle of attack values with a minor amount of further tuning. This could also be achieved by varying the level of torque extracted by the arm. Note that the target levels are different for the up and down-strokes since the attainable speeds are different due to gravity effects.
- There is a noticeable oscillation in the power generated, which is evident on both the hydraulic and electrical traces. This may be due to instability in the load generated using the stalled condition drag loads. This may be a significant draw back in this type of cycle.
- In the limited time available the control was not made very intelligent – note the stall of the main arm in the later part of Figure 44. The hydroplane is stalling towards the end of the sweep and it brings the arm to a halt before it has reached

the trigger point at which the hydroplane reversal for the start of the up-stroke is triggered. Manual recovery from this situation is required to re-start the machine cycle.

- Interestingly the angle of attack actually exceeds the hydroplane angle to horizontal in some cases which is unexpected – normally the arm motion results in a reduction in angle of attack when this comparison is made. This effect can be attributed to the x component of the relative velocity which seems to be more significant in these cases since the arm picks up speed at a greater rate that the other cycles examined, particularly for the down stroke.

In summary, the brief experimentation carried out indicates that there may be significant mileage in these relative angle cycles. However further work would be required to investigate the feasibility fully and there are some possible issues, most notably the oscillation in the power curve, that need to be resolved.

7.5 Actuation Loading

Key points

- All of the cycles are limited by the available flow. Introduction of the accumulators overcomes this issue but introduces its own control issues.
- The majority of power is consumed at the hydroplane reversal points – power consumption from rotational drag through the stroke is relatively low (Although it may become more significant for faster cycles)
- The 'cleaner' control achieved in the dSPACE cycles results in low levels of actuation power.
- Relative angle cycles - Torque requirements through the steady state section of these cycles are low if the angle of attack achieved is inside the stall range.

Improved understanding of the actuation loading and power consumption will be key in further cycle development – particularly for faster cycle times. The first stage of this should be to compare against the assumptions used in the current mathematical model.

7.6 Summary of Detailed Cycle Analysis Findings

Examining the range of cycles achieved via the various methods of control applied, the key conclusions are as follows:

- On examination of the detail for the range of cycles investigated, there is generally a big improvement over the cycles achieved in 2002. The link between good angle of attack control and a well-formed power curve has been further demonstrated, as have the possibilities of using stall within the machine cycles. The various control approaches all show significant promise, with the key to improvement in PLC and dSPACE control being the successful introduction of the additional accumulator flow to allow faster cycle times (or an alternative actuation arrangement which achieves the same end).

- Torque control with PLC – Further development should include:

    Extraction of the most promising settings across all 2003 operations

    Further development of the torque set-point calculation

- dSPACE – The angle of attack control for the cycles achieved is very promising and certainly indicates that this approach can provide a route to achieving the 'ideal' sinusoidal cycle. The key areas for further development would be:

    Identification of the hydroplane actuation system including accumulator switching

    Identification of coupling effects between arm and hydroplane

    Investigating and taking account of tide speed effects on the identified models

    Design of a new controller on the basis of the above

- Accumulator firing – the fastest cycle times, and highest powers, were achieved with accumulator firing. The additional flow is critical to achieving the required rates of hydroplane reversal. There were control issues with bringing in the additional accumulator flow due to the abrupt nature of its introduction to the hydroplane circuit. This prevented it from being adopted for more than a few brief experimental periods. Further cycle developments need to look in detail at additional flow provision – if it is from accumulators then the control system needs to be developed to cope with the abrupt nature of their introduction. It may be that a different approach is required.

- Relative angle cycles and stall – A brief amount of testing was carried out in this area. It shows reasonable promise and may be a route towards simplification of the hydroplane control and reduction in actuation power requirements. However it does require further tuning to achieve the desired cycle and there are some characteristics, such as the oscillations visible in the power curves, which may limit the effectiveness of this approach. Further testing and development would be required to investigate these effects.

8 TEST RESULTS - OVERALL POWER COLLECTION

Objective: Demonstration of cumulative power collection over a continuous operation period.

8.1 Derivation of Power Output from Test Results

Hydraulic power is calculated using the pressure drop across the motor ports (measured by individual A and B port transducers), using this with the standard motor torque constant on 7.96Nm/bar to calculate a torque, then multiplying by the motor speed (radians/s) as provided by the generator encoder to give power. The calculation is straightforward and spot checks have been carried out in the data to ensure it produces the correct numbers for a given set of inputs. However, if there was an error in the pressure or speed inputs used in the calculation this could give rise to an incorrect value. Fortunately it is possible to check the pressure and speed against other independent measurements:

- Main transmission cylinder pressure measurements - The motor pressure drop can be compared with the pressure drop measured across the main transmission cylinders which is measured by a separate set of transducers.
- Main transmission cylinder length measurement – The cylinder length measurements can be differentiated with respect to time to provide cylinder speed. This can then be used to calculate the cylinder flow. Since this is the flow which is driving the motor, dividing it by the pump displacement constant of 500cc/rev should give the motor rotational speed. (Note that this neglects motor volumetric efficiency however inclusion of this would not significantly effect the calculated levels)

Both of these checks have been carried out and the independent measurements are a good match.

8.2 14 Tide Continuous Operation

A specific 14 tide period of operation from 9th to 16th September was identified for this purpose and the energy produced by the machine was totalled for each tide and added to a running total. Figure 46 shows a typical tidal cycle within this period of continuous operation.

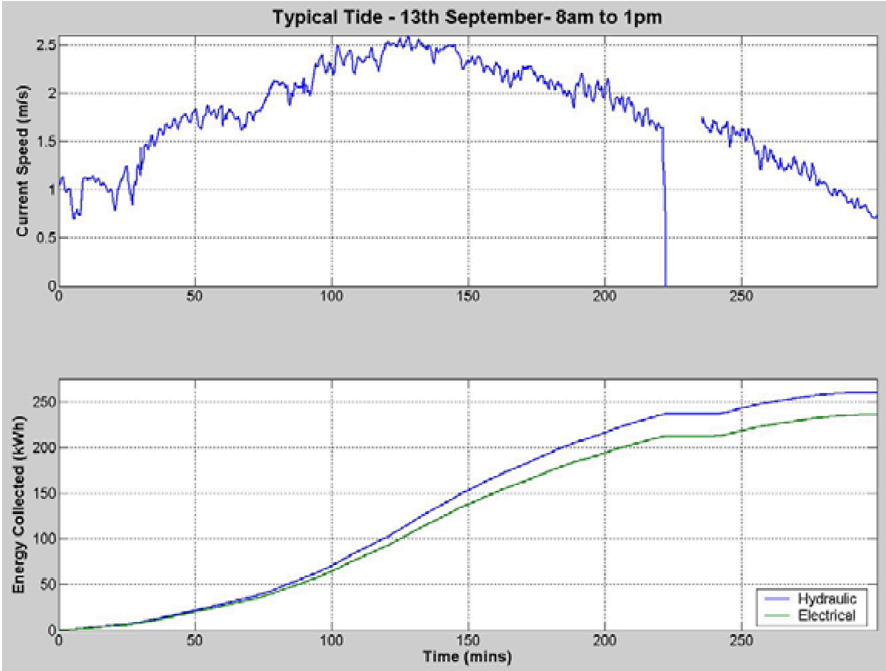

Figure 46

The top section of the Figure shows the tide speed as measured at the machine during the operation period. The lower section shows the cumulative hydraulic and electrical power. As can be seen the total power collected in this particular tide was 236 kWh measured electrically at the cable between the Variable Speed Drive and the generator or 260 kW hydraulically as measured at the motor. Unsurprisingly, the steepest gradients of the cumulative graphs clearly coincide with the periods of highest tidal flow velocity. It is interesting to note that the time spent at different tidal speeds can be quite random, with abrupt changes and considerable periods of relatively constant levels.

Note that there is a period of no generation in the data – at around 11:40am the barge generator tripped and recovery from this situation prevented the machine from being run for approximately 20 minutes – occurrences such as this were relatively common due to the experimental nature of the ongoing cycle development.

The record of power collected from 9th to 16th September (Figure 47) shows an electrical energy collection of 1963kWh for the 14 tide period although it should be noted that there were two tides with no generation and two to four tides with significantly sub-optimal generation due to machine failures within this period.

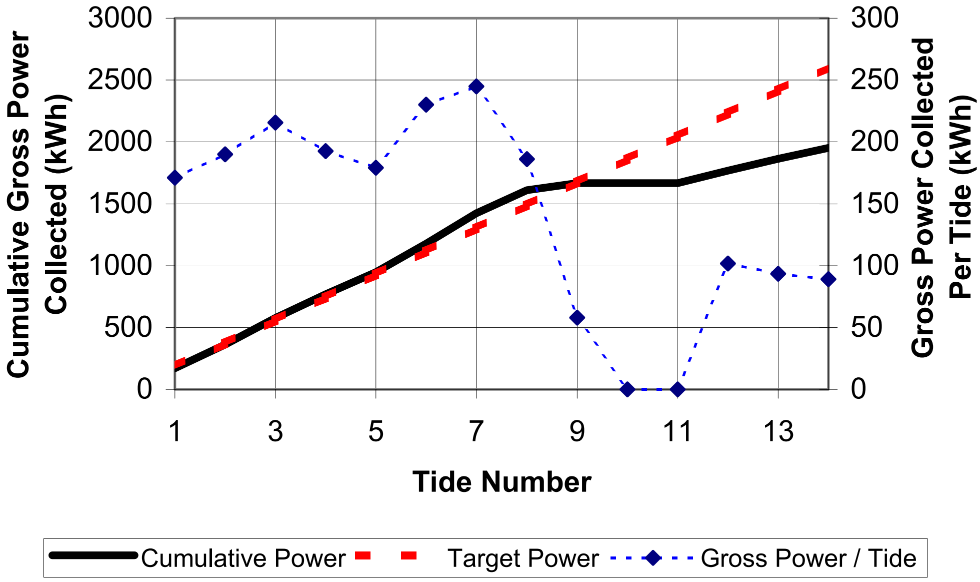

Figure 47

Note also that the on site totalisation of electrical power was slightly higher than the 'true' figure due to the way the PLC totaliser was set-up – it was configured to record positive (generating) electrical power only so for brief periods when power was being input to the machine this was not totalised. This only gives rise to a small error – for example the case given in Figure 46 reduces from 244 kWh to 236kWh ie 3%.

The data recorded clearly demonstrates the qualitative nature of energy collection that can be expected from the Stingray machine through a tidal cycle. It is only the quantitative measures such as the gradient of the energy curve and its final value that will change as the machine performance is improved.

9 TEST RESULTS - TRANSMISSION PERFORMANCE & EFFICIENCY

The main analysis carried out in this section is for conversion of the hydraulic power at the motor to electrical power at the generator – it does not look in to the efficiencies of the variable speed drive (VSD) in detail. This is principally because of the difficulties encountered in obtaining suitable measurement devices of acceptable accuracy which were compatible with the data logging systems used – a task which proved significantly more complex than originally envisaged. However, some assessment of the VSD efficiencies has been made from analysis of the results of the Factory Acceptance Tests.

9.1 Hydraulic Power at Motor to Electrical Power at Generator

This efficiency is the key measure that has been gained of the conversion of hydraulic power generated, via the Stingray mechanical machine, to electrical power. The hydraulic power figure is calculated using the motor torque, as derived from the pressure drop across the unit along with its ideal torque constant (assuming 100% efficiency), which is then multiplied by the measured speed to give power. The electrical power is measured using the Vydas PH-1000 Hall effect meter, which was installed at the drive end of the generator 3-phase supply cable.

The cumulative hydraulic & electrical power collection figures presented in the previous section were constructed from these measurements; hence a good measure of the average efficiency for this conversion, in the context of a complete tidal cycle, can be taken from the final values. This gives an efficiency of 90.7%. Given that the best efficiency for the hydraulic motor itself is around 92%, this suggests that the electrical losses up to this point are quite low.

9.2 Electrical Power at Generator to Electrical Power at Load Bank

It was not possible to log detailed measurements of the electrical power generated at the load bank. The equipment necessary to accurately measure the complex waveforms involved could not be integrated with the established logging systems hence the measurements taken were limited. Reasonably detailed measurements were taken during the Factory Acceptance Tests.

Data measured during the FAT and on site is for an overall conversion efficiency of 75% and a hydraulic to electrical (at the generator) conversion efficiency of around 85%. This gives a drive efficiency of 88%, compared to the theoretical efficiency of 96%. The economic model assumes a drive efficiency of 90%.

10 TEST RESULTS - CURRENT DATA ANALYSIS

During the 2003 operations a significant amount of extra monitoring equipment was introduced to provide more detailed information on the tidal currents at and around the Stingray machine. This data is required for three specific reasons:

- As a control input to allow selection of appropriate transmission and hydroplane set-points.
- To provide improved understanding on the tidal flow regime and variation across the water depth
- To demonstrate the interaction between the Stingray machine, in it's various modes of operation, and the tidal environment. Particularly with regards to upstream and downstream flow.

To this end a total of three Acoustic Doppler Current measurement devices (ADCPs) were installed. The primary unit mounted on the Stingray machine itself was as used in 2002 testing. This gave a single reading for the tidal current velocity vector at just above machine mid-stroke height, close to the centre of the base structure, which was used as the primary control input. To demonstrate the machine interaction, two additional measurement units on stand-alone mounting frames were procured. These units could then be located as required upstream and downstream of Stingray (within the limits of the data cables from the devices running back to the barge). The additional units had full profiling functionality, allowing them to measure current velocity vectors for a range of discrete cells across the full water depth at their installed location. The location of the units was as outlined in Figure 48 below.

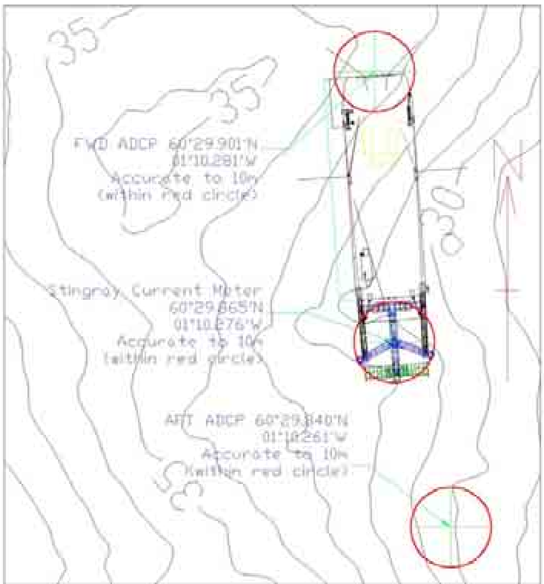

Figure 48

Note that there is variation in water depth between the three ADCP sites. By plotting the locations of the three ADCPs on a plot of the bathymetric data for the area, the water depths at each location can be read off relative to Chart Datum. These are shown in Table 11 below.

ADCP	Water Depth Relative to Chart Datum (m)
Forward	33.5
Stingray	31.4
Aft	30.1

Table 11

10.1 Stingray Mounted Sensor (Argonaut MD)

Data from the Argonaut sensor mounted on the Stingray machine itself was used as the key measure of tide speed and the primary control input. A sample of the data collected by this instrument across a typical tide is shown in Figure 49.

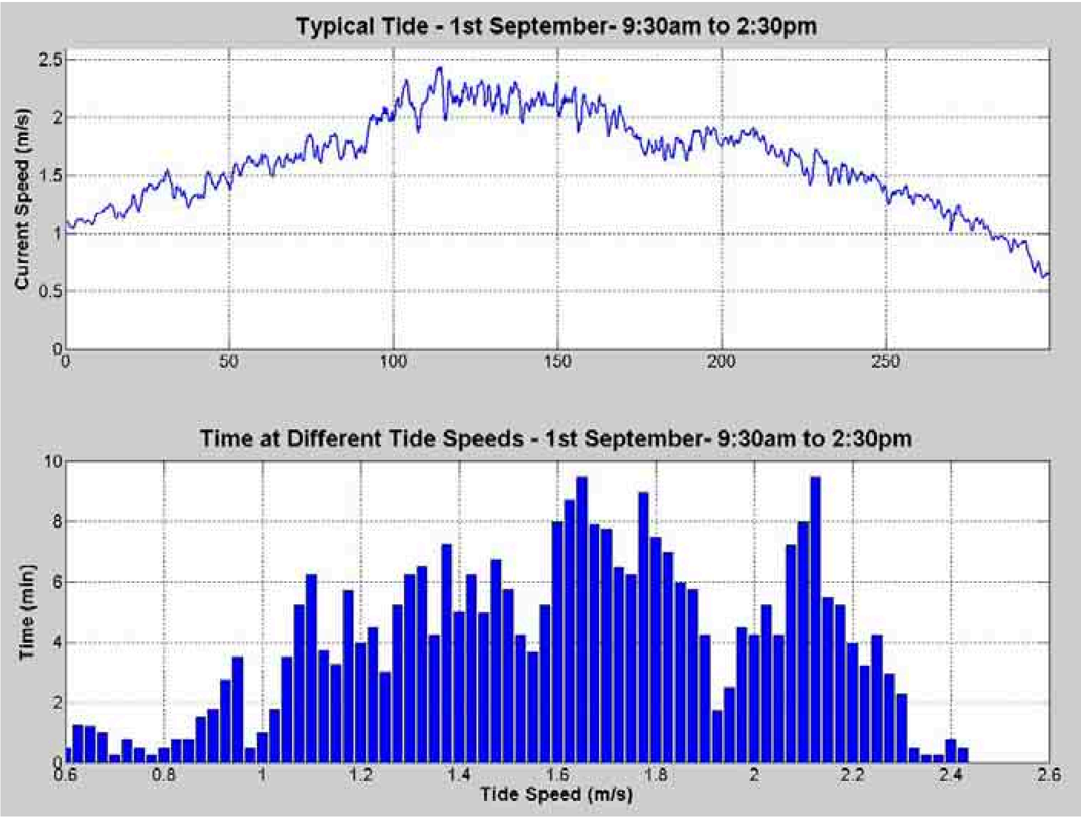

Figure 49

The key point of interest arising from this data was the manner in which the tide speed varied, both during the course of a single tide and between different tides. Figure 49 shows that the distribution of the tide speed does not follow the kind of sinusoidal variation that is often assumed. Comparatively long periods are spent at specific tide speeds for no apparent reason (for example at 2.1 m/s) with several low occurrence patches where the tide speed has stepped through a particular speed range, again for no apparent reason (for example 1.95 m/s). All of the tides for which data was collected exhibited occurrence variation of this nature to some degree although the exact speeds involved varied, as did the intensity of fluctuations.

These characteristics underline the complex site specific nature of the tidal flow and emphasise the need for good survey data to properly assess the potential of a particular location.

10.2 Fore and Aft ADCP Data and Effects of Machine operation

In order to better understand the characteristics of tidal flow across the full channel depth and the effect Stingray has on the tidal flow when it is operating, a comparative analysis of the data collected by all three ADCPs was carried out. This analysis took the form of comparing the velocity profiles at the forward and aft ADCP locations at various stages during the machine installation and operation. The results of this analysis, with possible explanations for the effects encountered, are presented below.

The following are graphs formed by taking the averages over a 30-minute period of the speeds at each ADCP cell and then plotting this against the depth of each cell as represented by its height above the Seabed. Each graph will be considered separately.

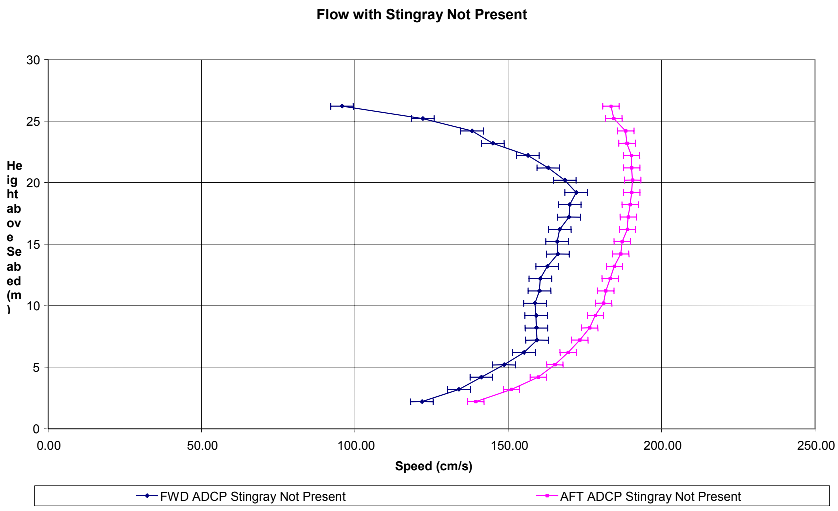

Figure 50

Figure 50 shows the output of the fore and aft ADCPs for the case where stingray is not present to give an indication of the basic flow characteristics of the site. Considering the aft profile first, the variation of current speed with depth appears to match the anticipated characteristic well. The velocity slows noticeably for the cells approaching the seabed and provides a reasonable match to the commonly assumed $1/7^{th}$ power law. The forward profile shows similar slowing close to the seabed, however there is also a noticeable slowing towards the surface. This is thought to be due to the proximity of the barge since the forward ADCP is lowered directly from its bow. Observing the 'law of the wall' which dictates the water must have zero velocity relative to the barge at its surface, this gives the velocity profile a characteristic similar to that that would be expected for pipe flow or flow between two parallel plates.

It is interesting to note that the increase in average speed between the forward and aft profiles approximately equates to that which would be predicted based on the change in water depth. The depth of the water at the aft location is 3.4m less than that at the forward location. This would have the effect of causing the flow to be faster at the aft location. If all other factors are assumed to be equal, unlikely but required for this estimate, and depth changes from 33.5m at the forward ADCP to 30.1m at the aft ADCP then by conservation of the mass flow-rate the speed can be expected to increase by approximately 10%, which is a close match to the observed change.

Figure 51 shows the effect of placing an inanimate Stingray in the tidal flow. The fore and aft profiles from Figure 50 are retained to allow a direct comparison. The presence of Stingray would appear to disturb the flow closer to the surface and slow the flow at greater depth. It should however be noted that this effect has not been reproduced as insufficient data was collected without Stingray in place, hence it is impossible to say whether it is caused by some other effect, such as a natural variation in tidal flow

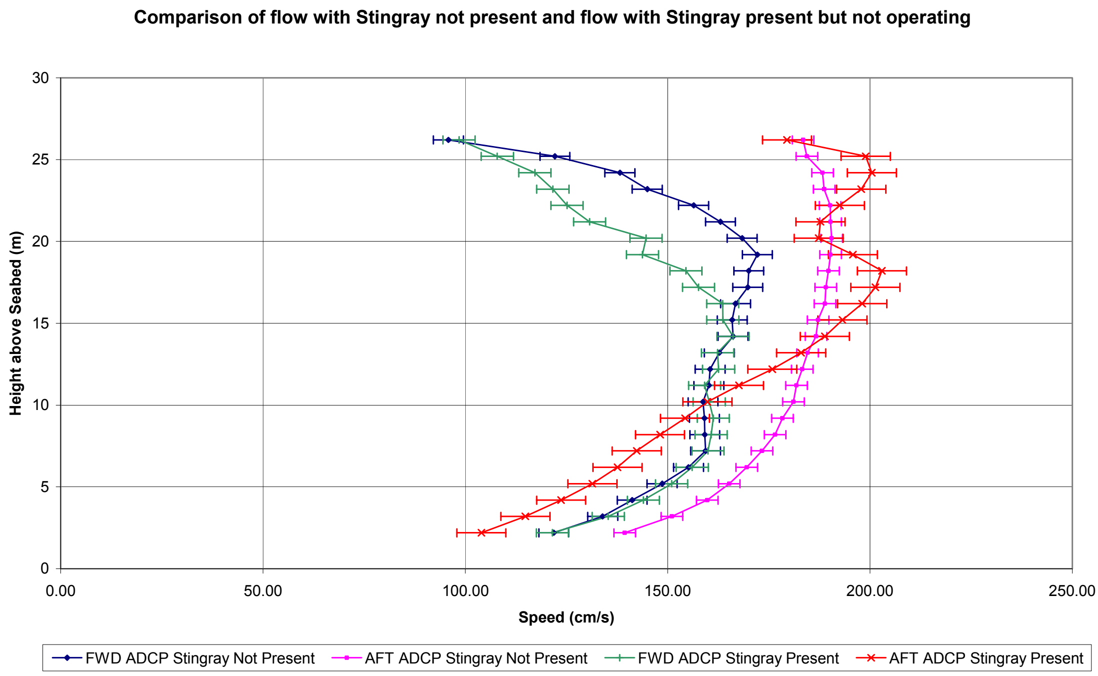

Figure 51

The most important effect to investigate is that when Stingray is generating power compared with when it is not. This is shown in Figure 52, where the comparison is made for a flow speed of approximately 1.5m/s as measured by the current meter on-board Stingray, with Stingray extracting 36.5kW. Again, it can be seen that Stingray is affecting the flow regime. However, as before, there is insufficient repeatable data for firm conclusions to be drawn.

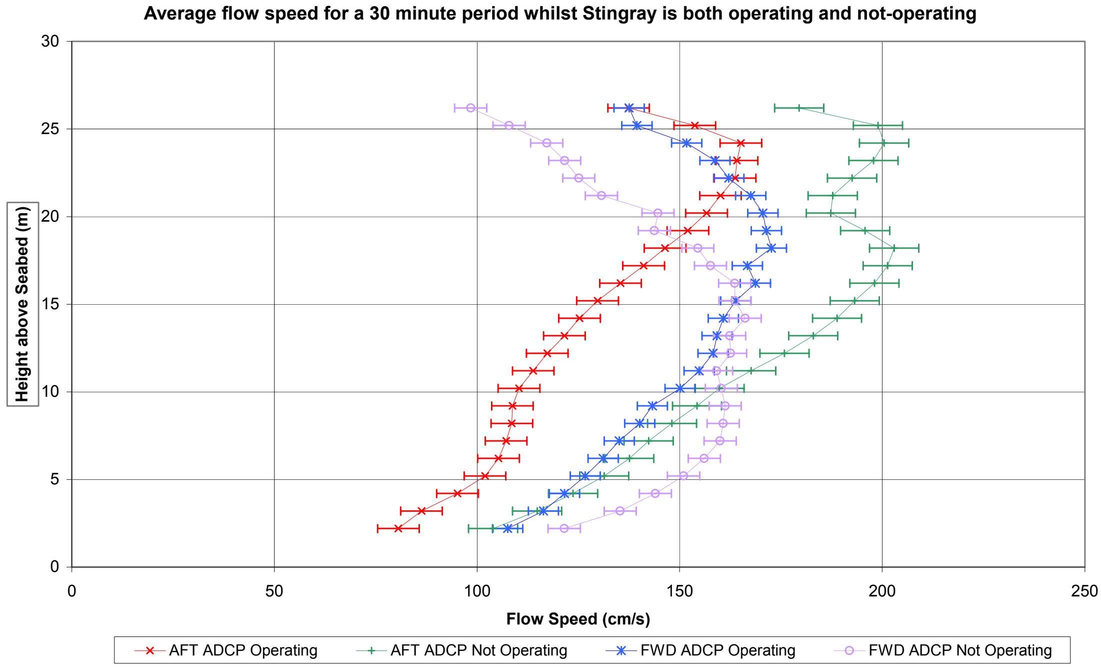

Figure 52

Figures 53 and 54 show the measured flow profiles when Stingray is operating within approximately 1.75 and 2.0 m/s currents.

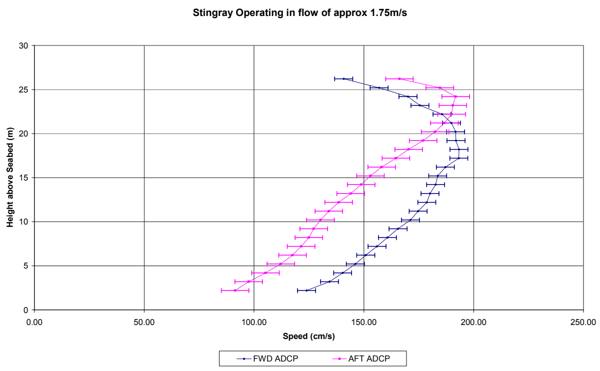

Figure 53

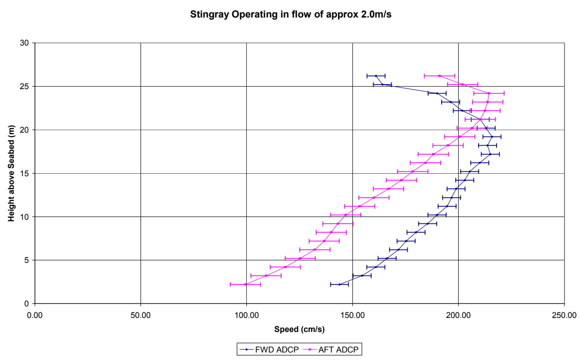

Figure 54

There is clearly a change in the flow in the locations being monitored. However, firm conclusions should not be drawn due to the limited nature of the data set.

10.3 Summary of Findings

- There is considerable variation in the tidal flow and the occurrence of specific tide speeds can be extremely variable. Assumptions of basic sinusoidal variation in tide speed do not hold true.
- The tidal velocity profiles observed with the machine not present match well with anticipated characteristics – the only anomaly is slowing of the flow close to the water surface at the forward ADCP location, which is considered to be due to the proximity of the deployment barge.

- The effect of Stingray when it is not operating appears to be to partially block the flow through the channel, causing the flow close to the surface to become disturbed and the flow at greater depth to be slowed
- With Stingray not operating the flow behind Stingray is faster than in front of it due to the change in water depth. However, with Stingray operating the aft flow is slower than the forward flow.
- Insufficient repeatable data sets exist for firm conclusions to be drawn.
- Further understanding of machine wake effects would be required to enable the planning of farm installations.

11 VALIDATION OF MATHEMATICAL MODEL

The main aim of this section is to provide a direct comparison between the performance of the Stingray machine, as measured in on site testing, and the predicted performance from the mathematical model. If the assumptions used in the mathematical model are correct, then the output of the model should match the on site test results for identical machine motions. To allow this comparison to be made quickly a simplified version of the model is employed instead of the full dynamic model. Normally the model would calculate all of the forces acting at each time step then evaluate the machine motion as a result. The simplified model turns this process around, following a prescribed motion and then calculating the forces, and hence powers, that would be generated as a result. This so called 'Forced Cycle' model allows specific detail cycles to be replicated without the need to go through the time consuming process of tuning the dynamic model control system to achieve the same effect.

The forced cycle model was originally developed to investigate the output of Stingray for idealised cycles, with the main arm motion taking its input from a sinusoidal or saw-tooth signal generator and the corresponding hydroplane motion following the profile necessary to provide optimum angle of attack. This model was modified so that arm and hydroplane motions could be defined by separate vectors of arm and hydroplane angular acceleration as recorded during site testing.

Comparisons were made for a number of different types of cycle, incorporating a wide range of motions and flow conditions to test the model as widely as possible. The key model outputs analysed were the generated power and the actuation power, both 'at the hydroplane' with no conversion to hydraulic or electrical power.

11.1 Generated Power

11.1.1 Complex Cycle – Including Stall

The first comparison was made with one of the power cycles achieved on 1st September in which high powers were achieved but the cycle was untidy with several instances of stall, including a complete stopping and re-starting of the arm in mid-stroke.

When comparing the outputs, it was found that the model power curve followed the measured hydraulic and electrical power curves reasonably well so long as the hydroplane angle of attack remained within its stall limits of ±15° – For example from 0 to 6 seconds shown in Figure 55. Outside of these stall limits however significant differences begin to appear with the model predicting a collapse in power and the actual machine data showing continued generation. Several instances of this are visible in Figure 55, in particular from 7 to 10 seconds and 14 to 17 seconds.

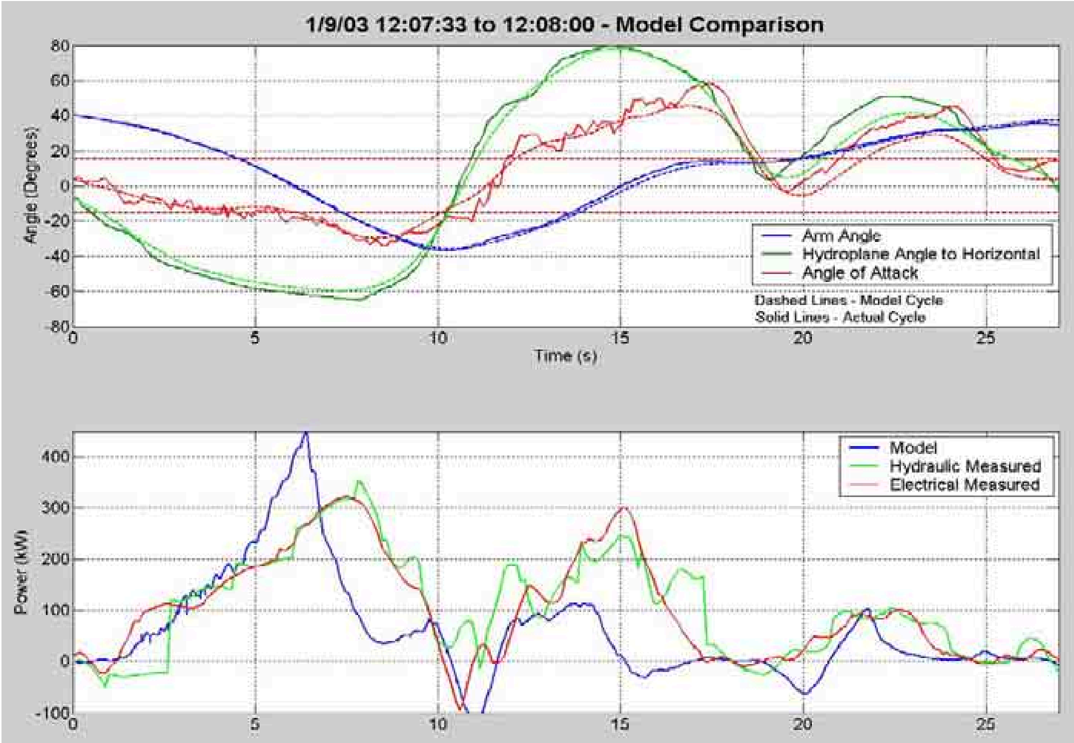

Figure 55

To find the reason for these significant differences, the individual torques which contribute to the model power output were examined separately. The Hydroplane Vertical torque Component has the biggest influence on the power generated from the model. The collapse in power seen in the model coincides with a collapse in this vertical torque component as the hydroplane moves into the stalled region. In reality, it appears that this vertical component is sustained significantly past the stall limits, most likely because of the contribution from unsteady hydrodynamic effects such as dynamic stall. The model does not account for such effects since operation of the hydroplane outside its normal stall limits was not considered likely in the original machine cycle. To enable the model to accurately reproduce cycles involving these types of effects, modifications would be required.

If the difference shown is due to unsteady hydrodynamic effects such as dynamic stall, this opens up the possibility of exploiting these phenomena and improving the power output of the machine from previously predicted levels.

11.1.2 Sinusoidal cycle – without stall

Examination of cycles with much smaller instances of stall provides confirmation of the ability of the model to predict the machine performance for such cases. Figure 56 shows a period of 200 seconds where the machine was operating generally inside its stall limits. In each section of the graph the model output and on site measurements are compared – the three measurements given are arm angle, hydroplane angle and output power.

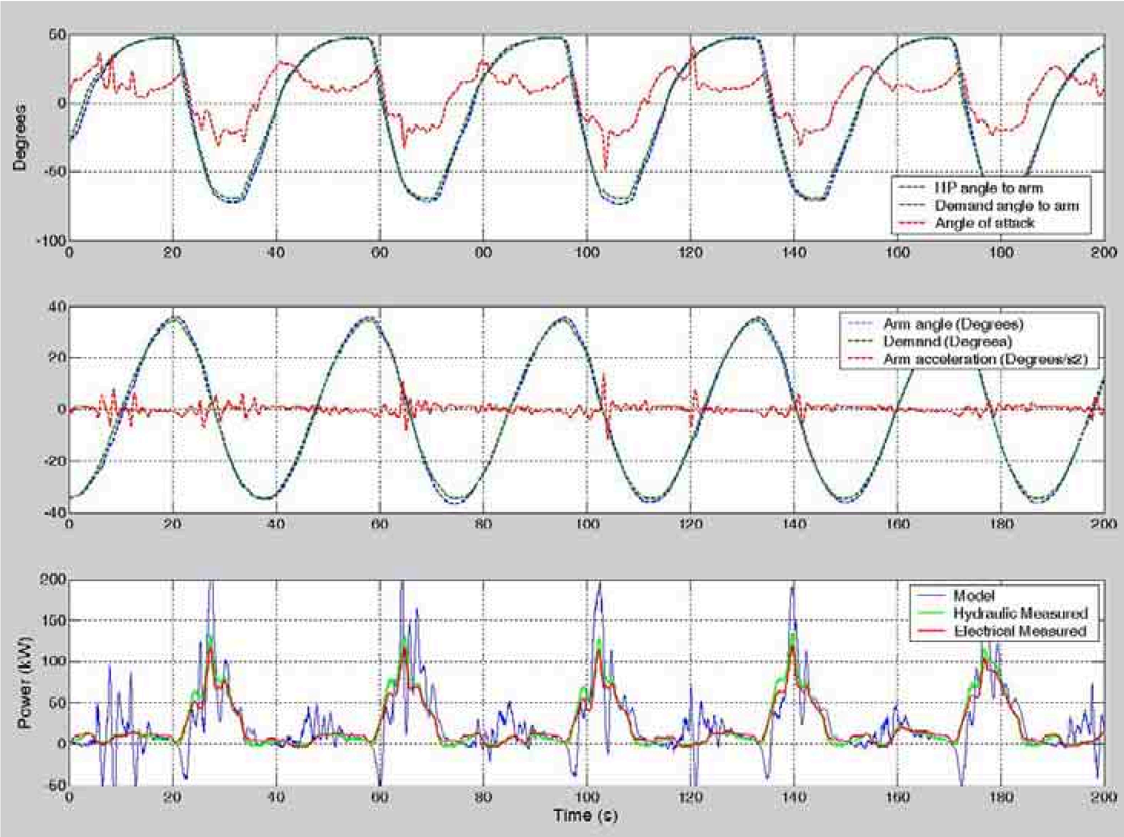

Figure 56

The angle of the hydroplane to the arm is shown in the upper two panels as the approximately sinusoidal trace, along with the angle of attack (upper panel) and arm acceleration (middle panel) represented by the peakier traces. For both of these panels, the 'demand' angle (in green) represents that measured on site during operations, whilst the other arm angle (in blue) is the simulated one. They follow a virtually identical trace, as would be expected of a valid simulation.

From the lower panel it can be seen that the power levels are a good match both qualitatively and quantitatively. There is quite a lot of noise on the model generated power curve, which is due to the noise levels created on the acceleration input vector to the model. The middle panel of the graph shows this acceleration noise which clearly correlates with the power fluctuations. Further validation is provided by examining the time average for power produced over the 200s period considered. The model predicts an average power 'at the hydroplane' of 21.2kW whereas the measured hydraulic power is actually 20.0kW – Matching within 6%. If the losses from converting the model power output power from power at the hydroplane to hydraulic power are considered the figures become an even better match.

11.2 Actuation Power

A comparison of the mathematical model output for actuation power can be made with the on site measurements in a similar way to the main transmission comparison carried out previously. Figure 57 shows the actuation power for the same period of data examined in Figure 56 – ie for a case with limited amounts of stall.

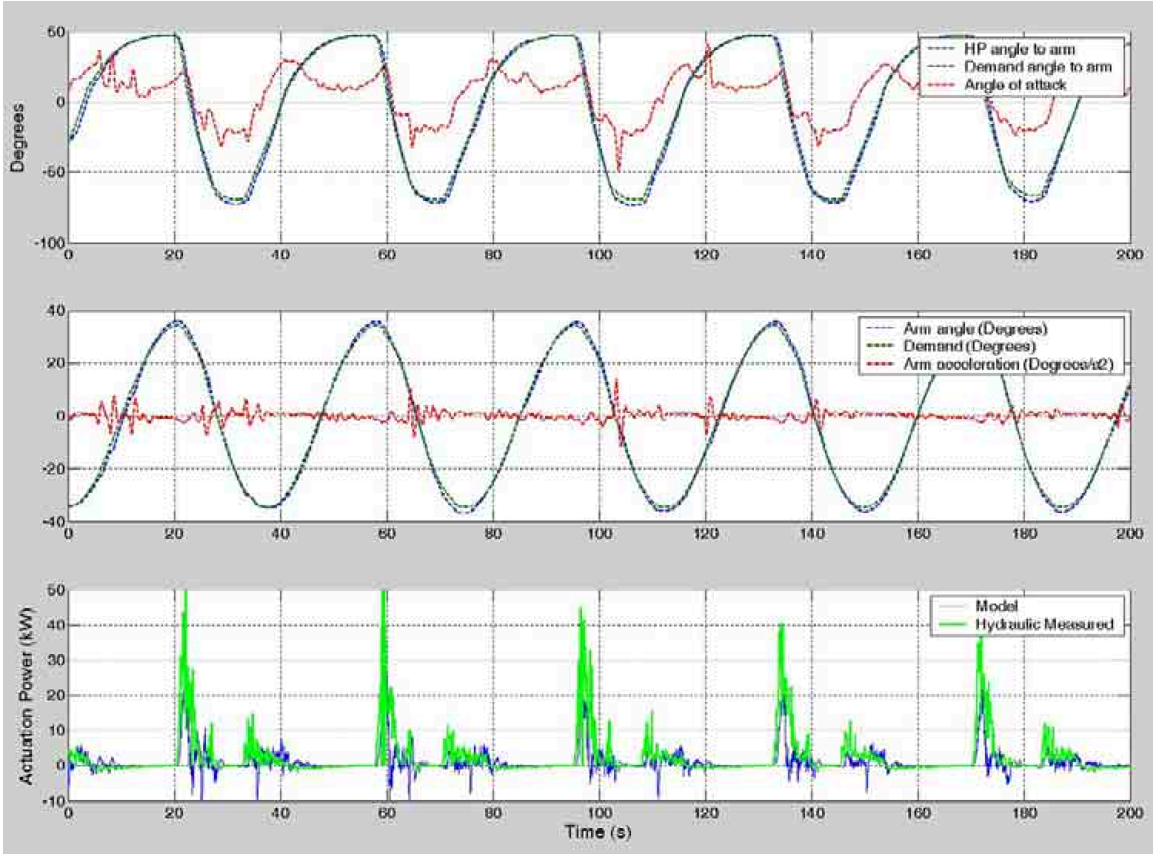

Figure 57

What is immediately apparent from the graph is that there is a good qualitative match between the power curve predicted by the model and the measured hydraulic power as shown in the third section of the graph. However, the quantitative match appears to be poor with the hydraulic power measured taking a generally higher value. This is confirmed by averaging the power levels across the full 200 seconds of data which gives a value of 1.21kW for the model and 2.57kW for the measured hydraulic power – out by a factor of 2.1.

This will be due in part to the efficiency of the various components between the hydroplane and the valve tank, where the hydraulic power is measured. The hydraulic losses and actuation linkage efficiency will all have some influence however it is unlikely these can fully explain the mismatch. Further work on predicting the actuation power through the machine cycle is needed to fully understand the levels seen and how they will change for different configurations of machine.

It should be noted that the actuation power levels, even when an x^2 factor is applied, are still very low in the context of generated power.

11.3 Mathematical Model Conclusions

- The mathematical model predictions for power generation show a good quantitative and qualitative match with the on site data for cases where the hydroplane is operating inside its stall limits, showing correlation within 6% for the data considered.

- In areas where the hydroplane is outside its stall limits the mathematical model – this difference is believed to be due to unsteady effects such as dynamic stall which are not represented in the model. The model would require modification to include these effects.
- If the difference in the stalled cases is due to unsteady hydrodynamic effects, It may be possible to exploit them in the machine cycle to improve the performance of the machine beyond previously estimated levels.
- The mathematical model predictions for actuation power show a good quantitative match with the on site data but the levels of power required are underestimated by a factor of two. This mismatch is not surprising given the basic nature of the actuation power assumptions and more work is required to fully understand the loading through the cycle.
- The mathematical model is adequately validated for it to be used to output estimate of power generation for the economic modelling.

12 ECONOMIC ANALYSIS – BACKGROUND

12.1 Conclusions from Phase 3 data analysis

The test programme principally involved the acquisition of data and investigation of various control strategies and technical options. The aim was to increase understanding of machine interaction with the flow, model this, and then improve and optimise machine performance.

The results demonstrate that:

- The tests yielded sufficient data to validate the mathematical model of Stingray performance to give us confidence for predicting output of the machine and future variants.
- Stingray is capable of collecting significant levels of energy from the tidal stream, across a wide range of flow velocities.
- The collected energy can be converted into electrical power at reasonable levels of efficiency.
- The mathematical model underestimates the amount of measured energy collected by the prototype. This is attributed to complex non-linear effects, such as dynamic stall.
- The levels of power generated by the prototype are in line with expectations and assumptions used in the cost modelling.

The power output used in the economic model is based on achieving certain powers at certain cycle times in certain current speeds. Figure 58 demonstrates that the measured power (designated 'x' for full cycles and 'o' for half cycles) exceeded the predicted power (as indicated by the solid lines) at all current speeds and cycle times. "Economic viability" becomes more achievable as the machine performance is developed to move steadily to the left on the graph - to deliver more power at faster cycles. Although the tests did not achieve the fastest cycle times, we are confident that there is no fundamental reason not to be able so to do as development progresses.

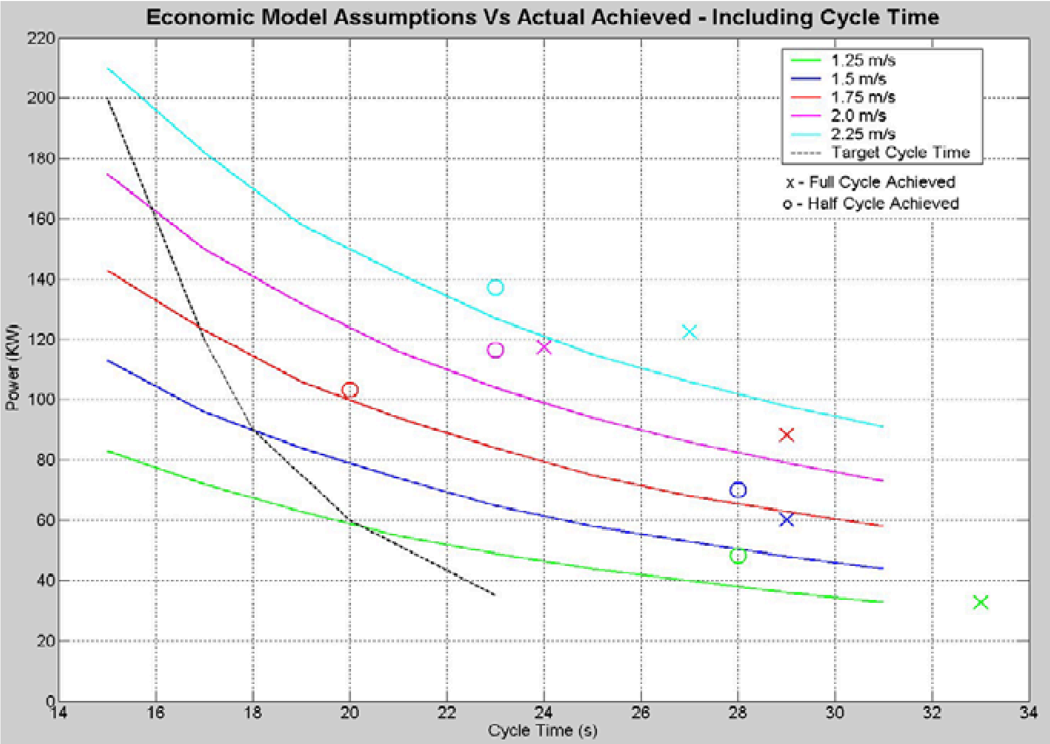

Figure 58

12.2 Concept development

Producing sensible estimates for cost of energy production requires a clear idea of the size, shape and performance of the equipment to be installed. Previous cost modelling has relied on the "as-built" cost data for the 150kW prototype machine. To improve our predictions we need costs that relate more closely to the anticipated "production" machines and associated equipment such as handling systems.

EB has, therefore, evaluated the test data and earlier work on parametric modelling to produce the outline design for a "second generation" 500kW machine. The full design specification document contains commercially sensitive information and remains confidential. The salient points are summarised here.

The process by which the new design has been reached required the review of various design options aimed at producing a more cost-effective machine in terms of delivered energy. Various design reviews were undertaken that covered aspects such as:

- Hydroplane chord length and aspect ratio
- Number of hydroplanes
- Ability to intercept tidal current in both ebb and flow directions
- Hydroplane actuation system
- Mechanical arrangement to provide vertical movement
- Hydraulic transmission system
- Electrical transmission and drive system

The mathematical model was used to produce estimates of output power for different configurations, and the cost and complexity of different options was evaluated. The initial concept, design specification and assumed power output for the second-generation machine are shown below.

12.2.1 Concept design & specification

Where the 150kW Stingray demonstration unit had its single hydroplane mounted on a trailing arm, with the whole arm being driven up and down by the forces acting on the hydroplane, the 500kW unit has three hydroplanes held in an assembly that permits them to travel vertically, somewhat like a 'lazy tongs' device. Unlike the demonstrator, which was designed such that the arm, when necessary, would yaw or flip, the hydroplanes can now rotate in their assembly. The 500kW general arrangement is illustrated in Figure 59.

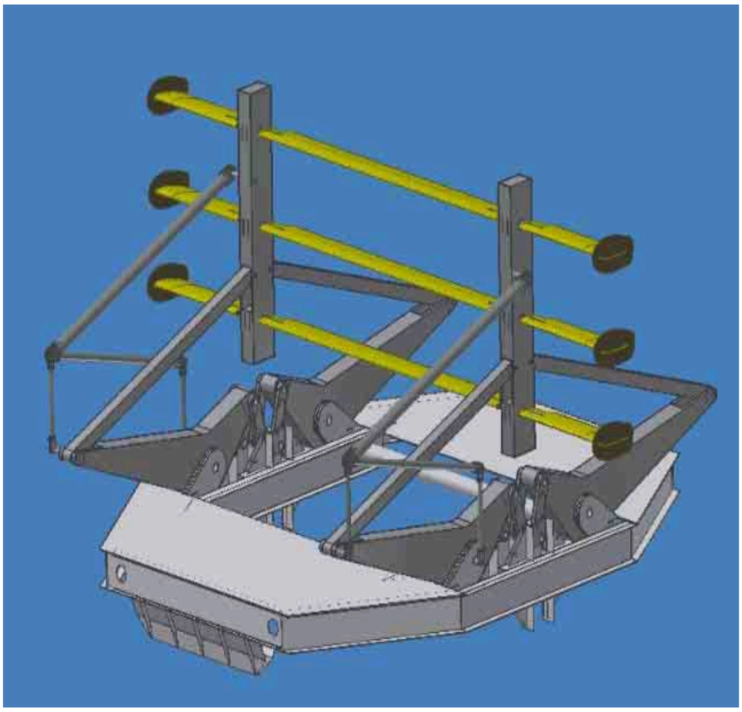

Figure 59: Second Generation Stingray Concept – General Arrangement

Rating - power - current speed - cycle time	 500 kW 2 m/s 20 sec
Hydroplanes - number - chord length - spacing - width	 3 1.77 m 3.54 m 27.7 m
Weight - machine only - including ballast	 300 t 500 t
Height - minimum - maximum working	 12 m 26 m
Swept height	19.1 m
Swept area	528.5 m^2
Footprint	25 x 20 m

Table 12

12.2.2 Power Output

The power output for the machine at various tidal stream velocities produced by the mathematical model is dependent on the cycle time and is illustrated in Figure 60.

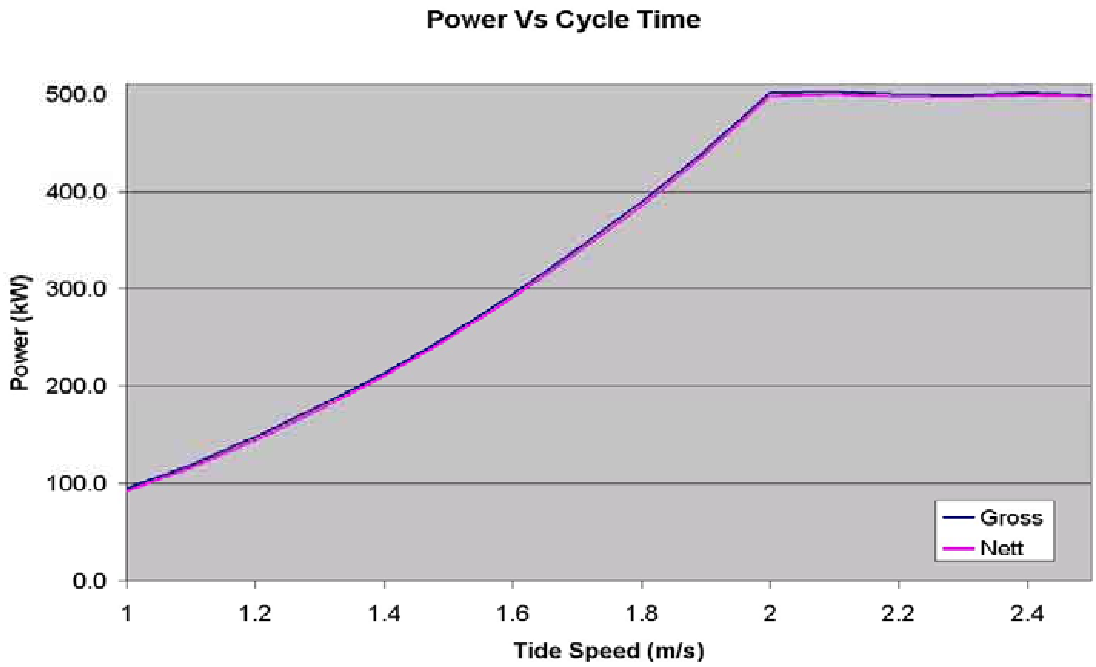

Figure 60

The second-generation machine has been designed for a 25-year fatigue life with reference to BS 7608: Fatigue Design and Assessment of Steel Structures" (1993), and DNV classification note no. 30.2, "Fatigue strength analysis for mobile offshore units" (1984). The structure was designed to withstand loadings for survival in extreme conditions. Frazer-Nash Consulting were commissioned to undertake a review of reliability of the 500kW concept design. This was undertaken using a Mean Time Between Failure (MTBF) approach, with the concept broken down into ten functional blocks. This highlighted the areas that detailed design would have to focus on when the concept is brought forward to development. This study also identified preliminary maintenance strategies.

Having produced an outline design, it was then possible to produce a costing for its design, manufacture, installation (including handling system, marine operations and grid connection) and operation. The individual costs of all these elements, broken down to sub-assembly or component level, as appropriate, were estimated. Advice on costs of particular elements has been received from acknowledged experts such as Econnect and Siemens.

12.3 Context of the economic model

The aim of the cost model is to produce an estimate for the unit cost of producing electricity that allows us to look at the effects of changing the energy generated and the costs of manufacturing, installing, and operating a farm of Stingray machines. Cost spreadsheets have been produced for different variants of the machine, representing different stages of maturity of the technology.

For the economic modelling to be useful, however, it is necessary to make a number of assumptions regarding future installed farm size and location. The effectiveness of the technology cannot be considered independently of the available resource or potential market – it must be tailored to match it. EB has, therefore, addressed the following:

12.3.1 Size of machine

At this time, it seems likely that the proposed second-generation unit size is sensible for production machines, given the practical constraints of installation and maintenance. At its nominal rating of 500kW it is the same as proposed tidal turbines. The cost model does not, therefore, take advantage of potential savings that would be realised by increasing physical size, or increasing power rating.

12.3.2 Size of farm, matched to resource

Considerable cost savings and economies of scale can be realised with increased farm size. The size of an appropriate commercial farm depends on what might be installed at a particular site, based on the available resource. EB has carried out an assessment of the UK tidal resource, with particular emphasis on the constraints of extracting energy.

Earlier studies have tried to quantify the amount of energy available, based on very limited tidal current data, without analysing the effect of removing the energy. EB has now carried out analysis based on open-channel flow, and calculated the reduction in flow velocity in relation to the amount of energy extracted. EB considers that the reduction in average velocity should be limited to 10% to avoid the risk of significant impact on both the overall flow regime in the area and on the environment. With this limitation, the amount of energy that can be extracted from the flow is of the order of 20%. EB has evaluated the total amount of energy that can be extracted from a number of sites previously identified as having significant potential, and the corresponding amount of installed capacity on the basis of anticipated capacity factor of 30%. The results are shown in Table 13.

Site	Equivalent ave. power in flow (MW)	Extracted average power (MW)	Annual energy output (GWh/yr)	Installed capacity (MW)
Hoy	574	0*	0*	0*
S. Ronaldsay	519	104	909	346
Stroma	666	133	1167	444
S.Ronaldsay/Skerries	566	0*	0*	0*
Pentland Skerries	789	0*	0*	0*
Duncansby	492	0*	0*	0*
Inner Sound	76	15	132	50
Rathlin	692	138	1212	461
Mull of Galloway	476	95	833	317
Barry	65	13	114	43
Foreland Point	807	161	1414	538
Alderney	418	84	733	279
Casquets	708	142	1241	472
NW Guernsey	487	97	853	325
Big Russel	242	48	424	161
NE Jersey	44	9	78	30
Portland Bill	205	41	359	137
Yell-Bigga	105	21	183	70
TOTALS	**7826**	**1081**	**9470**	**3604**
* These sites have been excluded because they are located "in series" with another site				

Table 13

From this table it can be seen that the maximum installed farm size on a single site, unconstrained by other factors such as local topography and shipping requirements, would be about 500MW. Taking a conservative view, EB considers that a realistic unit size for a farm would therefore be 100MW installed. Whilst larger farms, with potential benefit for reduced costs may be feasible, they are not considered in the analysis at this stage.

12.3.3 Location and layout of farm

Whilst EB has identified that there are a number of potential sites for large scale development, each specific location has to be assessed to see whether it is possible to install the required number of machines. EB has examined the site at Yell Sound for which it has survey data and identified 30 separate locations at which it should prove possible to place a machine that meet the following criteria:

- water depth > 30m
- seabed slope < 8.5°
- spring velocity (from current model) > 2m/s
- machine spacing, 3 x hydroplane width across flow, 5 x width in flow direction

This demonstrates that in a relatively small area (0.7km^2, covering only one third of the total Bigga-Yell channel), it is reasonable to assume that sufficient machines can be installed to establish a farm.

12.3.4 Size of potential market

In order to justify the development necessary to drive the costs down, there must be a sufficiently large overall market that is commercially attractive for investors. From the table above, it can be seen that EB's conservative estimate of the amount of installed tidal stream generators in the UK sites shown is nearly 4 GW, yielding 10TWh/yr. This represents about 2.5% of current UK demand, and at an installed cost of £1 million per MW, the size of the UK market for Stingray technology would be £4 billion. In addition, there are many UK sites not considered in the initial assessment that can yield significant amounts of energy. It is reasonable to assume that this is sufficiently large to attract the investment required for Stingray to achieve commercial viability.

12.4 Power Outputs used in cost model

The amount of power produced by Stingray at any particular current velocity is calculated using the mathematical model of the second generation machine. The total energy collected over a year depends on a number of variables including velocity occurrence and efficiency of conversion from collected power to delivered power. For the economic modelling, this is calculated on the basis of operating in Yell Sound, using the data collected from Phases 2 and 3 of the Stingray programme and modelling work for tidal velocity magnitude, occurrence, and annual variation. An example of the spreadsheet used to calculate the total energy collected is given in Appendix A.

EB considers the tidal resource at Yell Sound to be representative of the typical site that will be exploited commercially. There are many sites identified in the resource studies carried out that have a significantly higher annual energy yield because of higher average velocity. Although these sites would undoubtedly allow Stingray to work at its nominal rated capacity for a longer period, thereby producing more energy, it is not clear whether the unit cost would be reduced, as the machine may have to withstand higher survival loads. EB has chosen, therefore, to ignore the potential benefits of selecting a more advantageous site in the current economic analysis.

The collection efficiency is a function of tidal velocity and machine cycle time, and the maximum output has been capped at 500kW to allow the generating plant cost to be minimised. A typical collection power and efficiency curve for the machine is shown in Figure 61.

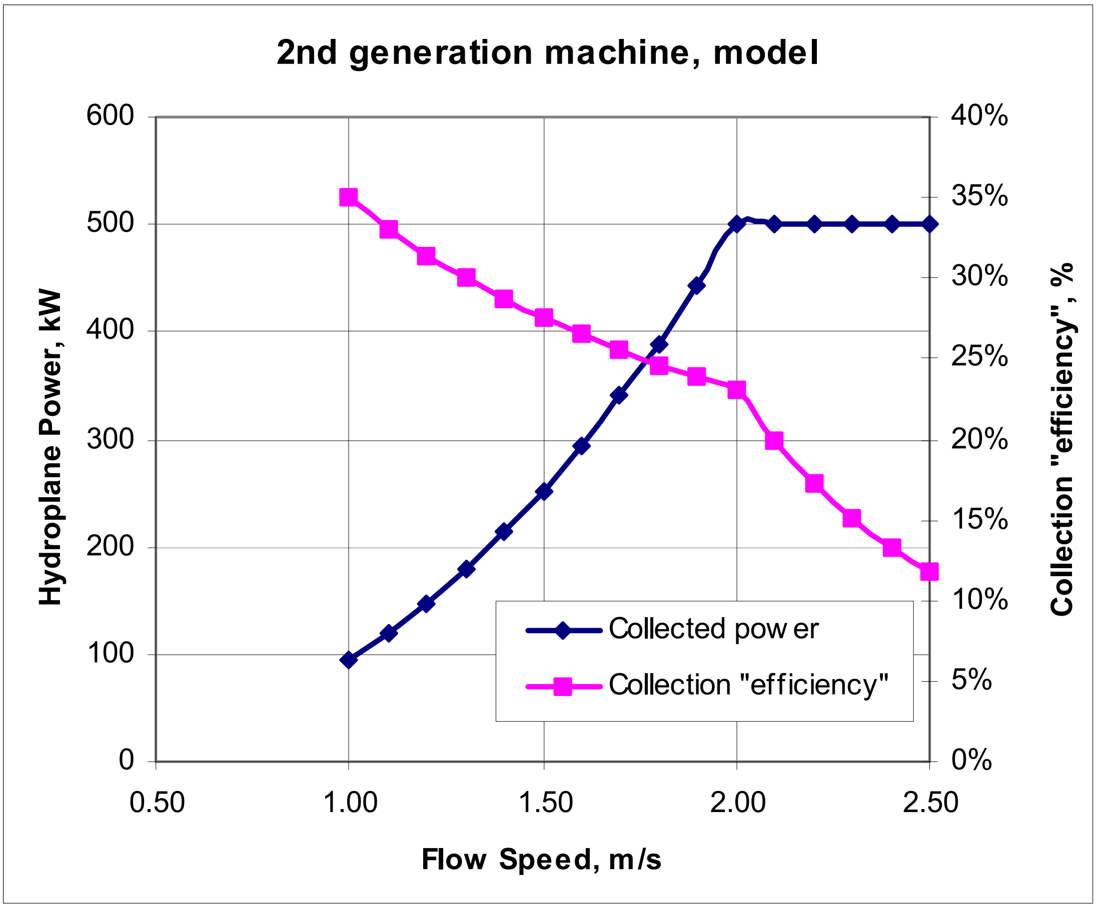

Figure 61

As mentioned previously, the present model predicts less power generation than measured experimentally so output estimates are conservative. EB has assumed that collected power will increase as the Stingray technology becomes more developed and operational methodology is optimised. For Phase 5 of the Stingray development (the 30MW farm) the power able to be collected at any particular velocity per machine is assumed to be 20% higher than that predicted by the model for the 500kW machine design at present. For Phase 6 (the 100MW farm), the collected power is increased by a further 20%. The total energy collected does not increase by the same amount, as the cap of 500kW is reached more quickly with the more efficient machines.

The efficiency of energy conversion from collected power to electrical power from the drive is 75%. This agrees with the measured efficiency from both the workshop tests on the transmission system and subsequent site testing. As technology and understanding improves, EB anticipates that this efficiency will increase. The conversion efficiencies used for Phase 5 and 6 machines are 79% and 82% respectively.

Other losses due to transmission and conditioning to meet grid standards have been included, although improvements expected for future machines have been ignored at this time.

The estimated power outputs and resulting capacity factor for the development stages modelled in Section 13 are given in Table 14.

Phase	Machine size (kW)	Estimated energy yield (MWh/yr)	Capacity factor (%)
2	150	150	11.4
3	150	225	17.1
4	500	873	19.9
5	500	1053	23.2
6	500	1200	27.4

Table 14

The Stingray technology is currently at prototype stage, and the economic model anticipates considerable improvements in output power as a result of investment in time and capital. It may be argued that such increases are difficult to realise, but there is considerable evidence from other technologies that the anticipated improvements are not only justifiable, but also conservative. In the paper "Progress in renewable energy" by Gross, Leach and Bauen (Environment International 987, 2002), some technical achievements in wind power are given. These include:

- Over the last 15 years, the annual energy output per turbine has increased 100-fold.
- Turbine rated capacity (for typical commercial machines) has increased from 55kW to 1MW or more.

Although comprehensive published data is not readily available, during this period turbine output and efficiency has steadily improved due to factors such as blade design, improved rotor performance coefficient, variable pitch, variable speed, drive train and electrical generator efficiencies.

A major contributor to increase in power output would arise from capitalising on the beneficial "non-linear" effects previously mentioned. EB is not relying on these to deliver the anticipated power increases as the Stingray technology is developed, but has commissioned a report from Frazer Nash Consulting to attempt to quantify the benefits on the basis of its experience in this field. Other researchers working in this area claim that hydroplane lift forces might be increased by up to 400% (with consequent increase in power) by adapting the machine to utilise these effects. Even if, say, only a 25% increase were available in practice, it would deliver the improvements in Stingray performance that are presently anticipated through other means.

12.5 Costs used in cost model

As previously described, the cost basis for the model is built up from a number of individual elements. The principal cost headers are:

Machine: Fabrications & Mechanical, Foundations, Hydraulics, Subsea Electrics, Subsea Drive, Topside Power & Control, and Machine Build Costs

Handling System

Farm: Grid Connection, Farm Connecting Cables, Machine Installation, Machine Removal, and Farm Project Management

Operations & Maintenance: Annual Operating Costs and Annual Maintenance

Within these headers, the costs are further broken down to assembly or sub-assembly level as necessary. An estimate of each cost element was made based on the following:

Fabrications and Mechanical

The outline machine design yielded the weight of the major fabrications. A price per tonne was estimated, depending on complexity and material, from EB's extensive experience in the manufacture of similar items. The major machined items (pins, etc) were identified and costed on the basis of similar items previously manufactured. An allowance was included for shot-blasting and painting of all items to a suitable marine specification. EB has high confidence in the realism of these estimates, based on its strong industrial experience.

Hydraulic, electrical and drive systems

The main components and sub-assemblies were identified and costed according to price estimates from manufacturers or recent EB purchases of similar items. EB has high confidence in the accuracy of the component costs, based on experience. However, the probability that the design of these elements will develop with time (possibly simpler system, but more expensive components) results in an overall medium confidence level.

Machine build

The cost of appropriate premises, facilities and services were estimated from EB's experience of utilising both its own workshops and larger facilities rented from third parties for the construction of equipment of a similar size and complexity to Stingray such as subsea pipe trenching ploughs and handling systems. The sub-contract labour requirement was estimated on a similar basis. Costs include transport from point of manufacture to assembly location, and necessary insurances. EB has high confidence in these costs.

Handling System

A specific handling system was designed and built by EB for the demonstrator machine. A new system has been developed and costed, at concept level, for the proposed commercial machines. EBs position as a world leader in specialist marine handling systems provides strong confidence in the realism of these costs. As a comparison, a quote for an equivalent shear-leg floating crane was obtained, giving similar overall costs.

Grid connection

Costs of hardware and other charges for grid connection were estimated as a result of discussions with a network operator and checked through a separate desk study commissioned from Econnect (a leading consultant in renewable energy and grid connection). The grid connection costs include shore station facilities, switchgear, onshore cabling, a new substation and civil engineering costs. The study reviewed four grid connection options for the Yell Sound site, providing approximate costs for them all. The special circumstances of the Shetland network result in higher than typical grid connection charges. Therefore a reduced connection rate has been included in the model. These factors result in a medium confidence level in the grid connection figures.

The costs of an appropriate facility to house the topside control, power conditioning and grid connection equipment were provided by Econnect, with an alternative, but similar, estimate based on EB's experience in containerised control and power systems.

Farm connecting cables

The cost of both infield and export cables, including end terminations, was estimated on the basis of similar cables used by EB for signal and power transmission cables to remotely operated vehicles. This was checked against manufacturer quotation and costs supplied by Econnect. The costs of a marine spread for installation and protection of the cables was based on quotations for appropriate vessels, equipment, crew, and products. This was checked against rates quoted by a marine contractor operating in the offshore wind farm market. An allowance of at least 50% of operational time was included to cover weather downtime. The choice of cable protection method is very site specific, dependant on factors such as length of cables, seabed and shoreline geology and bathymetry / topography, site location and facilities, and stakeholder / consent issues. In assessing the cost, EB reviewed suitable techniques (burial by plough, jet-tool and tractor, directional drilling, protection by rock dump or concrete mattresses, and protection by synthetic ducting. Depending on specific site conditions, the most cost-effective and environmentally acceptable method is likely to be burial by plough or mattressing / ducting. The costs of these techniques, particularly the marine and plant costs, are sensitive to market conditions. EB has medium to high confidence in these costs.

Marine Operations (Installation and Recovery / Decommissioning)

The costs of a marine spread for installation and protection of the Stingray machines was based on quotations for appropriate vessels, equipment and crew. An allowance of at least 50% of operational time was included to cover weather downtime. Costs included a full team of installation engineers and commissioning engineers for the full duration of marine operations plus weather downtime. Estimates were also made for provision of positioning services, operating permits/licences, seabed clearance on decommissioning and insurance. From its experience in the marine industry, and specific experience from the Stingray project, EB has high confidence in these figures. However, as noted above, marine costs are sensitive to market conditions, resulting in the confidence level being reduced to medium to high.

Farm project management

Estimates for desk studies, site survey and environmental impact assessment were based on EB experience and quotations received by EB. An allowance was included to cover permits and consents, travel and legal fees involved in establishing the farm. EB has high confidence in these costs.

Operating and maintenance

Allowances were made for rent, rates and running costs of shore facilities and for seabed use, insurance and network charges. A suitable level of personnel to provide continuous operation and support was included. Spares and consumable parts requirements were estimated as a percentage of initial build costs based on EB's experience of subsea operations and warranty provisions. The annual costs of a suitable vessel spread for offshore maintenance were included based on allowing one full maintenance day per machine. In general, EB has high confidence in these figures. However, the insurance cost assumed is lower than industry standards of about 2% of capex. Being seabed mounted, with significant clearence between the top of the structure and the sea surface, EB believes that, once the 'novel technology' earlier phases have been passed (up to and including Phase 4), a lower insurance premium can be negotiated resulting from the reduced risks associated with such a structure. However, this elemnt of the O&M costs must be considered to have low to medium confidence limits at this stage.

An example of the spreadsheet used to calculate the total farm cost is given in Appendix B. The working sheets for the detailed cost breakdown contain commercially sensitive information that remains confidential, with only a summary of the cost breakdown sheets included.

Table 15 summarises the estimated costs used for the different phases:

Phase	Farm size (no. x kW)	CAPITAL COSTS (£ million)				O&M COSTS (£ million)
		Machine	*Handling*	*Farm*	Total	Annual
2	1 x 150	-	-	-	1.87	0.16
3	1 x 150	-	-	-	1.37	0.15
4	10 x 500	11.54	0.46	3.35	15.35	0.46
5	60 x 500	51.33	0.70	13.45	65.48	1.96
6	200 x 500	96.15	1.02	29.97	127.14	3.81

Table 15

In estimating the costs for the 30MW and 100MW future farms, using the Phase 4 (5MW) farm as a basis, the following average reductions in capital costs were assumed (Table 16):

	30 MW farm	100 MW farm
Bought-out cost reduction due to design optimisation/specification improvements		
- machine	17%	35%
- handling system	10%	25%
- farm	2%	9%
Bought-out cost reduction for multiple units		
- machine	7%	33%
- handling system	20%	25%
- farm	30%	50%
Overall capital cost reduction per MW installed	28.9%	58.6%
Average "progress rate" in cost reduction	87.6%	81.5%

Table 16

In terms of annual operating and maintenance costs for Phases 4, 5 and 6, the analysis assumes a figure that is a fixed at 3% of total capital costs. EB's cost estimation produces figures similar to this, and 3% has been used as a realistic level that also allows for simple sensitivity analysis to be undertaken. Other researchers have used figures ranging from 1-3%. In addition, EB has undertaken sensitivity analyses for O&M costs ranging from 2-10%.

12.5.1 Justification for cost reductions

From the above table, it is clear that very significant reductions in cost are anticipated as the Stingray technology develops. For the cost modelling to be credible, it is necessary to consider whether such cost reductions are feasible. It is difficult to identify in detail where the cost savings and economies of scale will be made, and EB has not attempted to do so, other than in general terms, as noted above.

A commonly accepted approach in addressing this problem is to rely on "learning" or "experience" curves as an indicator to how the costs of any technology might decrease in relation to the amount of investment made in it. In relation to tidal stream energy there is insufficient historical data to be able to make accurate predictions, so it is necessary to consider other similar technologies.

The International Energy Authority has studied cost reductions in electrical technologies extensively, and the results are detailed in the publication "Experience Curves for Energy Technology Policy", (IEA, 2000). It has calculated "progress ratios" for a range of technologies, both established and emerging. For each doubling of energy production, the price will reduce by the progress ratio. The progress ratios over the period 1980-1995 for wind power and energy from biomass are given as 82% and 85% respectively. For photovoltaics, the progress ratio is as high as 65%.

In other words, to achieve a 60% reduction of costs at a progress ratio of 82% requires 4.5 doublings of production, or an increase of 25 times. Starting from 5MW means that we have to install 125MW of capacity to achieve the required cost saving used as the basis for the Phase 6 farm – surprisingly close to the planned cumulative installation of 135MW. There is no fundamental reason why the Stingray technology should not benefit from a similar level of progress to wind power.

It is reasonable, therefore, to assume that the level of cost reduction anticipated is achievable on the basis of established "learning curve" principles.

It should be noted that this initial analysis considers the progress rate based on cost only, which does not take into account the improvements in output also anticipated. A discussion of the implications of this are included in Section 13 on Cost Modelling.

13 COST MODELLING

13.1 Aim of cost modelling

The overall objective of Phase 3 of the Project has been stated as "to demonstrate that electricity can be generated at a potentially commercially viable unit energy cost".

The cost modelling therefore aims to predict what future unit cost of energy may be possible given reasonable development from the current position in terms of the cost and output of a farm of Stingray generators. It identifies the assumptions used, and also considers how the size of a commercial farm is matched to the exploitable tidal stream resource.

The results from the cost modelling aim to demonstrate how the anticipated unit energy cost will fall, and whether this appears reasonable in comparison with available data for technology development.

The model also aims to allow some sensitivity analysis in terms of how the unit energy cost will be affected by changes in energy output, capital and operating cost, and capital grant.

13.2 Description of the cost model

The essence of the model is a discounted cash flow (DCF) method that calculates the unit energy cost for a farm of Stingray machines from a number of inputs, as illustrated by Figure 62.

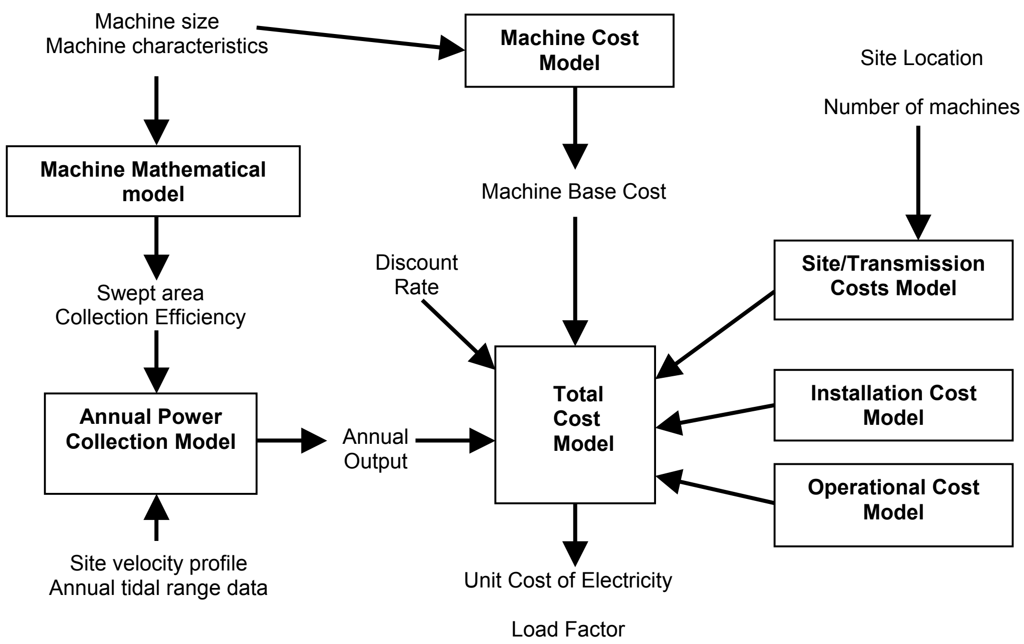

Figure 62: Basic Structure of Cost Model

An example of the model spreadsheet used is given in Appendix C. This is for the 5MW (10 x 500kW Stingrays) Phase 4 farm. The unit cost calculation is a straightforward net present value (NPV) calculation that calculates the electricity "price" required to produce a zero balance of revenue against capital and operating costs.

The key inputs, with an indication of the value and source of the values from the example given, are:

Input Parameter	Phase 4 Example	Source
(a) Capital cost of design, manufacture and construction	£15.35 million	Appendix B Summary
(b) is an output parameter	--	--
(c) Capital grant	0	Table 16
(d) Percentage of capital cost defrayed on installation of farm	95%	Table 16
(e) Operating and Maintenance costs	3%	Table 16
(f) Annual machine energy output (MWh/yr)	873	Appendix A, Step 13
(g) is an output parameter	--	--
(h) Machine availability	95%	Table 16
(i) is an output parameter	--	--
(j) Nominal size of Stingray machine (MW)	0.5	Project Specification
(k) Number of machines installed	10	Project Specification
(l) Discount rate	8%	Table 16
(m) is an output parameter	--	--
(n) Construction period	1 year	Table 16
(o) Operating life	25 years	Table 16

Table 17

The spreadsheet also allows the sale price of electricity, ROC value, price and cost inflation and tax rates to be included to enable calculation of pre- and post-tax return. These factors are not included in the calculation of unit cost of energy.

The spreadsheet produces the following outputs:

Model Output	Phase 4 Example	Source
(m) Unit cost of energy (p/kWh)	22.2	NPV Calculation
(b) Capital cost of installed capacity (£/MW)	£3.07 million	a / (j x k)
(g) Capacity factor – the annual machine energy output (MWh/yr, assuming 100% availability) divided by the nominal installed capacity (MW) x 8760 (hours per year)	19.9%	(f/(j x 8760)) x 100
(i) Annual farm energy production (MWh) incorporating the effect of machine availability	8294	f x h x k

Table 18

13.3 Development stages modelled

The model is used to look at a number of stages of development of the Stingray concept, starting with the prototype 150kW machine (Phases 2 and 3). Projecting forward, the cost model starts from a baseline cost and power output estimated for a single 500kW second-generation machine. This machine is derived from the new design described in Section 12.2. From this, EB has made assumptions regarding the cost reductions that will be made as a result of factors including:

- design optimisation
- technology improvements of individual components
- increased structural efficiency due to improvements in materials
- reductions in factors of safety as uncertainty reduces
- economies of scale in design, manufacture and operations

The five principal stages that have been modelled are:

- Phase 2 – as-built, 150kW prototype
- Phase 3 – based on cost of building 150kW machine with less development costs
- Phase 4 – 5MW farm, second generation machine
- Phase 5 – 30MW farm, with machine performance improvements
- Phase 6 – 100MW farm, further optimised machine

Sensitivity analysis has been carried out for the Phase 6 farm to consider how the levels of power output, capital grant, and operating and maintenance (O&M) costs affect unit energy cost.

13.4 Inputs used in model

The following variable inputs were used (Table 19):

	Number of machines	Energy yield per machine (MWh/yr)	Total capital cost (£ millions)
Phase 2	1 x 150kW	150	1.87
Phase 3	1 x 150kW	225	1.37
Phase 4	10 X 500kW	873	15.35
Phase 5	60 x 500kW	1053	65.48
Phase 6	200 x 500kW	1200	127.14

Table 19

The methods used to calculate the energy yield and capital cost are given in Sections 12 and 13 and the Appendices.

The following constant inputs were used, not varying with the different development stages:

Capital grant	0%
Percentage of capital cost defrayed on installation of farm	95%
Operating and Maintenance costs	3% of capital cost, annually
Machine availability	95%
Discount rate	8%
Construction period	1 year
Operating life	25 years

Table 20

13.5 Results

The unit cost of energy production for the power outputs and costs for each of the different development stages was calculated from a DCF analysis over a 25-year operational period.

13.5.1 Baseline case

The cost model yielded the following unit cost of energy for the baseline inputs:

Phase	Installed capacity (MW)	Capital cost per MW installed (£m)	Annual energy production (MWh)	Unit cost of energy (p/kWh)
2	0.150	12.47	143	229.0
3	0.150	9.14	214	127.3
4	5	3.07	8294	22.2
5	30	2.18	57912	13.5
6	100	1.27	228000	6.7

Table 21

13.5.2 Sensitivity analysis

The cost model has been used to investigate the sensitivity of the unit cost of energy to changes in the following variables:

- Improvements in power output
- Operating & Maintenance costs as a proportion of initial capital expenditure
- Level of capital grant
- Discount rate

The results of the analysis are presented for the unit energy cost (p/kWh) for the 100MW Phase 6 farm (8% discount rate), as this represents the nearest stage to commercial exploitation that EB can reasonably project at this time:

Power Output			
-10%	**Baseline**	+10%	+20%
7.2	**6.7**	6.3	5.9
O&M costs (as percentage of initial capital cost)			
2%	**Baseline, 3%**	5%	10%
6.1	**6.7**	7.8	10.6
Level of capital grant			
	Baseline, 0%	10%	20%
	6.7	6.2	5.7
Discount rate			
5%	**Baseline, 8%**	10%	15%
5.5	**6.7**	7.5	9.9

Table 22

13.6 Discussion of results

The cost modelling provides a calculation for the unit cost of energy on the basis of assumptions made regarding the present and future costs of manufacture and operation, and the amount of energy captured by the Stingray machine. EB has generally taken a conservative approach in producing its estimates, and in basing outputs on known tidal and machine data from Yell Sound.

The starting point for predicting future cost is the outline design of a 500kW Stingray machine, for which a best estimate of the total cost of design, manufacture and installation has been added to the estimated costs of establishing, commissioning, operating and decommissioning a Stingray farm. The resulting unit cost of energy at this stage in the technology is 22p/kWh for a demonstrator farm with 5MW installed capacity.

The model then assumes some reasonable improvements in power output and reductions in cost as the technology is further developed with a resulting reduction in unit energy cost for the first 100MW farm to a figure of 6.7p kWh.

Given that it is not possible to unequivocally quantify a unit cost at which any electricity generator would be viable in future market conditions, it is important that Stingray demonstrates its potential by way of a steady progression in the reduction of unit energy cost with time. The cost modelling clearly demonstrates the potential for this reduction.

In terms of whether it is reasonable to expect the total cost of energy to fall to the necessary level, whatever that might end up being, it is sensible to consider the learning curve "progress rate" that might be required to produce the cost reductions. Figure 63 considers how the costs might change from the starting point of 22p/kWh for a 5MW farm for different progress rates.

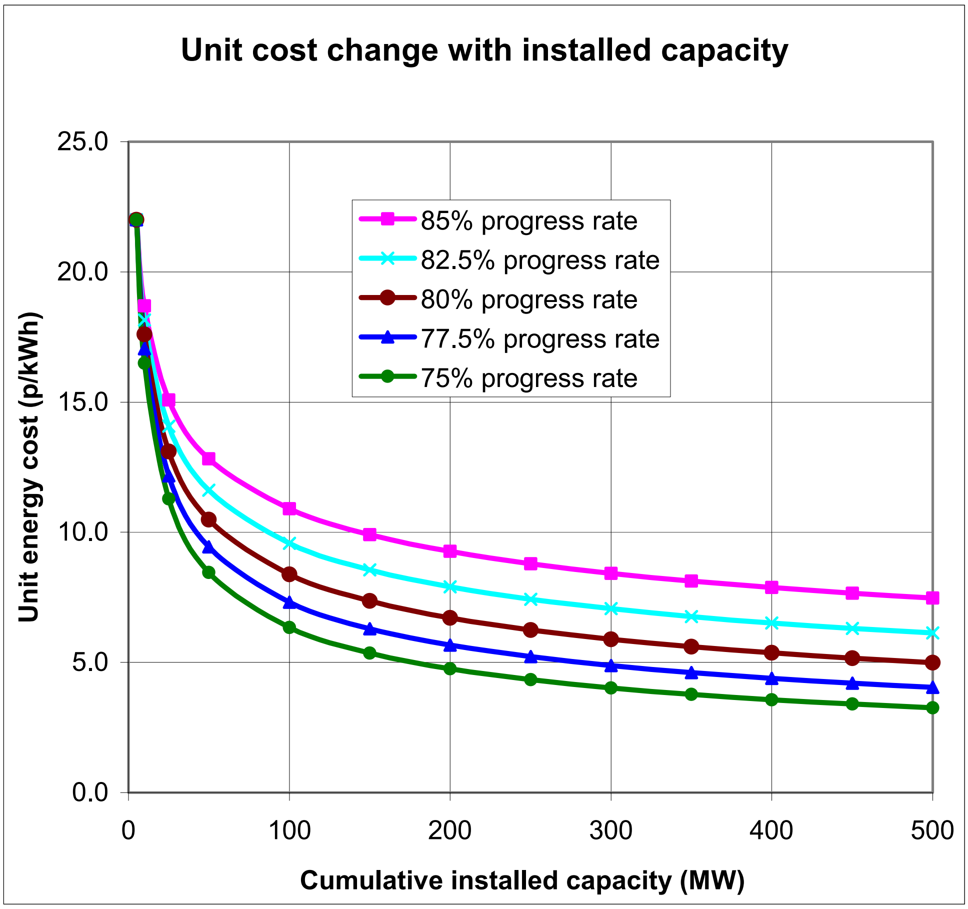

Figure 63

This graph illustrates that the progress rate to reach a unit cost of between 5p/kWh and 7p/kWh with 500MW of installed capacity is between 80% and 85%. This is not as ambitious as the developments actually achieved by wind power, where we already have over 40,000 MW of installed capacity (Source, EWEA). (At 85% progress rate, the unit cost from Stingray would drop to 2.7p/kWh at that level of capacity.)

Most importantly, it must be recognised that whilst time is a significant factor in reducing cost, the level of investment (reflected in the amount of installed capacity) is far more important.

In simple terms, the Stingray Phase 3 cost modelling can only be expected to provide an indication of future potential. Realising the potential for commercial viability is then contingent on the amount of time and investment committed. The Stingray technology is still immature and there should be no expectation at this stage of making a very rapid commercial return from electricity generation.

13.7 <u>Conclusions</u>

The aim of the cost modelling was to predict the unit energy cost on the basis of projections for the future output and costs of Stingray. The principal conclusions that the cost modelling supports are:

- The projected future cost of electricity produced by a 100MW farm is 6.7 p/kWh. This can be considered as economically viable given current projections for the price of electricity and value of ROCs.
- The results from the Phase 3 site testing indicate that the technology is capable of capturing significant levels of energy and converting this to saleable electricity.
- The baseline power output is based on a conservative analysis of machine performance and site characteristics. There is considerable potential for future increase.
- There is sufficient exploitable resource to provide a potential market for Stingray in the UK.
- The cost model is based on a detailed breakdown of all cost elements involved.
- There is independent justification for the cost reductions anticipated for future Stingray farms.
- There is strong evidence that Stingray can generate electricity at a potentially commercially viable unit energy cost.

14 DTI TARGETS

At the outset of the 2003 test program, specific targets were agreed with the DTI WAPTAP panel. These targets are reviewed here.

14.1 Peak To Mean Power

Target: The time average of the mean power produced over an operating cycle is to be greater than half the value of measured instantaneous peak power (based on a data logging frequency of approximately 10 measurements per second).

Performance: Assuming that the target was intended to refer to 'machine operating cycle' rather than 'tidal operating cycle' it should be attainable on the evidence available (a number of half cycles show a gross peak to mean ratio of 2:1).

14.2 Automatic Control at Specific Cycle Times

Target: Automatic control of the machine to allow continuous operation over a 10-minute period with cycle times not greater than:

23 secs. @ 1.25 m/s average tidal speed measured at the machine

21 secs. @ 1.5 m/s average tidal speed measured at the machine

20 secs. @ 1.75 m/s average tidal speed measured at the machine

19 secs. @ 2.00 m/s average tidal speed measured at the machine

Performance: Strictly speaking these targets were not met, however their relevance is diluted given that the longer cycle times achieved yielded more power than predicted. Hence there is reasonable confidence that the implications to power generation are not adverse. The key design implication is the need for review of actuation provision.

14.3 Automatic Control

Target: Continuous operation using automatic control for at least 3 hours per 12.5 hour tidal cycle on at least one occasion.

Performance: In the later stages of test work the machine operation whilst generating was generally automatic (ie no manual intervention) in terms of hydroplane and arm control. The only essential operator action was to periodically update the tide speed reading in the PLC – automating this is only a question of sorting out some communication difficulties between the current measurement equipment and the PLC.

14.4 Average Hydraulic Power at Specific Tide Speeds

Target: The average hydraulic power measured at the motor over a 30-minute period of continuous operation to be:

45 kW @ 1.5 m/s average tidal speed measured at the machine

60 kW @ 1.75 m/s average tidal speed measured at the machine

75 kW @ 2.0 m/s average tidal speed measured at the machine

Performance: Table 23 demonstrates how the cycles achieved compare against these targets. Clearly single cycles easily exceed the targets set, however these were only maintained for short periods due to issues with the actuation system discussed previously. There is no reason why these higher power cycles should not be maintained consistently over longer time periods given suitable revisions to the actuation system. Even with the longer cycle times which were maintained over the required half-hour period two of the three targets were met or exceeded and the third was within 87% of the target level.

Tide Speed	Best Cycle		Best Down-stroke (Gravity adjusted)		Longer Timescale Power Averages		DTI Targets
	Cycle Time	Average Power	Cycle Time	Average Power	10 Min	½ Hour	½ Hour Average
1.5	29	60.2	28	70.0	42.1	39.0	45
1.75	29	88.4	20	103.2	73.4	59.7	60
2.0	24	117.5	23	116.7	85.3	85.4	75

Table 23

14.5 Total Hydraulic Energy Collection for 14 Tides

Target: The total energy collected (measured in terms of hydraulic pressure and flow at the motor) over a 14 tide cycle period of operation to be 2600kWh

Performance: The data collected on site clearly demonstrates that this target is easily attainable, however it was not fully attained due to minor machine reliability issues. The actual figure achieved in 14-tide cycle was 1963kWh (electrical) which included two tides with no generation and two to three tides with partial generation or relatively unfocussed tuning. Assessments of the hydraulic to electrical efficiency indicate that hydraulic power may be around 9% higher than electrical power so the total figure should increase to 2160kWh hydraulic.

14.6 Total Hydraulic Energy Collection for 56 Tides

Target: The total energy collected (measured in terms of hydraulic pressure and flow at the motor) over a 56 tide cycle period of operation to be 10,000kWh

Performance: This target was not achieved due to the limited time on site. However, the cumulative power results obtained clearly indicate that the machine is capable of comfortably exceeding the target given reliable operation over a 56 tide period.

14.7 Total Electrical Energy Collection for 56 Tides

Target: The total energy collected (measured in terms of input to the load bank) over a 56 tide cycle period of operation to be 8,000kWh.

Performance: This target was not met for two reasons:

1) The power at the load bank was not logged through the continuous operation period due to difficulties in finding and integrating suitable instrumentation.
2) The machine was not run for a 56-tide cycle due to the lack of development time on site.

In terms of proving the efficiency of the conversion from electrical power at the generator to electrical power at the load bank, some test work was conducted at the system FAT with load bank power measurement equipment in place. It may be possible to deduce this efficiency by analysis of the associated logged data but this has yet to be investigated. If this is not possible then further stand alone transmission tests on a suitable test rig set up should deliver results with a high level of confidence.

14.8 Tidal Current Measurement

Target: Current velocity upstream and downstream of the machine measured continuously and simultaneously for at least 15 minutes with the machine operating at steady cycle times of 23, 21, 19 seconds.

Performance: All current measurement data collected was at longer cycle times hence, following the exact wording, the target was not met. There is however, enough data to give an indication of tidal speed slowing effects due to machine power extraction at a range of operating conditions and this was the broader aim of the target.

14.9 Conversion Efficiency

Target: Drive power conversion efficiency to be measured/calculated for a range of input powers and waveforms that represent the output from the Stingray generator.

Performance: The conversion efficiency from hydraulic power at the motor to electrical power at the generator has been clearly demonstrated. Conversion efficiency beyond this point (through the variable speed drive to the resistor load bank) was not demonstrated during on site testing, however analysis of data collected during the factory acceptance tests indicates that it is in line with expectations.

14.10 Validation of Performance Model / Production of Cost Model

Target: The performance model to be validated against measured experimental data and then used to predict the performance of the next generation of Stingray devices.

A transparent, robust and detailed cost model is produced and used to evaluate the cost and resulting unit energy cost of energy from future Stingray devices.

Performance: As has been demonstrated in Section 11, the mathematical (performance) model has been validated against the recorded test data. A detailed cost model has been produced (Sections 12 and 13), using performance predictions for future generations of Stingray, output from the mathematical model, as one of the inputs to evaluate the unit energy cost.

14.11 Unit Energy Cost

Target: The above models should indicate that a commercial Stingray farm could profitably sell electricity to the grid assuming current electricity prices, current renewable energy support mechanisms and current commercially available cost of finance, from sites where the peak tidal velocity during a mean spring tide is not more than 3.0m/s.

Performance: As has been demonstrated in Sections 12 and 13, the cost model predicts that electricity can be generated at a potentially viable unit energy cost once over 100MW of Stingray capacity has been installed.

14.12 Environmental Impact

Target: Post-decommissioning site survey demonstrates no significant environmental impact

Performance: The operational monitoring and post-decommissioning surveys have been independently reviewed by Entec UK. Entec concluded "concurrent with the conclusions of the original assessment, impacts of the Stingray device demonstration phase – where assessed – were minimal and/or temporary". It can therefore be concluded that this target has been achieved in its entirety.

14.13 Summary of Compliance with DTI Targets

To summarise the level of compliance with the targets, Table 24 gives an assessment of how the on site test work measures against them when considering the exact target wording, the broader aims of the target and the demonstrated potential of the machine to achieve the target.

Target	Estimated Degree of Compliance		
	Exact Wording	Broad Aims	Potentially
Peak to Mean Power	0%	80%	100%
Automatic control at specific cycle times	0%	0%	-
Automatic control with Self Start Stop	0%	75%	100%
Average Hydraulic Power at Specific Tide Speeds	67%	67%	100%

Target	Estimated Degree of Compliance		
	Exact Wording	Broad Aims	Potentially
Total Hydraulic Energy Collection for 14 Tides	83%	83%	100%
Total Hydraulic Energy Collection for 56 Tides	0%	20%	100%
Total Electrical Energy Collection for 56 Tides	0%	0%	100%
Tidal Current Measurement	0%	80%	100%
Conversion Efficiency	90%	90%	100%
Mathematical and Cost Models	100%	100%	100%
Unit Energy Cost	100%	100%	100%
Environmental Impact	100%	100%	100%
Total level of compliance with technical targets	45%	66%	92%

Table 24

14.14 Summary of Performance Against Targets & Assumptions

- On average, the best cycles and half cycles achieved generate about 66% and 77% of the power levels assumed in the economic model.
- The actual performance of the machine exceeds the assumptions of the economic model if like for like cycle times are considered.
- There may be reasonable grounds for increasing the estimates of machine power capture used in the economic model.
- The match between actuation power assumed in the economic model and the power consumed in the actual cycles achieved is not good – this area requires further analysis and possibly test work to demonstrate a clear understanding of the relationships involved.
- Power generation against the DTI targets for specific tide speeds looks promising, particularly considering the longer than anticipated cycle times.
- Following the exact wording of the DTI technical targets, around 45% of the stated aims have clearly been achieved. If the broader meaning of the aims is considered then it is arguable that this figure should rise to 66%.
- The data collected on site gives sufficient confidence to indicate that 100% compliance with all targets that remain relevant is feasible with the Stingray technology.

15 CONCLUSIONS

The test programme and subsequent analysis demonstrates that:

- Electricity can be generated through the oscillation of hydroplanes in a moving fluid.
- Basic Machine Characteristics – Brief testing was conducted to confirm the basic machine characteristics such as hydroplane performance and added mass. The results were found to be in reasonable agreement with previous test work.
- Power Cycle Development – Significant gains were made on the levels achieved in 2002, with further gains clearly available. Full cycle times of 24 seconds in a 2 m/s current provided an average hydraulic power output of 117.5 kW. Control through the cycle still remains the key issue particularly as regards the introduction of the high actuation flows required for faster cycle times.
- Actuation power consumption – This was higher than expected at the cycle times achieved although much of the reason for this lies in poor control and significant efficiency gains should be realisable once this area is improved.
- Overall Power Collection – Cumulative energy collection through the course of a tide was demonstrated on several occasions. A continuous operation period over 14 tides was also attempted – the levels of power collected would have been in excess of target values but machine downtime due to minor failures prevented operation on some of the tides.
- Current data analysis and interaction with the tidal environment – Useful data on the interaction of Stingray with the tidal environment
- Review against DTI targets – Although complete compliance with the targets set by the DTI was at a lower level than would have been hoped, the broader aims were met in the majority of cases. There is evidence to suggest that the technology is capable of full compliance with all targets that remain relevant.
- Review against economic model assumptions – The on-site performance compares well with the assumptions used in the economic model. One particular area of encouragement is that the levels of power generated at specific cycle times and current speeds actually exceed expectations, suggesting there may be a case for taking a more optimistic view.
- Review against mathematical model assumptions – Initial comparisons with the mathematical model indicate that there is a reasonable match where the machine cycles do not include significant stalling of the hydroplane. If cycles including stall are to be considered then a representation of transient hydrodynamics will have to be introduced to allow the model to accurately reproduce the performance.
- Marine operations can be undertaken in a safe, efficient and cost-effective manner

- Interim studies indicate that Stingray has no discernible impact on its surrounding marine and coastal environment
- The technology can be fully developed to exploit the resource effectively.
- Sites exist where the technology can be effectively operated.
- Identifying, commissioning, operating and decommissioning ocean energy test sites can be effectively and efficiently carried out within a demonstration project.

Areas where significant performance improvements can be made have been identified – particularly in control, cycle time and actuation power. Although the demonstrator is far from a commercial system, the lessons learned from it and our existing supply-chain experience, have enabled us to design and cost a second generation concept, and develop cost models reflecting the experience-curve improvements for this and subsequent systems. These bring the critical unit energy cost down from high levels for the demonstrator, through 22p/kWh for a pre-commercial 5MW demonstration farm, to 6.7p/kWh for the first fully commercial system.

We have demonstrated that:

- Stingray technology is technically viable for the generation of electricity at a potentially commercially viable unit energy cost.
- Many viable sites exist for this technology (and the variable geometric configuration of Stingray ensures as wide as possible a range of sites can be considered viable)
- The system does not generate any significant environmental impacts
- If an optimistic view is taken of potential developments in harnessing the unsteady hydrodynamics, step-change improvements in energy capture beyond those already considered viable for the commercial systems are possible.

However, although EB understands that further investment is available to continue with Stingray development, there is no clear route to profitability in the next stage of the programme. This makes further development commercially unattractive to EB in the current climate.

16 ACKNOWLEDGMENTS

The keen support of many individuals and organisations has been essential for the realisation of Stingray, the worlds first operational full-scale tidal stream generator. First and foremost amongst these is the Department of Trade and Industry, without whose initial and continuing confidence and financial support the project could not have succeeded. The support of the New and Renewable Energy Centre in Blyth has also been crucial for Phase 3 and ongoing developments. The encouragement and pragmatism of the statutory consenting organisations, and all stakeholders, have enabled Stingray to be installed and operated in a manner with least environmental impact. Finally, but by no means least, the enthusiasm demonstrated by the project team, partners, contractors, and supporters, especially the people of Shetland, has been vital.

Appendix A

Example Total Energy Collection Spreadsheet

Source File: C133-03-total power 12.5.04 P4 Baseline

1. Power available in flow

Width 27.7 m

Height 19.1 m

rho 1025 kg/m^3

Swept area 529.07 m^2

Speed m/s	0	0.5	0.75	1.00	1.10	1.20	1.30	1.40	1.50	1.60
Power kW	0	34	114	271	361	469	596	744	915	1111
Speed m/s	1.70	1.80	1.90	2.00	2.10	2.20	2.30	2.40	2.50	--
Power kW	1332	1581	1860	2169	2511	2887	3299	3748	4237	--

2. Hydroplane Power from EB sinusoidal analysis

Excluding actuation power; 3 plane machine (Output from File C133-04-001)

EB calc kW	Speed m/s	Cycle sec	Improved output kW	Efficiency tide	Comment
95	1.00	29	105	39%	
119	1.10	27.6	131	36%	
147	1.20	26.3	162	35%	
179	1.30	25.1	197	33%	
214	1.40	24.2	235	32%	
252	1.50	23.3	277	30%	
295	1.60	22.5	325	29%	
340	1.70	21.8	374	28%	
389	1.80	21.2	428	27%	
443	1.90	20.6	487	26%	
500	2.00	20	500	23%	Capped at 500kW
500	2.10	20	500	20%	
500	2.20	20	500	17%	
500	2.30	20	500	15%	
500	2.40	20	500	13%	
500	2.50	20	500	12%	

3. Factor for imperfect control 95%

4. Factor for two hydroplanes 100% model assumes 3 planes

5. Factor for loss of lift -unsteady flow 100% dynamic effects may increase lift

Total 95%

6. Hydroplane power to drive aux hydraulics 4.0

(constant value based on C133-04-001.AMC)

7. Resulting hydroplane power

Speed m/s	cycle sec	Power kW	Efficiency tide
1.00	29	95	35%
1.10	27.6	120	33%
1.20	26.3	150	32%
1.30	25.1	183	31%
1.40	24.2	220	30%
1.50	23.3	259	28%
1.60	22.5	304	27%
1.70	21.8	351	26%
1.80	21.2	403	25%
1.90	20.6	459	25%
2.00	20	471	22%
2.10	20	471	19%
2.20	20	471	16%
2.30	20	471	14%
2.40	20	471	13%
2.50	20	471	11%

8. Hydraulic transmission losses

Before motor:	Cylinder	98%
	Pipework	99%
	Total	**97%**
Through Motor:	Motor Volumetric	95%
	Motor Mechanical	95%
	Total	**90.3%**
Overall Hydraulic		**88%**

9. Electric motor and drive losses

Motor	95%	
Drive	90%	
Total	**85.5%**	77.2% through hyd. motor and drive
TOTAL transmission efficiency	**74.9%**	

10. Electrical power out of the drive

Speed (m/s)	Cycle (sec)	Power (kW)	Efficiency / Machine	Efficiency / tide
1.00	29	71	68%	26%
1.10	27.6	90	69%	25%
1.20	26.3	112	69%	24%
1.30	25.1	137	70%	23%
1.40	24.2	164	70%	22%
1.50	23.3	194	70%	21%
1.60	22.5	228	70%	21%
1.70	21.8	263	70%	20%
1.80	21.2	301	70%	19%
1.90	20.6	344	71%	18%
2.00	20	353	71%	16%
2.10	20	353	71%	14%
2.20	20	353	71%	12%
2.30	20	353	71%	11%
2.40	20	353	71%	9%
2.50	20	353	71%	8%

11. Other Factors

DC bus losses to shore	99%	
Maintenance and repair	100%	in "availability"
Weather and wave effects	100%	in "availability"
Power consumed during standby and slack water	99%	
Power conditioning for grid connection	98%	
Total other factors	96.0%	

12 Effective power sold into the grid

Speed (m/s)	Cycle (sec)	Power (kW)	Efficiency / Machine	Efficiency / tide
1.00	29	69	66%	25%
1.10	27.6	87	66%	24%
1.20	26.3	108	67%	23%
1.30	25.1	132	67%	22%
1.40	24.2	158	67%	21%
1.50	23.3	186	67%	20%
1.60	22.5	219	67%	20%
1.70	21.8	253	68%	19%
1.80	21.2	289	68%	18%
1.90	20.6	330	68%	18%
2.00	20	339	68%	16%
2.10	20	339	68%	13%
2.20	20	339	68%	12%
2.30	20	339	68%	10%
2.40	20	339	68%	9%
2.50	20	339	68%	8%

13. Power collected over tide cycle

The efficiency figures calculated in Step 12 are interpolated to allow them to be used in relation to the calculated velocity occurrence (based on analysis undertaken by Robert Gordon University, described in the Stingray Phase 1 report, ETSU T/06/00211/00/REP, 2002).

from above	width	27.7	m
	height	19.1	m
	rho	1025	kg/m^3
	Swept area	529.07	m^2

Average Velocity	Velocity Occurrence FROM RGU Table 3, 13m deep	Energy Available Occurrence Watts-hrs 12.5 hrs	Efficiency	Energy Collected 12.5hrs kWatt-hrs	Average power kWatts	
0.125	0.1005	665	0.0%	0		
0.375	0.1135	20286	10.0%	2		
0.625	0.1307	108152	20.0%	22		
0.875	0.1636	371471	27.0%	100		
1.125	0.1589	766829	23.7%	182		
1.375	0.1377	1213274	21.5%	261		
1.625	0.0883	1284215	19.5%	250		
1.875	0.0534	1193059	18.0%	215		
2.125	0.0323	1050501	13.0%	137		
2.375	0.0118	535784	9.4%	50		
2.625	0.0043	263617	7.0%	18		
2.875	0.0017	136924	6.0%	8		
TOTAL	**0.9967**	**6,944,778**	17.9%	1,245	**100**	kW average
	Mwh/yr	**4867**	**365 days**	**872,719**	**873**	**MWh/yr**
			per m^2	**1,650**		

This value of 873 MWh/yr is carried forward to Stingray Discounted Cashflow Model (Appendix C, parameter f).

Appendix B

Example Total Farm Cost Spreadsheet

	Unit BOC	Farm BOC	Farm Labour	Total Farm Cost
Fabrications and Mechanical	£534,260	£4,006,950	£154,050	£4,161,000
Foundations	£356,000	£2,670,000	£31,800	£2,701,800
Hydraulics	£160,350	£1,202,625	£109,575	£1,312,200
Subsea Electrics	£43,300	£324,750	£88,125	£412,875
Subsea Drive	£104,750	£785,625	£99,150	£884,775
Topside Power and Control	£55,200	£414,000	£102,750	£516,750
Machine Build Costs	£183,000	£1,372,500	£177,000	£1,549,500
Handling System	£400,000	£400,000	£62,500	£462,500
Grid Connection	£79,200	£79,200	£15,850	£95,050
Farm Connecting Cables	£798,800	£798,800	£26,000	£824,800
Machine Installation	£1,358,000	£1,358,000	£24,450	£1,382,450
Machine Removal	£772,000	£772,000	£18,500	£790,500
Farm Project Management	£210,000	£210,000	£44,750	£254,750
Total	£5,054,860	£14,394,450	£954,500	£15,348,950
Annual Operating Costs	£230,000	£230,000	£67,000	£297,000
Annual Maintenance	£83,956	£83,956	£33,500	£117,456
Total	**£313,956**	**£313,956**	**£100,500**	**£414,456**

Notes

This is a summary of the detailed cost-breakdown worksheets used for the cost modelling. The detailed sheets contain information on suppliers, costs, labour rates and specific components and assemblies which is considered commercially sensitive.

BOC = Bought Out Costs

Farm-scale machine BOC includes a 0.75 multiplier to allow for economies of scale. Farm BOC does not include a multiplier, since they apply just once.

Manufacture labour and installation / recovery BOC allows for 3 phases of development. If all carried out in one phase, cost reductions would occur.

Total Farm Cost (£15,348,950) carried forward to Stingray Discounted Cashflow Model (Appendix C, parameter a).

Appendix C

Example Discounted Cash Flow Spreadsheet

Stingray cashflow model

Phase 4 - new 500kW machine, 5MW demonstrator farm (calc. only works @ 0% inflation)

Capital costs (£million)		
Installed cost (a)	15.350	Notes 2,
Cost per MW installed (b)	3.070	
capital grant % (c)	0.0%	Note 4
Capex on installation (d)	95.0%	

Pricing (£/MWh)		p/kWh
Electricity	300	30.00
ROCs	see Note 3	

NPVs (£,000) @ Discount rate of	Pre-tax	Post-tax	UNIT COST (p/kWh) (m)
0%	35,338.8	24,894.7	12.96
5%	13,111.5	8,704.0	18.22
8% (l)	6,434.3	3,791.1	22.15
10%	3,409.8	1,549.8	25.02
15%	(1,303.9)	(1,977.4)	32.80

Inflation	
Price inflation	0.0%
Cost inflation	0.0%

Operating & Maintenance costs	
Percentage of installed capital cost (e)	3.0%
Annual O&M cost (£,000/yr)	461

Output efficiency (%)		
Delivered Output per machine (MWh/yr) (f)	873	Note 1
Capacity Factor (g)	19.9%	
Availability (h)	95%	
Annual farm production (MWh) (i)	8,294	

Tax	
CT rate	30%
WDA rate	25%

Indicators		
Capex	£/GWh/yr	1,758.3
Opex	£/MWh	55.5

Capacity (MW)	
Nominal device capacity (j)	0.5
Number of devices (k)	10
TOTAL installed capacity (MW)	5

Notes

1. Outputs from "C133-03/WAPTAP/total power 12.05.04"

2. costs from "C133-03-stingray 500kW, Phase 4, 19.05.04"

3. ROC value not used in calculating "unit energy cost"

4. Capital grant is on percentage of costs incurred on installation

Year	Production (MWh)	Electricity price	ROCs price (see Note 3)	Revenue in £,000,s	Capital cost in £,000,s	Operating cost in £,000,s	Net cashflow in £,000,s	Taxable profit	CT payable	Post-tax cashflow in £,000,s	Post tax IRR
1 (n)		300.0	48.0	-	14,582.5	-	(14,582.5)	(3,645.6)	(1,093.7)	(13,488.8)	
2	8,293.5	300.0	47.0	2,488.1	-	460.5	2,027.6	(706.7)	(212.0)	2,239.6	-83%
3	8,293.5	300.0	47.0	2,488.1	-	460.5	2,027.6	(23.1)	(6.9)	2,034.5	-52%
4	8,293.5	300.0	54.0	2,488.1	-	460.5	2,027.6	489.6	146.9	1,880.7	-32%
5	8,293.5	300.0	62.0	2,488.1	-	460.5	2,027.6	874.1	262.2	1,765.3	-19%
6	8,293.5	300.0	66.0	2,488.1	-	460.5	2,027.6	1,162.4	348.7	1,678.8	-11%
7	8,293.5	300.0	63.4	2,488.1	-	460.5	2,027.6	1,378.7	413.6	1,613.9	-5%
8	8,293.5	300.0	60.9	2,488.1	-	460.5	2,027.6	1,540.9	462.3	1,565.3	-1%
9	8,293.5	300.0	58.3	2,488.1	-	460.5	2,027.6	1,662.6	498.8	1,528.8	1%
10	8,293.5	300.0	55.8	2,488.1	-	460.5	2,027.6	1,753.8	526.1	1,501.4	4%
11	8,293.5	300.0	53.2	2,488.1	-	460.5	2,027.6	1,822.3	546.7	1,480.9	5%
12	8,293.5	300.0	50.6	2,488.1	-	460.5	2,027.6	1,873.6	562.1	1,465.5	6%
13	8,293.5	300.0	48.1	2,488.1	-	460.5	2,027.6	1,912.1	573.6	1,453.9	7%
14	8,293.5	300.0	45.5	2,488.1	-	460.5	2,027.6	1,940.9	582.3	1,445.3	8%
15	8,293.5	300.0	42.9	2,488.1	-	460.5	2,027.6	1,962.6	588.8	1,438.8	9%
16	8,293.5	300.0	40.4	2,488.1	-	460.5	2,027.6	1,978.8	593.6	1,433.9	9%
17	8,293.5	300.0	41.2	2,488.1	-	460.5	2,027.6	1,991.0	597.3	1,430.2	10%
18	8,293.5	300.0	42.0	2,488.1	-	460.5	2,027.6	2,000.1	600.0	1,427.5	10%
19	8,293.5	300.0	42.8	2,488.1	-	460.5	2,027.6	2,007.0	602.1	1,425.5	11%
20	8,293.5	300.0	43.7	2,488.1	-	460.5	2,027.6	2,012.1	603.6	1,423.9	11%
21	8,293.5	300.0	44.6	2,488.1	-	460.5	2,027.6	2,016.0	604.8	1,422.8	11%
22	8,293.5	300.0	45.5	2,488.1	-	460.5	2,027.6	1,827.0	548.1	1,479.4	11%
23	8,293.5	300.0	46.4	2,488.1	-	460.5	2,027.6	1,877.1	563.1	1,464.4	11%

Year	Production (MWh)	Electricity price	ROCs price (see Note 3)	Revenue in £,000,s	Capital cost in £,000,s	Operating cost in £,000,s	Net cashflow in £,000,s	Taxable profit	CT payable	Post-tax cashflow in £,000,s	Post tax IRR
	8,293.5		46.4	2,488.1	-		2,027.6	1,877.1			
24	8,293.5	300.0	47.3	2,488.1	-	460.5	2,027.6	1,914.7	574.4	1,453.1	12%
25 (o)	8,293.5	300.0	48.3	2,488.1	-	460.5	2,027.6	1,942.9	582.9	1,444.7	12%
26	8,293.5	300.0	49.2	2,488.1	767.5	460.5	1,260.1	1,772.2	531.7	728.4	12%
27		300.0	50.2	-	-	-	-	(191.5)	(57.4)	57.4	12%
28		300.0	51.2	-	-	-	-	(143.6)	(43.1)	43.1	12%
29		300.0	-	-	-	-	-	(107.7)	(32.3)	32.3	12%
30		300.0	-	-	-	-	-	(80.8)	(24.2)	24.2	11.8%
Total	207,337.5			62,201.3	15,350.0	11,512.5					
NPV	88,531.3			24,592.0	14,694.6	4,915.7	6,949.1	9,515.8	2,854.7	4,094.3	
					19,610.3		6,434.33	8,810.90	2,643.27	3,791.06	