4 PRODUCTION (MANUFACTURE AND ASSEMBLY)

4.1 Fabrication

4.1.1 Steelwork fabrication

As different phases of the design reached completion, production (fabrication, painting and assembly) started, with the first order being placed in April 2002. The main supporting frame steelwork (base and post) was completed by May 2002, with the hydroplane root structure and base feet complete in June.

Fabrication progress is illustrated in the attached photographs of the pivot post assembly (Figure 15, Figure 16, Figure 17 and Figure 18), base (Figure 19and Figure 20), foot (Figure 21) and brace (Figure 22).

Figure 15: Main Pivot Assembly

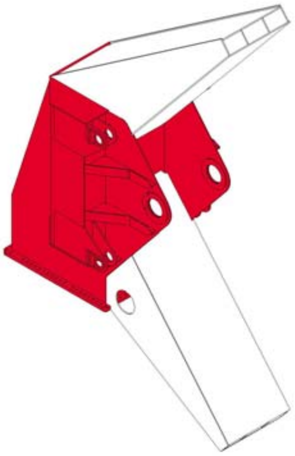


Figure 16: Bump Stop Support

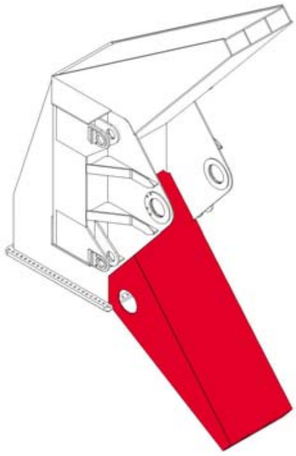


Figure 17: Pivot Post Assembly

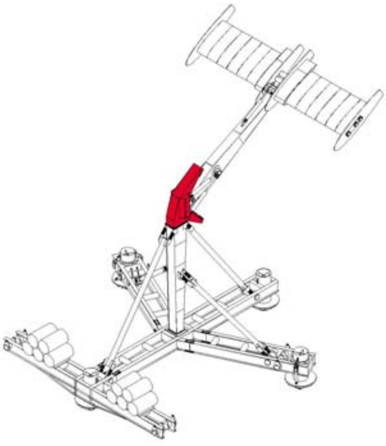


Figure 18: Pivot Post Lower Section

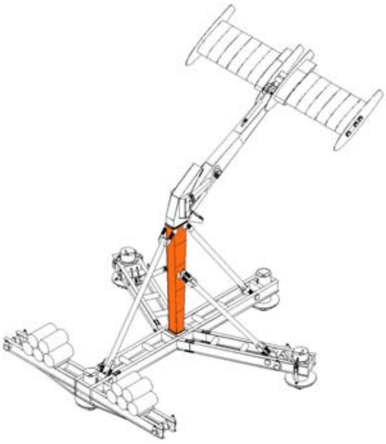


Figure 19: Main Base Fabrication Front Section

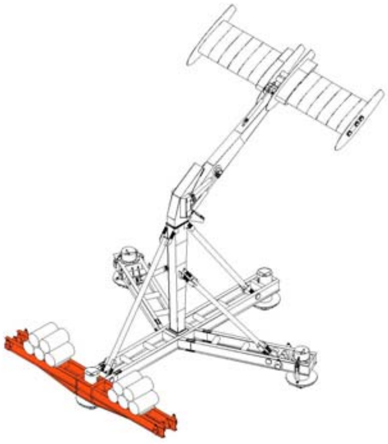


Figure 20: Main Base Fabrication

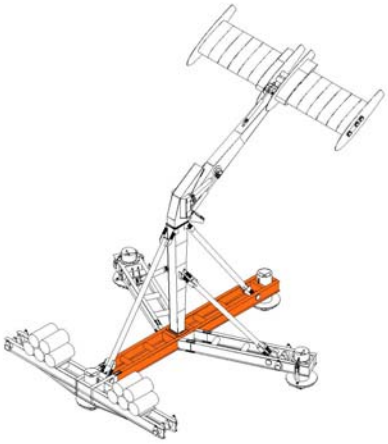
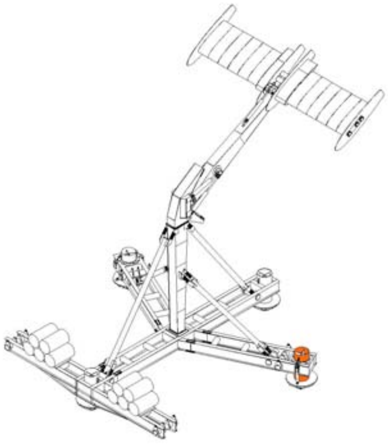


Figure 21: Foot Assembly



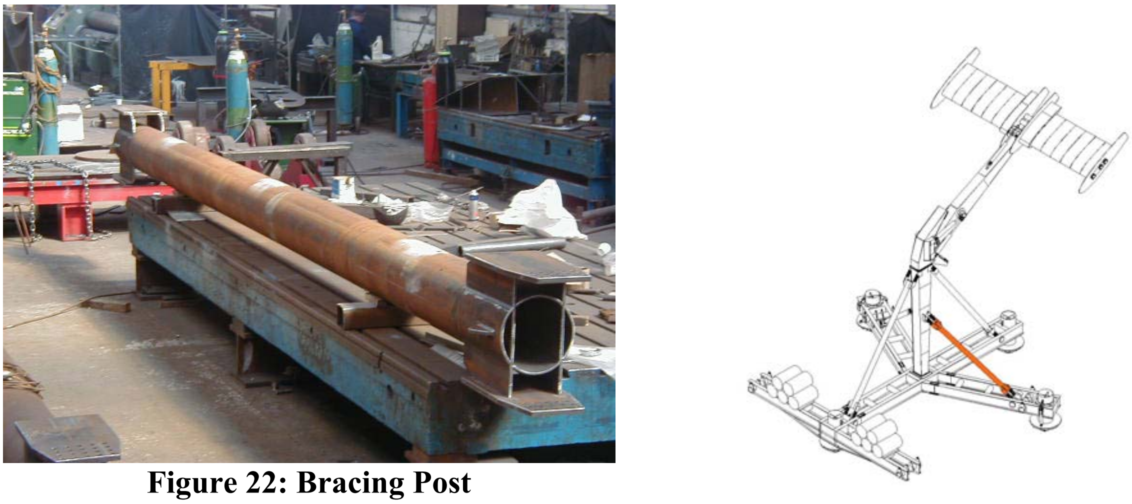


Figure 22: Bracing Post

4.1.2 Painting

The painting order was placed in May 2002, such that, as steel components became available, they were shot-blasted (starting in May) and painted before delivery (in June) to the Amec Howdon Supply Base on the River Tyne for assembly.

4.1.3 GRP hydroplane fabrication

The design for the hydroplane comprised a steel root structure onto which slotted pre-formed foam-filled GRP hydroplane sections. Steel and wooden (glued marine plywood) end-plates were also included.

4.2 Stingray Assembly

The size of the Stingray structure was such that the existing EB workshop facilities could not be used for the main assembly. An order was therefore placed in early June for use of the Amec Howdon Supply Base. The first parts were delivered from the paintshop on 5th June, with the preliminary assembly completed by June 18th. Stingray assembly (Figure 23) was undertaken by EB personnel, with welding by local fabricators and additional assistance provided by Amec, as required.

An Open Day was held on June 18th (Figure 24 and Figure 25). This was attended by over 120 guests, with Stingray formally ‘launched’ by Mr Brian Wilson, MP, Minister of State for Energy and Construction.

After the Open Day, the hydroplane and main arm were removed to allow installation system load testing and wet tests to take place. Stingray was then disassembled and sea fastened to the barge for transport to Shetland at the end of June.

Figure 23: Stingray base part assembled

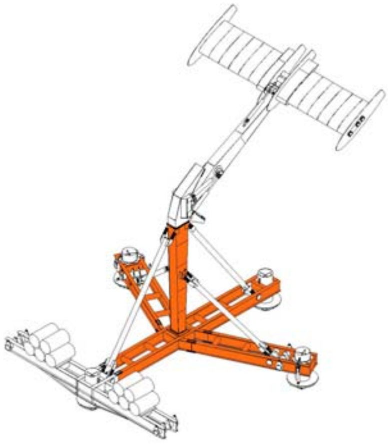


Figure 24: Stingray assembled for Open Day

Figure 25: Brian Wilson and the Stingray Project Team

4.3 <u>Factory Acceptance Tests</u>

Factory acceptance tests (FATs) are required to ensure that the manufactured equipment (in this case, Stingray) can be safely assembled and operated and fulfils the design brief. For equipment such as a winch, this could take the form of a load test. However, Stingray, by its nature, could not have its core function tested until it is present in a tidal stream. Therefore a number of tests were undertaken on the key components to ensure fabrication and assembly met the design requirements. The FAT did not cover calibration of the final system – that was part of the commissioning process. The scope of the tests included ensuring that all bolts fitted their holes, pins fitted their linkages, cylinders could be stroked, electrical systems could communicate, etc.

4.4 Deployment System

4.4.1 Installation Options

A number of installation options were considered during the Phase 1 project, including existing tried-and-tested technologies such as jack-up rigs, barge-mounted systems using technology transfer from existing EB systems, and new innovations. After thorough review, it was considered that the existing systems were too expensive for a low-cost demonstration project, the new innovations were impractical, and that the optimum solution would be to use EBs strong experience in deployment systems, developed in the submarine telecommunications and oil and gas industries, to develop a simple, cost-effective barge-mounted system with as wide an operating window as possible.

A concept design, incorporating a strand-jack lift system operating through a frame of lift beams was identified (Figure 26 and Figure 27).

Figure 26: Strandjacks

Figure 27: Strandjacks

A key component of the installation system is the barge, therefore this was selected with care.

4.4.2 Vessel Specification and Selection

An early stage of the Phase 2 contract reviewed available vessels and installation contractors. At the end of this process, the Harry McGill barge, owned and operated by Briggs Marine Contractors, was selected for use as the installation vessel for Stingray. The main factors leading to its selection were:

- The barge was of sufficient size (approximately 20m by 40m)
- Existing facilities, such as crane / mooring winches, reduced conversion requirements (Figure 28).
- Existing day accommodation facilities, coupled with a well laid out bridge (Figure 29), would aid successful operations.
- The owner / operators (Briggs Marine Contractors) are experienced marine contractors.
- The location of the vessel in Fife resulted in smaller mobilisation fees compared with other suitable vessels located in Norway and Holland.
- Competitive charter rates

An inspection visit was carried out in February 2002 at the Briggs facilities at Burntisland. Layout information was obtained to allow preliminary design to be undertaken to confirm the vessel suitability.

Figure 28: Harry McGill Deck showing crane and mooring winches

Figure 29: Harry McGill Bridge

4.4.3 Preliminary Design

Based on the data acquired during the inspection, a preliminary design of the lifting system was undertaken. A design review of the stability of the barge during lifting operations was commissioned from the naval architects Armstrong Technology Associates. This confirmed that, with minor modification, the barge would be stable when operating with the lift system and Stingray in place.

On confirmation of the suitability of the barge, a formal request was made to Briggs at the end of May 2002 for a proposal for marine operations, resulting in a Charter Party Agreement being put in place. Once the Stingray design had been finalised, the lift system and barge modification designs were completed.

4.4.4 Barge Conversion

The barge arrived at the Amec yard on 10th June 2002, with conversion work commencing immediately. This included strengthening the vessel and fitting the strandjack-based lifting system. The barge conversion work was undertaken by a local contractor, under the supervision of EB and Briggs Marine. The lifting frame assembly was fabricated and painted in the North East before being delivered to Amec in mid-June.

When all the lift gear components had been procured or fabricated, they were assembled and installed on the barge moored alongside the Amec yard on Tyneside to enable a lift test to be undertaken on July 1st 2002.

4.4.5 System Testing

The load test (Figure 30, Figure 31, Figure 32 and Figure 33) was undertaken to lower, and recover, the equivalent weight of Stingray (180 tonnes) plus an applied safety factor. Although the full Stingray assembly was not deployed, the additional weight was made up using ballast blocks. Static load testing of the strand-jack system held 192 tonnes. The dynamic load test, however, only achieved 165 tonnes. This was less than required, and was traced to excessive friction in the bearings on the lift beams. A review of this element and its operation remedied the problem. The load tests were witnessed by an independent surveyor from DNV.

Figure 30: Crane support until strand jacks take up the load

Figure 31: The Static Load Test

Figure 32: Ballast being loaded onto the Stingray assembly

Figure 33: The strand jacks in operation

4.4.6 Sea Fastening

Once Stingray had completed fabrication, assembly and FATs, it was disassembled to allow packing onto the barge deck for transit. The design of this layout and seafastening (Figure 34) was subject to a review of the barge stability in transit by the naval architects and then certification by DNV. The vessel left the Tyne, under tow from the Forth Drummer tug, on 17th July 2002 (Figure 35).

Figure 34: Final Sea Fastenings

Figure 35: Leaving the Tyne

4.5 Reassembly and Commissioning

A faster than expected passage saw the barges arrival at the Shetland Islands Council (SIC) Tug Jetty at Sella Ness on Saturday 20th July. The Briggs construction vessel, Forth Constructor, was already present to assist with reassembly operations and the installation of the moorings (Figure 36).

Figure 36: Briggs vessels on Tug Jetty, Sella Ness (Forth Constructor foreground left, Harry McGill with Stingray components foreground right, Forth Drummer background).

Limitations on the maximum crane size available on Shetland meant that only partial assembly was possible, since a 36 tonne lift was the maximum allowable over the required 16m radius.

Once the main base elements (base frame, main post and fore and aft braces) had been assembled on the Construction Jetty, they were lifted into position and suspended from the lift beams on the stern of the Harry McGill barge. The remainder of the assembly was completed suspended off the stern of the barge (Figure 37 - 42). While Stingray was being reassembled, the Forth Constructor installed the moorings at the Yell Sound site.


Figure 37: Unloading Stingray components at Construction Jetty


Figure 38: First mooring anchor assembled on Forth Constructor


Figure 39: Base assembly suspended from lift beams (photo courtesy of BP)


Figure 40: Base assembly suspended from lift beams (photo courtesy of BP)


Figure 41: Base assembly suspended from lift beams (photo courtesy of BP)


Figure 42: Base assembly suspended from lift beams (photo courtesy of BP)

Stingray was fully assembled by 5th August 2002. Basic commissioning of the hydraulic and electrical systems was then undertaken. This was to be followed by a wet test (testing the lift system and the subsea functions). Once all commissioning was complete, the barge and Stingray would be towed to the moorings on Yell Sound, from which full installation could then be undertaken. Once installed, operation was to follow a pre-defined test plan.

5 MARINE OPERATIONS

5.1 Installation

The Harry McGill (carrying Stingray) left the Construction Jetty, towed by the tug Forth Drummer (with a Pilot onboard) at 0230 on Wednesday 7th August. The Delta Marine vessel Voe Venture was in attendance to assist. The vessels arrived at the moorings approximately 2 hours later and were able to pick up three of the four moorings at and just after slack water. However, as the flood tide developed, the fourth mooring was unable to be picked up due to the strength of the current. This final mooring was picked up at the next slack water at approximately 1030. The Shetland Islands Council Pollution Control helicopter overflew the site during the morning to photograph the deployment (Figure 43 and Figure 44).

Figure 43: Stingray on the Harry McGill, attended by the Forth Drummer (photo courtesy of SIC)

Figure 44: Stingray on the Harry McGill, attended by the Forth Drummer (photo courtesy of SIC)

The barge was moored on station on 7th August (Figure 45 and Figure 46), with the intention of deploying Stingray at the earliest opportunity. Some work was still required on Stingray and the deployment system before installation could take place.

On August 13th a review of the general situation was undertaken by the site team. This led to a decision being made to return to the Construction Jetty to allow final modifications to be completed more effectively and for the project team and partners, such as the marine contractor, to review operations. The tug, barge and Stingray returned to the Construction Jetty during the night of Wednesday 14th August.

Figure 45: Effect of tidal current on mooring buoy

Figure 46: Strong tidal current passing Stingray on moorings

With the tug, barge and Stingray still moored alongside the Construction Jetty, work continued on the strand jack systems, the pod, accumulators, hydraulics and electric / control (Figure 47 and Figure 48). Hydroplane actuation testing was performed. Revision of all operating procedures and safety systems on the barge and Stingray was undertaken in light of the conditions experienced while on the moorings.

Friday 23rd saw a visit by Scottish Executive Deputy Environment Minister. A visit to the Construction Jetty and moorings by representatives of the DTI, ETSU, SIC, RGU and EB took place on Wednesday 28th / Thursday 29th (Figure 49).

Stingray was brought to a state of readiness such that, weather permitting, it could be returned to the moorings on Saturday 31st August and deployed on the neap tide of Sunday 1st September.

Figure 47: Working on the drive interfaces in the Control Cabin

Figure 48: Working on the pod

Figure 49: DTI, ETSU and SIC visiting Stingray

However, having brought Stingray and the installation system to the state of readiness required for deployment during the neap tide window of 1st and 2nd September, the decision was taken to abandon the installation attempt due to winds up to gale force being forecast for that period. Restrictions on the mooring system were that the barge had to leave the moorings and return to port in winds exceeding Beaufort Force 8, and that Stingray could not be installed in currents exceeding 2.9knots. The decision not to deploy was vindicated by the extreme weather conditions of the following days.

A full launch and recovery test was undertaken on 2nd September, using the strand jack system to lower Stingray through 9m to approximately 1m above the seabed while moored alongside the Construction Jetty (Figure 50 - 55). During the test the main lift beams (the black beams on the stern of the barge) worked well, with the main rollers operating effectively in both directions. Weather dropped from Force 8 to a virtual calm in about 3 hours. Unfortunately, by that time, the window of suitably slow currents had passed until the next neap tide around September 14th.

Figure 50: Deployment test underway

Figure 51: Current meter in position

Figure 52: Deployment test underway

Figure 53: Video camera mount

Figure 54: Recovery almost complete

Figure 55: Ballast, pod and accumulators visible on recovery

This initial trial was followed, on subsequent days, by other alongside tests and deployment practices. The hydroplane control system was tested in air to assess its performance characteristics.

A series of controlled tests aimed at gaining data on various aspects of the machine characteristics were run. In particular these investigated:

- Moving the hydroplane in a series of steps through its full range of movement in both directions - aimed at determining the static loads due to gravity
- Moving the hydroplane at a range of fixed speeds - will allow us to quantify speed dependent rotational drag.
- Accelerating the hydroplane with step torque inputs - should allow assessment of rotational added mass effects.
- Move arm in series of steps through full range of movement - same aim as 1 but for complete arm hydroplane assembly.
- Moving the arm at a series of fixed speeds with the hydroplane held fixed - quantifies rotational drag of whole assembly etc.
- Accelerating the arm assembly - allows assessment of the added mass of the complete assembly. Also allows effect of hydroplane mass and added mass on hydroplane rotation about its pivot to be looked at.
- Items 3 to 6 were repeated for a range of hydroplane angles - the data should allow us to see how the added mass and drag change as a result.

5.2 Marine Operations

The Harry McGill was towed to site by the Forth Drummer, leaving the Construction Jetty at 4am on September 12th. They were met on site by the Forth Fighter construction vessel to assist with installation. A fifth anchor was installed on arrival at the site. Forecasts obtained on the morning of 13th September for the next two days indicated winds of Force 2-3, WNW to NNE, such that a launch could be attempted. On that afternoon, Stingray was deployed to the seabed, in 30m of water, in 2 hours.

Once Stingray was on the seabed, the lift system was made secure and control systems checked. On site testing commenced later that evening. The tests undertaken over the following days investigated:

- Arm steady state and torque impulse at slack water (hydroplane 0 degrees)
- Response to step hydroplane input
- Manual power cycle
- Static loads, varying arm angles, varying hydroplane angle, different current speeds
- Hydroplane lift, varying arm angles, varying hydroplane angles, different current speeds
- Open loop hydroplane lift – range of hydroplane angles
- Initial angle of attack / sinusoidal cycle control
- Power cycle development

- Arm torque impulse
- Hydroplane lift sweep

For the tests, Stingray was controlled through the control screen situated on the bridge of the Harry McGill (Figure 56). All onboard sensors, including the subsea video camera, could be accessed through this screen, as can be seen below:

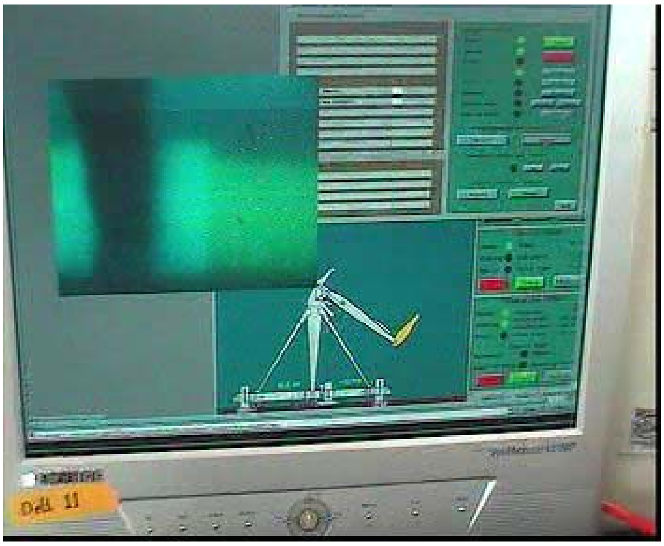


Figure 56: Stingray control screen, with subsea video of hydroplane

On 16th September a recovery and reinstallation was undertaken to investigate a sensor indication of a small amount of water ingress into the pod and to test the deployment system in a controlled manner, before any forced recovery might be required. The recovery sequence is illustrated in Figure 57 - 62.

Figure 57: Stingray post-top breaks surface, with Forth Fighter in background

Figure 58: Stingray post-top breaks surface

Figure 59: ADCP surfaces

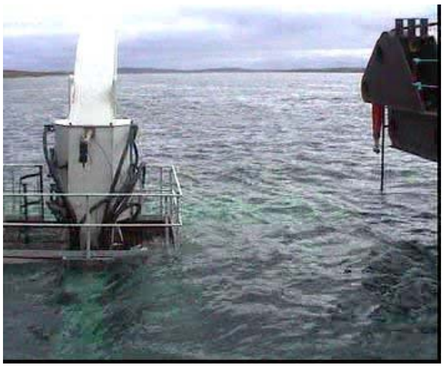


Figure 60:Upper platform appears

Figure 61: Hydroplane breaks surface

Figure 62: Pod visible

The marine operations were ended by the recovery on 25th September 2002. Although the operating period had been relatively short (12 days), a great quantity of data had been obtained for analysis. It was noted that, while permissions were in place to maintain the barge on station until mid-October, it would then have to be moved off station and Stingray either removed, left on the seabed and operated from onshore control facilities via a subsea cable, or left on the seabed in a locked down position with no subsea cable or control system (and essentially just wet stored) until the following Spring. Although planning permission for the onshore facilities had finally been obtained mid-September, the onshore control facilities and submarine cable could not be in place in time to allow initial onshore control to be undertaken while the barge was still on station. It was therefore decided that, since onshore control would not be possible this season, it would be preferable to remove Stingray rather than wet store it. This would permit modifications or reconfigurations to be made in light of any findings of the data analysis to be undertaken over the winter months.

5.3 Recovery

The earliest possible recovery window was 25th September. To this end, personnel and vessels were remobilised to meet this date. Once recovered, the Harry McGill, with Stingray on its lift beams, was towed to Sullom Voe to inspect Stingray, strip down minor components and secure for storage / transport. The barge was then towed to Lerwick to allow stripping down major components and unloading to the quayside for overwinter storage. Although this was all complete within 10 days of recovery, the barge had to remain on Shetland for a further 22 days awaiting a suitable weather window for demobilisation and return to Burntisland.

5.4 Health and Safety

As well as taking place under the Health and Safety at Work Act, the Stingray operations were also subject to the CDM (Construction, Design, Management) Regulations. These requirements arose from the 2001 Order amending the HSWA extending its remit to include operation of energy generating structures in the UK territorial sea. The construction, repair, maintenance and demolition were already covered by the Act.

The implications of CDM are such that the management of project risk has to be understood by all levels of the project team (client, designers, contractors, etc) and implemented from the earliest design stages, as risk assessments, right through construction and should also cover requirements for demolition.

6 PHASE 2 EXTENSION WORKSCOPE

6.1 Overview

The initial findings of the Phase 2 operations were presented to the DTI in December 2002. At that time, it was also identified that an intermediary step between the completed operations and the planned 5MW demonstration farm would be required. This stage, Phase 3, would involve returning Stingray to Yell Sound in the summer of 2003 to provide further validation of the mathematical model and to undertake a period of continuous operating cycles.

However, to complete the reporting of Phase 2, and undertake specific activities believed necessary for the decision as to whether progression to Phase 3 was sensible, an extension to Phase 2, known as Phase 2E, was requested. This extension was granted on 11th March 2003.

This extension covered two main areas. Firstly, the additional operational costs incurred as a result of bad weather in Shetland had to be included, and reporting the findings of the work completed. In addition to this, EB also proposed to incorporate some additional tasks within Phase 2. These are identified below, and include certain tasks that were specifically requested by the DTI.

6.2 Close-out of 2002 Activities

A review of all 2002 activities (operations, component performance, HSE issues) was required for inclusion in the existing Phase 2 reporting requirements and to enable the fully optimised reconfiguration of Stingray (Mark 2) to be determined. This also identified operating procedures that needed modifying or improving.

6.3 Desk studies

As part of Phase 2E, a wide range of desk studies were undertaken into topics that had been identified as knowledge gaps, issues of concern or possible performance improvement areas. These included investigations into the power transmission (focussing on drive and generator technology), the control system (hydroplane and hydraulic control), sensors / instrumentation, pod design and development of the system to permit yaw of the hydroplane.

Specific areas of study requested by the DTI included the technical and economic value of hydraulic power smoothing devices and yaw systems, and a full review of the instrumentation requirements.

Following on from the desk studies, specification and selection of suitable components for modification and improvement of Stingray was undertaken.

6.4 Mathematical Modelling

The existing EB mathematical model was to be updated in line with the characteristics obtained from analysis of the demonstrator results. It was also necessary to further validate the model against the performance seen during the Phase 2 testing.

For developing the system towards a Phase 3 deployment, it was considered necessary to develop further the control system in the model. In particular, this would permit better hydroplane control leading to faster cycle times and allow the limitations of the Mark 1 machine to be more fully explored. It was also considered important to improve the modelling of the transmission and actuation systems, to make them more representative of the demonstrator system and allow identical control implementation between the model and the demonstrator.

Once fully validated, the model could then be used as a basis for assessing other alternative machine configurations, transmission arrangements and control strategies.

6.5 Resource Studies

A set of studies was identified that would contribute to a greater understanding of the interaction between Stingray and the tidal stream resource. There are three main elements – understanding where the energy is in the tidal stream, what happens to the resource when it is extracted, and how the flow regime changes in the proximity of a Stingray machine. This also leads to a way of assessing the allowable spacing of multiple Stingray machines. An essential aspect of the demonstration farm definition is quantifying the expected energy capture, for which this type of research is necessary.

The first element is aimed at quantifying the distribution of available power within the tidal stream as it changes with time during its 12½ hour cycle. As power is proportional to the cube of the stream velocity, it is important to understand whether the highest velocities occur frequently enough to justify designing a machine to capture that energy, knowing that the higher the velocity, the stronger (and more expensive) the machine is going to be to withstand the loads applied.

While knowing how much energy is available is important, equally important is to understand what proportion of that energy it is possible to extract without altering tidal regime and flow patterns within the channel to the extent that further capture is not possible. This study took a fundamental look at the physics of open channel flow from first principles, and accounted for an energy-removing device positioned in the flow. This was not undertaken as an assessment of specific local or national resources, rather a theoretical assessment of the previously identified resource potential.

Parallel work was also planned, utilising Newcastle University to carry out mathematical modelling of the flow around a Stingray machine. The purpose was to investigate whether it was possible to determine a maximum power output from a single Stingray device (Stingray equivalent of the Betz limit for wind turbines) and also to quantify the wake / flow effects a Stingray generator would develop. The plan is to validate the findings by further marine trials (Phase 3). A specific request was made by the DTI that this modelling should include a review of the effect of varying time for hydroplane reversal at the end of each stroke.

Through a combination of the outputs of the work carried out by EB and Newcastle University, an assessment was to be made of the spacing limitations between individual Stingray generators within a farm array.

6.6 Site Acquisition (Grid Connection and Permits)

Work was commenced on grid connection issues, in the form of a review of the existing legislation and requirements. It has been indicated that the grid connection process has a long lead-in time (12 months or more). This information is essential if a grid connection is to be contemplated for Phase 4, and will provide the data necessary to start the process of applying for a grid connection.

A review was also undertaken of the existing Yell Sound permits and consents to cover Phase 3 operations.

7 PROJECT RESULTS

7.1 Summary of Achievements

Stingray was finally deployed on the seabed for only 12 days, shorter than all had hoped for. However, in terms of overall project output, a huge amount was achieved in a very short time (just over a year from the start of feasibility studies in September 2001 to recovery in September 2002). This has been driven by a very ambitious, fast-track programme. Slight delays in the target schedule occurred, such that the onshore control facilities were not in place at the end of the operating season. Therefore, with the barge off station, leaving Stingray on the seabed would not allow further testing until the Spring. By removing it, it was possible to use the results of the ongoing data analysis to reconfigure the system, permitting improved operations / performance if further testing is undertaken in 2003.

Research and development at this scale, while costly, produces a wide range of benefits beyond the obvious performance / power generation data. As well as installing and operating the first ever full-size tidal stream generator, information has been developed on:

- Validation of the mathematical modelling work undertaken in the feasibility study and design periods, and collection of power generation performance data.
- Development of an efficient and cost-effective deployment / recovery system.
- The permitting and consents process.
- The environmental impact of tidal stream power generators, including obtaining preliminary acoustic monitoring data and information on cetacean behaviour.
- The limitations and deficiencies of conventional seabed surveys in a strong tidal environment, and determination of methods of improving on them.
- Marine operations in a very harsh environment, including implementation of the HSE CDM regulations in an industry to which they are only just being applied.
- Team-building and information gathering to strengthen EB in developing the ROPG business.

In addition to this, the Stingray project has raised the public and industry profile of marine renewables in general, and tidal stream in particular.

7.2 Power generation performance

These results were described to the DTI in a presentation in December 2002. The output and results covered four major aspects – basic elements of machine performance, tidal flow, transient characteristics in tidal flow, and power / cycle development.

7.2.1 Basic Characteristics

Here the basic elements of machine performance such as masses, inertias & hydroplane characteristics were extracted and analysed. These included arm assembly gravity torque, hydroplane assembly gravity torque, hydroplane torque and angular velocity characteristic, hydroplane inertial loads, arm assembly drag loads, arm assembly inertial loads, hydroplane hydraulic system compliance, steady state lift and steady state pitching moment.

The results obtained were largely in agreement with those assumed during the mathematical modelling.

7.2.2 Tidal Flow Characteristics

This examines short time scale variations in the tidal flow measured on site and their influence on machine operation. These included lift stability (flow field turbulence, flow velocity and torque variation), velocity profile effects and structural interference.

The data obtained during the site trials confirmed that there is measurable variation in transient flow velocity due to turbulence. The scale of this turbulence is not entirely clear as flow has been measured over a relatively small area, however the lack of response in the measured lift to flow variation suggests the effects may be averaged out over the full machine width. There are some measured load changes that occur without any change in the measured velocity – this may be due to significant variations in the flow outside the measurement volume.

However, for the steady state, there is good correlation between changes in velocity and changes in lift when considered over longer periods.

The data indicates good evidence of velocity profile effects. The rate of velocity decrease with increasing depth may be slightly higher than predicted by the 1/7th power law.

It is possible that some of the flow variation and velocity profile effects may be due to structural interference. If this is the case, the level of interference does not appear to be at particularly damaging levels as regards machine performance.

7.2.3 Transient Characteristics in Flow

Having established the basic machine characteristics, the way in which the basic transient characteristics (e.g. added mass) vary due to the additional effects of the tidal flow velocity were investigated. These included stall recovery, dynamic stall, hydroplane inertial loads in tidal flow and the arm assembly drag and inertial loads in tidal flow.

All of the tests involved here are of a transient nature and in most cases only a limited amount of data was collected hence it has not been possible to reach a conclusion in most of these cases. Preliminary conclusions can be drawn for stall recovery. This is the time taken for a stable, fully attached, flow regime to re-establish around the hydroplane when it is recovered from a stalled condition. Early theoretical reviews had indicated this to take 3 to 8 seconds and, as such, raised concerns about the detrimental effects on the Stingray cycle time were such an event to occur. Although the testing of this area was limited, it appeared that any delay in stall recovery was not at a level that caused particular concern. The previously quoted delays may still occur, but it is probable that the level of lift lost from the flow not being fully attached may be a small enough proportion of it to be neglected.

7.2.4 Power & Cycle Development

Here the power extracted during testing was analysed along with some discussion on cycle development. These included power stroke, power cycle, comparisons with the mathematical model and discussion of transmission system efficiencies.

Following initial test work to characterise the machine, effort was then directed towards power generation and development of a repeatable cycle. This was done in two stages:

- Experimentation with the machine in manual control mode. (set transmission torque with operator control of hydroplane angle via manual driving of proportional valve)
- Development of automatic sinusoidal cycle (controlling the arm to follow a sinusoidal cycle and controlling the hydroplane to maintain the angle of attack near optimum)

Note that in the discussion that follows all of the powers quoted are hydraulic. They are calculated from the measured pressure drop across the hydraulic motor that is used to calculate torque using the standard motor constant of 7.96Nm/Bar (no torque efficiency accounted for). This is then used with the measured generator speed to calculate power.

Initial attempts to extract power from the tidal flow were carried out in 'manual control'. This involves setting the transmission speed demand (and hence main arm speed) to zero and imposing a current limit on the drive system. Any motion of the arm is now dynamically braked by the drive system up to a maximum torque as prescribed by the current limit. The hydroplane can then be manually controlled by the operator to create lift & drag to move the arm through a stroke or cycle against the arm braking torque, generating power.

This arrangement was experimented with in current speeds of up to 2m/s with a range of current limits and significant power levels were seen to be generated. Peak power observed was 245 kW in a 1.5m/s current (3 knots). Figure 63 shows one such power stroke.

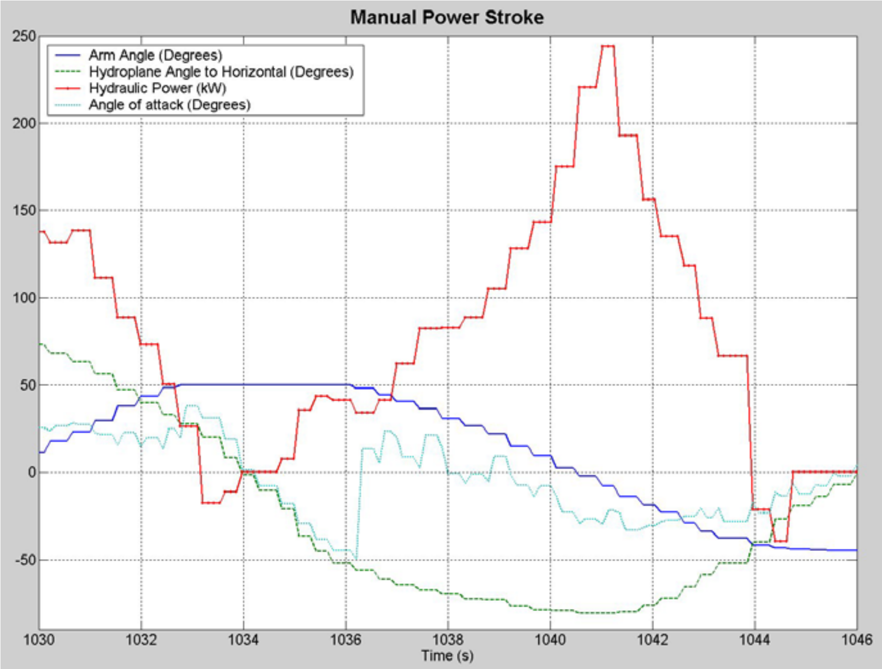


Figure 63: Typical Power Stroke

Power cycle development centred on implementation of the 'sinusoidal cycle'. Here the drive system controls the motor speed, and hence arm speed, so that the arm follows a sinusoidal profile. The hydroplane angle is controlled through this cycle so as to maintain the angle of attack as near to its optimum level as possible. If this angle of attack control is achieved well then the transmission will be braking the motion of the arm through most or all of the cycle, hence generating power.

A considerable amount of experimentation and tuning was required to achieve a working cycle and the hydroplane control used required a number of modifications. This was primarily due to the fact that full hydraulic power was not available to the hydroplane actuation system and it was running out of flow at the points in the cycle where more rapid movement was required. This lack of flow was due to the fact that the actuation system was not fully implemented.

Fairly consistent power was generated on each stroke. However, the overall power levels were quite low with a peak value of 145 kW and an average of 40 to 50 kW.

To give a first indication of how closely the mathematical model corresponds with the behaviour measured on site some simulations were run in similar conditions. The model specification was ‘as built’ but without any revisions from what has been learnt from the on site test work.

It should be emphasised that neither the model nor the cycle presented here are fully representative of the on site situation. Significant further work, including updating the model parameters and recreation of the exact cycle, is required for full validation of the model. It does however give some indication of how valid the modelling approach taken is. The comparison graphs are presented as Figure 64.

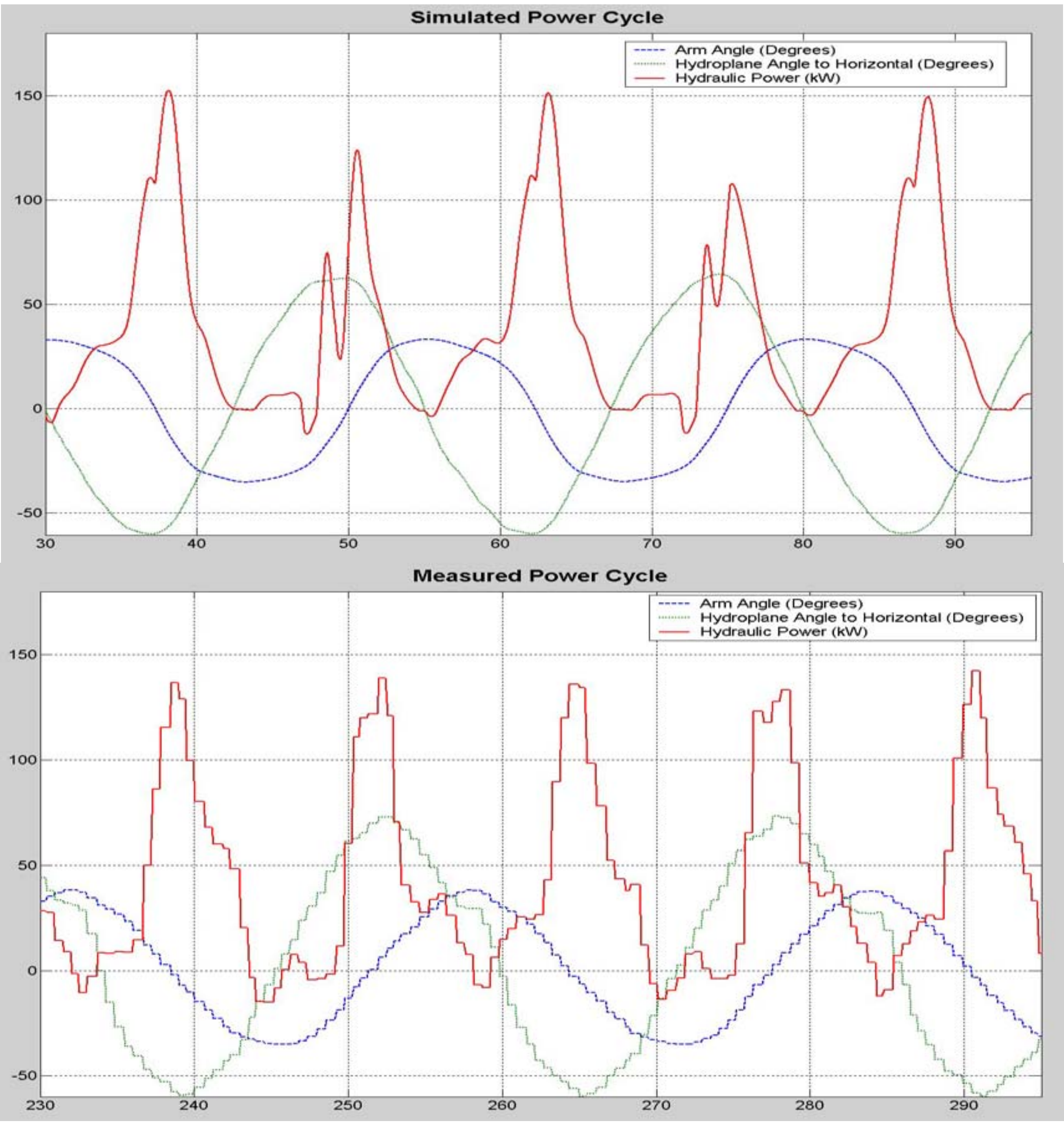


Figure 64: Comparison of Modelled and Achieved Cycles

From comparison of the graphs, the following should be noted:

- The peak powers and the shape of the power curves match very well – particularly for the down-stroke.
- The phase of the hydroplane cycle is not directly equivalent for both cycles – in the case of the measured cycle it lags further creating more stall at the start of the cycle.

- The up-stroke for the simulated case is underestimated - this is because the control in the model was not optimised for this case and the hydroplane was stalling mid-stroke. The phasing of arm/hydroplane control is very important, which is demonstrated by this. With improved control there is no reason why the cycle should not be the same as for the down-stroke.

There are of course a number of detail differences, but what can be taken from the analysis is that the modelling approach taken appears to be reasonable.

7.2.5 Summary of Test Results

An overview of the main test work findings is as follows:

- The basic characteristics measured during test work are in good agreement with anticipated characteristics. There are some detail differences but all of the major elements match well.
- It was not possible to extract some of the more transient characteristics from the data – further test work with improved instrumentation and test methods would be required for any further analysis.
- Power cycles and experiments on site clearly indicate that significant power is available and that it is possible to construct a repeatable cycle. Analysis to date indicates that control development is key to moving closer to an ideal cycle.
- There is good agreement in initial comparisons of measured power cycles and those generated in mathematical simulation studies. This indicates that the simulation model basis is sound. Further work is required to fully validate the model.
- Significant power is clearly available with 250 kW peak powers seen in a 3 knot current for a single sweep.
- Repeatable power cycles were achieved with peak power levels of 145kW and average power of 40 to 50kW in a 3.5 knot current.
- Faster cycle times required for higher levels of power generation were not achievable due to limitations in the actuation system.
- The phase relationship between arm and hydroplane control is very important in moving towards the ideal cycle. Further power cycle development work must concentrate on this area.
- It may be possible to incorporate stall within the machine cycle and this should be considered in any further developments.
- All powers quoted are hydraulic – they take no account of the losses in conversion to electricity. The drive output powers require further investigation.
- Initial cycle comparisons with the mathematical model are promising, showing similar characteristics and levels of power. Further work is required to run a directly equivalent cycle with a fully updated model before it can be considered to be fully validated.
- Further instrumentation is required for future programs of test work.

7.3 Component Performance

Generally the components used on Stingray performed as expected, although, as with any system, possible improvements or replacements were identified for future operations. These changes cover many areas of the design although none alter or effect the intended operation of the machine.

The components used were selected with availability, reliability, and maintainability in mind, and with careful consideration given to purchasing of the components and materials from respected suppliers.

7.4 Operational Procedures Performance

The Stingray testing was conducted in Yell Sound, a very harsh environment where the tide speeds could reach over 5 knots (2.5 meters per second), and wind speeds up to 60 knots. All operations were thus planned with safety as the primary concern before starting, and during, any procedure.

The procedures for Stingray operation off the Harry McGill were written specifically for the project and were produced in accordance with HSE regulations, including CDM (which now extend to offshore renewable energy projects). These procedures were very important to the health and safety of all personnel onboard the barge, ensuring that everyone involved understood what they were expected to do in various circumstances and who they were to report to.

In line with this aim, the procedures gave instructions on what action to take on occurrence of a number of identified events, including normal operation, man overboard, emergency medical assistance, machine abandonment and vessel abandonment.

The procedures included information on areas such as working instructions, safety, launch and recovery limitations, personnel transfer, and actions and responsibilities in the event of an emergency. These procedures worked well with no incidents reported during the marine operations.

7.5 Environmental Performance

A thorough environmental appraisal, supported by seabed and shoreline benthic surveys, indicated that no significant environmental impacts should be anticipated during installation, operation or recovery. Acoustic monitoring of Stingray operations was undertaken, with control recordings made when Stingray was offsite. Third party studies of cetacean activity (Harbour Porpoises, in particular) were also performed during the operations period.

8 DESK STUDIES

8.1.1 Drive and Generator Technology:

By its nature, Stingray represents a very unconventional way of generating power. Conventional generators aim to operate unidirectionally at constant speed, with variable torque, to export power. Stingray, however, runs bi-directionally at variable speed, with variable torque, with a bi-directional electricity flow (i.e. while being a net exporter, electricity is imported at times to operate the hydroplane arm).

Conversion of linear kinetic energy from the tides to export quality power for the grid is via the route indicated in Figure 65.

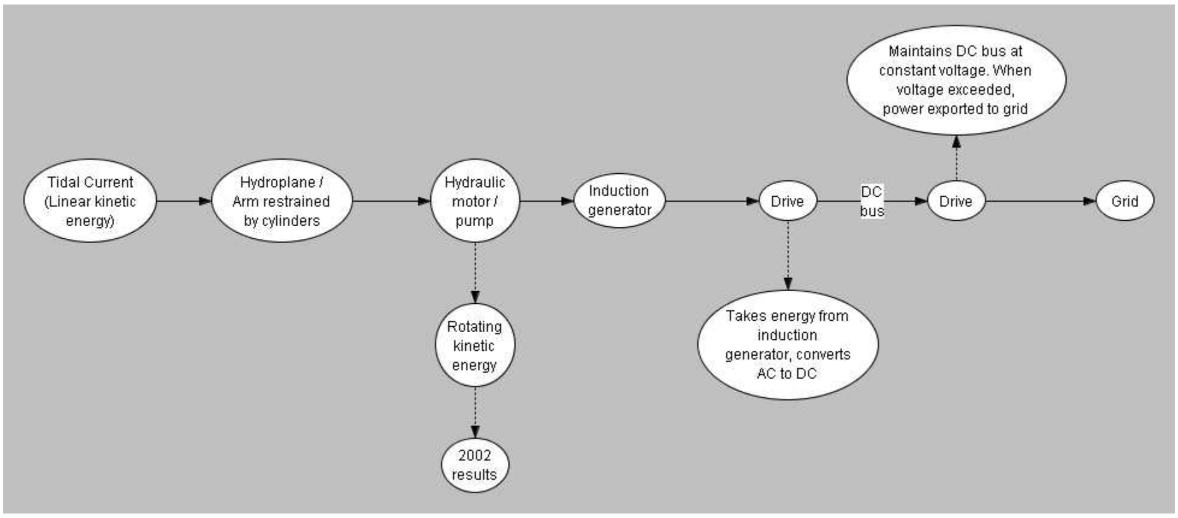


Figure 65: Power conversion route

The focus of this work was an investigation of how efficiently power could be extracted. Preliminary work identified the possibility that the efficiency loss between the induction generator and the land-based drive could actually be significantly more than originally assumed. This was based on in-house theoretical reviews of the system and a detailed dynamic model produced by Mathworks (creator of the Simulink modelling software). The results from the Mathworks model were pessimistic, indicating an expected efficiency ranging from less than 20% up to a maximum of about 90%, with the maximum efficiency occurring at low speeds and low torques. The results were at odds with the accepted wisdom that induction machines are at their most efficient when running at their rated speed whilst 75-100% loaded. Further work was done to attempt to validate the model and understand the mechanisms behind the inefficiencies.

A review by Durham University produced a simplified steady state representation of the induction generator, with input parameters (particularly rotor resistance) obtained from the manufacturers. It is understood that Durham has validated its model using physical motor tests.

This suggested efficiencies of 91-96% could be possible – noticeably greater than the initial EB assumptions (70-80% maximum), and markedly greater than the Mathworks efficiencies.

However, the Durham model is a simplified system which does not allow for frictional losses or losses in the drive system. EB therefore reran the Mathworks dynamic model using the new induction generator parameters obtained from the manufacturer by Durham.

This more complex model suggests efficiencies of 60-90% should be achievable. What is of particular interest here is that the curves are relatively constant across a range of motor speeds and torques. This means that the mode of operation does not adversely effect the efficiency. This was a surprising discovery, since the Stingray motor is being operated in an unconventional manner, with variable speeds and torques. Conventionally, motors / generators are operated in a steady-state, within a defined speed and torque envelope.

In parallel with this work, and incorporating its findings, was a review of available generator technology. This encompassed the performance and suitability of the Phase 2 motor, and possible alternatives for Phase 3. Possible generators for subsequent development phases were also investigated. This was achieved through determination of the selection parameters, duty cycles and performance criteria for the different scenarios envisaged.

The machines investigated included singly fed induction machines, doubly fed induction machines and permanent magnet machines.

In conclusion, the modelling work gives us significantly more confidence in the selected induction generator. With hindsight, it may not be the most suitable for the end-use (its benefits were that it was relatively cheap with a short lead-time), but we are reassured now that it should give sound results. It is probable that the existing motor will be used for the initial stages of Phase 3, while a longer lead-time 4-pole induction motor is procured for use in the later stages. For Phase 4, it is possible that a permanent magnet motor could be used for further increases in efficiency, or that the drive train is re-designed to be at a fixed speed and highly variable torque so that a synchronous generator could be used. It is becoming apparent that commercial advantages may be available to electricity producers that can displace existing conventional synchronous generators with synchronous generators where renewable energy sources are the prime mover. These advantages centre around the desirability of a proportion of the network connected generators to be able to contribute substantial fault current and frequency stability to support the inductive load that is increasing in the UK supply network.

8.1.2 Hydroplane / Hydraulic Control

Control of the hydroplane through the machine cycle was clearly identified in testing as an area critical to achieving optimum performance from the Stingray machine. There are a number of aspects which impact upon this question.

- Physical limitations – To move the hydroplane through the desired cycle the mechanical and hydraulic elements of the actuation system must be capable of providing the necessary forces, pressures and flows.
- Dynamic stability – the configuration of the hydraulic circuit can give rise to dynamic instabilities in the system. Consideration of these aspects is required to make sure this doe not impact on the controllability of the system
- Control system – This must be developed to achieve the required levels of response and accuracy. It must also be able to cope with non-linear performance of many of the system elements – for example the actuation linkage.

Reviews of the above elements have resulted in a number of modifications and ongoing work will continue to develop this area. Key developments are as follows:

It was found in 2002 testing that the rotational drag on the hydroplane was considerably higher than originally anticipated. In the light of this, the loads on the actuation system have been recalculated to establish the cycle time limits of the existing cylinder and linkage system.

Development of more advanced control algorithms has been identified as a necessary part of the ongoing work and this will be carried out via the mathematical model before return to site.

8.1.3 Sensors / Instrumentation

This study reviewed:

- The system variables to be monitored, including the reasons for, and importance of, their monitoring
- The measuring frequency for each monitored variable, and required immediacy of availability after acquisition
- Transducer types suitable for conversion of variables to usable signals
- The cost benefits of the identified options, recommending the optimum hardware and software to produce acceptable data within the broad budgetary constraints.

The transducers identified as being required are detailed below, with their locations, indicated in square brackets, given on Figure 66.

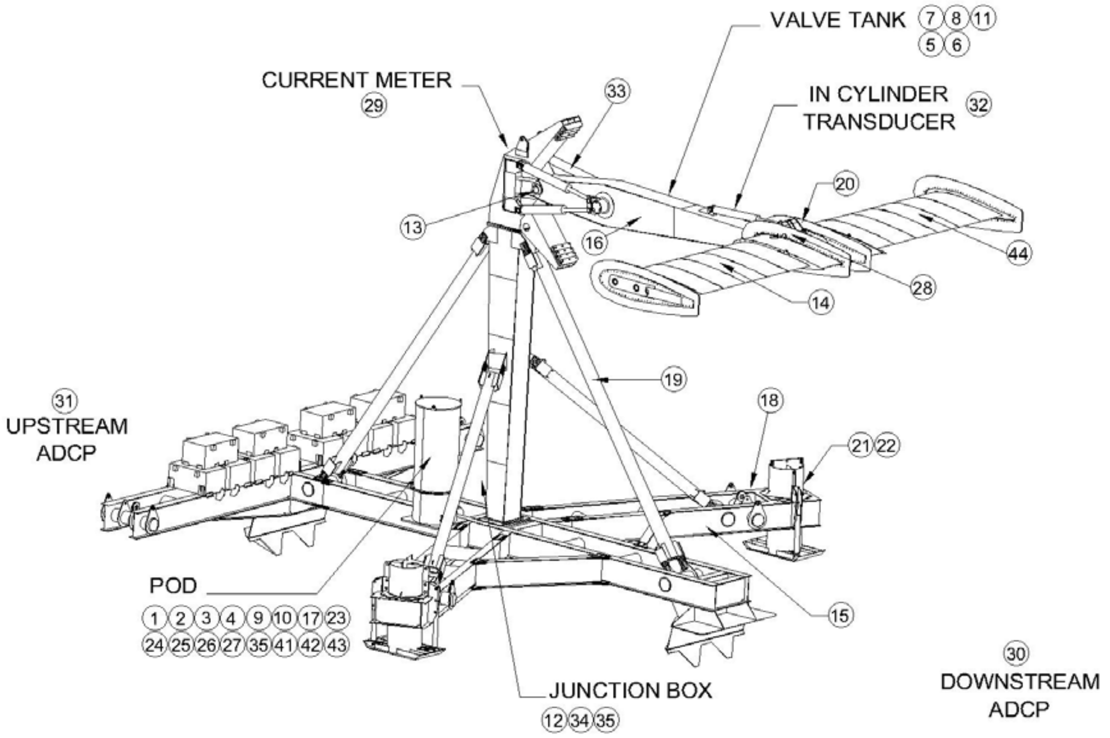


Figure 66: Proposed Phase 3 instrumentation

- Fluid pressure (hydraulic system pressure, ambient water pressure and hydroplane counterbalance valve sensors) [Locations 1-12, 22]
- Load cells for hydroplane loads (lift and drag) [13]
- Strain gauges for tensile, compressive and torsional forces within the Stingray structure. Precise number and locations will be determined as redesign progresses [14-16]
- Video cameras viewing the adjustable foot and on the hydroplane [17-19]
- Vibration sensors for hydroplane vibrations [20]
- Humidity sensors in pod [23]
- Pod water / oil level sensor [24,34]
- Motor and drive sensors (drive system data, voltages, currents, motor parameters – temperature, speed, frequency) [25-27, 36-39]
- Hydrophone for cavitation detection / acoustic monitoring [28]
- Current meters – ADCPs fore and aft of Stingray, a horizontal profiler forward of the hydroplane and the existing single cell meter (as used in 2002) [29-31]
- Hydroplane differential pressure transducer mounted on the trailing edge of the hydroplane [44]

- Adjustable foot extension [21]
- Machine component movements (hydroplane, arm) [32-33]
- Oil temperature [35]
- Location (water depth, heading, pitch, roll) [40-43]

In addition to the existing and additional sensors, the existing data logging capabilities are under review, and additional hardware / software requirements are to be specified.

The review concluded that there was no major problem in sourcing or obtaining the required transducer hardware in line with the deployment schedule, and within the budget. However, substantial engineering design would be required to interface correctly and efficiently the transducers with the existing monitoring systems.

8.1.4 Yaw Mechanism

For the Phase 2 'Proof of Concept' work, it was considered not to be necessary for the Stingray arm/hydroplane unit to operate in all states of the tide (ebb and flow), since this would increase the complexity, and cost, of design and manufacture. Although a simple system to 'yaw' the arm/hydroplane unit round for reversals of current direction was developed, it was not implemented. The Phase 2 demonstrator was, therefore, only operated on the flood tide. On the ebb tide the arm/hydroplane unit was 'parked' near the seabed, away from the higher current velocities.

For the demonstration and commercial systems (Phases 4 and 5, respectively) it will be essential that the units operate on both the flood and the ebb. A yawing system should also permit fine-tuning of the hydroplane orientation to cope with perturbations in current direction during each tide. Therefore the yawing system has been further developed such that, if required, it may be possible to implement it during the later stages of Phase 3.

8.2 Mathematical Modelling

8.2.1 Mathematical model development

The original model used in Phase 2 is undergoing development to make it more suitable for addressing the areas of the concept which require further work. This includes:

- More detailed modelling of the hydroplane hydraulic elements – this allows the hydroplane control to be developed.
- Detailed modelling of the variable speed drive and generator system – this has been completed and has already been used to investigate the electrical system efficiencies. It will be integrated with the main model in the ongoing program of work.
- Modelling of the controller architecture and ongoing development of the control algorithms.
- Update of the model parameters in line with findings from 2002 test work
- Validation of the completed model including the revisions above
- Cycle development using validated model to fully explore limits of as built machine

This work is ongoing and is aimed to feed into the control development work that will be carried out on site in 2003.

8.3 Site Acquisition

8.3.1 Grid Connection Requirements / Network Connection

The Stingray Phase 2 programme included an option to connect the machine to shore and operate connected to the local distribution network. Moving forward to the Phase 3 programme, this option is retained, however the benefits of doing so in terms of scientific investigation compared with the commercial costs of this connection were reviewed.

The Phase 2 or Phase 3 machine is unlike the proposed commercial Phase 4 or Phase 5 machines in that a single collector head is deployed. With a single collector head, there are periods of time at the top and bottom ends of stroke where actuation power is consumed by Stingray and no generation is produced. In a Phase 4 or Phase 5 farm, the multiple collector heads are synchronised such that the actuation demand from one head at the end of stroke is covered by the generation of the remainder of the farm.

Any distribution network connection has to possess sufficient capacity to accept:

- Maximum actuation power being drawn at cycle ends
- Peak generation being accepted during the cycle
- Worst case wrongly controlled power flows resulting from experiments in the drive train – the supply network has to provide sufficient power in these cases to perform a safe shut-down and park of the collector.

It is clear that with only a single collector, the maximum per-unit costs of connection are present since, for a farm, these over-capacity issues would be shared equally amongst each of the collectors given that a “one fault at a time” model would be expected.

The distribution network codes covering connection were studied to ensure that there was no impediment to connecting Stingray:

- Stingray operations would be bound by The Electricity At Work Regulations 1989. Since Stingray is electrically designed and operated in accordance with BS7430, then this should present no impediment.
- The harmonic performance of the variable speed drive needs to be within the target set by Electricity Association G5/4. Since the drive is configured with a fully controlled network facing inverter rather than a simple rectifier, then harmonic performance should be comfortably within those requirements.
- The protection systems employed must comply with Electricity Association G59/1 and ETR113. Since Stingray Phase 2 or Phase 3 operates at a nominal voltage of 400V and a power level not exceeding 400kW, then it is expected that a reduced level of system protection, akin to that fitted to an ordinary industrial process that net consumes energy would be appropriate, however this would need to be agreed with a DNO.
- It is expected from early discussions with Scottish and Southern Electricity (the incumbent DNO for the Shetland test site) that it would be possible to achieve a connection agreement between EB and SSE. It is expected that SSE and EB could enter into a bilateral agreement for the Master Connection and Use of System Agreement required and obtain an exemption of the requirement for a Generation License under the same terms. Simplified metering arrangements would be appropriate since the likely amount of energy net generated by a Stingray Phase 2 or Phase 3 machine in the relatively short operation periods would not offset the costs of bi-

directional metering, and that any net energy generated would thus not be reimbursed by SSE. In a similar vein a Residuals Agreement would not be struck since EB would have no plans to strike any Power Purchase Agreements for the experimental device.

No technical impediment was found to connecting Stingray to a distribution network, however there were large commercial costs associated with the connection for little benefit.

8.3.2 Consents and Permits

As described in Section 2, the Phase 2 Stingray operations were carried out under the limitations of five licences or consents. These comprised the Harbour Works Licence and onshore Planning Permission, both administered by Shetland Islands Council, the Food and Environment Protection Act (FEPA) Licence and Coast Protection Act (CPA) consent, both administered by the Scottish Executive, and the Crown Estate Lease.

9 COST ANALYSIS AND PROSPECTS FOR COMMERCIAL DEVELOPMENT

9.1 What do we mean by economic viability?

The overall aim of the project is to determine whether the Stingray technology can be economically viable. Whilst this may seem a perfectly reasonable ambition, it is very difficult to quantify the target for "economic viability". For the foreseeable future renewables will be more expensive than conventional alternatives in the vast majority of circumstances. Furthermore, tidal stream may be more expensive than, for example, wind power, but its predictability should command a premium in allowing better management of risk and security of supply. "Viability" depends on the market, the alternatives and non-quantifiable political factors. This is demonstrated by the fact that the UK electricity market requires cheaper power than that required by isolated locations or for alternative uses for Stingray (such as desalination or hydrogen production for fuel cells).

There is no "right" answer, certainly not one that EB can provide. The approach being taken is to try and determine the cost of producing power with Stingray, and test that price in the market to see whether the technology can attract commercial investment. It must be recognised that in the present energy market, which is deregulated and fragmented, the incentives are small to invest in any generating capacity, and the risks are high. The Stingray programme is designed to provide a steady reduction in those risks with time so that government backing can be replaced by commercial investment at the appropriate time.

To allow us to set some targets at this time, EB considers that renewable electricity produced at a cost of less than 15p/kWh will have some takers, but that 5-7p/kWh would need to be achieved to allow large-scale connection to the UK grid, taking into account the likely value of the Renewable Obligation Certificates (ROC) that power produced by Stingray would attract.

9.2 Basis of economic argument

In assessing the prospects for commercial development of the Stingray device, we have used discounted cashflow modelling to evaluate the net present value and internal rate of return of various generations of the technology.

Our discounted cashflow modelling is based on validated inputs. These include:

- detailed cost estimates for different stages in the development of the Stingray device, compiled with reference to the experience gained in the demonstration phase,
- assessments of likely power outputs from the different versions of the technology derived from mathematical models and
- commercial views of possible prices for electricity and ROCs.

9.3 Economic Modelling

EB has developed a simplified economic model used for assessing the commercial potential for the Stingray technology.

The model draws inputs from detailed technical performance and costing models, and allows comparison of the commercial viability of possible evolutionary stages for the Stingray device. In extrapolating from the base data, we have to make various assumptions regarding how costs may change as the technology matures. The key areas to be covered are:

- How much does a "base" machine cost to build, and how can that be scaled up to a bigger machine?
- What savings can we expect as a result of engineering a second- or third-generation machine, having learned from the first attempt?
- What savings can we expect when building second- and subsequent generation machine?
- What savings can we expect from cost-engineering machines to eliminate the inefficiencies inherent in building a prototype that "must not fail"?
- What savings can we expect from building multiple units for commercial production rather than one-off prototypes?
- How much energy can we expect the "base" machine to capture from a known site?
- How far can we improve that through improved methods of operation (control strategies)?
- How far can we improve efficiencies, and at what cost?
- How much does it cost to install one machine, and how does that cost change for multiple machines?
- Are the costs of operating and maintaining a farm of machines clear?
- What does it cost to connect to the grid?

By actually designing, building, installing and operating a large-scale machine, the base data for many of the elements that are used to build up the cost model have been obtained. The route to scaling-up from this data to a farm of commercial machines relies on making assumptions based on experience and published data from other similar technology developments, and testing these assumptions against the knowledge of others, particularly people involved in large-scale capital projects and offshore operations.

We have identified four stages in the Stingray technology's development:

- **Phase 2 – "as-built".** Phase 2 comprises the demonstrator unit as tested in Yell Sound in the summer of 2002. Total capital costs amounted to some £1.87 million for the demonstrator project. Annualised operating costs were estimated to be some £160,000.
- **Phase 3 – redeploy upgraded demonstrator.** Phase 3 involves rebuilding and reinstalling the Phase 2 demonstrator device to gather further data on long term operability and to test more efficient operating approaches. If a new device were to be built, we estimate that the total capital cost would be some £1.37 million, and the annual operating cost would remain around £150,000.
- **Phase 4 – demonstration farm.** Comprising 10 larger machines, the Phase 4 installation would demonstrate commercial potential, and allow EB to gather further operating experience, to assess the interaction effects of multiple devices and to develop reduced cost mass production construction, installation and operating methods.

- **Phase 5 – commercial farm.** Again comprising 10 larger machines, the Phase 5 installation would be a commercial installation of Stingray machines, optimised for cost and performance for the specific location.

9.4 Phase 2 – "as-built"

The Phase 2 demonstrator Stingray was installed in Yell Sound in the Summer of 2002 and operated for a period of 12 days. It provided base information on capital costs and the technology's potential to capture tidal stream energy and convert it into useful hydraulic energy.

It only provided very limited information on reliability and operating costs over an extended period.

Capital cost estimates

Phase 2 – the "as-built" demonstrator involved total capital costs of about £1.87 million, comprising approximately £1,350,000 of materials costs (including marine operations) and £524,000 of EB time costs.

Operating cost estimates

EB estimates that the annualised operating costs for the Stingray demonstrator would be about £160,000, roughly equally split between time costs and materials.

Performance

The Stingray device placed in Yell Sound in 2002 yielded hydraulic power output as described in Section 7 of this report. EB has extrapolated from the limited data set produced during the demonstrator project to produce an annual electrical power output of some 150 MWh, taking into account the losses resulting from both imperfect control and expected inefficiencies in the drive and power conversion systems.

It is recognised that the amount of power consumed by actuating the hydroplane to "flip" it over at the end of each stroke is a significant consumer of the power produced, and the control strategy needs to be changed to reduce this effect.

9.5 Phase 3 – redeploy upgraded demonstrator

The Phase 3 project will involve upgrading and redeploying the demonstrator Stingray unit in Yell Sound in the summer of 2003, with the aim of testing improved control systems.

Capital cost estimates

Phase 3 will not involve building a new Stingray unit. However for the purposes of assessing the reduction in costs with increased installed capacity, EB has estimated the capital costs which would be incurred if a new device were to be built.

This would involve total capital costs of about £1.4 million based on saving 10% in materials cost and 70% in time costs. The cost reductions in materials would arise from improved procurement derived from lessons learned during the Phase 2 construction phase, and the time costs would be lower as the existing design work would be largely reused.

Operating cost estimates

EB estimates that the annualised operating costs for the Stingray demonstrator would reduce slightly to about £150,000.

Performance

EB expects to achieve considerably higher energy capture from the upgraded Stingray device, as improved control systems and methodologies should allow the device to capture power more effectively in a wider range of tidal stream conditions. The amount of energy captured from the tidal stream would increase, and the power required to actuate the hydroplanes decreased, but the inefficiencies inherent in some of the components used would still reduce the amount of energy that could be usefully exported. An annualised output of 225MWh has been estimated to be achievable for the Phase 3 machine.

9.6 Phase 4 – pre-commercial farm

The economic model for the Phase 4 demonstrator farm comprises a deployment of 10 Stingray devices, each larger than the demonstrator unit, and connected to the grid. The farm will be installed in Yell Sound and operated for an extended period, exporting power and selling electricity and ROCs. The farm will provide information on the effects of interaction between Stingray units and experience of grid connection and power export as well as detailed cost data.

Capital cost estimates

Phase 4 is estimated to involve capital costs of about £12.3 million – representing a unit capital cost reduction (per MW installed) of about 70% from the Phase 3 installation. The bulk of the cost reductions come from the benefits of optimising the design by reducing the degree of overdesign inherent in the first prototype, sharing design time costs over multiple machines, as well as improved procurement producing benefits from economies of scale.

Operating cost estimates

EB estimates that the annualised operating costs for the Stingray demonstrator farm would be about £260,000. The large unit operating cost reduction from the level incurred by Phase 2 and 3 is attributable to the very high proportion of those costs which were constant for both phases – specifically barge costs, as well as by the reduction in capital costs leading to lower costs for spares/replacement parts.

Performance

Detailed mathematical modelling, again underlain by a foundation of experience gained in Yell Sound, suggests a base level of annual power output from the 5MW pre-commercial farm of 750 MWh, accepting that the machine control and actuation will still be imperfect and capable of significant improvement.

9.7 Phase 5 - commercial farm

The Phase 5 commercial farm model comprises an installation of 10 larger Stingray devices, probably in Shetland, exporting power to the grid and benefiting from the sale of that power and ROCs. The tidal stream characteristics are based on those at Yell Sound, but the site selection procedure may identify an alternative location with more favourable current velocities.

All of the phases prior to the commercial installation involve over-engineering the Stingray devices to ensure their survival in relatively uncertain tidal stream conditions. For example, the demonstrator was built to survive a load induced by a relative current velocity acting on the hydroplanes in excess of 5.5m/s even though the maximum relative velocity (combining current and arm movement) encountered at the Yell Sound site is now anticipated to be less than 3.5m/s at the planned maximum cycle times of about 15-16 seconds. As loads grow with the square of velocity, it can easily be seen that the production machine can benefit from dramatic savings in fabrication cost by eliminating the overdesign of the structure

The commercial units in Phase 5 will be more precisely engineered, to use less steel and involve lower construction costs whilst still offering commercial power production. They are also likely to adopt a different energy capture approach, with significant energy capture at lower tidal stream speeds and “de-tuning “ at higher speeds to ensure device survival.

Capital cost estimates
The commercial farm is expected to involve total capital costs of about £6.3 million, but it is assumed for the purposes of the economic model that a capital grant of £100,000 per MW will be available to reduce the capital expenditure to £5.8 million. The significant cost reduction from Phase 4 will be achieved by building lighter, simpler, more structurally efficient machines more precisely engineered for the known tidal currents at their proposed location.

Operating cost estimates
EB estimates that the annualised operating costs for the Stingray demonstrator would be reduced slightly from Phase 4, resulting from of the cost-engineering benefits that contribute to the reduction in capital cost. EB anticipate these to be approximately £236,000.

Performance
The Phase 5 devices are expected to achieve average power export of 1063 MWh per year per machine, with the increase in useful power conversion (from the total available in the stream) increasing from just over 20% in Phase 4, to over 28% in Phase 5. This is largely due to the improved energy capture and reduction in actuation power resulting from an optimised control approach, and improvements in efficiencies by careful selection of the most appropriate drive and generator components.

9.8 Summary of economic modelling results

Table 5 summarises the results of the modelling of the different phases of the Stingray development. The total model allows investigation of variance in all the key inputs – installed capacity, power collected, collection and conversion efficiency, uptime, capital cost, operating cost, inflation rate, market price of electricity, value of ROCs. The table illustrates what EB considers to be a reasonable estimate of the outcome of the Stingray developments to date, without taking an overoptimistic view of either the useful power that can be collected, converted and fed into the grid, or the costs of producing that power.

The economic model calculates the sale price of electricity (including the associated ROCs) on the basis that each phase has a 25-year operating life. It gives the range of “price” that would be required to generate a return on investment varying from 0% (break-even) to 10%. As it already assumes an inflation rate of 2%, EB considers that the most sensible benchmark is to look at the 5% level of return, as this represents a significant income in the market sector at the moment.

The p/kWh price figures for Phases 2 and 3 are of little relevance, because it is accepted that the prototype cannot be a commercially viable machine as it stands, and is not suitable for a 25-year life. More important is to look at how the required price falls dramatically with ongoing development, to a level that could be argued to be “economically viable” in the UK grid market.

	Phase 2	Phase 3	Phase 4	Phase 5
Capital costs (£ million)				
Fabrication	1.87	1.37	12.28	5.83
Cost per MW	12.47	9.14	2.46	1.17
Operating costs (£000s/yr)				
Operation	160	150	258	236
Output efficiency				
Installed capacity (MW)	0.15	0.15	5	5
Delivered output (MWh/yr)	150	225	7,500	10,630
Useful power conversion (%)	9.0%	13.4%	20.3%	28.7%
Uptime (%)	95%	95%	95%	95%
Indicators				
Capex (£/GWh/yr)	13123	6415	1681	563
Opex (£/MWh)	1145	716	37	24
Price required to achieve pre-tax return of (p/kWh)				
0%	199.2	117.4	11.5	5.3
5%	**232.7**	**132.8**	**16.4**	**6.9**
8%	258.9	145.1	20.1	8.1
10%	278.4	154.3	22.8	9.0

Table 5: Stingray Cashflow Modelling

9.9 Factors contributing to increased viability

9.9.1 Experience curves

Experience curves offer a means of validating expectations about reducing unit costs with increased scale. An analysis of the cost reductions from Phase 2 through to Phase 5 suggests that unit cost reductions of around 25% are achieved for each doubling of installed capacity from the original demonstrator capacity of 150 kW.

Analysis by the International Energy Agency (2000) shows cost reductions of between 62% and 85% for Solar PV and Wind technology. The expectations of EB for cost reduction in the Stingray technology as captured in this review lie within this range.

9.9.2 Upside potential in pricing – Power Purchase Agreement

The Phase 5 Stingray installation is likely to be in Shetland, where Scottish and Southern Energy (SSE) currently operate diesel generators to provide electricity. EB believes that the marginal cost of diesel-fired generation is markedly higher than the cost of conventional coal or gas-fired generation. A preliminary estimate suggests that each MWh generated on Shetland may cost as much as £50-80, as compared with the more typical wholesale electricity price of £15 - £20 per MWh on the mainland.

EB plans to negotiate a Power Purchase Agreement (PPA) with SSE for the Phase 5 farm which will recognise that the value of its electricity is comparable with SSE's alternative of diesel fired generation, thereby realising a higher price than the conservative baseline we have used in this analysis.

Furthermore, no account has been taken of the potential contribution of Levy Exemption Certificate value, currently £4.30/MWh, to the value of the Stingray project. Although the contribution is relatively marginal, it would again add to the value of the technology if the EB (or any Stingray farm developer) could capture some or all of this value in its PPAs.

9.9.3 Upside potential in pricing - ROCS

This analysis has assumed that ROC prices return to their floor level of £30/MWh increasing at 2% per annum with inflation by 2015. Current estimates for new renewable capacity do not support this assumption, and it is likely that prices will remain considerably above the floor level for some time.

The valuations in this analysis are therefore likely to be conservative.

9.9.4 Upside potential in pricing – security of supply

It is increasingly becoming recognised that security of supply is of increasing importance to the UK electricity market. The significance of "distributed generation" within the UK will increase as the contribution from renewables increases.

The "grid codes" governing the connection of generators to the distribution network (Distributed Generation) are constantly evolving as OFGEM seeks to implement government policy by adjusting trading rules to achieve those policy desires.

The latest set of rule changes recognises that with the CO2 producing central generators set to decline to allow the UK to comply with the Kyoto 2010 obligation, that system security and stability will require the distributed generators to take on part of this responsibility. The Electricity, Safety, Quality and Continuity Regulations (January 31st 2003) implement a framework whereby the security contributions from distributed generation can now be recognised through rebates and payments.

The combination of the enabling legislation outlined above and the revised P2/5 "grid code" would open the way for Distribution Network Operators to offer either rebates or reduced, or even negative Distribution Network Use of System (DNUoS) charges. Provided that Stingray was designed to take advantage of such commercial terms, renewable embedded generators with predictable "fuel sources" such as Stingray could realise a substantial commercial advantage over the position with the grid codes that were previously in force. The precise level of advantage is difficult to quantify until the precise nature of the revised grid codes is known, and a proposed location for a commercial Stingray investigated.

9.9.5 Upside potential in pricing – select committee proposed fiscal changes

The recent House of Commons Science and Technology Committee report (HC55-I) criticised the current government policy and energy white paper as being insufficient to meet the stated aims of moving to a low carbon economy. In particular it advocated more powerful tax penalties for conventional generation and fiscal incentives for renewables (on a sliding scale to provide more support from less mature technologies such as Stingray) as being necessary. Any such moves would certainly increase the economic viability of Stingray within the UK domestic market.

9.9.6 International potential

It has always been recognised that the best opportunities for exploiting the commercial potential for Stingray technology may lie outside the UK, where energy prices are higher, and the tidal stream resource potentially larger. Table 6 shows ranges of power prices in various countries:

Country	**Year**	**p/kWh**
South Africa	2002	<1
Canada, Finland, USA, Australia, Luxembourg	2000-2002	2-3
Norway, Poland, Argentina, Denmark, Germany, Chile, France, Taiwan, South Korea, Greece, Spain, UK, Czech Republic, Portugal	1997-2002	3-4
Netherlands, Israel, Belgium, India, Singapore	2000-2002	4-5
Austria	2000	5-6
Ireland, Italy, Japan	2002	6-7
Dominican Republic, Nicaragua, Germany (West and South West)	1996-1999	7-8
Suriname, Germany (North), Japan	1996 - 1999	8-9
Barbados	1999	9-10
Grenada	1999	10-11

Sources:
1: Electricity Association, International Electricity Prices Issues 23 (1996) and 29 (2002) (World Industrial Electricity Prices)
2: Energy Prices and Taxes – Quarterly Statistics (Third Quarter 2000, Part II, Section D, Table 19, and Part III, Section B, Table 18) Paris, International Energy Agency, 2001

Table 6: International Industrial Electricity Prices

In addition to these prices, some countries offer higher feed-in tariffs for renewably generated power, most notably Portugal, where new renewable technologies are encouraged with a feed-in price of €0.235 for the first 20 MW.

There is clearly considerable potential for international application of the technology, as the Norwegian tidal turbine demonstrator installation at Hammerfestrøm also confirms.

9.9.7 Predictability

Wind and wave renewable power generation are intermittent, as they depend on unpredictable sources of energy. Tidal stream has a unique advantage in this regard, as its energy source is accurately predictable months (even years) in advance. We expect that the output from Stingray will therefore realise a premium price to wind and wave power, as it will benefit from this predictability.

9.10 Conclusions

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

To achieve this level of cost requires two significant steps – improving the power output from the Stingray machine as built and tested in Phase 2 and reducing the costs of producing, installing and operating a commercial farm of Stingray machines.

The ability to capture and convert the required levels of power requires that the machine can be designed to operate most effectively in current velocities between 1.25 and 2.25m/s, and that the power required to actuate the hydroplane at the lower velocities is decreased. The ability to convert the captured power to usable electricity requires improved efficiencies at several stages of the power chain – hydraulic system, generator characteristics and drive performance. EB is developing strategies to improve Stingray performance in all these areas, and plans to validate these by extended testing in Phase 3 of the programme.

The costs of design and manufacture of the machine will be reduced as a result of the lessons learned in the design of the prototype and the elimination of overdesign as the ability of the machine to avoid overload through control and better knowledge of the tidal currents at the selected site is improved. The costs of production, installation and operation of the machines will fall as the benefits of making multiple units are realised, and the installation and maintenance methods are refined.

The required levels of cost reduction are entirely consistent with other technologies, and with other industries, as demonstrated by published experience curves.

There are many factors that can affect the long-term viability of the Stingray technology. EB has generally taken a conservative approach to the financial modelling, but has identified a number of potential developments that would provide a financial upside and which would have the effect of making Stingray more commercially attractive to investors.

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

10 CONCLUSIONS

10.1 What did we set out to achieve?

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

10.2 What did we achieve?

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

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

10.3 How much power did we generate?

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

- Significant power is clearly available with 250 kW peak powers seen in a 3 knot current for a single sweep.
- Repeatable power cycles were achieved with peak power levels of 145kW and average power of 40 to 50kW in a 3.5 knot current.
- Faster cycle times required for higher levels of power generation were not achievable due to limitations in the actuation system.
- All powers quoted are hydraulic – they take no account of the losses in conversion to electricity. The drive output powers require further investigation.

10.4 How much power could we generate?

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

- Power cycles (both manually and automatically controlled) and experiments on site clearly indicate that significant power is available and that it is possible to construct a repeatable cycle. Analysis to date indicates that control development is key to moving closer to an ideal cycle.
- The phase relationship between arm and hydroplane control is very important in moving towards the ideal cycle. Further power cycle development work must concentrate on this area.
- It may be possible to incorporate hydroplane stall within the machine cycle and this should be considered in any further developments as a potential way of reducing the actuation power required.

10.5 What are the economics like?

The modelling undertaken indicates that Stingray technology could generate electricity at a price of between 5p and 10p per kWh within a foreseeable and achievable timescale.

10.6 Is Stingray technically and commercially viable?

- The Phase 2 operations have demonstrated the Stingray proof of concept – power can be generated from the oscillation of hydroplanes driven by moving water.
- Reasonable power generation levels have been recorded, and improvements to the system, particularly the control strategies and cycle times, should result in demonstrable improvements.
- There is strong evidence that Stingray has the potential to be commercially viable both within the domestic UK electricity market and in alternative markets.

10.7 What did we learn about improving Stingray?

- The current Stingray design is well suited to extract significant amounts of power from relatively high tidal current velocities – at lower velocities it is limited by the amount of power required to actuate the hydroplane.
- In Yell Sound, which may be typical of UK sites, most of the energy in the tidal stream occurs within the velocity range of 1.25-2.25m/s (2.5 – 4.5 kts). We need to ensure that Stingray is optimised to work over this velocity range.
- Power required to actuate the hydroplanes can be significantly reduced by changing the machine shape (longer, narrower hydroplanes), slower “flipping” of the hydroplanes, and optimising the control strategy.
- The efficiency of all elements of the drive train and power conversion and transmission must be increased, and incremental increases can be anticipated at each stage in the development.

11 REFERENCES

The Engineering Business Ltd, 2002. Research and Development of a 150kW Tidal Stream Generator. ETSU report T/06/00211/00/REP

International Energy Agency, 2000. Experience Curves for Energy Technology Policy