ISLAY LIMPET WAVE POWER PLANT

The Queen's University of Belfast

Contract JOR3-CT98-0312

PUBLISHABLE REPORT

1 November 1998 to 30 April 2002

Research funded in part by
THE EUROPEAN COMMISSION
In the framework of the
Non Nuclear Energy Programme
JOULE III

1 Executive Summary

In 1998 Queen's University Belfast in partnership with Wavegen Ireland Ltd., Charles Brand Ltd, Kirk McClure Morton and I.S.T. Portugal were commissioned to construct and test a 500kW shoreline wave power plant. The system known as LIMPET (Land Installed Marine Power Energy Transmitter) was installed on the Isle of Islay off the west coast of Scotland and was commissioned in November 2000. The plant has been operating remotely since that time and is supplying energy to the electrical grid in the United Kingdom. The successful unattended operation of the plant since commissioning has demonstrated the potential of shoreline wave energy for contributing towards national energy supplies.

The device comprises three water columns contained within concrete tubes each measuring internally 6m by 6m and inclined at 40^0 to the horizontal giving a total water surface area of $169m^2$. The upper part of the tubes are inter-connected and power conversion is via a single turbine generator unit connected to the central column. The water columns with an external width of 21m are located 17m inland from the natural shoreline in a man-made recess with a water depth of 6m at mean water level. The sides of the recess are virtually parallel and vertical.

The power take off system comprises a single 2.6m diameter counter-rotating Wells turbine in which each plane of blades is directly mounted on the shaft of a modified wound rotor induction generator rated at 250kW, giving an installed capacity of 500kW. The output from the generators is rectified and inverted prior to the grid connection and this enables variable speed operation with the range of 700 and 1500 r.p.m. The operational characteristic of the plant is software driven and can be altered. Noise produced by the airflow past the turbine rotors is attenuated in an acoustic chamber prior to discharge to the atmosphere. The turbine generator module also comprises a butterfly and a vane valve between the rotors and the plenum chamber.

The data acquisition system monitors all the main operational parameters throughout the power conversion process. In addition the incident wave energy has been monitored for a limited period using seabed pressure transducers, the wave loads on the front and back walls have been monitored and the water column movements have been measured using both pressure and ultra-sonic transducers.

The project has meet all the objectives originally specified and has been a significant achievement. A considerable amount has been learned about design, construction, power train matching, plant rating and costing. The operational experience gained will be vital to the future development of wave power systems both in the nearshore and offshore locations.

The most significant conclusions and observations are as follows:

1) The project has demonstrated the physical practicability of building a shoreline wave energy device in the lee of a natural rock wall cofferdam formed by excavation.

2) Subject to normal commissioning maintenance and minor problems, the collector and turbo-generation equipment have proven to be both robust and reliable.

3) The “Harbour wall effect” which has been shown in model tests to be beneficial to the performance of near-shore OWC systems is not effective in the LIMPET shallow water gully where the effect of the gully is, contrary to expectation, reducing pneumatic power capture. The reasons for this are not well understood and merit further study.

4) The control systems have operated well to allow safe automatic operation of the plant in all weather conditions.

5) With the reduced pneumatic power collection the plant operates at around 20% of its installed capacity for a significant part of the year. A most important consideration for future designs is that power train efficiency is maximised at part load. In addition it is probably not cost effective to install M&E plant rated to accommodate the peaks in the pneumatic power delivery. This results in high capital expenditure which is under utilised, and poor efficiency at average power production due to energy overheads related to installed capacity. However, reduced installed capacity necessitates either a bypass or in-line valve to limit the pneumatic power reaching the turbine.

6) The contra-rotating Wells turbine does not appear to offer a sufficient improvement in either peak efficiency or bandwidth performance relative to a bi-plane configuration to justify the additional cost of duplication of the mechanical / electrical components.

7) The natural rock cofferdam gave less protection against the weather than had been originally anticipated. Whilst this did not prevent completion of the device the construction time and hence the cost of the device was more than planned and to permit commercialisation of the technology we need to drive costs down further. Measurements of structural load on the plant have shown that in future designs this can be accomplished by significantly reducing the concrete and steel in the structure and by making more use of mass-produced elements and novel construction techniques. This will permit a significant reduction of in-situ construction with the subsequent reduction in construction time and cost.

8) The commercial exploitation of OWC’s will benefit from the development of a standard range of turbine generator sizes which can be installed either in parallel or even in series and the water columns would be sized to suite the M&E plant as well as the prevailing wave climate. These machines along with their air valves and their electrical control and monitoring systems should be tested in a purpose built facility in order to assure reliability of all components. Wavegen has initiated a design programme for such modular units.

Following on from this work new designs are being developed in combination with different construction methods and new materials. In future a simpler turbine generator module and control system is envisaged which in combination with the reduced structural content of the chambers will result in energy prices competitive with offshore wind systems.

The work completed has formed a vital step in the development of wave power technology and will result in the development of the next generation of oscillating water column systems as well as other types of device. LIMPET continues its grid connected operation on the island of Islay where it has become a major tourist attraction both enhancing the local economy and serving to demonstrate to the public at large the potential of wave energy generation and the role of the EU in supporting the development of renewable energy technologies.

2 Partnership

1. Queen's University Belfast
   Wave Power Research Group
   Dept. of Civil Engineering
   Queen's University Belfast
   Belfast
   BT9 5AG

   Prof. Trevor J.T. Whittaker
   t.whittaker@qub.ac.uk

2. Wavegen
   50 Seafield Road
   Longman Industrial Estate
   Inverness
   IV1 1LZ

   David Langston
   david.langston@wavegen.com

3. Charles Brand Limited
   21-23 Sydenham Road
   Belfast
   BT3 9HA

   Nick Fletcher
   info@charlesbrand.co.uk

4. Kirk McClure and Morton
   Elmwood House
   74 Boucher Road
   Belfast
   BT12 6RZ

   Dr Mike Shaw
   info@kmm.co.uk

5. Instituto Superior Tecnico
   Department of Mechanical Engineering
   Avenida Rovisco Pais, 1
   1096 Lisboa CODEX
   Portugal

   Prof. Antonio F. de O. Falcao
   falcao@hidro1.ist.utl.pt

3 Objectives of the Project

The industrial objectives of the LIMPET project were to:

- Develop a viable system for the production of electrical power from sea waves using a shore based energy conversion system.
- To develop the manufacturing infrastructure within the EU for exploiting the power generation system on a global basis.

The LIMPET project set out to evaluate different techniques to those used on the 75kW prototype in order to gain experience in a range of techniques and technologies.

The specific technical objectives were:

- To construct a shoreline oscillating water column wave power device with three columns giving a plane water area of $170m^2$.
- Install a counter rotating Wells turbine generator module with two generators of 250kw each.
- Connect to the electrical distribution grid and run the plant as a power station during the final phase of the work, producing an average annual output of up to 1,800MWhrs in a year with an average wave resource of 20kW/m.
- Fully instrument the plant, monitor the performance of the power transfer from wave to wire and compare with the predicted values obtained from the physical and mathematical models.

Provide the necessary information to improve the design of future wave power plant with a view to commercialisation of the technology both in Europe and Worldwide.

3.1 Economic Gains Forecast

The ETSU report R122 indicates, for the UK alone, an accessible shoreline wave energy resource exceeding 200MW of delivered power from the “most favourable sites”, which assuming a load factor of 40% indicates a scope for installing 500MW of shoreline plant. At an estimated installed cost of ECU 1,700/kW this suggested a potential business for hardware supply in the UK of MECU 850. A high proportion of this work is in mechanical and civil engineering and given that the majority of favourable sites are in Scotland, will offer valuable opportunities for traditional engineering industries now in decline to compete for the new business. In addition to the hardware supply there will be employment in maintenance and management of energy supply projects with an annual value estimated to be in excess of MECU40. This aspect alone may be expected to sustain full employment for 1000 persons.

In addition to the business generated in equipment supply and operation there will be a second major opportunity in the generation and supply of renewable power. The R122 estimate of 2TWh is worth annually 75MECU at a fully competitive unit price of 0.037ECU/kWHr. There are also indications that a higher price will be sustainable in the deregulated market where premium prices are available for “green” power.

The global market is likely to exceed that in the UK by a factor of at least 15:1.

3.2 Impact on the Environment

Shoreline wave energy is tied to coastal locations. The most favourable sites are in remote areas with small populations that are typically in decline. Reasons for decline are complex but the poor electrical supplies usually found in such areas may contribute significantly to the lack of development and development opportunity. The availability of wave energy will provide an economic stimulus during the installation phase and ongoing employment during operation. It will thus make a major contribution to the economic renewal of remote and isolated communities.

Whilst all power generation technologies have an environmental impact it is increasingly recognised that shoreline wave energy is amongst the most benign of all methods of power generation. By virtue of its placement the generating plant has a low visual intrusion and minimal impact on local flora and fauna. This minimal disturbance is a result of the structure replicating existing natural phenomena rather than imposing an alien culture on the locality. The low environmental impact was further demonstrated by the QUB 75kW prototype that was recently successfully decommissioned, returning the site to nature.

3.3 Future Development

The LIMPET plant as constructed is designed for research and development; consequently there are several aspects of the device that would not be replicated in a commercial unit. This applies to the main structure, the mechanical & electrical plant and the various control systems.

With the completion of the collector structure valuable information has been derived from the work performed to date, particularly with regard to effective construction techniques in the shoreline environment. It is believed that this experience will lead directly to a development of LIMPET offering significant commercial advantage over the current design.

The successful completion and commissioning of the LIMPET device has engendered confidence in the technology and has stimulated commercial interest. There are three market sectors where electricity generation from shoreline plant will prove attractive:

- Direct supply of electrical power to a grid system.
- Combined electricity supply and coastal/harbour defence.
- As an integral part of a stand-alone generation system in a remote location.

In addition to these general market areas in electricity supply the shoreline device has attracted great interest as a potential producer of pressurised seawater for a reverse osmosis desalination plant. In this application the turbine is not connected to an electrical generator but to a hydraulic pump/motor which is used to provide a constant pressure/variable flow supply of seawater to the RO plant.

4 Scientific and Technical Description

4.1 Introduction

The technical feasibility of a shoreline wave energy plant based upon an oscillating water column coupled to a Wells Turbine/Induction Generator combination was ably demonstrated in the UK by the 75kW prototype unit built by the Queens University of Belfast (QUB) with the support of the Department of Trade and Industry (DTI). This device was commissioned in 1991 and operated as a research tool for a period of eight years until it was decommissioned in 1999. During this period a wealth of information was gathered in respect of the problems of building energy gathering structures in remote shoreline locations, in designing for survivability, efficiency and low maintenance and in correlating field data to laboratory prediction. Whilst successful as a technology demonstrator the QUB prototype could not address many of the questions which need to be answered before shoreline wave energy could move towards commercial operation. For example:

- The construction method employed for the 75kW prototype device was developed specifically for the particular natural gully in which the unit was situated. Given the desirability of applying the technology beyond the range of suitable natural sites it was important that a more generally applicable construction concept was developed.
- The turbo-generation system of the 75KW prototype was connected direct on line to the grid and offered little flexibility for performance optimisation.
- The output of the prototype was insufficient to permit the development of an understanding of integrating a commercial scale wave energy generating plant into a supply network.

4.2 Location

QUB had previously performed a survey of potential sites which identified the north coast of Scotland, the western coast of some of the Scottish islands together with the northern coastline of Cornwall and Devon as the most promising areas. In selecting the LIMPET site there were a number of considerations:

- Wave climate.
- Availability of grid connection.
- Accessibility for the project team.
- Likely response of the local community to the project
- Tidal Range

The northern coastlines of Devon and Cornwall have an excellent wave climate for wave energy generation but have a large tidal range. The accommodation of large tidal variations increases the structural cost and this combined with the long distance from the base of the main project partners and an uncertain response to the project from the local population mitigated against this choice of location. There were a number of potential sites on the north Scottish coast between Strathy Point and Cape Wrath but all of these are remote from a useable electricity grid. The favoured sites were thus on the Hebridean islands and in particular on Lewis and on Islay. Islay was favoured because of its relative closeness to

Belfast and because of the good experience with the prototype device. At the start of the project it was considered that the Islay site offered the following:

- A good wave climate with an annual average intensity at the chosen site of approximately 20kW/m at the 10m depth contour.
- A close connection to the 11kV grid, which according to a report previously prepared for QUB, could accept the proposed 500kW generation capacity of the LIMPET device.
- A reasonable access via land and ferry or via air transport.
- Known local support for the project and a history of good relations with the local community.
- A low tidal range.

Within the island there were a number of suitable locations for LIMPET but for convenience a site at Claddach Farm near Portnahaven was chosen adjacent to that of the 75kW prototype.

4.3 Task 1 – Preliminary Work

4.3.1 Objectives

The primary objective of Task 1 was to complete all detailed design work on both the oscillating water column structure and the mechanical and electrical plant, including the production of all detailed construction and manufacturing drawings and the component procurement specification.

4.3.2 Partners Involved

Partner	**Task Responsibility**
QUB	General Specification of Plant
WGI	Detailed design of turbine generator
CBL	Construction aspects of civil design
KMM	Civil Engineering Design

4.3.3 Description

The LIMPET plant comprises three discrete elements:

- A shoreline oscillating water column collector.
- A turbo generation unit
- Control and monitoring station

It should be stressed that the primary design consideration was not the construction of a commercially viable design of wave energy collector but the building of a research station which would permit the future development of a commercial unit. To that end the design incorporated, within the allowable budget, a range of features to provide a flexibility of operation and which would give a wide scope for adjusting operational parameters in the search for optimal performance.

4.3.3.1 Oscillating Water Column Collector

The design of the OWC collector took into consideration a large number of factors including:

- Target generation capacity
- Environmental loads
- Site accessibility
- Preferred construction materials.
- Proposed manufacturing technique
- Applicability of the design to a "general" site.
- Decommissioning

The actual design process is an iterative procedure and the development of the final LIMPET design only emerged after numerous consultations between the project partners.

4.3.3.1.1 Form of the Collector and Manufacturing Method

Whilst there was early agreement by the project team that the LIMPET project should be firmly based on an OWC there was considerable debate as to the form of collector, the materials of construction and the manufacturing technique. For a wave energy device to be successful it must be situated in a location with an energetic wave regime and a fundamental consideration of any design is the construction of the device in that hostile environment. With the 75kW prototype device the problem was overcome by isolating the construction site from the sea by placing a cofferdam across the entrance to the natural gully forming the site. This was possible as the gully was only 5m wide. It was only partially successful and a complete seal was not achieved. However, it did insulate the construction from the worst effects of the weather during the build period and allowed for a successful completion of the structure. The practicality of the cofferdam in the device resulted from the relatively sheltered position of the prototype site and the narrow width of the collector. This solution would have been disproportionately expensive for the much wider LIMPET device in deeper water on a more exposed site. The decision was therefore taken to remove the construction from the exposed site and two main ways of achieving this end were considered.

4.3.3.1.2 Remote Manufacture

The first consideration was to completely remove the construction from the exposed site. In one variant a cylindrical steel collector would be fabricated at a suitable location and then floated to the site for fixing to the prepared housing in the cliff face. Steel was the preferred construction material in this instance in that the draft would be much lower than that of a reinforced concrete unit of similar external dimensions thereby making both the tow and the installation relatively easy. Whilst conceptually simple there are fundamental problems with this concept:

- Experience had shown that the costs for marine activities similar to that described are extremely difficult to control. The activities are highly dependent on local weather conditions and the costs can vary dramatically with vessel availability at the required time. For a relatively small project variations in marine costs can play havoc with the initial budgetary estimates.

- It proved difficult to develop an installation technique for a steel structure that did not involve a high risk of damage during installation.
- Budgetary estimates for the steel structure were out with the initial estimates rendering the concept non-viable.
- A requirement remained for preparing connections to the cliff face in exposed conditions.

The second option was to build the collector close to the cliff edge and then slide the completed unit into position. Again the proposal was initially developed around a steel structure (and rejected on cost grounds) but could also be applied to a lower cost reinforced concrete construction. The weight of each concrete collector chamber element was in excess of 400 Tonnes. That was considered to be too difficult to handle at the remote Islay site. In addition the problems of preparing the connection to the cliff face still remained. The concept of remote manufacture was thus rejected for this project although in future it might be suitable for other locations.

4.3.3.1.3 Protective Excavation

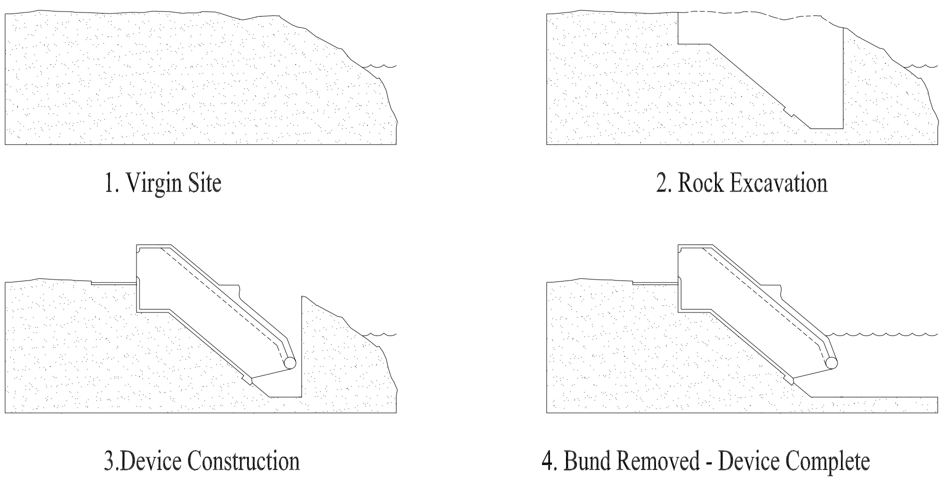


Figure 1. Construction Concept for LIMPET

The construction procedure finally adopted for LIMPET is described in Figure 1**.** Instead of building directly at the cliff edge, an excavation was made a little way back from the edge leaving a rock bund between the construction site and the sea. The construction was then performed in the protective lee of the bund and when the structure was complete, the bund was removed to allow the ingress of water into the OWC. There were two important considerations with regard to this concept. Firstly, the protection offered by the bund proved to be imperfect so that there were still interruptions due to waves. Secondly, there were performance implications in moving the OWC from the cliff edge to a position set back 17m from the edge. There was conflicting evidence on the effect of the change of position on performance and these are not well understood. The expectation was that moving the device back from the cliff edge would create a “Harbour” effect and broaden the response bandwidth of the device leading to an improvement in power capture. Initial testing in the Wavegen tank in Inverness however indicated a drop in performance. This was thought to result from the shallow water depths of between 5 to 7 m while previous research had been with deeper water. This testing was not however wholly rigorous and a more thorough investigation of the influence of device position on performance is one of the topics for further research

4.3.3.1.4 Collector Shape

Whilst curved forms have a clear structural advantage and offer a better economy of material use the low intrinsic cost of concrete makes it more cost effective to thicken wall sections of a flat slab structure rather than adopt a curved form. It was therefore decided to use a rectangular water column.

It was also decided that the water column should be inclined. This has two distinct advantages in relation to a vertical water column such as used on the 75kW prototype:

- The inclined column offers an easier path for water ingress and egress resulting in less turbulence and lower energy loss. This is particularly true at the shoreline where shallow water effects have increased the surge motions relative to heave.
- The inclination of the water column increases the water plane area of the water column for a given chamber cross section. This reduces the structural spans and assists with tuning the natural period of oscillation of the water column to the prevailing incident wave periods.

The improved performance of inclined water columns in comparison to their vertical counterparts had previously been established in tank tests both by QUB, and independently by Wavegen.

4.3.3.1.5 Size of Collector

During the operation of the 75kW prototype device the team at QUB developed a significant database on the energy incident of the prototype test site. Through a detailed analysis of this information a set of 53 sea states were developed as representative of the wave climate. These seas are summarised in Table 1. From this data an annual average incident wave energy of 15.9 kW/m was estimated. The reference location for the source data was 300m from the actual LIMPET site and was located in the side of a headland. Consequently it was expected that the average incident power at LIMPET would be greater as the site directly faced the waves.

Determination of the optimal size of a LIMPET type device was and still is a difficult process. It was considered that the next stage of development after the 75kW prototype should represent a significant size increase and offer the basis for modular development. An installed capacity of 500kW and a utilisation of 40% to give an annual average output of 200kW appeared to be reasonable targets and formed the basis of the design process.

Testing at both QUB and at Wavegen in Inverness indicated that correctly tuned OWC/Wells turbine/Induction generator systems should offer an overall conversion efficiency to electricity of 50% of the power incident on the collector width and on that basis an overall collector width of 21m was selected as suitable to meet the power output objectives.

Sea State	Tz (s)	Hs (m)	Power (kW)	% Occurrence
1	10.0	1.5	8.8	1.85
2	12.4	1.6	9.6	0.40
3	7.6	1.6	8.9	2.87
4	9.8	1.5	9.4	8.18
5	10.0	2.5	24.8	1.42
6	11.9	1.6	10.1	0.76
7	11.8	2.4	23.3	1.13
8	11.9	2.9	33.6	0.18
9	14.7	2.2	21.4	0.18
10	7.6	1.5	8.9	9.23
11	7.6	1.5	21.6	0.33
12	9.6	1.6	10.0	10.83
13	9.6	2.5	25.5	4.98
14	10.0	2.9	34.2	0.36
15	11.8	1.6	10.7	0.87
16	11.3	2.4	22.7	2.18
17	12.2	2.9	35.3	1.53
18	12.3	3.5	48.8	0.33
19	13.1	2.8	34.2	0.15
20	13.6	3.4	50.9	0.15
21	7.6	1.6	10.4	9.49
22	7.7	2.6	25.2	0.98
23	9.7	1.6	10.5	8.98
24	9.6	2.4	23.0	7.09
25	10.1	3.0	37.8	1.67
26	10.1	3.6	51.6	0.18
27	11.5	1.6	11.5	0.62
28	12.3	2.3	22.2	0.87
29	12.0	2.9	35.9	1.49
30	11.8	3.5	51.9	0.87
31	11.7	4.0	66.4	0.55
32	7.6	1.5	9.5	3.60
33	7.8	2.4	23.5	0.62
34	9.6	1.5	10.1	3.09
35	9.5	2.4	23.4	2.51
36	9.7	3.0	38.9	1.93
37	9.8	3.6	56.1	0.47
38	9.9	4.0	67.3	0.07
39	12.6	2.2	21.1	0.36
40	11.7	3.0	38.1	0.73
41	12.2	3.6	56.2	0.76
42	11.7	4.1	75.5	0.47
43	11.3	4.4	83.7	0.15
44	14.8	3.5	56.9	0.07
45	13.6	3.9	71.8	0.04
46	13.5	4.4	89.9	0.11
47	10.0	2.5	26.6	0.25
48	9.7	3.0	37.3	0.47
49	10.1	3.7	58.5	0.29
50	11.9	2.9	37.3	0.15
51	12.1	3.6	56.6	0.40
52	11.9	4.1	73.9	0.44
53	13.4	4.4	92.6	0.07

Table 1. Representative Sea-States for Islay Site

4.3.3.1.6 Collector Cross Section

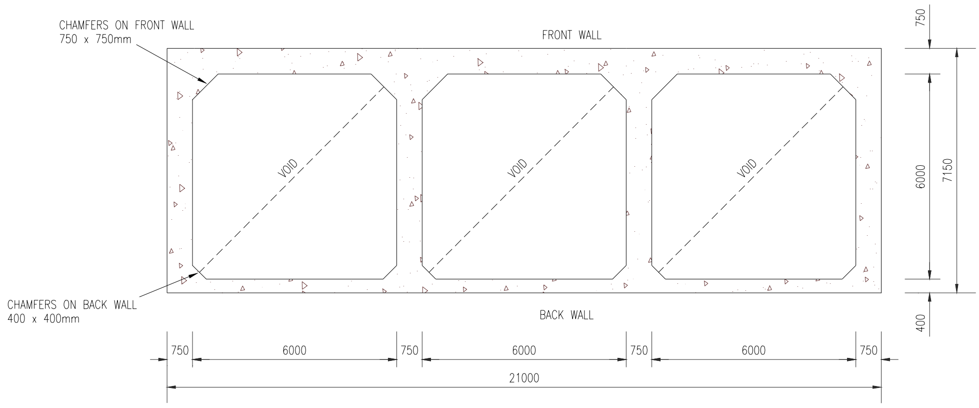


Figure 2. Axial Section through Collector

Having established the width at 21m it was decided that it would be necessary to divide the water plane into three separate columns. This is for two reasons:
As the width of the column increases there is an increasing risk of transverse wave excitation within the water column. This reduces the energy capture performance of the column. Whilst the 6m width of the prototype device is known to perform satisfactorily it is believed that a significant increase above this might cross the limit of acceptability.
The depth of roof required to span the 21m width of the column without additional support is so large as to be economically inefficient.

Having established the cross section of the working chamber a decision was required as to what method should be adopted to hold the four walls to the base rock. There were two clear choices; either the walls could be fixed directly to the excavated slope with rock anchors or a rear wall could be cast on the excavated slope so that the cast structure formed a closed circuit in terms of load containment. For a number of reasons the latter option was selected. The roof is subject to downward loads from external wave action and upward forces from the internal pressure generated by the OWC action. Model tests had indicated an internal design pressure of 1bar which translates into a linear load on the walls of approximately 450kN/m. Whilst this figure does not take account of the weight of the structure there remains a substantial anchor requirement. This coupled with the fact that the quality of the surface to which the walls would be anchored would not be known until after the excavation was complete and that a rough surface on the rear water column would detract from the column performance reduced the attraction of direct fixing. The role of the LIMPET as a research tool again weighed heavily in the thinking and despite the likely cost penalty the closed option as shown in Figure 2 was selected.

4.3.3.1.7 Sectional Side Elevation

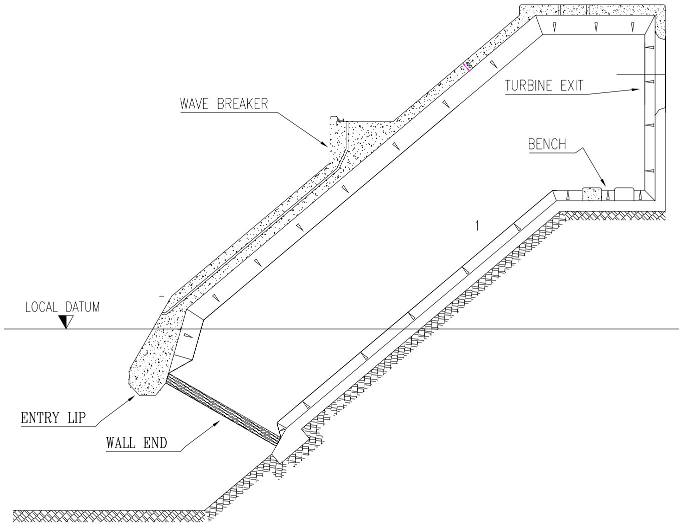


Figure 3. Sectional Side Elevation

Features of the sectional elevation of the collector are described with respect to Figure 3. For the majority of the length of the collector the front and rear walls are parallel and make an angle of 40^{o} to the horizontal. Close to the entry lip the exterior surface of the front wall steepens to 60^{o}. This has the effect of reducing the 6m separation of the front and rear walls to approximately 4.5m over the area of water entry. The restriction of the entry area is important both for proper tuning of the device but also has a secondary influence on power smoothing. The team at QUB has established that the form of constriction adopted for LIMPET appears to act in a non-linear fashion in that the outflow seems to suffer a greater restriction than the inflow. This is extremely useful in that it greatly reduces the susceptibility of LIMPET to inlet broaching. It is quite common with OWC devices that as the water level outside the collector falls to a point below the level of the entry lip a direct air passage can be opened between the working chamber and atmosphere. When this happens there is a rapid equalisation of pressure between the chamber and atmosphere and no useful work can be done by the turbine. The wave height at which this broaching starts to occur is a function of the depth of penetration of the entrance lip of the water column at still water, the state of the tide and the dynamic characteristics of the water column. The LIMPET form however appears to eliminate inlet broaching in that the restriction on outflow is sufficient to ensure that the water forced into the chamber during the inflow continues to flow from the chamber throughout the down stroke even when the external water level is two to three metres below the entry lip. The test results indicate that this effect does not result in power loss but is achieved by decreasing the peak efflux velocity thereby smoothing the power on the outflow.

The entry lip is has a 1.5m diameter to reduce turbulent losses at the entry. It is desirable that the diameter at the entry should be as large as possible and the size chosen is a compromise between the technically desirable and the economically practicable. In the construction the entry lip is formed from rolled steel plate keyed into the concrete by rebar. This steel acts as a permanent shutter. The rebar connected to the steel section is separated from the structural reinforcement and is likely that over the life of the structure the entry steel may corrode badly or even be totally lost. Under these circumstances the reinforced concrete cast inside the circular form will maintain structural integrity.

Collector Roof	12.50
Turbine Axis	9.84
Top of Turbine Slab	8.30
Bench Level Inside Collector	4.94
Top of Wave Breaker on Front Wall	8.30
Start of 60o slope on Front Wall	2.40
Mean High Water Spring Tides	0.76
Local Datum	0.00
Mean Low Water Spring Tides	-1.34
Underside of Entry Lip	-2.63
Bottom of Diaphragm Walls	-4.52
Sea Bed under Lip	-7.00

Table 2. Reference Heights for the Collector

The ends of the two diaphragm walls are similarly formed using a half section of 750mm diameter steel tube with the dual function of smoothing water entry and acting as a permanent shutter.

Model testing at Wavegen had indicated that amongst the most severe of the load conditions to which an OWC collector may be subjected is internal water slam. This occurs when the inrush of water is sufficient to completely displace the air in the chamber. As the water flows into the collector it flows freely upwards displacing air through the turbines. If however the collector chamber should become full then the water in the column will decelerate rapidly in respect of the added resistance to the flow of water through the ductwork as compared to air. The loss of momentum of the suddenly arrested water can result in extremely high pressures within areas of the collector chamber. Notwithstanding the danger of excessive internal loading there is a high risk of damage to the turbo generation equipment in the event that bulk water flows into the duct. For both these reasons care has been taken to make the water column sufficiently long that the water within the collector will not rise higher than the bench level. As a further precaution a number of chute blocks have been incorporated into the bench floor so that in the unlikely event that water does reach this high the flow is disturbed before it hits the rear wall. Any water reaching bench level still has nearly 5m to rise before reaching the turbine axis (see Table 2) and as such, whilst there will inevitably be heavy spray passing through the turbines, it is believed that this precautionary design will prevent any bulk ingress of water into the turbine ductwork. Similar considerations exist in respect of water flows outside the collector during storm conditions. The sloped front wall provides an excellent ramp to encourage storm waves to flow up the wall and crash down on the turbo-generation equipment mounted behind the collector. The wave breaker on the front wall is designed to interrupt such flow and to ensure that the water falling behind the collector is highly aerated reducing the effective density. A smaller secondary wave breaker is positioned at the top of the collector.

Air exits the collector through one of two 2.6m diameter circular openings in the back wall and into the turbo-generation duct. The central opening is used whilst the second opening is blanked off but may be used at a later date to test alternative equipment. To allow the air from all three of the water columns to be fed into the single central generation system, 3m x 2.4m openings are provided in each diaphragm wall at bench level. To give further research opportunities the potential for closing off these openings was included in the design.

One metre square openings were left in the roof of the two northern collector chambers to allow for the fitment of a pressure relief valve if required at a future date. Again it is anticipated that one opening will be used and one will act as a spare. Both these orifices were blanked at the time of initial commissioning.

4.3.3.2 Turbo-Generation Equipment

4.3.3.2.1 Overview and General Description

The operational design parameters for the Wells turbines to be fitted to the collector were specified by QUB. The responsibility for the design and construction of the turbo generation equipment conforming to these parameters lay with Wavegen. The basic turbine parameters are as listed in Table 3.

Turbine Diameter	2.6m
Nominal Operating Speed	1050rpm
Number of Turbines	2
Arrangement	In Line Contra-rotating
Blade Form	NACA0012
Number of blades	7
Blade Chord	320mm
Hub to Tip Ratio	0.62

Table 3. Turbine Parameters

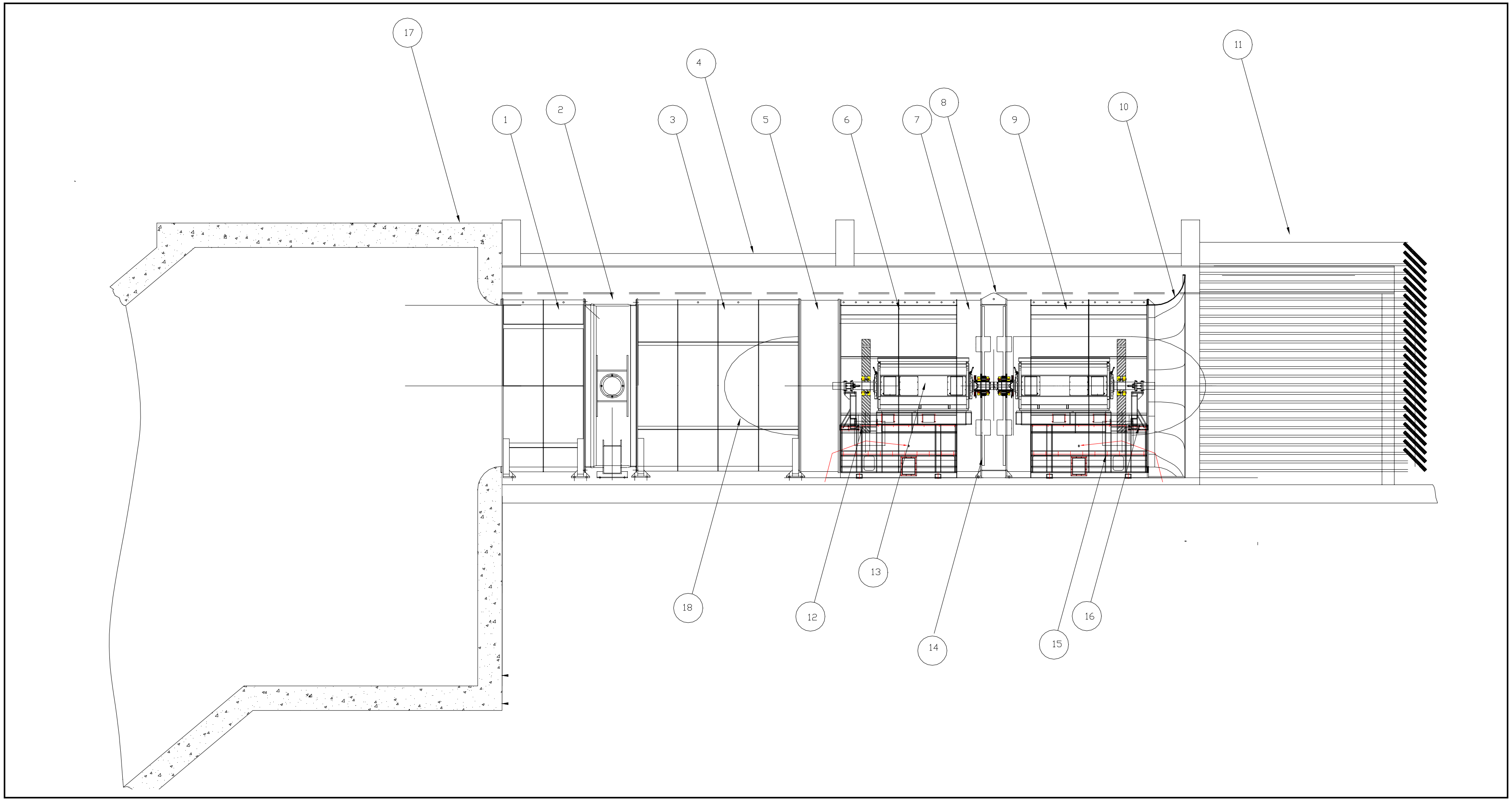


Figure 4. Arrangement of Turbo Generation Equipment

Wavegen had built full size Wells Turbine systems both for the Osprey bottom standing OWC and for the wave power plant on Pico in the Azores. Through these projects they had gained extensive experience relevant to the design and construction of the units for LIMPET. This was supplemented by the operational experience of QUB with the 75kW prototype.
Figure 4 shows a side view of the layout of the mechanical components of the turbo-generation equipment and Figure 5 a cross section at the turbine. Air from the collector (17) flows into a 2.6m diameter duct 1342mm long (1) which is connected to the collector by a ring of 32 M24 screws. A butterfly valve (2) is connected at the outer end of the duct section. The prime function of this valve is to isolate the turbines from the collector either for maintenance purposes or in the event of an emergency. The actuator was designed to permit modulation so that at times of excessive wave activity it would be possible to reduce the power input to the turbines. The valve system was initially assembled using an hydraulic actuator and controls but during testing at the assembly facility of Wavegen in Inverness it was concluded that the system was overcomplicated and likely to suffer an unacceptable rate of breakdown in service. Before delivering to site, this was replaced with an electrical actuator. This actuator drives the valve into the demanded position against a counterbalance weight. Once in position it is held steady by an electromagnetic brake. In the event of a power failure or a demand for an emergency closure the brake supply is interrupted and the valve closes under the influence of the weight.

A further duct section (3) 2658mm long separates the butterfly valve from a second valve. Immediately prior to the second valve is an elliptical nose cone (18) which constrains the flow to an annular ring at the outside of the duct. The second valve (5) is of a radial vane configuration and is pneumatically operated. It duplicates the function of the first valve but offers a faster closure in emergency. It is less suitable for long-term usage in a modulating mode.

The use of two valves of different design and with different actuation systems was a cautious approach to the introduction of untested equipment into a new environment. Whilst air is driving the turbines the only restriction on them accelerating beyond their bursting speed is the torque imposed by the generators. If at any time there is a control failure or the grid connection is lost then it is imperative that driving air is removed from the turbines. The isolating valves achieve this. In the longer term it is likely that a single valve will suffice but

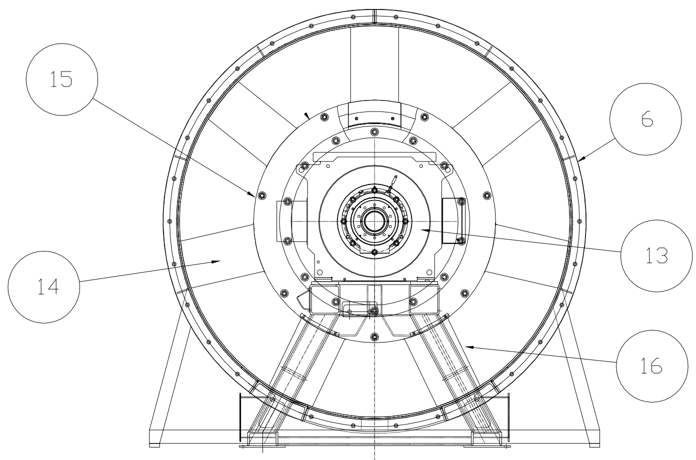


Figure 5. Axial section of Turbine Generator Duct at Turbine

until operational experience has been gained and history of reliability established it was considered prudent to operate with two independent systems.

Air from the collector passing through the variable vane valve enters the first of two turbine/generator modules. Each module comprises:

- Frame (16)
- Generator (13)
- Turbine (14)
- Flywheel (12)
- Inner ducting (15)
- Outer ducting (6)
- Encoder
- Parking Brake
- Turbine Runner (8)

The generator has a through shaft and is fitted with bearings designed to accommodate the alternating axial thrust imposed by the turbine action. The turbine is mounted at one end of the generator and a flywheel, for energy storage, at the other. The combined inertia of a single assembly was estimated to be $1300kgm^2$.

The two turbine/generator modules were fitted back to back so that the turbines are separated by approximately one blade chord.

When initially commissioned, at the exit from the second turbine/generator module the air flowed into a settling chamber (11) with louvered exits. This chamber prevented line of sight into the turbine ducting and provided a first level of attenuation for duct-borne noise. The installation design used wooden slats for the louvres but following a noise survey performed after commissioning these were replaced by an acoustic chamber. A nose cone was fitted to the exit end of the second module to smooth the transition of the airflow.

4.3.3.2.2 Turbine Mounting

A fundamental design choice was the decision either to mount the Wells Turbine on independent bearings or to mount it directly on to the generator shaft. Standard generator bearings are unsuited to carry the large alternating axial loads which are generated by the action of the alternating airflow on the Wells turbine. Certain generator manufacturers are however willing to manufacture to a purpose design based upon their standard range and this offers a compact arrangement with the generator placed within the diameter of the turbine hub. (It should be noted that for assemblies rated below 200kW the inner annulus will probably be too small to contain the generator and as such the mounting of the turbine on the generator shaft is not an option below this size). The use of non-standard generators carried a significant cost penalty at the development stage. Conversely the mounting of the turbines on independent bearings and the use of standard generators would have given a direct saving on generator cost but would have incurred additional expenditure on the turbine frame, shaft, bearings and couplings.

There are also maintenance implications. Mounting the turbine directly on the generator shaft reduces the total number of bearings so that there are fewer components to fail. Conversely the bearings on an integral turbine generator module are likely to be more heavily loaded than those on a separate turbine assembly and as such will probably require more frequent maintenance. Furthermore it is also likely that the cost of maintenance of the combined turbine generator will be more than that of the separate installation.

There are thus a number of factors which influence the decision on turbine mounting and the optimal choice may only emerge with more operating experience. In the longer term it is considered desirable to do all that is possible to reduce the capital cost of wave generation since it is this cost that is currently the prime determinant of the cost of wave generated electricity. In a fully developed system it is likely that the generator mounted turbine route offers a lower capital cost by virtue of the smaller number of components. Under these circumstances it was considered important to gain field experience of the generator mounted turbine and this system was adopted for LIMPET.

4.3.3.2.3 Generator Bearing Loads

During model testing of the LIMPET device in the ART wave tank in the 53 representative sea states, a series of measurements were made including a record of chamber pressure. Each record comprised 4096 data points scanned at 32Hz giving a total of more than 200,000 readings of chamber pressure over the full range of likely operating conditions. The individual measurements for each sea state were sorted by the team at QUB into a pressure distribution with a bandwidth of 1kPa. This distribution was combined with the proportion of time for which each sea state was applicable to give a weighted pressure distribution which was taken as representative of the chamber pressure during the life of the device. The distribution is shown in Figure 6. These pressures will act upon the turbine to provide an axial thrust which must be resisted by a thrust bearing within the turbo/generator support system. An equivalent constant mean load (Fm) may be calculated from the instantaneous loads from:

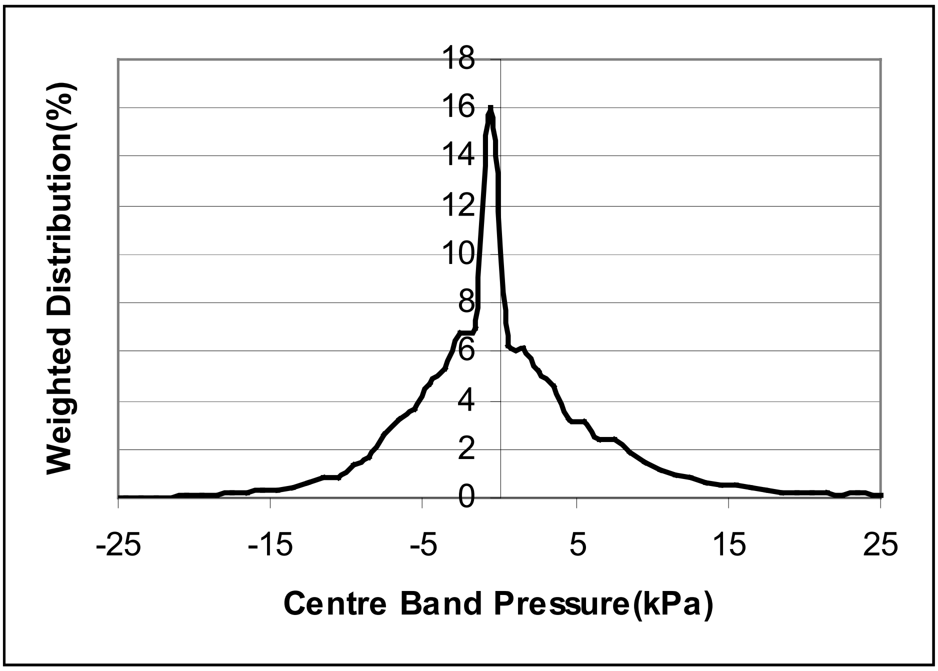


Figure 6. Pressure distribution with LIMPET collector

$$Fm = \sqrt[3]{\frac{F_1{}^3U_1 + F_2{}^3U_2 + F_3{}^3U_3 + \ldots\ldots\ldots}{U}}$$

where

$F1, F2\ldots$ = constant loads during U1, U2... revs

U= total number of revs

Since a different element of the bearing assembly may take the axial load in the positive direction to that in the negative direction, a separate summation was made for the positive and negative loads. In each case the value of U used in the divisor was the total number of occurrences, both positive and negative. Using this assumption the equivalent constant Pressures (in respect of equivalent bearing load) were:

For positive axial loads $P+ = 8.7kPa$
For negative axial loads $P- = 5.5kPa$

It was decided for design purposes to take an equivalent constant pressure of ±9kPa, this is the pressure drop across both rotors and therefore must be halved to give the effective axial loading on each generator bearing set.

These effective mean values compare with a maximum recorded positive pressure of 111kPa and a minimum negative chamber pressure of -47kPa.

4.3.3.2.4 Form of Controls

The input power to any wave energy generator is variable in both the short and long term. Each wave cycle producers two power cycles giving a short-term variation, and fluctuation in the medium and long-term wave environment gives a corresponding change in the output of the generator. Subject to the local conditions a control strategy is necessary to accommodate these fluctuations. Four basic control strategies, and combinations, were considered:

- Direct on line (DOL) connection.
- Variable Rotor Resistance
- Dump Load
- Inverter Drives.

a) DOL Connection

DOL is the simplest form of connection but offers no active control over the generation. It relies upon the grid being able to absorb all the power spikes generated and also being able to supply power when losses (friction and windage) exceed generation at times of low wave activity. A system-connected DOL will normally use a low slip generator with low rotor currents and hence offer a high generator efficiency. The small speed range of a low slip generator will also mean that little energy can be stored in the system inertia and as such power smoothing is extremely difficult. A further disadvantage of the system is that the generator is effectively operating at fixed speed so that there is no opportunity to tune the system using turbine speed as a variable. As a consequence of the narrow flow coefficient bandwidth of a fixed geometry Wells turbine, it is essential to operate at variable speed to accommodate significant variations in airflow and to avoid excessive periods of stall in the rotor blades. The grid at the LIMPET site is however not capable of accepting the full generation of the LIMPET and as such a simple DOL connection is not acceptable.

b) Variable Rotor Resistance

If a wound rotor induction machine is used the rotor resistance may be altered to change the torque/slip characteristic of the generator thereby varying the electrical power generated at any particular speed. In general terms the higher the rotor resistance the steeper the torque/slip characteristic. By softening this characteristic it is possible to increase the speed variation within a single wave cycle so giving the opportunity to feed power into, or to take power from an inertial store. By this means the output power can be smoothed so that in principal the system can be connected into a weaker grid than would be required by a DOL system. The low rotor resistance necessary to give a useable speed range will however result in significantly higher rotor currents and a consequent loss of conversion efficiency. Cost is also involved in the mechanism for continually changing the resistance and for the external resistances themselves.

c) Dump Load

Whether the generator is connected DOL, or DOL with resistor control the average generation will be much less than the peak and it is likely that there will be times with LIMPET where the electrical generation exceeds the capacity of the grid to accept power. Under these circumstances it is necessary either to predict the occurrence and prevent the input power reaching the turbine or to dump the power before or to dump the excess via a parallel connection to a bank of resistors.

d) Inverter Drives

Inverter drives for induction machines take the grid supply and convert it to DC. The DC is then inverted to an AC supply of a voltage and frequency which may be varied in real time to suit the particular application. It thus offers the electrical generation to be varied over a very wide speed range so that a much higher degree of power smoothing can be obtained from a given inertia and the mean operating speed can also be varied to change the column damping. In principle the system permits generation from any finite speed up to the system maximum but in practise since the ability of the turbine to absorb power falls with the cube of speed, power extraction at low speeds can create a situation where the turbine can no longer absorb enough power to accelerate back towards its ideal working range and overall efficiency falls dramatically. The inverter drives also allow the power factor of the power delivered to the grid to be set thereby avoiding the cost of additional power factor correction. Despite this there is a substantial additional cost to adopting inverter control of generation as the inverters must be rated for the maximum output from the generators. However, in the research environment, there is no doubt that the system offers a range of operational options which would not otherwise be available.

4.3.3.2.5 The LIMPET System

The control philosophy originally determined for LIMPET was to use a wound rotor machine with thyristor switched rotor resistance, coupled direct on line with dump resistors to absorb excess power. There were however a number of concerns with the system. Not least of these were that both the rotor and dump resistances could only be switched in discrete blocks leading to both inefficiency of operation and potential problems with system transients. Wavegen decided that, because in the longer term they were seeking to maximise revenue from the sale of power under the SRO, and because they were anxious to learn as much as possible from LIMPET they would bear the additional cost of the full inverter drive system. By this time the wound rotor machines had already been ordered and are now used with a fixed rotor resistance and internal connections replacing the external rotor connections. At the same time the external dump resistors were removed from the specification whilst leaving provision within the layout of the control hardware to reintroduce them at a later time.

4.3.3.2.6 Generator Type & Source

The generator specification is summarised as shown in Table 4 and was put out to tender.

The cooling air circuit for the generators enters and exits through the underside of the generator. The legs of the generator support frame have a sandwich construction and the core of the sandwich provides a convenient path for the inlet and exit of the cooling air and also the generator instrumentation. An external fan is fitted to provide forced circulation.

<table>
<tr><td colspan="2">Power at Generator Terminals</td><td colspan="2">250kW</td></tr>
<tr><td colspan="2">Duty Type</td><td colspan="2">Continuous with Slip adjustment 1-20%</td></tr>
<tr><td colspan="2">Rotor Type</td><td colspan="2">Wound Rotor</td></tr>
<tr><td colspan="2">Service Factor</td><td colspan="2">1.00</td></tr>
<tr><td colspan="2">Rated Voltage (Delta Connected)</td><td colspan="2">400V 610%</td></tr>
<tr><td colspan="2">Rated Speed</td><td colspan="2">1016RPM</td></tr>
<tr><td colspan="2">Maximum Test Speed</td><td colspan="2">1500RPM</td></tr>
<tr><td colspan="2">Number of Poles</td><td colspan="2">6</td></tr>
<tr><td colspan="2">Starting Type</td><td colspan="2">Fixed Rotor resistance or Inverter Drive</td></tr>
<tr><td colspan="2">Generator Inertia</td><td colspan="2">11.5kgm2</td></tr>
<tr><td colspan="2">Load Inertia</td><td colspan="2">1300kgm2</td></tr>
<tr><td colspan="2">Estimated Starting time</td><td colspan="2">Machine is capable of being started as a motor from rest. Estimated starting time is 14min per machine due to current limit of 125A on local supply</td></tr>
<tr><td colspan="2">Number of Successive starts</td><td colspan="2">3 Cold, 2 Hot</td></tr>
<tr><td colspan="2">Ambient Temperature</td><td colspan="2">≤40oC</td></tr>
<tr><td colspan="2">Enclosure Protection</td><td colspan="2">IP56</td></tr>
<tr><td colspan="2">Cooling Air Flow</td><td colspan="2">0.5m3/sec</td></tr>
<tr><td colspan="2">Pressure Drop in Generator air Circuit</td><td colspan="2">400Pa</td></tr>
<tr><td colspan="2">Bearing Type</td><td colspan="2">Spherical Roller 22326</td></tr>
<tr><td colspan="2">Generator Life Expectancy</td><td colspan="2">30 years</td></tr>
<tr><td colspan="2">Bearing Life expectancy</td><td colspan="2">100,000hrs</td></tr>
<tr><td colspan="2">Shaft material</td><td colspan="2">Marine Grade 316 stainless</td></tr>
<tr><td colspan="2">Lubrication</td><td colspan="2">Grease – Lubrication Interval 8000hrs</td></tr>
<tr><td></td><td>Full load</td><td>¾ Full Load</td><td>½ Full Load</td></tr>
<tr><td>Efficiency (%)</td><td>94.6</td><td>94.5</td><td>93.5</td></tr>
<tr><td>Power Factor</td><td>0.82</td><td>0.78</td><td>0.65</td></tr>
<tr><td>Current (A)</td><td>465.2</td><td>376.5</td><td>296.9</td></tr>
<tr><td colspan="2"></td><td>%</td><td>Nm</td></tr>
<tr><td colspan="2">Rated Torque</td><td>100</td><td>2350</td></tr>
<tr><td colspan="2">Breakdown torque</td><td>260</td><td>6100</td></tr>
<tr><td colspan="2"></td><td>V</td><td>A</td></tr>
<tr><td colspan="2">Rotor Characteristics</td><td>435</td><td>351</td></tr>
</table>

Table 4. Generator Specifications

4.3.3.3 Control Hardware

The core of the LIMPET control is a microprocessor control unit. This system takes in the various input signals from sensors and supplies appropriate output signals.

The hardware comprises:

No	Description
1	Primary control unit including 2x16 bit microprocessors and one 24 bit digital signal processor. RS232/RS485 communications 43 digital inputs,4 Thermistor inputs, 4 high speed inputs,11 temperature inputs, 4 analogue inputs, 3 current inputs via external trafo, 3 voltage inputs via external trafo, 24 relay, 2 analogue outputs opto insulated.
1	Multi I/O computer
1	Grid surveillance module. (Provides G59 protection)
1	4-Channel analogue input board
1	4-Channel analogue output board
2	Instrument interface
1	RS232 interface
1	Graphic service module
1	Plastic fibre optic interface

Table 5. Control Hardware

The hardware is programmed in "C" to fulfill the following core functions:

1) Determine whether it is safe and desirable to operate the plant.
2) Start up the equipment.
3) Control the generation and monitor the operation of the plant, instituting an appropriate shutdown in the event of problem.

4.3.3.3.1 Pre-start Check

Before allowing the plant to start the software performs a number of checks including:

· E-stop circuit closed.

- No warnings from any monitoring equipment
- Adequate energy entering the water column

4.3.3.3.2 Start up

The start routine includes the following:

- Operates the vane valve to check function
- Operates the butterfly valve to check function
- Starts generator 1 and motors to a set speed. Generator 1 then enters production.
- Starts generator 2 and motors to a set speed. Generator 2 then enters production.

4.3.3.3.3 Power Production

Once in power production the control system enters a monitoring and checking phase. Valves are periodically cycled to check function and the unit will shut down either in the event of a fault condition or if the input wave energy falls below a minimum level. Fault conditions include:

- Excessive turbine speed
- High bearing temperature
- Excessive bearing vibration
- G59 Fault (over/under voltage/frequency, phase imbalance etc)

The controller software also provides control signals to the two valves and to the two generators. The generators are inverter driven via a torque demand signal from the control unit. The control algorithms are written in "C" and can be changed by Wavegen. There are two key algorithms, one controlling the generator speed and the second the valve positions. These may be explained with regard to the graph in Figure 7.

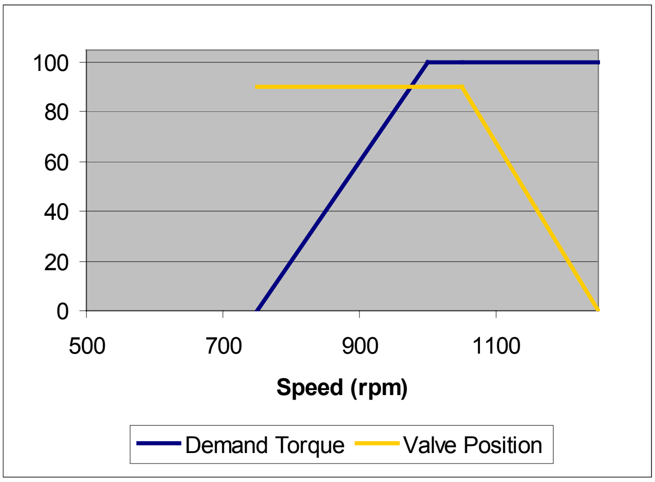


Figure 7. Control Algorithm Schematic

4.3.3.3.4 Generator Speed Control

There is a large rotating mass associated with each of the two turbines (1250kg.m^2 per unit) and as the energy input varies through the wave cycle power is either fed into or is drawn from the inertia in order to smooth the power supply to the grid. This is achieved by varying the torque reference signal to the inverters. The demand torque is determined as follows:

- ·If the turbine speed falls below a set minimum the demand torque is zero. This prevents the turbine falling to a low speed from which it cannot absorb sufficient power to recover.
- ·When the turbine speed is above the minimum speed but below a second set speed (action speed) the demand torque varies linearly from zero to the maximum available (the maximum available being determined either from grid or generator limitations).
- ·When the turbine speed is above the action speed the maximum available torque is drawn.

A separate but identical algorithm controls each generator.

4.3.3.3.5 Valve Position Control

The function of the two in line valves (vane and butterfly) is to reduce airflow to the turbines in storm conditions and to shut down the system in an emergency. The butterfly valve is held fully open in normal operation but is fully closed in the event of a shutdown. The vane valve modulates during operation but closes in the event of a shutdown. The position of the vane valve is determined as follows:

· If the turbine is running beneath a first set speed the valve is fully open.
· Between the first and second set speeds the valve closes linearly to zero.

4.3.3.3.6 Hard Wire Controls

In addition to the controller there is an additional level of protection offered by hard wire controls. These provide an emergency shutdown in the event of an earth leakage fault or a turbine overspeed (measured by a different speed sensor to that feeding the controller unit).

4.4 Task 2 – Civil Construction

4.4.1 Objectives

The main objective of Task 2 was to construct the oscillating water column structure complete with the site infrastructure and control room building.

4.4.2 Partners Involved

Partner	Task Responsibility
QUB	Project management to ensure objectives are met, provision for instrumentation
WGI	Overall management as plant owner and compatibility with turbine generator mountings
CBL	Civil engineering construction
KMM	Quality assurance

4.4.3 Description

Preparation of the site for excavation commenced in November 1998. The virgin site (see Figure 8) formed a shallow gully which provided some natural wave focusing. The surface was cleared of rock outcrops to provide access for construction equipment and the plan form of the area to be excavated was defined by pre-splitting the periphery by drilling and blasting. A further pre-split was made down the back slope of the collector. With the edge of the excavation now defined a bulk blast was

Figure 8. Virgin Site before Construction

Figure 9. Wave overtopping at site

made to shatter the contained rock. Excavation then commenced and the rock taken from the hole provided material for site roads and landscaping. Towards the turn of the year the weather became increasingly inclement with frequent overtopping of the front wall by wave action.

In mid December 1998, the contractor Charles Brand, decided to cease operations until the following spring. After re-mobilisation the excavation continued and by mid-June 1999 the hole was well advanced (see Figure 10).

Figure 10. Excavation at mid-June 1999

The front wall left by the excavation was 5m above the mean water level but despite the general reduction of the wave climate during the summer months there were still significant periods where waves overtopped. In June for example 8 days were lost and in July 9. By comparison only 5 days were lost due to wave action in November 1998. This highlights an important lesson; whilst the average wave activity is undoubtedly lower in the summer months than in the winter the potential for interruptions to work due to adverse weather conditions persists throughout the year and the concept of easy working during a summer weather window should be treated with caution and can vary from year to year. It was also noted that the potential for wave overtopping is highly dependent upon wind direction with an onshore wind dramatically increasing the potential for overtopping. In storm conditions waves break over the bund wall and can land 20m+ inshore from the bund. In relatively calm conditions there can be occasional overtopping of the bund wall. Both occurrences prevent working in the excavation. To reduce the frequency of overtopping the height of the bund wall was increased by approximately 1m with a beneficial effect on working time. In retrospect it may have been preferential, in order to gain a greater protection, to select a site where the initial level of the cliff edge was higher despite the additional volume of excavation. The in-situ reinforced concrete construction commenced on completion of the excavation with the initial emphasis being the completion of the rear wall of the structure. Concurrently blinding was laid in the base of the hole to provide a stable platform from which to support the false-work and shuttering required for the forming of the interior walls and roof of the collector. By mid October 1999 the rear wall, top bench and back walls to the level of the turbine slab were complete together with the majority of the splays.

It had originally been envisaged that the civil engineering construction would have been completed within the first twelve months of the contract. In practice, the main factors that delayed progress were:

Figure 11. Excavation with additional wave wall

1. It was not possible to work through the winter months due to the severity of the weather that resulted in waves overtopping the rock bund. The winter of 1998/1999 was particularly severe and resulted in the site being closed from the start of December 1998 until late April 1999. Thus 4 ½ months were lost from the scheduled programme.

2. The rock excavation proved to be much more difficult and time consuming than originally envisaged. The excavation method involved stitch drilling around the periphery of the proposed excavation hole and blasting to pre-split the rock. The bulk of the rock was removed by drilling a pattern of holes and blasting the rock. This was done at three progressive levels. It was found that this method resulted in the loose rock compacting after the blast. Thus at the bottom of the excavation it was difficult and time-consuming to extract the rock. Originally 1½ months was scheduled for this activity and it took 4 months thereby causing a 2 ½ month setback to the programme.

3. The solid rock bund did not provide as much protection as originally envisaged and particularly at high tide. As overtopping by waves had contributed to the delay in digging out the excavation, it was decided to increase the height of the wall by 1m. The crest level of the wall was lower than expected due to fractured rock and the surface being loosened during the blasting process. Overtopping prevented safe working below sea level in the excavation. Typical downtime varied between 20% and 50% from June to November. Excessive downtime and short working days again forced the closure of the site at the end of November 1999.

In order to ensure that the civil construction was completed during the Summer 2000, three significant changes were made. CBL recruited a new contracts manager and a second site manager was permanently based on Islay. Additionally, WGI based one of their senior project engineers permanently on site to ensure that the project was progressing satisfactorily relative to the revised construction schedule.

CBL resumed work on site in March 2000 and a revised construction schedule was drafted. To reduce the downtime on site during periods of unfavourable weather, an alternative method of constructing the roof of the device was devised. Precast concrete beams could be cast in safety during overtopping of the rock bund and then lifted into place on the device. Corresponding changes were made to the steel fixing design of the roof. The civil construction was completed on 18th August 2000.

Figure 12. Back wall of the chambers substantially complete. Steel-reinforcing for the diaghram walls is being assembled.

Figure 13. The blue pipe is the access ducts for instrumentation that has to be laid before concrete is poured into shutters

Figure 14. Permanent steel shutter for the front lip being prepared for installation on site.

Figure 15. Diaphragm wall rolled steel lips being fixed into position prior to concrete pouring.

Figure 16. Diaphragm walls near completion. The front lip rolled steel shutter is visible.

Figure 17. The rear wall of the chambers and the shuttering for the central duct.

Figure 18. The internal opening through a diaphragm wall that “connects” all columns together.

Figure 19. The collector roof takes shape with precast concrete beams.

Figure 20. A precast concrete beam is lifted into place.

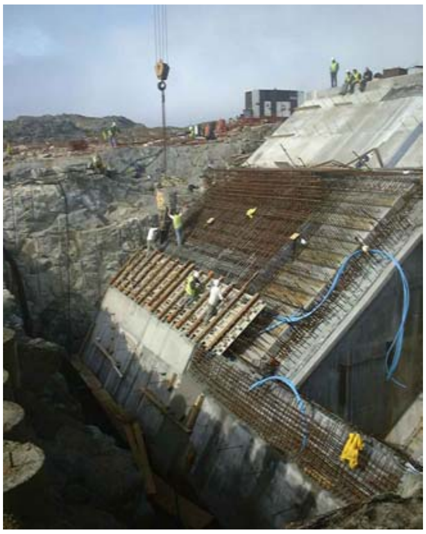


Figure 21. A concrete cap of 0.7m is poured over the precast concrete beams.

Figure 22. The completed structure. The drill rig is visible on the rock bund preparing for demolition.

4.4.3.1 Rock Bund Removal

The wave wall was blasted on 29th August. The placement and firing of the explosive charges had been designed to throw the shattered rock to seaward and to a large extent the desired objective was achieved. A small percentage of the 2,500 m3 of rock removed did however travel landward and caused superficial damage and significant damage to the seaward wall of the control room. Figure 24 shows the shattered rock lying in and about the gully immediately after the blast. Figure 25 shows the 40T long reach excavator sitting on a rock mound in the centre of the gully. This was at the start of the removal of the broken rock from the gully. The intention of the contractor was to use the 16m reach of the excavator to draw the rock towards the collector and the sides of the gully from where it could be lifted onto the land. In the initial stages when the sea was calm this approach was successful. As the weather deteriorated however the technique became increasingly less productive. No sooner had a platform for the excavator been established than the wave spread it out again. After an overnight storm the rock became piled against the collector and was graded like a shingle beach (see Figure 24). Wave action moved the surface rocks against the collector grinding away the surface cover. This grinding continued until the rock removal reached the stage where the rock was no longer in contact with the collector surface. Where storm conditions prevented excavation work so that the "grind region" was static for a period of some days there are signs that as much as 20-25mm of surface concrete may have been removed. This was however in an area where the full concrete thickness was in excess of 1.25m with minimum nominal cover of 50mm and consequently structural problems are not expected as a result of this loss of cover. With the rock constantly moving under wave action the excavator moved out of the gully. It was able to reach down to the native seabed from each side remove rock even in adverse weather conditions (see Figure 26). Rather surprisingly it was observed that when working from the sides wave action was beneficial in that as rock was removed the sea brought additional material within reach of the bucket. The rock removed from the gully was used to landscape both the site and, by arrangement with the landowner, the area immediately adjacent to the site. The objective was to provide a screen to minimise the visual impact of the structure and to discourage casual visitors from walking to the edge of the gully. As with natural gullies along the coast the rock to the side of the gully can be subject to unexpected overtopping which could be of danger to the unwary. The excavator was demobilised on 4th October and the excavation of the gully, including weather delays, took 35 days. The contractor had originally planned on 7 days.

Figure 23. Rock from wave wall against collector after the demolition of the rock-bund.

Figure 24. Gully filled with rock after rock-bund demolition.

Figure 25. Removing shattered rock after blasting wave wall.

Figure 26. Excavating from side of gully

The contractor was demobilised from site and a Certificate of substantial completion of the civil engineering contract was issued on 7th November 2000.

On 15th November 2000 a visual survey was made by divers in the outer section of the gully. The general observations were as follows:

a) There was a large boulder (approximately the size of a small car) at the north side of the entrance to the gully.
b) With the exception of this boulder the gully floor was clear of rock debris or kelp up until the line of the rock wall blast.
c) At the line of the blast of the rock wall (moving from the sea towards the land) the sea floor fell sharply from the natural sea floor to the 7m blasted excavation. The sea floor past this point was not visible and it was not possible to see whether there was debris at the lower level or under the entry lip of the collector.

4.5 Task 3 – Mechanical – Electrical Plant Construction

4.5.1 Objectives

The objective of Task 3 was to manufacture all the elements of the mechanical-electrical plant described in Section 3.3.3.2 and install them on the water column structure.

4.5.2 Partners Involved

Partner	Task Responsibility
QUB	Ensure compatibility with other tasks such as instrumentation and electrical aspects
WGI	Supply M&E plant and coordination of M&E sub-contractors
CBL	Install heavy components

4.5.3 Description

The butterfly valve which connects the turbo-generation system to the collector was dispatched from Inverness on 16th August 2000 arriving at site on the morning of the 18th. It was fitted immediately without problem. A second valve was fitted over the alternative outlet to the collector. Some additional work was required on the second valve to provide an adequate seal in operation. The fitted valves are shown on the rear collector wall in Figure 16.

The valves, together with covers for the blow off valve exits (see Figure 27 and Figure 28) were fitted prior to the wave wall removal to avoid the potential problems in handling this equipment when the water column was live. By contrast the remainder of the turbo generation equipment was not fitted until after the wall wave had been drilled and blasted. This was in respect of concerns that some blasted material might fall back on the turbine slab where it could damage any machinery in place. This proved to be a wise decision.

The turbo generation equipment had been scheduled for delivery to site the day after the blasting of the wave wall. This was not possible as a consequence of the necessity of removing the “stray” rock from the turbine slab after the blast of the wave wall. The clean up only took one day and the equipment was unloaded at site on 31st August. Assembly was substantially complete by 4th September having been achieved without significant problem and in less time that planned. Figure 29 and Figure 30 show the equipment on the slab shortly after the start and on completion of mechanical assembly.

Figure 27. Butterfly Valves on collector rear wall.

Figure 28. Blow-off Valve Cover Plates

Figure 29. Turbo-machinery being assembled on the turbine slab.

Figure 30. The assembled turbo-machinery prior to the construction of the surrounding building.

4.5.3.1 Electrical Connections and Control Equipment

The commencement of the electrical connection of the turbo-generation equipment to the control cabinets already installed in the control room was scheduled to commence immediately after the blasting of the wave wall but had to be postponed in respect of the need to clear the slab of debris. The team from Hydro-Contracting, who had been contracted to do the work, were rescheduled and arrived on site on 12th September. The work was completed on 28th September, the 17-day duration being 7 days longer than estimated. The extra time on site was partially a consequence of the necessity to repair damage within the control room and partially due to adverse weather slowing work on the exposed equipment (the installation occurring later in the year than planned). The installation was however sufficiently advanced to enable the commissioning of the control system.

4.6 Task 4 – Instrumentation and Data Retrieval System

4.6.1 Objectives

The objective of Task 4 was to design, procure and install an instrumentation system which would provide information on wave loads, power train performance and energy output.

4.6.2 Partners Involved

Partner	Task Responsibility
QUB	Design, procure and installation of data acquisition system
WGI	Overall management and quality assurance
IST	Supporting role

4.6.3 Description

4.6.3.1 System Overview

The LIMPET device was designed to accept an extensive range of instrumentation.

An Ethernet network comprises the backbone of the Data Acquisition and Management System. Two dataloggers form the core of the data acquisition system and are housed in a cabinet at the collector rear wall and enclosed by the turbo-machinery building. One datalogger is configured for high-speed burst-mode scanning for wave-loading data

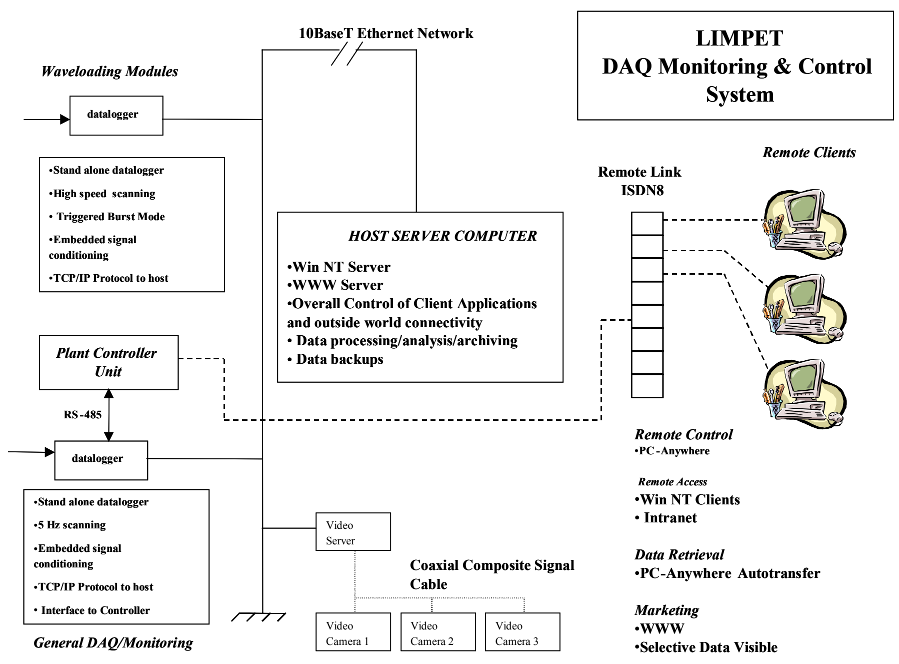


Figure 31. LIMPET DAQ Monitoring & Control System

acquisition and the second logger operates at 5Hz and acquires plant operational data from various sources. All instrumentation cables terminate at the cabinet housing the loggers. A server computer situated in the control room 50m away from the device handles the remote control of the loggers via the Ethernet local area network (LAN). Included on this network is a video server that controls a maximum of four video cameras and streams live video images onto the LAN. The video cameras are used to monitor column movement, sea-state conditions and potentially for streaming to the Internet.

It is important to note that the plant controller system operates entirely independently of the data acquisition system. However, an interface between the two disparate systems was devised to permit synchronised data flow between the two systems.

Four ISDN2 connections in the control room provide remote dial-up access to the system for authorised download of data and video images, real-time monitoring and remote control of the plant.

Figure 32 depicts the regime of plant parameters that are monitored and these are discussed in the following sections:

4.6.3.2 Seabed Pressure Transducers

The incoming wave climate at a site is arguably the most difficult of all the plant parameters to monitor. Commercially available systems are expensive and tend to provide statistical data only via wave buoys moored a safe distance offshore. There has always been a requirement to acquire time-series data of the incoming waves close to the device itself to investigate the device response and performance fully. The OWC responds to a wave-by-wave excitation and a statistical description of the wave climate regime is sufficient mainly to describe the design space the device should fall within. Additionally, real-time time-series wave amplitude data can be used for real-time device control to optimize productivity.

A stipulation for real-time data acquisition presents the biggest problem for any remote instrument in a harsh environment; namely the power source for the instrument and less

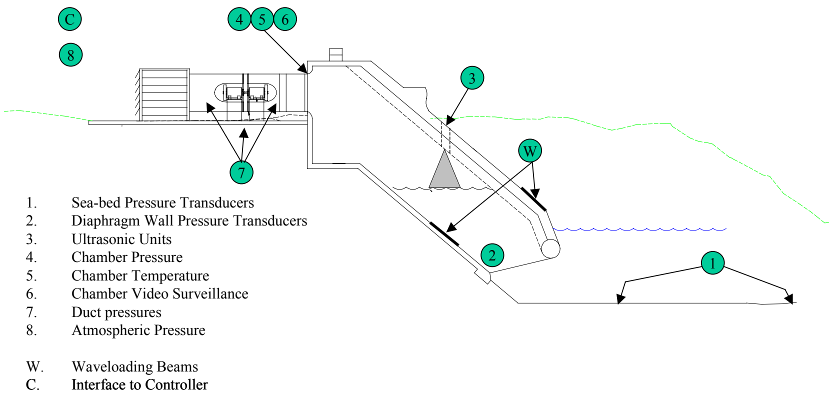


Figure 32. LIMPET Instrumentation Coverage

importantly, data storage. Indeed, it is these factors that constrain most remote systems to statistical observations in order to conserve battery power.

QUB has extensive experience in monitoring the waves created by fast ferry vessels in coastal waters. A portable battery-powered system was developed that measures the static head of water above the seabed and which is then calibrated to provide the time series of wave amplitudes passing overhead (maximum battery power 4 hours, maximum data storage 3 hours @ 2Hz). A similar system was developed for LIMPET with the exception that the undersea rig housing the pressure transducer was connected to the shore via an umbilical pipe fixed to the sea-bed by rock-anchors. Stainless steel modules were developed that housed the pressure transducer, an expandable outer rubber locking diaphragm and the cable connections. The cables consisted of a power cable, data cable, airline to the diaphragm and a steel cable for retrieving the module. The umbilical pipe thus provided a reusable passage for the modules to be transported to the seabed rig by compressed air. Once in position at the rig, the modules would be locked into position by pressurizing the outer bladders. A bank of pressurized cylinders would maintain pressure in the locking diaphragms. The cylinders' pressure would be electronically monitored and maintained by a small air compressor. Laboratory trials with the system proved very successful. However, the system relied inherently on the use of divers for deployment on site and an accompanying weather window. Local divers on Islay were contracted to install the rigs and pipes to minimize the logistical overhead in bringing divers from Belfast. Disappointingly, the divers failed to meet their obligations despite several suitable weather windows, and it became apparent that an alternative solution had to be devised before the onset of winter storm activity.

New pyramid-shaped rigs were constructed from rolled steel joists (RSJ) of sufficient weight to eliminate dragging and the umbilical pipes were replaced by armoured cable weighted with galvanized chain. The cables and rigs were deployed from a local fishing boat at distances of 44m and 66m from the front lip of the device in an operation that took only 3 hours. Critically, the researchers from QUB were able to identify the favourable weather window and to mobilize the resources to site within 4 hours. This highlights the desirability of maintaining control of such tasks in-house; the reliance on local sub-contractors in projects of difficult (or remote) location introduces an additional complexity to the likelihood of success or failure in the task.

The critical zone in this system is the air-water interface where the cable is routed from the seabed to land. No obvious route to land on the shoreline existed. Ideally the cable should have been routed through the device chamber entrance and up the rear wall, thereby avoiding the extremely aggressive turbulent area in the gully during storms. Deterioration of the weather eliminated this possibility and the cable/chain was routed up the Northern side of the gully wall and up the front wall of the device.

Approximately two weeks of data was acquired from the two rigs before the cable of the 44m rig was destroyed during storm conditions. A further two months of data was acquired from the 66m rig before it too was destroyed. In both instances, the damage occurred at the front wall where the cable and chain were subjected to the severest fatigue loads. However, sufficient data was acquired in various sea-states to permit analysis of the device response to specific wave excitation. Importantly, valuable operational experience was gained from the deployment of this system and it is envisaged that new cables will be deployed in the summer 2002 and routed up the rear wall of the device.

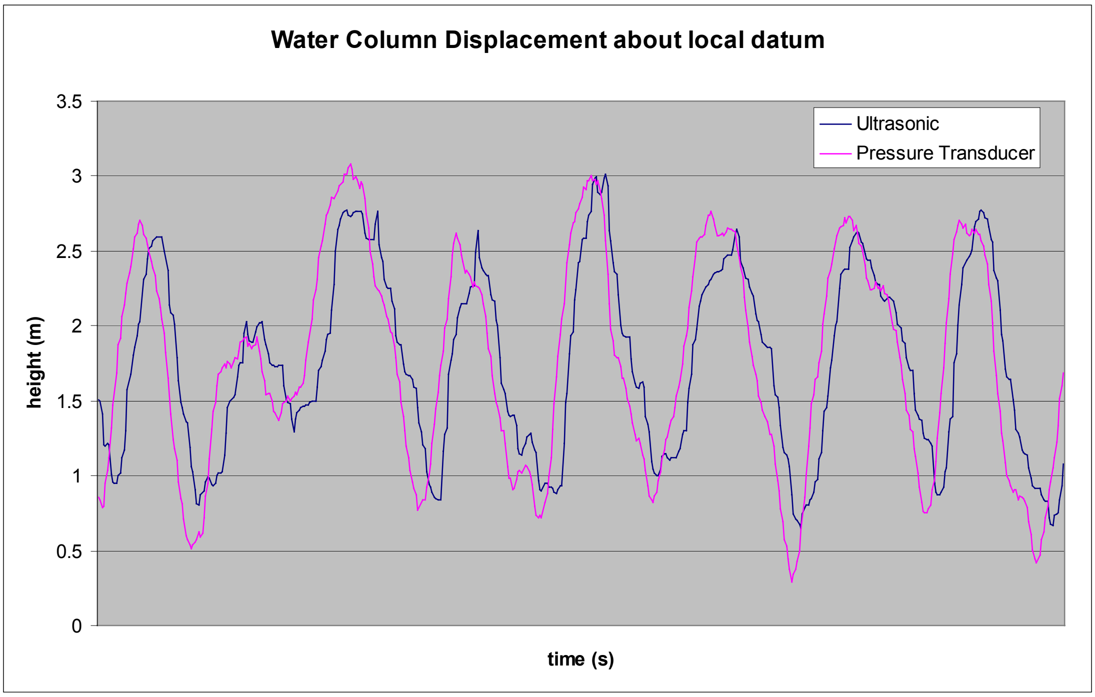


Figure 33. Comparison of Water Column Displacement

4.6.3.3 Water Column Displacement

In addition to ultrasonic units positioned in the roof of the collector, wave column displacement is measured by pressure transducers that record the static head of water in the chambers. These transducers are located at the bottom of the diaphragm walls via ducts that run the length of the diaphragm walls and exit at the rear wall of the device. The pressure transducers are of the same design as described in the previous section and thus may be retrieved should failure occur. The pressure transducers are advantageous in that the recorded head inherently integrates across the surface of the water column, thereby minimising the effects of sloshing and the uneven surface of the water columns. Ultrasonic signals are vulnerable to erratic behaviour because of the latter factors. Additionally, video footage of the chamber revealed the occurrence of water vapour that appears in the chambers once the pressure drops below a certain threshold and especially during the colder winter months where the relative humidity of the air is higher. Pressure transducer readings are unaffected by this vapour while ultrasonic signals are again vulnerable. Access to the ultrasonic units for maintenance or installation requires favourable weather conditions while pressure transducer maintenance is independent of weather conditions.

To date, these instruments have performed reliably and Figure 33 shows the close correlation between the systems. There is a discernible phase lag between the ultrasonic signal and the pressure transducer signal. The ultrasonic units employ some real-time statistical features that incur some processing overhead that results in the slight time delay. This time constant was established from laboratory tests to be approximately 2 seconds; corrected ultrasonic readings and the pressure transducer readings appear to track the column movement accurately.

From an operational perspective, the ultrasonic units require favourable weather windows for installation or servicing as access to the front wall of the device is required. The pressure transducers can be retrieved at any time for replacement or servicing. As with all the instrumentation, however, adequate provision for access ducts must be detailed prior to and during construction. In this instance, ducts for the pressure transducers were specified for all the longitudinal diaphragm walls of the chambers for redundancy. This decision was justified when some of the ducts were found to be impassable by the pressure transducer modules; due most likely to poor routing of the ducts or distortion of the ducts during concrete pouring.

4.6.3.4 Chamber and Duct Pressures

Pressure transducer units were installed in the rear walls of the chambers. The turbo-generation duct was comprehensively fitted with pressure transducers:

1. between the butterfly valve and vane valve (pos. 3, Figure 4)
2. between the vane valve and first rotor (pos. 5, Figure 4)
3. between the turbine rotors (pos. 6, Figure 4)
4. after the 2nd rotor and before the bellmouth (pos. 7, Figure 4)
5. in the acoustic baffle room

The progressive train of pressure transducers have performed reliably to date.

4.6.3.5 Chamber Temperatures

Incorporated into the chamber pressure units of the southern and central chambers are temperature sensors. While these appear to have performed reliably, preliminary analysis of thermodynamic models has predicted higher temperature swings than those recorded by the thermocouples. This is possibly due to the moisture content of the air within the chambers.

4.6.3.6 Waveloading

Two waveloading beams were fitted to LIMPET; an external beam on the lower front lip of the device and an internal beam on the rear wall of the device (at mean water level). This operation required very calm sea conditions for access down the front wall and into the chamber. Two members of the team, Boake and Ellen, achieved a Level 1 qualification in Industrial Rope Access to comply with Health and Safety regulations for such access.

The beams were successfully installed and have been operating reliably to date. The signals from the pressure transducer arrays are routed to a dedicated datalogger. In the initial phase of monitoring, the datalogger was configured to operate in statistical mode whereby the following parameters were reported every hour:

- average pressure
- standard deviation of pressure
- maximum pressure
- time and date of maximum
- minimum pressure
- number of samples

- time and date of minimum

During severe storms in January 2002, pressures of 4.5 bar were recorded on the front wall of the device. To validate these maximums, the datalogger has since been configured for triggered burst mode operation at 1kHz scan speed. Time series traces of the pressure readings at the front wall during storm conditions in future will reveal whether these high recordings are feasible.

Pressure readings from the internal beam have not been significant.

4.6.3.7 Video Surveillance

Two CCTV analogue video cameras were installed on LIMPET:

- In the central chamber rear wall and angled downwards to observe the water surface motion. Illuminating spotlights were installed at the outer sides of the rear wall to illuminate the interior.
- On a 3m mast 30m to the south of the device and providing a view of the sea and gully.

Both videos were connected to a video server that converts the composite video signals into the TCP/IP protocol for Ethernet transmission. The video server is allocated an IP (Internet Protocol) address; remote clients logging in to the host server computer are then able to view the video images in a local Internet browser courtesy of the intranet connection. The quality of transmitted images to a remote ISDN2 connection was of an acceptable standard with high refresh rates.

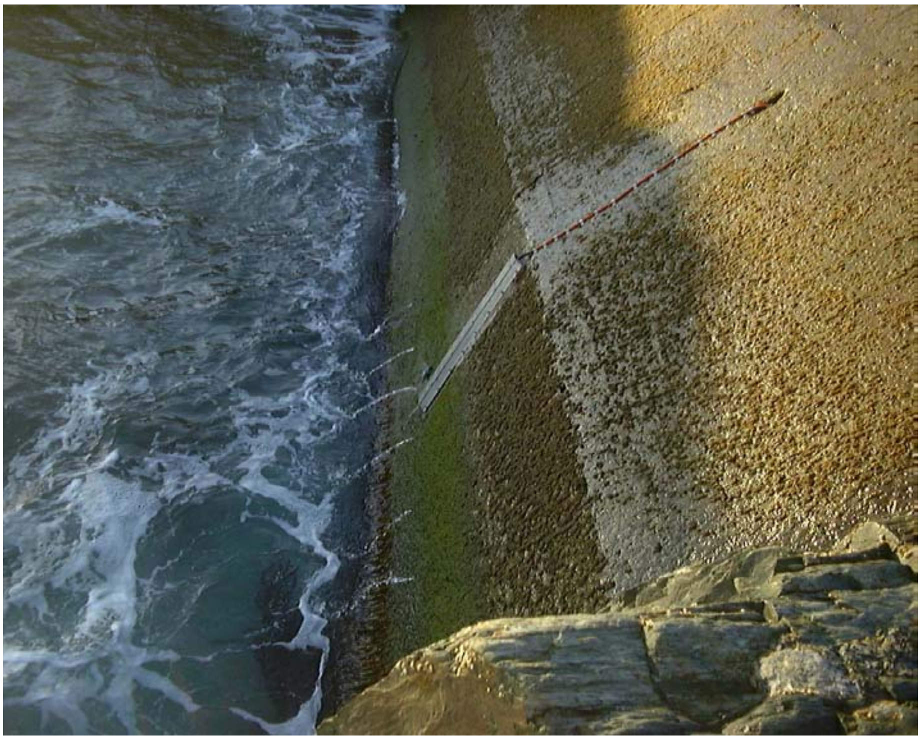


Figure 34. Waveloading Beam installed on the front wall

- Video streaming from the column video gave a valuable insight into the characteristics of the column motion and which was compared to a model scale investigation into the flow characteristics of LIMPET (Folley, M., Whittaker, T.J.T., 2002).

4.6.3.8 Interface to Controller

The plant controller system (operating completely independently) monitors numerous plant operating parameters not included with the data set as acquired by the dataloggers. Thus a RS-485 interface and communication protocol between the plant controller system and the main datalogger was devised to permit synchronised data acquisition of all the relevant plant parameters. An instantaneous snapshot of the plant operation is available at 5Hz. The following parameters are supplied by the controller to the datalogger:

- Grid voltages - 3 Phases
- RPM Generators 1 & 2
- Chamber Pressure (independent)
- Butterfly Valve Position (demand & actual)
- Vane Valve Position (demand & actual)
- Power Factor Generators 1 & 2 (demand & actual)
- Output Power Generators 1 & 2
- Torque Demand Generators 1 & 2

This interface operates reliably apart from instances of high turbine acceleration when data "dropouts" occur. No data string can be received by the datalogger from the controller before the 5Hz timeout occurs. It is possible that signal noise is responsible for disrupting secure transmission between the systems; this has since been addressed with a revised interface protocol.
An essential parameter supplied by the controller is the plant power output (Figure 35). It can be seen that the output of Generator 2 is approximately half that of Generator 1 although the corresponding generator speeds (Figure 36) are within a few RPM of each other. Since the torque demand to each generator is speed dependant, this is an unlikely scenario and thus it has not been possible to analyse the power train from pneumatic power to electrical power with any degree of confidence. It is proposed to perform independent power measurements to investigate this discrepancy.

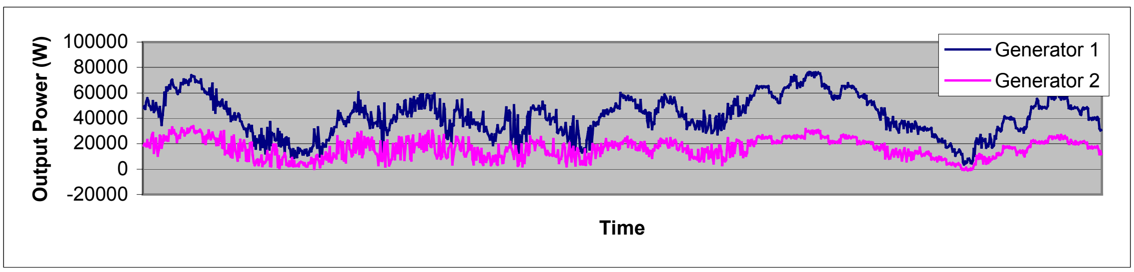


Figure 35. Power Output – supplied by Plant Controller

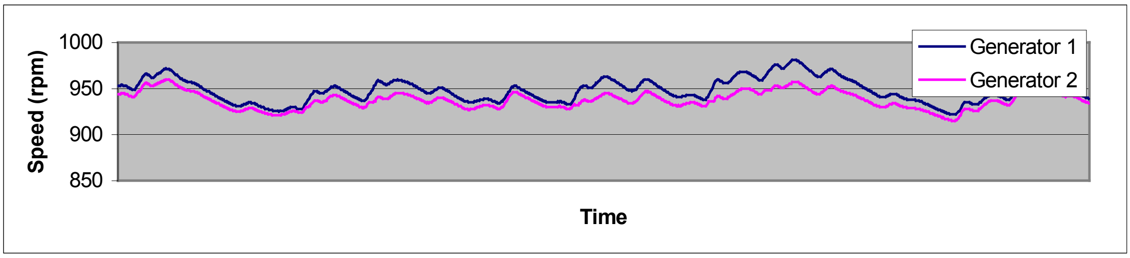


Figure 36. Generator RPM – supplied by Plant Controller

4.6.3.9 Remote Communications

This is an essential aspect of the plant operation in lieu of the remote device location. After a period of instability, the host computer system and associated telecommunication equipment has performed reliably. The following system specification proved to be the most reliable:

- Host Computer running WIN 2000 Server.
- Remote Windows Clients login via dial-up connection into an ISDN2 Terminal Adaptor.
- Automatic reboot at midnight every night eliminates lockouts of more than 24 hours.
- Remote control of server using a Symantec PC-Anywhere TCP/IP session over a dial-up connection. This allows upgrading of software or data transfer from the host computer.

4.7 Task 5 – Plant Commissioning

4.7.1 Objectives

The main objective of Task 5 was to connect the plant to the electricity distribution system and undertake a series of trials to ascertain the operational characteristics of the plant prior to the detailed experimental program.

4.7.2 Partners Involved

Partner	Task Responsibility
QUB	Complete system testing
WGI	Grid connection, testing

4.7.3 Description

The commissioning of the plant in general proceeded satisfactorily with the first generation to the grid occurring on 2nd November 2000 when a single turbine was operated. Both turbines were run the following day in light wave conditions with a peak generation of 55 kW. It was noted during these tests that there was significant noise generation from the plant. Subjectively this noise had two distinct components. The first derived from the turbines and has previously been heard when the units were motored. The second appeared to be directly related to the flow through the duct having previously been heard when the duct valves were opened with the turbines static. It was thought to be a consequence of stall on the turbine blades No operational tests were possible from then until 16th November in respect of the modifications that Scottish and Southern Electricity were making to the grid. On 16th November a number of tests were made with the turbine controls demanding mean operating speeds of between 700 and 1000rpm. It was noted that as the turbine speed increased the output of the plant also increase and the noise level decreased. This was by virtue of the increased back pressure resulting from the faster running turbines reducing the air flow in the duct and thereby the associated noise. Whilst running at 1000rpm the plant output to the grid was typically 50kW with an instantaneous peak of 120kW.

At this turbine speed the noise levels adjacent to the plant were uncomfortably high and it was decided that in respect of a possible adverse reaction of visitors to the site and local inhabitants, that the plant should not be run on a continuous basis until a noise attenuation chamber had been fitted.

A further series of trial were then made over the period of 11th-21st December during which time input power levels were monitored whilst generating to the grid. In this period the maximum generation reached 150kW, the limit on the grid capacity.

4.7.3.1 Control System

The commissioning team was greatly encouraged by the stability of the baseline control system during the preliminary testing. A number of software glitches were identified and rectified during the commissioning period prior to the start of generation but once operational, the controls worked generally as intended. Communications were established between Wavegen in Inverness and the site controller to allow remote operation.

4.7.3.2 Unplanned Maintenance/Modifications

The commissioning revealed no significant problems with the exception of a stiction in the butterfly valve. It had been noted that on two or more occasions the valve had not closed under simulated emergency conditions. This is a safety critical item and occurred because of an increase in the resistance to turning of the combination of valve shaft and gearbox. The problem was overcome by increasing the counterbalance weight.

4.8 Task 6 – Research and Plant Operation

4.8.1 Objectives

The main objective of Task 6 was to acquire the necessary data to improve understanding of the characteristics of the plant necessary to advance the design process for future replication of the technology.

4.8.2 Partners Involved

Partner	Task Responsibility
QUB	Overall responsibility for data acquisition, analysis and mathematical modeling
WGI	Marketing, dissemination of information, assistance with analysis
IST	Assistance with mathematical modeling and data analysis

4.8.3 Description

This section forms the main body of the work performed on LIMPET post the construction and commissioning phases. The discussion in Section 4.8.4 then synthesises the preceding sections into a summary of the overall plant performance and all the associated issues therewith.

4.8.3.1 Plant Operation and Monitoring

The plant has proved to be reliable since the commissioning in November 1999 and there have been no major mechanical or electrical breakdowns. Since May 2000, save for periods allocated to research and planned maintenance, the plant has been running under full automatic control with remote monitoring from the Wavegen offices in Inverness. During this time there have been numerous shut downs which have been caused either by a reported fault or by a decline in wave activity. Of the reported faults, approximately half have been a consequence of false signals from the instruments and half due to local grid faults. In the longer term the outage due to local grid faults gives cause for concern and the lack of stiff grids at suitable sites for wave energy plant is one of the major barriers to development.

Table 6 gives a summary of the production figures. The operating data for January 2002 is incomplete in respect of running hours and availability. Some data was lost from the monitoring controller for reasons as yet unknown.

		KWh		hours				
Year	Month	Prod	Cons	OK to Run	Running	Stopped	Grid OK	Pressure OK
2000	september	0	2	5.8	0	40	41.7	0
	october	16	101	22.5	0	639	638.7	120
	november	63	62	7.9	0	466	215.3	472
	december	226	37	9.5	0	733.4	266.1	728
2001	january	245	286	17	12.7	723.3	369.9	730.9
	february	1030	2098	193.1	192.4	476.7	668	656.2
	march	1096	1284	121.7	120.8	621.6	486.4	701.8
	april	1653	999	114.9	113.4	604.1	574.9	650.1
	may	716	623	251.1	40.8	492	572.7	395.4
	june	509	233	509.7	40.2	209.6	651.1	115.9
	july	690	402	502.4	68.8	241.6	743.9	119.4
	august	1619	713	407.3	127.8	336.7	743.9	159.8
	september	1398	476	354.8	78.6	365.2	719.9	211.7
	october	6469	1114	554.1	287.9	187.9	741.2	309.5
	november	9495	1224	359	298.1	305.9	645	405.1
	december	2161	402	284.9	77.5	341.2	616.5	315.2
2002	january	15235	1187	387	358	X	X	X
	february	18	103	2	0.9	656	385	634
	march	4444	662	235	183	507	742	459

Table 6. Summary Production Figures

Year	Month	Plant Monitoring	Research
2000	November	4	0
	December	26	0
	January	5	0
	February	41	0
	March	15	0
	April	1	0
2001	May	6	0
	June	0	33
	July	0	0
	August	1	0
	September	53	35
	October	400	457
	November	418	14
	December	40	0
2002	January	491	0
	February	21	0
	March	384	0
	April	595	0
Total		**2501**	**539**

Table 7. LIMPET Data Coverage

Table 7 indicates the data acquisition coverage since the plant began operation. Each file represents 4096 data points at 5Hz scanning speed of a full spectrum of plant operating parameters. Full automatic data acquisition was established from October 2001 and the system performed reliably until the end of the reporting period in April 2002. The lack of coverage in December 2001 was due to a defective plug socket in the turbine room. In February 2002 the data acquisition cabinet was flooded during severe storms. In both instances the damage was repaired and precautions taken against a repeat occurrence.

The data acquisition system has performed reliably in conjunction with the remote communications system and this implementation would be recommended for any future wave power devices.

A Microsoft Access Relational Database was developed to archive all data files, for ad-hoc interrogation and for producing summary reports of plant performance.

Table 6 indicates the ostensibly poor performance of the plant relative to the predicted output and plant rated capacity. An audit of fundamental characteristics of the plant was thus necessary to investigate this deficiency and the following research tests were performed on the plant.

- Orifice Tests – Column Damping
- Turbine Flow Calibration
- Power Train Performance
- Comparison of Theoretical Prediction and Plant Performance

4.8.4 Discussion

The power delivered to the grid by LIMPET is substantially lower than originally estimated. The reasons for this have been identified and a number of important conclusions have been reached which are significant to the design and siting of future plant. The lower power delivery is best understood by first considering the initial design specifications, then reviewing each stage of the power conversion from wave to electrical energy and finally considering their combined effect on device productivity.

4.8.4.1 Initial design specifications

When the plant was originally designed as part of contract JOU2-CT94-0276, the collector was positioned at the cliff edge and the model test programme conducted in a wavetank with a seabed slope of 1:8. As part of this study a characteristic set of seas was postulated based on the earlier work conducted with the previous 75kW plant at an adjacent site. The performance characteristics of the contra-rotating turbine had been obtained from 0.6m diameter model tests in unidirectional steady flow using a test facility in IST Lisbon. This had produced an average power production at the generator terminals of 206kW. When a generator rating limit of 500kW was introduced and a 5% allowance made for mechanical losses, the figure was revised downwards to 183kW and this was the figure used in the original project description .

As the civil contractor required that the construction of the water columns take place behind a natural rock cofferdam, it was necessary to move the chambers 17m inland from the coastline. Consequently, a further set of model tests were conducted in the Wavegen tank. The sea bed slope was altered to a more representative value of 1:25 and the productivity tests were re-run in the 53 seas. It was assumed that the 1:25 seabed slope started at the original shoreline. These tests revealed that the average power production was reduced to 113kw when the plant was at the cliff face falling to 57kW when recessed 17m in a parallel sided gully. The tests also revealed that the performance could be increased from 57kW to 140kw by flaring the sides of the gully at 45^0. The design of the mechanical and electrical plant was sized and designed based on the latter figure.

4.8.4.2 Conversion of wave energy to pneumatic energy

The plant was finally constructed with a parallel-sided recess to facilitate the contractor and to allow commissioning in the early part of the winter 2000 before the onset of larger seas. In addition, a post construction bathymetric survey revealed that the 1:25 seabed slope did not extent to the cliff face as originally assumed. The survey revealed that the seabed is approximately horizontal for the first 80m from the water column lip before sloping down to the 30m depth-contour offshore. This has resulted in a significant limitation of the maximum wave energy reaching the shoreline, which together with the parallel gully and a change in the hydrodynamics reduced the potential production to 45% of the original expectations.

Further studies using the Wavegen wavetank indicate that a relatively small change in seabed profile can have a profound influence on the performance of LIMPET. This unexpected result was due to the high non-linearity of shallow water waves and could not have been predicted easily. The shallow water changes the fundamental hydrodynamics of the waves so that the majority of the wave energy becomes associated with predominantly horizontal motion of the water particles. Wavetank based flow visualisation experiments show that this increased horizontal motion causes a larger wave run-up on the front wall of LIMPET, together with sloshing of the water column. Both of these represent parasitic losses with a consequential reduction in the conversion from wave to pneumatic energy. Whilst these studies identify some reasons for the reduction in performance, further research is required to fully understand the influence of the gully and seabed slope have on performance.

4.8.4.3 Conversion of pneumatic energy to mechanical energy

The performance of the counter rotating Wells turbine has been found to be lower than expected. This is due to the random oscillatory nature of the flow through the turbine when driven by waves. The random oscillating flow causes an earlier onset of stall in the turbine than when the flow is steady and unidirectional, with the occurrence of stall reducing the turbine efficiency. Such a dramatic difference between the unidirectional and oscillating flow performances of Wells turbines had not been previously observed. The lack of suitable oscillating flow facilities for testing the turbine meant that this effect could not have been predicted.

In addition, the increased amount of turbine stall meant that a more substantial silencer was required. A noise attenuation chamber was retrofitted onto the end of the turbine ducting to solve this. Although no significant pressure drop occurs across this chamber, studies of the flow distribution around the annulus of the turbine ducting indicate that the chamber causes a mal-distribution of flow during the intake stroke of the turbine. The increased airflow at the bottom of the turbine ducting causes a further increase in stall with an associated reduction in turbine performance.

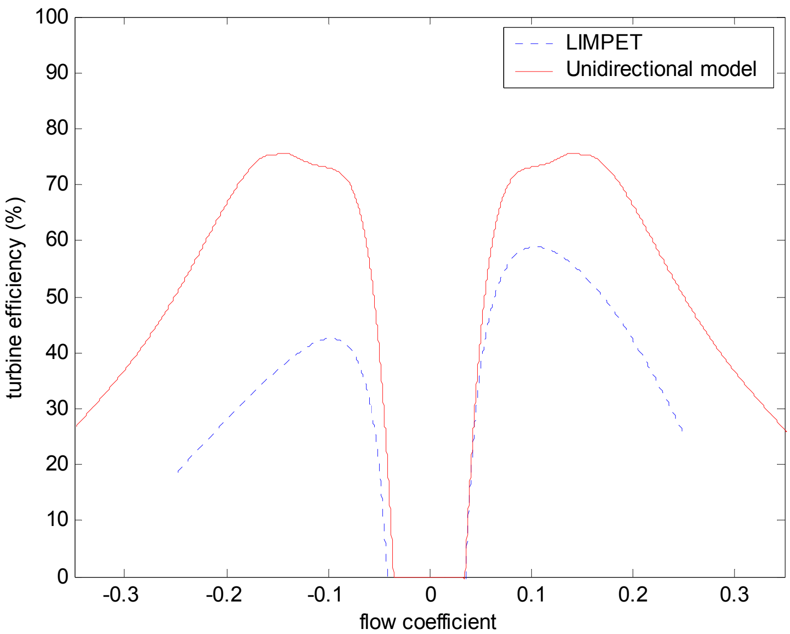


Figure 37. Turbine Efficiency vs Flow Coefficient for Predicted and Actual Results

The influence on turbine efficiency of these two effects is shown in Figure 37, where the turbine efficiency derived from unidirectional model tests is shown for reference. This illustrates that not only is the peak turbine efficiency reduced by the earlier onset of stall, but also more significantly the turbine bandwidth is reduced. The average cyclic efficiency of the turbine will depend on the wave climate, however data from the plant currently indicates that the average turbine efficiency is approximately 35%.

4.8.4.4 Conversion of mechanical energy to electrical energy

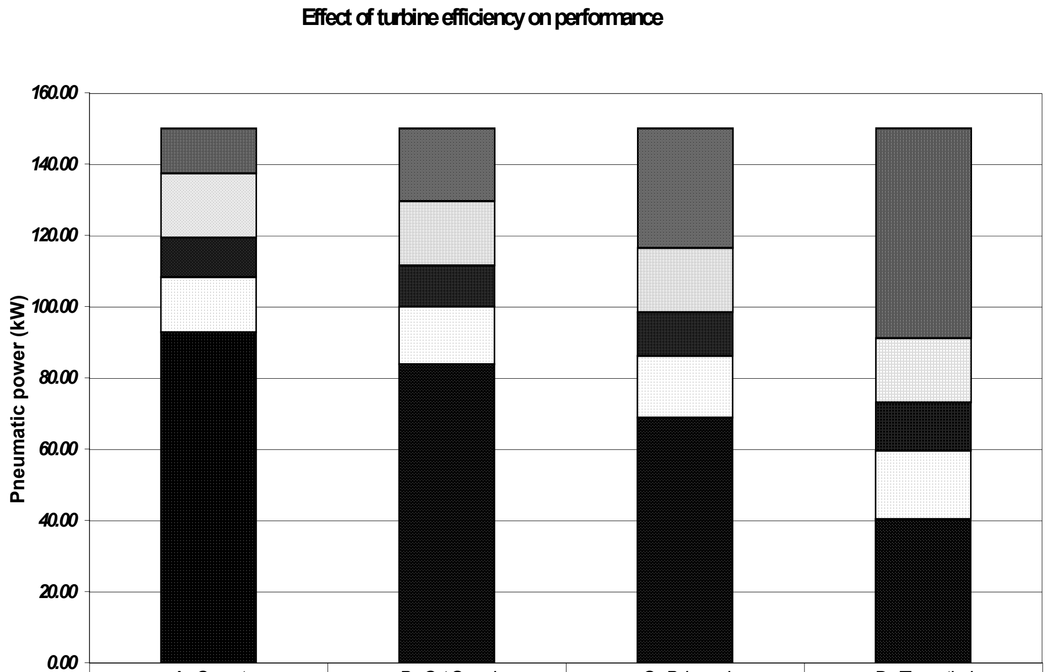
The combined effect of the factors discussed in the sections above mean that the shaft power on the generator is significantly lower than the original design level. This has resulted in the mechanical and electrical plant being overrated. The M&E plant had been completed prior to the decision not to flare the gully and consequently it was not possible to properly match the elements of the power conversion chain to the device as constructed. In addition, as this is primarily an R&D plant, it was decided to install rectification and inversion of the generator output, which allows operation at variable speed within the range 700 to 1500 r.p.m.

With the reduced pneumatic power collection and the lower than expected turbine performance, the electrical system operates at between 10 and 20% of its capacity for a significant part of the year. This limits its conversion efficiency to between 70 and 84%. Further losses in the system, which must be supplied by the turbine, include inverter losses and windage/bearing losses in the mechanical system.

4.8.4.5 Productivity

The net result of all these factors is best described by looking at the power loss at each stage of the conversion cycle. By way of example, Figure 38 shows the power breakdown when there is an average 150kW of pneumatic power for the current plant and three alternative scenarios. Bar A, shows the power breakdown of the current plant, where the turbine losses account for 93kW, the total mechanical and electrical losses account for 45kW, leaving only

12kW to supply to the grid. Bar B shows how the current situation can be improved by changing the generator control algorithm and allowing the machine to rotate faster thus reducing the amount of time spent in stall. The production is increased from 12 to 20kW. Bar C shows the improvement of output to 33kW by improving the turbine performance during the intake so that it equals the performance during the exhaust flow. This could be achieved by installing guide vanes in the acoustic chamber. Finally bar D shows the projected performance if the counter rotating Wells turbine had produced the theoretical performance observed in unidirectional steady state model tests. This shows an electrical production of 58kW. It is interesting to note that if the turbine was reconfigured so that it became a bi-plane machine the electrical production would be close to that shown in bar D. The biplane turbine on the previous 75kW plant in its final configuration gave a pneumatic conversion efficiency of around 50% compared to an average of 35% with the current contra rotating machine.



	A - Current	B - Opt Speed	C - Balanced	D - Theoretical
Supplied power	12.53	20.34	33.51	58.85
Inverter losses	18.00	18.00	18.00	18.00
Generator losses	11.08	11.49	12.18	13.52
Windage losses	15.39	16.16	17.31	19.14
Turbine losses	93.00	84.00	69.00	40.50

Figure 38. Effect of turbine Efficiency Performance

A further consequence of the poor cyclic turbine performance and the high power overhead in the mechanical electrical system is that it requires an average minimum pneumatic power of 100kW before energy is supplied to the electrical grid. This results in too high a threshold and means that the plant does not operate for 50% of the year. A smaller installed generating capacity, in a single generator, the better performance of the bi-plane turbine and removal of the inverter system would significantly reduce the threshold pneumatic power for generation and as a consequence increase the plant availability and average electrical generation.

4.8.4.6 Wavetank and numerical modelling

Though initial predictions of device performance were inaccurate, further studies have indicated that these inaccuracies were due to the scenario modelled and not due to anything fundamental to the wavetank modelling. The original model trials of LIMPET coupled with the revised model trials covered a wide range of potential site scenarios and it is encouraging that the productivity figure (57 kW) relating to the scenario deemed most representative of the actual site, was within acceptable limits of the actual power production.

In conjunction with the physical model tests, a numerical model was developed by IST Portugal. These models were based on the original bathymetric survey and turbine performance and are thus more representative of the first LIMPET model trials that the device design was based on. The linear numerical models have reduced accuracy as the water depth decreases and non-linearity increases.

4.8.5 Further work

- A fundamental requirement exists to determine the actual incoming wave climate at the LIMPET site. This would allow a complete description of plant performance from wave to grid. A period of monitoring with offshore seabed transducers is necessary.
- A fundamental investigation into the non-linear hydrodynamic effects of near-shore shallow water bathymetry leading to improved numerical models.
- Performance predictions from steady-state tests on monoplane and bi-plane Well's Turbines have accurately predicted the performance in cyclic flow. However, this has not been the case with the contra-rotating turbine and further work is required to understand the reasons for this.
- Improved plant performance can be achieved by:
    - flaring the gully on site
    - resizing and changing the turbine configuration.
    - further optimization of the control strategies
    - airflow control to reduce stall

5 Comparison of Planned and Accomplished Activities

There were no major deviations from the work content of the project programmme. However, due to the construction issues detailed in this report, a 6-month project extension was granted so that an additional winter of monitoring the plant was possible.

Task No	Planned Timing Month	Actual Timing Month	Description	Status
1	6	6	Detailed design, specifications, design variations	Complete
2	12	24	Completion of civil construction	Complete
3	12	24	Completion of M&E plant	Complete
4	12	24	Instrumentation	Complete
5	18	30	Working wave power plant	Complete
6	36	42	Improved design capability	Complete

Table 8. List of deliverable items

Planned Timing Month	Actual Timing Month	Type	Criteria	Status
6	6	1st Mid-term Review	Completion of detailed design work Ordering of all components Commencement of civil construction Acquisition of components for DAQ system	Complete Complete Complete Complete
18	18	2nd Mid-term Review	Completion of civil engineering construction Installation of M&E plant Installation of instrumentation Grid connection Research and electricity production started	Complete Complete Complete Complete Complete
36	42	Final Review	Plant monitoring for 18 months, assessment of: • Environmental loads • Environmental impact • power train performance • comparison with predictions • completion of some control experiments • supply of electricity to grid	Complete Complete Complete Complete Complete Complete Complete

Table 9. List of major milestones

6 Conclusions

6.1 Modelling of LIMPET

- The project has shown that model tests on shoreline wave energy plant provide good correlation with site measured data.
- Data capture from site has shown that the performance of LIMPET is particularly sensitive to changes in wave profile due to changes in water depth.
- It has been shown that non-linear theory must be applied to waves in shallow water situations and that in consideration of factors such as harbour wall effects, linear theory can give misleading results.
- Turbine characteristics derived from steady state unidirectional flow tests are inaccurate due to the inherent unsteadiness of the flow though the turbine of an OWC. Inaccuracies appear particularly significant for contra-rotating turbines.
- Non-linearity of the turbine and collector performance means that frequency domain analysis is generally inadequate for productivity estimation, thus requiring the analysis to be performed in the time domain.

6.2 Project sequencing

- The design and construction of the plant reinforced the interaction between the various engineering disciplines and highlighted the need to ensure that any design changes in one area were fully reflected in other design aspects. This was particularly important in respect of the design of the turbo generation equipment which was significantly influenced by any changes to the collector form or performance.
- For OWC's, the pneumatic power available needs to be defined accurately, based on detailed modelling of the final collector design, prior to design of the turbine/generator sets.

6.3 System design

- The operation of the plant has shown that the notional load factor of 1/3 often quoted for wave energy plant is too low in that the fixed equipment losses become a disproportionately high proportion of generated power. The ideal load factor has yet to be established but operational experience to date indicates that it is likely to be close to 50%. The appropriate load factor will depend on the marginal changes in estimated unit costs with load factor.
- The project has demonstrated the potential of inverters to provide a reliable variable speed drive which gives both control flexibility and the ability to adjust turbine speed to optimise turbine efficiency. The designer must however be mindful of the fixed losses associated with this form of equipment and ensure that due account of this is taken in the overall system design.
- Detailed measurements of the performance of the turbo-generation equipment has reinforced the need for system matching throughout the chain of turbine/generator/control valve/sound attenuator/ducting etc. The full assembly should

be designed as a standard integrated unit to maximise overall performance and minimise costs.

- Measurements of asymmetry of the inlet and outlet flows to the collector have shown that there is an opportunity to improve the overall turbine performance by introducing a matching asymmetry to the turbine characteristic.
- In the absence of flow control, a large speed range is required to ensure that turbine efficiency is kept close to optimal.

6.4 Construction

- The constructional techniques developed for LIMPET proved successful and allowed the completion and commissioning of a robust structure which has survived without problem, the worst storms recorded on Islay. It was however observed that the protection offered by the bund wall was less than hoped for. In recognition of this that better device performance will be achieved if the collector is at the cliff edge rather than set back in a gully as per LIMPET, further development of construction system is required. It is anticipated that such developments will not only allow LIMPET derivatives to be built directly on the coast but will also reduce structural mass by a factor of two thereby improving both the productivity and economic potential of the system.