ISLAY LIMPET PROJECT MONITORING FINAL REPORT

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CONTRACTOR – WAVEGEN

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1 Executive Summary

The project has monitored the LIMPET wave energy project on the island of Islay during the later stages of collector construction, the installation of turbo-generation equipment and the commissioning and operation of the plant. This report summarises observation of the plant and describes:

- The choice of technology
- The choice of location
- Power take off operation
- Construction of the collector
- Installation of turbo-generation equipment
- Maintenance issues.
- Performance and performance limitations
- Operation of the plant.

Management and planning issues are discussed. The plant has operated for nearly two years connected to the local grid with minimal maintenance. Save when shut down for research activities or through grid faults remote to LIMPET availability has been very high confirming the long term viability of wave energy as a contributor to national power supplies.

Whilst the power output of the plant has at times been limited by the local grid capacity the overall performance is lower than expected. The reasons for this have been identified and are associated with project issues rather than fundamental aspects of the technology. It is most encouraging that when conditions at site are reproduced either in wave tank testing or in numerical simulations that the site data closely matches the test information. This confirms that a correctly structured test programme can be used with confidence to predict the performance of the next generation of shoreline devices.

Both the collector structure and the turbo-generation equipment has survived extreme storm conditions with minimal damage. The damage which did occur is avoidable through design modification. This gives confidence that in the longer term this type of wave energy system will operate reliably in the marine environment.

The experience of building and operating LIMPET is invaluable not only in respect of furthering the development of more shoreline generation but also in respect of developments offshore. In particular experience with the LIMPET instrumentation and control systems together with grid integration issues is directly applicable to the current round of offshore developments.

LIMPET continues in grid connected operation both as a power generator and as an equipment test bed.

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3 A Review of the Project Background



3.1 Objectives

The objective of the project was to provide a series of 14 reports to ETSU describing firstly the status of the LIMPET wave energy device at the commencement of the project and subsequently the performance and operation of the unit over the two year period of the project.

3.2 Historical Review

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 Dti . This device was commissioned in 1991 and operated as a research tool for a period of eight years until it was decommissioned at the end of its useful life 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 is important that a more generally applicable construction concept be developed.
- The turbo-generation system of the 75KW prototype was connected direct on line to the grid and offered little flexibility for performance investigation or 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.

The LIMPET project was conceived by QUB as a logical development of the 75kW prototype and at the instigation of Professor T.J.Whittaker a project grouping was established to apply to the European Commission for support under the JOULE III programme. Wavegen were the major industry partner in this grouping being responsible for the development and installation of the complete turbo generation system and for operating and maintaining the plant. This application was successful and construction work commenced after the signing of contracts with the EU on 1st November 1998. The JOULE III programme was based upon a construction period of one year followed by two years of plant operation to permit the collection of representative data on the performance of the device. In practise delays in the EU schedule meant that the commencement date did not allow any significant work to be performed in the first year and to allow for this the contract period was extended to the summer of 2002.

At the time of the start of work on LIMPET the UK national renewable energy programme did not allow for any direct support in addition to that provided by the EU. The commencement of the new millennium saw a revival in interest in wave energy as a contributor towards the UK's renewable energy generation and it was considered important that information from LIMPET be fed back to the UK national programme. To that end the current project was established in parallel with the JOULE contract in order to give a bi-monthly update on the status and performance of the device.

4 Design Considerations

4.1 Choice of Location

QUB have previously performed a survey of potential sites for ETSU 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 for shoreline wave energy development. 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 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 excellent cooperation of the local community in establishing the 75kW prototype device and their enthusiasm for further developing their island resource. In summary Islay offered:

- A good wave climate with an annual average intensity at the chosen site believed to be approximately 20kW/m.
- 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.

4.2 Form of Device and Selection of Equipment

The LIMPET comprises three discrete sections:

• 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 tool which would permit the future development of such a commercial unit. To that end the design has incorporated, within the allowable budget, a range of features to maintain a flexibility of operation and which will give a wide scope for adjusting operational parameters in the search for optimal performance.

4.2.1 Oscillating Water Column Collector

The design of the OWC collector takes 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.

4.2.2 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 QUB 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 only partially successful and no complete seal was achieved but it did insulate the construction from the worst effects of the weather during the build period and allowed for a successful completion of the prototype site and the narrow width of the collector. This solution would be 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.

4.2.2.1 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 simple in principle there are fundamental problems with this concept:

- Experience has 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 which did not involve a high risk of damage during installation.
- Budgetary estimates for the steel structure were outwith the initial estimates rendering the concept non-viable.
- A requirement remains 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 the projected concrete collector chamber would be in excess of 2500Tonnes which could prove difficult to handle at the remote Islay site. The problems of preparing the connection to the cliff face still remain. The concept of remote manufacture was thus rejected as the optimal approach for LIMPET.

4.2.2.2 Protective Excavation

The construction procedure finally adopted for LIMPET is described in figure 2. Instead of building directly at the cliff edge an excavation is made a little way back from the edge leaving a rock bund between the construction site and the sea. The construction is then performed in the protective lee of the bund and when complete the bund is removed to allow the ingress of water into the OWC. The installation of LIMPET and the subsequent operation of the plant lead to two important considerations with regard to this concept. Firstly the protection offered by the bund was imperfect



so that there was significant weather interruption during construction.. Secondly there are performance implications in moving the OWC from the cliff edge to a position set back 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 the well reported "Harbour Wall" 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 has subsequently been confirmed at site and it has been established that in shallow water a parallel gully can be highly detrimental to the overall performance of the collector. Further studies into the mechanics of this effect could be highly beneficial in further improving shoreline collector performance.

4.2.2.3 Collector Shape

Having rejected a conventional steel construction on cost grounds and determined a reinforced concrete structure as suitable, preference was given to a flat-sided structure. 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 low rise 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 are increasing the surge motions relative to heave.
- The inclination of the water column increases the water plane area of the column for a given chamber cross section. This permits the primary water column resonance, which is influenced by the ratio of the water plane area to the entry area, to be better coupled to the predominant period of the incoming waves.

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

4.2.2.4 Size of Collector

During the operation of the 75kW prototype device the team at QUB developed a significant database on the energy incident on 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. From this data an annual average incident wave energy of 17.9kW/m was estimated. The reference location for the source data is some 400m from the actual LIMPET site and is relatively sheltered. As such it was confidently expected that the actual power incident on LIMPET would exceed the estimated value.

With the information available at the commencement of the LIMPET project the optimal size of collector was difficult to judge. It was however considered that the next stage of development after the QUB 75kW prototype should represent a significant size increase and offer the basis for the modular development. An installed capacity of 500kW and a utilisation factor of 40%, giving an annual average output of 200kW, appeared to be reasonable targets.

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.

4.2.2.5 Collector Cross Section

Whilst we had a good general perception of the likely loads to be borne by the collector structure we have no accurate information on which to base the design and as such the collector design was necessarily conservative. Having established the width at 21m it was decided that it would be necessary to divide the water plane into three separate columns. This was 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 there was concern 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 was considered too large to be economically efficient.

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 have 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 could 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 3 was selected.



4.2.2.6 Axial Section

Features of the axial section of the collector are described with respect to Figure 4. For the majority of the length of the collector the front and rear walls are parallel and make an angle of 40° to the horizontal. Close to the entry lip the exterior surface of the front wall steepens to 60°. This has the effect of reducing the 6m general separation of 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 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 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 take on the task of minimising entry losses.

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 has indicated that amongst the most severe of the load conditions to which an improperly designed 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 wave breaking blocks have been incorporated into the bench floor so that in the unlikely event that water does reach this high the flow will be disturbed before it hits the rear wall. Any water reaching bench level will still have nearly 5m to rise before reaching the turbine axis. As such, whilst there will inevitably be heavy spray passing through the turbines, it is believed that the plant was correctly sized to prevent any bulk ingress of water into the turbine ductwork.

Similar considerations existed 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 was designed to interrupt such flow and to ensure that the water falling behind the collector is highly aerated rather than of high 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 from there passes into the turbo-generation duct. The central opening is used to connect the collector air flow to the turbo generation system whilst the second opening is blanked off. The second opening 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 were left in each diaphragm wall at bench level. To give further research opportunities the potential for closing off these openings was also included in the design.

One metre square openings were left in the roof of the two northmost collector chambers to allow for the fitment of a pressure relief valve as part of control strategy development; there are however no immediate plans to use this facility.

4.3 Turbo-Generation Equipment

4.3.1 Overview and General Description

The operational design parameters for the Wells turbines 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 figure 5.

Turbine Diameter	2.6m
Nominal Operating Speed	1050rpm
Number of Turbines	2
Arrangement	In Line Contra-rotating
Blade Form	NACA12
Number of blades	7
Blade Chord	320mm
Hub to Tip Ratio	0.62

	-	
Figu	re	5.

The QUB 75kW prototype used a monoplane Wells turbine whilst a monoplane with guide vanes was fitted to the shoreline plant on the island of Pico in the Azores. The choice of the contrarotating biplane unit was made both on the expectation of a better performance than the two options previously tested at the full scale and also to gain field experience of a turbine option previously untested at the full scale.

Figure 6 shows a side view of the layout of the mechanical components of the turbo-generation equipment and figure 7 an indicative 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 is however designed to permit modulation so that at times of excessive wave activity it is possible to reduce the power input to the turbines. An electrical 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 air operated. To an extent it duplicates the function of the first valve but offers a faster closure in emergency but 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 until sufficient operational experience has been gained and history of reliability established it is 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 has been estimated at 1300kgm².

The two turbine/generator modules are fitted back to back so that the turbines are separated by approximately one blade chord. A nose cone is fitted to the exit end of the second module to smooth the transition of the air flow.

At the exit from the second turbine/generator module the air flows into an exit chamber (11) providing acoustic attenuation of the turbine and flow noise prior to discharge.

4.3.2 **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 thrust 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. This offers a compact arrangement with the generator placed within the inner diameter of the turbine annulus. (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 does carry a significant cost penalty at the development stage. Conversely the mounting of the turbines on independent bearings and the use of standard generators gives a direct saving on generator cost but incurs additional expenditure on the turbine frame, shaft, bearings and coupling.

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 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 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 Form of Controls

The input power to any wave energy generator is variable in both the short and long term. Each wave cycle produces 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.

4.3.3.1 DOL Connection

DOL is the simplest form of connection but of itself offers no active control over the generation. It relies upon the grid being able to absorb all the power 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. Since it has already been assumed that the grid is stiff the lack of a power storage facility is not important. 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. This may not be critical in a production unit but it is an important consideration for a research tool. 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.

4.3.3.2 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 principle 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.

4.3.3.3 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 excess via a parallel connection to the grid.

4.3.3.4 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 enables 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 water column damping should this be desired. In principle the system permits generation from any finite speed up to the system maximum. In practice since the ability of the turbine to absorb power is proportional to the cube of speed, low 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 power factor correction. There is a substantial additional cost to

adopting inverter control of generation but in the research environment there is no doubt that the system offers a range of operational options which would not otherwise be available.

4.3.3.5 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 power output from the plant, 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. To facilitate inverter drive they have been operated with a fixed rotor resistance and internal shorts replacing the external rotor connections. At the same time the external dump resistors have been removed from the specification whilst leaving provision within the layout of the control hardware to permit a reintroduction.

4.3.4 Generator Type & Source

The generator specification was summarised as shown in figure 8 and put out to tender. Of those suppliers willing to consider the special requirements in terms of through shaft and axial load capability the preferred quotation came from Alstom.

Generator Type	F3GTS 400 G8G
Power at Generator Terminals	250kW
Duty Type	Continuous with Slip adjustment 1-20%
Rotor Type	Wound Rotor
Service Factor	1.00
Rated Voltage (Delta Connected)	$400V \pm 10\%$
Rated Speed	1016RPM
Maximum Test Speed	1500RPM
Number of Poles	6
Starting Type	Fixed Rotor resistance or Inverter Drive
Generator Inertia	11.5kgm ²
Load Inertia	1300kgm ²
Estimated Starting time	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
Number of Successive starts	3 Cold, 2 Hot
Ambient Temperature	≤40°C
ENCLOSURE PROTECTION	IP56
Cooling Air Flow	0.5m3/sec
Pressure Drop in Generator air	400Pa
Circuit	
Bearing Type	Spherical Roller 22326

Generator Life Expectancy	30 years
Bearing Life expectancy	100,000hrs
Shaft material	Marine Grade 316 stainless
Lubrication	Grease – Lubrication Interval 8000hrs

Figure 8. Generator Specification

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.

4.3.5 Control Type and Source

The main aspects to the LIMPET control system are:

- Safety
- Functional Operation
- Grid Integration

For each of these activities the primary control functions through a microprocessor based controller. Additional control functions are provided by parallel hard wiring and from within the inverter drive.

4.3.5.1 Grid Protection

Grid protection to the G59 standard is an integral part of the controller and no other specific G59 protection is provided. It was necessary to demonstrate the efficacy of this protection to the supply utility at the time of commissioning.

4.3.5.2 Safety

When running the potentially most serious situation for the system is turbine over speed. This could happen if, for whatever reason, the generator torque was insufficient to prevent the acceleration of the turbine to an unsafe speed. The software programming of the controller operates a layered control strategy to deal with this situation. A maximum desired operational speed is set and if this speed is approached the controller calls for the airflow to the turbines to be reduced by a partial closure of the primary control valve. Whilst both valves can fulfil this function the butterfly valve is normally used. If this action does not have the desired effect and one or both of the turbines continues to accelerate past a maximum set speed then the controller will call for a controlled stop of both turbines. The controlled stop involves:

- Electrical braking of the generators.
- Emergency closure of both valves
- Application of parking brake when speed falls below 100rpm.

In practice the most likely cause of a potential overspeed event will be a loss of grid power through a local power cut. Under these circumstances electrical braking will not be possible but since the

controller operates via a UPS and the emergency closure of the valve is not powered from the grid, the security of the system is maintained.

The butterfly valve is held open by an electromagnetic brake and in the event of a loss of signal to the brake it will deactivate and the valve will close under gravity. The variable vane valve is opened pneumatically. In the event of a loss of actuation signal the opening cylinder is opened to atmosphere and a reservoir dumps air in to the closing side of the piston. In the event of a loss of grid connection or other interruption of actuation signal to the valves both will close. A further layer of safety is included by the provision of a hard-wired circuit which maintains the supply signal to the two valves. This circuit will be interrupted if the speed, sensed by a second set of speed sensors (independent of those feeding the controller), exceeds the maximum set speed. Other circumstances which will initiate a controlled stop include:

- Excessive vibration of either generator
- High bearing temperatures
- High generator temperatures
- A G59 fault
- An inverter error message
- A loss of air pressure to the variable vane valve
- A Manual stop signal

4.3.5.3 Functional Operation

The internal controllers of the CEGELEC inverters used to drive the generators are set to respond either to an external speed reference or an external torque reference. In the initial stages of operation the function control of LIMPET centred on the provision of a torque reference signal by the controller to the local processors on each of the two inverters.

On receipt of a signal to initiate a start sequence the controller executes the following steps:

- Checks that the incoming wave power as indicated by recent chamber pressure readings indicates that start up is justified.
- Cycles both valves to check function then returns both to the closed position.
- Checks that air pressure is available for an emergency closure of the variable vane valve.
- Checks that there are no faults signalled from the G59 protection or from the inverters.
- Motors generator 1 to a start up speed.
- Motors generator 2 to a start up speed.
- Opens the butterfly and variable vane valves
- Allows the turbines to accelerate to the minimum desirable operational speed.
- Activates the power take off control algorithm.

The plant then operates normally supplying power to the grid until a shut down signal is received either from the safety system, or from the functional controls. The functional controls might for example initiate a shut down in the event that there was insufficient input power to justify the system losses.

4.3.5.4 Functional Control Algorithm

The torque reference value to be supplied to the on board inverter controllers is generated within the controller software by an algorithm written in "C" by Wavegen. In general terms the objective of the algorithm is to maximise the power output from LIMPET with due regard to the various operational limitations. The algorithm uses the parameters listed below to provide an individual torque reference signal for each of the generators.

- Collector Pressure
- Turbine speeds
- Minimum speed at which generation will occur
- Maximum desired operational speed
- Maximum set speed
- Butterfly Valve Position
- Variable Vane Valve position
- Maximum Power which the grid will accept

The baseline algorithm was based upon the following philosophy:

- The objective is to export the maximum possible average power to the grid.
- There is a minimum operational speed below which the turbines will be ineffective.
- There is a maximum speed beyond which it may be unsafe to operate.
- There is likely to be an optimal mean operating speed which gives the best combination of applied damping to the water column and efficiency of turbine operation.
- The above considerations will lead to there being a desirable speed range in which it is beneficial to run.

In its initial embodiment it operates for each generator by:

- Checking the generator speed and comparing it to the desired value.
- Adjusting the power drawn by the generator in relation to the deviation of the generator speed from the desired value.
- If the generator speed approaches the maximum desired operational speed restrict the airflow by reducing the opening on the butterfly valve.
- If the generator speed exceeds the maximum set speed use the emergency close facility on both valves.
- If the generator speed falls below the minimum desired operational speed set the demand torque to zero.

To test the control algorithms prior to application at site a mathematical simulation was developed by Wavegen and the control algorithm was bench tested using model test data prior to full scale commissioning. Subsequent modifications to the strategy have been similarly tested as part of ETSU contract V/06/00183.

5 Status of LIMPET at the Commencement of the Project

5.1 Summary

In June 2000, at the commencement of the monitoring contract the collector of the LIMPET plant was well advanced and would be structurally complete by 17th August. The turbogeneration equipment had been built and tested at the premises of Wavegen in Inverness and was awaiting the removal of the protective wave wall from the front of the structure prior to shipment to site and installation on the collector.

5.2 Civil Engineering



Figures 9 & 10 show the part constructed collector at the commencement of the monitoring project. The rear sloped wall was completed the previous year and the side walls are nearing completion A the bottom of the excavation one half of the entry tube permanent steel shutter is in position and a wall pour is being prepared. To the rear of the collector, beyond the turbine slab, the control room structure is nearing completion (not shown). The completion of the structure was critically dependent upon completing the down hole working during the summer weather window but even in June and July there were storm periods during which the construction area was completely flooded and temporary works subjected to wave loading (figure 11). When wave overtopping occurred there was not only a direct loss of time due to cessation of work during storms but typically a longer delay caused by the requirement to pump the excavation dry, to clear the site of debris and to repair



the damage to temporary works. This places a high penalty on a failure to complete and secure a particular construction operation within a predictable weather window. The contractor used a weekly, 10 day weather forecast prepare for the site locality by the Belfast Meteorological Office. These were typically accurate for the first 3-5 days with increasing variability thereafter. In principle therefore with suitable planning and organisation of resource all of the construction activities could be broken down into segments which could be completed and secured within a predictable weather window. In practise this did not occur. The main reason was that the operational parameter which drove the day to day site planning was not the completion of the work at the lowest cost and within the contract time scale but, in the belief that this would lead to a minimum cost, the full utilisation of the labour on site. The result was that, particularly in the entry lip area, that some concrete pours had to be prepared three or four times before being successfully completed. This led to programme delays and much repeat working, the majority of which, it is believed, could have been avoided by the adoption of alternative working practises, not typical of civil construction sites, but appropriate to the particular project.



Figure 12

per unit material placement costs.

Despite weather interruptions the construction continued and by the end of June 2000 the turbine outlets were being prepared for casting into the rear wall of the collector.(figure 12) and the electrical control equipment was being installed in the control room. Figure 12 gives an indication of the very high density of reinforcement used in the concrete construction. The unusually high density of rebar created problems in access both for steel fixing and concrete pouring. It is expected that as the structural loads imposed by wave and water column action become better understood the design loads can be reduced and steel density reduced to more normal levels thereby reducing



In mid August after completion of the rear wall the two butterfly valve sections were shipped from the Wavegen workshop in Inverness to site and fitted to the back wall of the collector (Figure 14). The valves fitted well to the cast in

During the year 2000 all of the concrete used on the structure was mixed on site using a self loading mobile mixer with 3.5m³ capacity. The mixed concrete was skipped into position using a 45T mobile crane. Figure 13 shows the delivery skip being craned to a pour. Also visible is the protective bund wall which rises approximately 6m above the water surface at low tide. A row of concrete cylinders was placed on top of the bund wall to give additional protection against mild overtopping.



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rings in the rear wall and installation was completed without difficulty. Figure 14 also shows access tubes cast into the collector wall to facilitate the fitment of lights and cameras to permit the observation of water column movement. The slot between the butterfly valves allows the introduction of a divider plate to isolate flow in the north collector chamber from the other two chambers. A similar slot exists between the centre and south chambers.

The original design of the collector called for all roof sections to be cast in situ. In response however to the losses due to weather down time the design was modified to create a

composite roof formed from a lower layer of pre-cast beams topped with an in-situ casting. Precast beam in position and awaiting the in-situ topping are shown in figure 15. The use of pre-cast beams in this manner offers two significant advantages. Firstly it avoids the necessity for the significant quantity of support structure and formwork which would be required if the original, wholly in-situ design, had been adopted. This is particularly important since the support would have been grounded on the slope. Secondly the production of the pre-cast beams on site gave fall back work when bad weather prevented access to the primary work fronts.



blast was progressive with the four rows of charges being fired successively from seaward to landward. To further encourage the rock to move away from the collector rather than towards it, the pumping system was reversed so that the excavation was full of water at the time of the blast and the blast was fired at low tide. In general terms the blast was successful with the material of the bund wall being wholly displaced and the majority moving to seaward. A proportion of the blast material did however move towards the collector and piled up against

The last pour was made on 17th August 2000 and at this time the collector was structurally complete (figure 16). It was then necessary To remove the bund wall to allow access to the sea and to activate the collector. This was done by drilling the wall to accept some 2 tonnes of commercial explosive in order to remove the 2,500m³ of the bund wall. This is overcharged compared to a standard rock blast with the objective of breaking the rock into relatively small sizes to facilitate subsequent removal. The





the structure. It is a tribute to the design and construction of the collector that there was no significant structural damage.

Immediately after the blast the work of excavating the debris from the gully commenced using a long reach excavator. In the first instance the excavator created a ramp so that it could track into the centre of the gully from where it could reach to the gully mouth to recover far flung material. This was then drawn back towards the collector and removed from the gully. Working in this manner and subsequently from the sides of the gully the majority of blast material was removed and the water column activated. Unfortunately there

was no way of removing material which had lodged under the collector lip or which had been thrown outwith the reach of the excavator. This progressively washed back into the gully and combined with the material already under the collector lip created, over time, a major blockage to the entry of water into the collector. This problem was addressed in the spring of 2001.

6 Turbo Generation Equipment Construction



susceptible to wave overtopping (figure 20) and to allow access to the turbo-generation equipment in all but the most severe of weathers a building was constructed around the equipment (figure 21). The walls turbine hall was constructed as a cavity wall formed from 100mm blocks. Because the turbine slab is lower than the surrounding land there is a danger of water collecting on the slab. Whilst there is relatively free drainage from the south side of the slab the only bulk drainage from the north side is around the end of the turbine hall and as such, due to the weight of water, there is a danger of a significant differential pressure developing across the walls of the turbine hall. To protect against this T20 rebars The mechanical and electrical hardware comprising the turbo-generation system was fully assembled at the Wavegen facility in Inverness and the turbines motored to nominal running speed before transportation to site. The mechanical assembly is formed from a number of sections which are bolted to the floor and which bolt together at flanged connections. The assembly broke down into convenient sections for transportation to site. These sections are shown part assembled on the turbine slab in figure 19. The mechanical assembly was performed over a three day period using a 25T mobile crane from an island supply. The completed assembly remained



1.5m long were drilled into the turbine slab in the wall cavity at 1m intervals and the cavity concrete filled thus providing a shear key against lateral loading. This proved to be prudent in that the water on the north side of the turbine slab rose to a height of at least 1.5m during winter storms



of 2001/2.. The roof of the turbine hall is formed from pre-cast slabs which were craned into position and which can be lifted off to allow access for major repairs. The process air exits the turbine hall via an acoustic attenuator which was fitted in the spring of 2001.

7 Operational Experience

7.1 Planned Maintenance

LIMPET was designed for a minimum of planned maintenance. Routine maintenance on the plant is limited but includes:

Item	Maintenance Interval
Grease generator bearings	8,000 running hours
Grease butterfly valve bearings	6 monthly
Visual check on plant	weekly
Drain air compressor/ check oiler	weekly

It is likely that the frequency of the last two items will be decreased within the near future. The visual check is made by a local engineer as a precautionary measure. As we become increasingly confident in the reliability of the safety and monitoring systems the need for frequent visual checks is decreasing. They will however remain necessary to protect against non-monitored items such as displacement of landscaped rock in storms.

Until recently the air compressor driving the vane valve was situated in the turbine hall with the result that salt laden water saturated air was drawn into the compressor as the working fluid. The effect of this was to overload the dewatering system necessitating frequent checks and intervention. The compressor has now been moved to the control room which is both warmer and drier with the expectation that the automatic dewatering should operate much more reliably without the frequent intervention. In the longer term it is expected that pneumatically operated systems will be designed out.

7.2 Unplanned Maintenance

There have been a number of significant items of unplanned maintenance occasioned as a consequence of unforeseen occurrences or design failure. The most significant of theses were:

7.2.1 Re-excavation of the gully.

From the initial commissioning on 2nd November 2001 until the March of the following year there was a gradual deterioration in the performance of the device. After considering a number of possibilities for this deterioration it was concluded that the most likely cause was a blockage of the collector entry. A divers survey was commissioned. The report from the divers plus video footage confirmed that there was indeed considerable blockage of rock at the mouth of the collector. The diver also reported that several large rocks are positioned at the mouth of the gully. The presence of bulk concrete and rocks with drilled holes confirms that the debris is from the original construction. This observation is further confirmed by the absence of rocks seaward of the gully. Figure 22 reproduces the diver's sketch of the build up of rock at the collector entrance and in the gully.



Figure 22 Rock distribution in gully and collector entrance

In order to remove the blockage and clear the gully of debris a Kocurek tracked excavator with 22m reach was mobilised to site. This was 6m longer than the machine originally used and able to reach



past the centreline of the gully to allow a full clearance of the gully floor. A rock breaker was available for fitment to the excavator and guided by divers was able to break up the large boulders on the sea bed so that they could be towed away from the site using a workboat. More than 350m3 of rock were removed from the gully and entrance to the collector and a post operation survey showed no significant quantity of rock either in the collector mouth or on the floor of the gully. There was a significant improvement in capture performance on the restart.

7.2.2 Vibration Loosening of Bolts and Crews

A visual inspection early in 2002 showed that there were a large number of screws on the plant which were working loose. These were retightened. The loosening was attributed to the excessive vibration which occurs on the turbines when the blades stall under high energy input conditions. Whilst no major problems had been encountered over the winter of 2001 the 2002 winter season on Islay included the worst storms in living memory causing massive blade stall and subsequent plant vibration. It is not acceptable in the long term for the turbines to run in continuous stall and the prolonged storm events have caused a rethink of the control strategy to minimise a reoccurrence.

7.2.3 **Positive Positioning of Vane Valve**

Whilst monitoring the vibration levels using a hand held meter at the side of the plant it was seen that the vane valve was partially closing at times of high flow but not in circumstances where this should occur under the action of the control system. The position control on the vane valve operates in such a manner that a force balance is maintained on either side of the pneumatic operating cylinder so that when the valve is in the set position there is no net force on the valve actuator. This meant that any aerodynamic imbalance will tend to move the valve until the control system responds to rest the desired position. This was clearly occurring and may have been causing a significant flow disruption and power loss. To avoid this situation the valve settings were adjusted so that when fully open the valve position sensor only reads 80° and as such the actuator continues to force the valve in the open direction. It is however prevented from moving past the fully open by a mechanical stop. Whilst not ideal this has prevented the valve flutter and ensures a positive positioning of the fully open valve.

7.2.4 Storm Damage

The extreme storms of the winter of 2001/2 caused both superficial damage to the site and actual damage to plant peripherals. Two of the external doors to the turbine room were burst from their hinges by external water pressure and there was evidence that the water level inside the turbine room had at some time risen to 1.3m. This had inundated the two generator cooling fans and the air compressor. After washing and drying the cooling fans were serviceable but as a precaution new bearings were fitted. The compressor motor was beyond economic repair and a new compressor was installed. In each case the new installation was such that the relevant items were more than 1.3m from the floor. The same inundation swamped the lower section of the QUB data logger and required a replacement of data cards. Again the installation has been lifted further from the floor.

The storm also washed a quantity of landscaped rock on to the turbine slab. This rock had been undisturbed during the previous winter and indicated the extremity of the recent storms. The majority of this debris has since been removed by local contractors.

7.2.5 Butterfly Valve Bearings

Over a period of time it had been noted that the butterfly valve was becoming difficult to move under actuation and would not close under gravity in an emergency stop. Investigations showed that the most probable cause of the problem lay in a seizure of the valve shaft bearings. Given the role of the valve in the plant safety system it was decided that the valve should be stripped and the problem rectified and this operation was performed in June 2002. On disassembly it was established that the interface between the self lubricated bearings and the steel shaft of the valve had lost its lubricity and that the mating components were effectively bonded with salt. The assembly was modified to allows grease lubrication and since this time the valve has operated satisfactorarily under all conditions.

7.3 Remote Operation

The plant was designed to be operated remotely from site with normal control instructions being sent from the Inverness offices of Wavegen to site via modem. This method of communication has worked well with the exception of occasional breaks in telephone availability. During these periods the plant continued to operate under autonomous control.

7.4 Grid Connection Issues.

The plant is fitted with a grid protection system to the G59/1 requirements. This system is designed to disconnect the plant from the grid in the event of any disparity between the condition of the grid at the point of connection and the grid standard. Disconnection will occur in the event of grid over or under voltage, over or under frequency, and if there is a phase imbalance (vector surge). The presumption in the requirement is that generator at the point of connection is causing the fault but this is often far from the case. To date there have been no grid faults caused by LIMPET but a myriad of faults on the grid which have been detected by the LIMPET grid protection system and which have thus caused LIMPET to shut down.

No problems have been observed to date in respect of supplying power from LIMPET to the grid.

8 Operational Performance

In general terms the LIMPET system has under performed in relation to the expectations reported in the Benchmark report for this project. Analysis of the shortfall has however showed that the shortfall relates more to inaccuracies in assumed wave input power and misunderstandings in the interpretation of turbine performance data than in failings of the plant.

8.1 Pneumatic Capture Performance

8.2 Influence of Sea Floor Profile

Prior to the construction of LIMPET a series of tank model tests were performed in order to assess the likely output of the plant. From the long term data recorded by QUB at a site close to their 75kW prototype a series of 53 spectra believed to be representative of the LIMPET site were developed. These spectra were reproduced in the Wavegen test tank and run at a 40:1 model of LIMPET. The annual average power in the 53 spectra was approximately 18kW/m. Based on the results of these tests the annual average power capture of the LIMPET collector was estimated at 243kW giving an overall average capture factor based upon the 21m device width of 0.64.

In the model tests the sea floor bathymetry was taken as that indicated by an existing survey of the site at the time of the start of construction. This indicated a 7m water depth at the cliff edge with a sea floor shelving at 1:25 from the waters edge. A new survey undertaken after the start of



construction showed the water to be less deep than indicated with a typical depth of 5m at the waters edges and a substantially flat plateau for some 80m before the commencement of the 1:25 slope. This difference in these profiles is indicated in figure 24 with the originally reported slope shown beneath the red hatching and the subsequent survey beneath the blue. The relative shallowness of the water has a dramatic influence on the wave energy reaching the collector. When the original 53 spectra were run at the LIMPET model but using the revised bathymetry then the pneumatic power capture fell to 160kW, some 66% of the original . It was also significant that in the shallow water tests the waves were steeper than in the original experiments so that the flow profile in the collector and hence through the turbine were much more peaky.

8.2.1 Influence of Gully Shape

It has been noted in 4.2.2.2 that it had been established prior to construction that the straight sided gully in shallow water was detrimental to performance and to improve primary power capture the LIMPET excavation was designed to provide a tapered gully with the sides at \pm -12.5° to the collector centreline. In respect of problems associated with the removal of the wave wall the tapered gully was not formed and the entry to the collector was left with straight sides. In a series of model tests performed under ETSU contract V/06/00183 it has been shown that the presence of the gully would have added some 25% to the pneumatic power capture. Consideration is being given to introducing the taper to the gully at a later date.

8.3 Turbine Conversion Efficiency

Accurate site measurements of instantaneous turbine efficiency are difficult to obtain as a consequence of uncertainty in the source data. To calculate the efficiency it is necessary to know both the input pneumatic power and the power absorbed by the turbine. There are difficulties in measuring each of these variables.

8.3.1 Measurement of Pneumatic Power

The monitoring programme for LIMPET includes a measurement of the water column movement via an ultrasonic transducer in the central chamber and through pressure transducers at the base of each of the three water columns. There is however no direct mapping between the output of these transducers and the volumetric displacement of the water surface. The pressure at the base of the water columns is not uniquely related to the height of the internal water column but is also influence by the external water height and the instantaneous flow velocity across the surface of the probe. Tilt or distortion of the water surface, coupled to a variation of height in the three water columns affects the relationship between the water surface motion indicated by the ultrasonic transducer and the volumetric displacement of the water column. Having estimated the water column displacement it is then necessary to assume a thermodynamic model and a turbine characteristic before a turbine flow can be calculated. Only then can the input power to the turbine be assessed. Experience has shown that this process is unreliable and leads to an unacceptable scatter in results. As an alternative the LIMPET turbine was calibrated by taking a large number of flow measurements in the turbine duct with the turbines constrained to run at a substantially fixed speed. By correlating the flow with chamber pressure it was established that the average turbine damping was linear with flow with a value of 93 Ns/m³ per 1000rpm. With this value the instantaneous pneumatic power can be calculated from pressure²/damping. Whilst the average turbine damping is linear, significant hysteresis occurs, particularly at the end of the pressure stroke so that the assumption of linear turbine damping will itself introduce a new element of scatter into the data set. Nonetheless with appropriate smoothing the technique gives the best available estimate of instantaneous input power.

8.3.2 Estimate of Power Absorbed by the Turbine.

The inverter drive control system demands a specified generator torque and if it is assumed that the manufacturers calibration is correct then this value when combined with the rotational speed gives an immediate figure for the shaft power to the generator. To give the shaft power to the turbine

from that for the generator requires knowledge of the windage losses in the flywheel, the bearing losses in the generator and the changes in stored energy in the system inertia. Whilst the changes in stored energy can be measured with reasonable accuracy the flywheel losses are estimates based on projections of run down tests. Thus the measurements of turbine shaft power are also subject to significant inaccuracy.



8.3.3 Site Measured values of Turbine efficiency.

Figure 25 shows initial estimates of the turbine performance measured on LIMPET compared with the published model data [1] on the contra-rotating biplane turbine used to predict the turbine conversion efficiency. The site data shows the turbine performance for both the exhaust and inlet strokes of the power cycle. It is seen that on the outflow of air flow from the collector the turbine efficiency is broadly similar to the model data but exhibits a lower peak efficiency and stalls earlier. A close examination of the source data for the model test performance shows that the

published data is for the aerodynamic performance of the turbine blades rather than the turbine assembly and if the windage losses of the turbine hub are subtracted from the laboratory results then they are very close to the site measured data in peak efficiency and much closer in respect of bandwidth. The data also reveals that the performance of the LIMPET turbine on the inlet stroke is substantially worse that during outflow. An analysis by the team at QUB has shown that this is a consequence of a non uniform flow distribution on inlet resulting from the flow around a resonator plate forming part of the acoustic attenuation system. The effect of this mal flow distribution is to reduce the overall conversion efficiency to approximately 75% of that resulting from a mirroring of the due consideration to flow distribution. In retrospect this was an error in that the influence of non-uniform flow on turbine performance has been clearly identified by White et al in previous studies. Applying the measured efficiencies on outflow to the time domain simulation gives and overall turbine conversion efficiency of 40%.

8.3.4 Electrical Conversion Efficiency and Parasitic Losses



8.3.4.1 Induction Generator

Induction generator are usually considered as high efficiency devices with over 95% conversion at high load factors. The LIMPET generators are often run at low load factors and rather than consider overall percentage efficiency it may be more appropriate to consider actual conversion losses. These consider a fixed element, which is primarily a consequence of the magnetisation current, to which must be added a variable factor dependent on the generator load (figure 26). For each of the LIMPET generators the fixed component of loss is approximately 9 kW to which is added a variable component at 250kW rated power of 7.5kW. At low power factors the fixed losses dominate with the effect that at an output of say 50kW/generator the generator efficiency falls to 80% with ever decreasing performance at lower powers. These figures do not include the power needed to drive the intermittent cooling fans.

8.3.4.2 Inverters



The inverter losses similarly comprise a fixed and a variable element. The fixed loss is 4.1kW per inverter with the total loss rising to 10.kW at full load.

8.3.4.3 Parasitic Losses

The Power take off system for LIMPET was designed to have the highest practical inertia in order to give the opportunity to smooth the power flow to the grid. The majority of this inertia is contained in the flywheels but these flywheels also create a significant windage loss. From run down tests the loss per flywheel in kW has been estimated at $6.5 \times 10^3 x$ (rotor speed in rpm). At a typical running speed of 1,000rpm this equates to 6.5kW.

8.3.4.4 Total Losses

The electrical and parasitic losses per unit are summarised in figure 28. Noting that there are two generation units the typical combined loss at 1,000rpm operating speed and 50kW power output is 44kW.

Generator	10 kW	
Inverter	5 kW	
Windage	6.5 kW	
Miscellany	0.5 kW	
Total loss per unit	22 kW	
Figure 28		

9 Discussion and recommendations with respect to performance, planning, management and efficiency in design, construction and operation of wave energy projects.

9.1 Performance

Despite the observation that a various times the grid limited output of 150kW has been reached the initial response of the LIMPET project team to the measured performance of the full scale device was disappointment that the output was not greater. As the performance details have been analysed however it has become increasingly clear that there are no fundamental problems with the concept of the shoreline wave energy generator. Indeed, when the site conditions have been accurately modelled the predicted performance matches very well with site observation. This means that further prediction as to the performance of further shoreline devices can be made with a very high degree of confidence. To that end the initially estimated annual average performance, that achieved at site and an achievable target have been summarised in figure 29.

	Initial estimate	Current Performance	Achievable
1.11//			
KVV/M	20	12	20
/ %	80	64	80
kW	336	161	336
%	60	40	70
kW	202	65	235
kW	0	44	22
kW	202	21	214
`	kW/m y % kW kW kW kW	Initial estimate kW/m 20 y % 80 kW 336 % 60 kW 202 kW 0 kW 202	Initial estimate Current Performance kW/m 20 12 y % 80 64 kW 336 161 % 60 40 kW 202 65 kW 0 44 kW 202 21

Figure 29

It is clear that in the formulation of the original performance estimate insufficient attention was given to accurately identifying losses and the influence such losses might have on optimal equipment selection. In addition to this, for reasons largely outwith the control of the project team, the incoming power at the site was not as initially predicted. This situation was compounded by the lower than expected turbine conversion efficiency and the losses occasioned by the acoustic attenuator leaving a lower than anticipated figure for average generation.

In identifying the divergence of the current performance from the initial predictions it has been possible to highlight solutions which can be applied to future designs and hence to establish a reasonable and achievable target for a next generation LIMPET.

Model tests have confirmed that with the correct bathymetry the primary pneumatic capture is achievable with current models giving overall pneumatic capture in excess of 80%. Finding the correct bathymetry is a matter of careful site selection and as part of feasibility studies performed for overseas contacts deepwater sites have been identified. With the establishment of the strong interaction between the performance of LIMPET and the water depth at the shoreline it is also considered important to investigate what changes can be made to the collector form to maintain performance at lower water depths.

In addition to the measurement of turbine performance at the full scale a series of model tests at Wavegen has led to the conclusion that the previously published data on Wells turbines typically represents an idealised upper bound performance which is unlikely to be reproduced in any commercial plant. The conclusion is therefore being drawn that an alternative higher efficiency turbine must be developed for OWC applications. Wavegen are advanced in the development of a variable pitch unit which is confidently expected to offer a whole cycle efficiency of greater than 70%.

Having identified and quantified the loss mechanisms and explored the potential of high inertia systems we are better placed to plan for the avoidance of parasitic loss. This is best achieved by setting the average generation to be a higher proportion of the nameplate capacity than has previously been accepted and to design for a single generator and minimum inertia compatible with acceptable power delivery. The time domain model developed for LIMPET is of great benefit in this process.

The overall effect of the lessons learned during the monitoring programme is to confirm that the targets set at the start of the programme could be met if the knowledge gained is correctly applied. This is considerable industry importance in that it will give confidence to technology suppliers, investors and users that provided that the correct procedures are followed the projections made at the commencement of project can and will be met.

9.2 Planning

9.2.1 **Pre-Construction Planning**

From the foregoing it is clear that the LIMPET project has suffered through a lack of detail in site data and in the planning and testing prior to the commitment to construct the device at its present location. The performance shortfall is largely associated with the location and could have been avoided if a more detailed and more accurate survey had been available at the start of the project. It is thus considered of prime importance that for any similar project a full survey of site bathymetry be available as part of project feasibility studies.

9.2.2 Planning for Construction

The site organisation for the civil engineering construction of LIMPET was focussed on maximising labour utilisation on the assumption that this would lead to the lowest cost structure. It is most unlikely that this assumption is correct. By not having a labour float to permit completion of key tasks within available weather windows a great deal of preparatory work was lost to the weather and the cost in both direct expense and perhaps more importantly time, of recovering after weather damage was a major cost item. It is thus considered critical that the construction planning is performed in relation to a weather spells analysis and that sufficient resources are available to complete tasks within likely weather windows even if this means that labour may be idle for some periods.

9.3 Project Management

In general the management of the LIMPET project has proved satisfactory. The one area where there were problems was with the civil engineering construction where there were significant delays. The construction which was scheduled for completion within a single summer season took a full two years to complete and it took a major effort on behalf of the contractors to complete within this time. From the clients standpoint the initial problems lay with the construction contractor devoting neither adequate management resources nor adequate equipment to the task in the early part of the construction. Early on in the 1999 construction season the client advised the constructor that they were in danger of missing the seasonal weather window and that they should mobilise

early. When the constructor did mobilise it was with inadequate resource and little was achieved in the first year. Whilst the constructor replaced his site management in the second year with an effective and experienced team mobilisation was again delayed so that completion was too late in the season to allow the gully to be correctly formed. Whilst these problems were recognised by the project management team the nature of the commercial contract with the constructor made it impracticable to overrule the constructors management preferences. It is thus important that careful consideration be given to avoiding any contractual terms which limit the ability of the project management team to fully manage the project.

9.4 Form of Construction

The method of construction adopted for LIMPET i.e. excavating behind a rock wall and building the collector in the hole so formed, whilst ultimately successful, did not offer the ease of construction which was initially proposed. A higher bund would have aided the situation but there would always have been periods of weather interruption. To reduce civil engineering costs a system of construction must be found which reduces working beneath the water line and in which individual operations can be planned with confidence for completion within predictable weather windows. A consideration of alternative construction techniques fulfilling this objective has been made as part of ETSU V/06/00183.

9.4.1 Operation

The day to day operation of the plant on Islay via a modem link from Inverness has proved extremely effective with the control and safety systems functioning satisfactorarily. A local engineer has been retained to allow a visual inspection of the plant on request and this facility has proved invaluable. The use of local labour has also helped to maintain LIMPET as an Islay community project.

10 Conclusions and Recommendations

- 1) After being in grid connected operation for nearly 2 years LIMPET has demonstrated the fundamental capacity of wave generated electricity to contribute to a national grid supply.
- 2) Whilst the plant output has not met the target output the shortfall is not associated with any basic limitation in shoreline wave energy technology but rather in a lack of detailed planning in respect to the site bathymetry prior to the plant construction. In this respect it is considered critical that a detailed survey be available as part of the assessment of any future project.
- 3) The site performance of fixed pitch turbines is unlikely to match that of laboratory tests. The current development of more efficient units such as variable pitch machines needs to be complete in order to achieve economic conversion rates.
- 4) Civil engineering site working practices suitable for inland projects are not appropriate to the construction of shoreline wave energy systems. At the shoreline maximum labour efficiency cannot be equated to minimum construction cost.
- 5) Both the collector and the turbo-generation equipment have proved robust and have survived extremes of weather with minimum maintenance. This demonstrates that wave energy can be extracted in a low maintenance environment.
- 6) The remote operation of the plant via modem has proved successful and without significant problem.
- 7) Overall the project has been a great success as a technology demonstrator, as a platform for testing equipment and as a vehicle for gaining much needed operational experience relevant to both shoreline and offshore generators. The plant will continue to operate supplying the national grid and will serve both as a generator and as a test bed for new power take off systems for the foreseeable future.