OCEAN ENERGY:

Development
&
Evaluation Protocol.

Always work to plan
but be prepared to improvise.

Part 1 : Wave Power

HMRC. September 2003

HMRC
HYDRAULICS & MARITIME RESEARCH CENTRE

Marine Institute
Foras na Mara

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Summary

This document describes a development and evaluation protocol that has been specifically adapted for the advancement of wave energy devices. The basis of the schedule is similar to that established by NASA and widely used by many engineering research establishments. It is geared towards the actual converter evolution and improvement rather than any of the equally important generic aspects of a wave energy extraction, such as resource investigation, site surveys, national grid location, permissions or licences etc. Theses latter categories are considerations that will be both country and policy dependent and will become important following on from this development programme, when a device is ready for the demonstration phase. Standard productivity and economic indices are required, however, to facilitate the evaluation section of the programme. Initially these can be based on the ratio between the size or weight of material required to build the device and the energy conversion potential (kW/m^3 or kW/tonne). Later, for convenience, the benchmark is taken as the European Union recommended objective of 5€c/kW (5 eurocents per kilowatt) of electricity fed into the distribution network. Energy absorption and conversion levels are therefore updated at each phase of progress as are the costs of fabrication, construction and fitting out of the devices (including mooring and power take-off). Naval architects and quantity surveys can be used to provide these realistic costs of the finished hulls. The **Protocol** is restricted to buoyant type devices or those termed 2nd Generation Wave Energy Converters (WEC) up to, and including, a prototype or pilot plant.

Following a standard development programme should prevent the trickle-down budget supply problem and consequent start - stop research that has slowed project progress in the past. It is divided into 5 main sections, or Test Phases and complies with the philosophy stated in the AnnexII report (2003) of the International Energy Agency regarding Ocean Energy Systems (IEA/OES). “Model tests are conducted before constructing in full scale to gain information on how the device will behave at sea. Model tests conducted in a systematic way can be used to establish generalities………Within ocean engineering there is a tradition for model testing in order to provide valuable information on loads and movements required to finalise the structural design.”

Phase 1: Validation Model; initial proof of concept trials to verify that the design operates as theoretically predicted. Simply, idealised models can be used at small (1:25-100) scale such that configurations may be quickly and easily change as required.

For efficient use of time and funds the test phase is divided into 3 sub-sets that can utilise the same model.

1. *Concept Verification.*
2. *Performance and Responses*
3. *Device Optimisation.*

1. Concept Verification; **s**ingle frequency, monochromatic waves of small amplitude will suffice for these trials together with a basic power take-off mechanism simulator. Results will be compared to the mathematical model under parallel development.
2. Performance and Responses; following satisfactory completion of Part One the same model can be excited by irregular waves to ascertain initial power absorption characteristics in real seaways. Classical spectra can be used. The section could be very important to aid the development of the computer model into irregular seas.
3. Device Optimisation; all new machines will have several (or more) variables that affect performance. In establishing that the device works in the first two sections some of the options will have to be investigated. Based on these findings the best dimension, dynamic characteristics and configuration for realistic, or site specific, wave climates should be conducted before advancing to Phase 2. Mathematical solutions can form an important part of this work.

Phase 2: Design Model; for this phase a new or modified model is required together with an extended sensor array. Depending on the complexity of the device a medium scale may be required, in the range of 1:10-25. A larger set of physical parameters will be measured and the PTO mechanisms should be more realistic. This will be especially important if active (wave by wave) control is envisaged. Short crested seas must be included to ensure they do not adversely influence response, forces or performance. Mean wave approach direction must also be varied to validate moorings and behaviour of non axi-symetric devices. It would be expected that some device design changes would still occur at this stage of development but the variable options list should be decreasing not expanding.

Although seaworthiness of the hull should be observed from the first set of tests the actual full-scale dynamics must be modelled accurately by Phase 2, verified by qualified naval architects. Early survival tests in high-energy seas should therefore be included to establish extreme motions and loadings, especially in the power take-off mechanism. Bench testing of the proposed PTO system can also begin, especially sensitivity estimates to ensure it is correctly simulated in the smaller scale models.

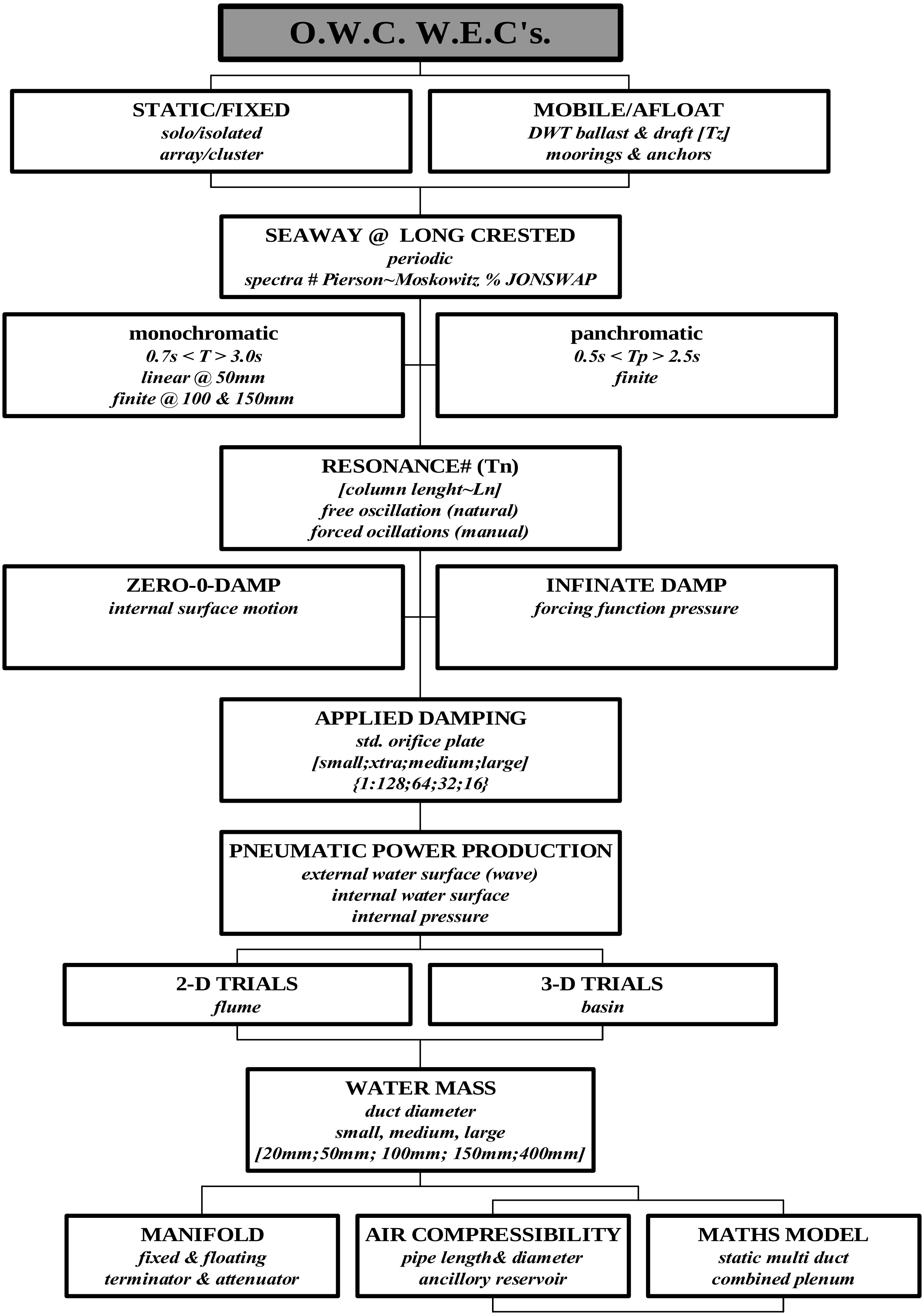
Phase 3: Process Model; this stage bridges the end of laboratory model testing and beginning of sea trials. As such two independent options exist, though a development programme can combine them as require. Device scale must advance to enable actual components to be incorporated, especially regarding the power take-off and mooring. A scale should be selected between 1:3-15, which means either a large-scale hydraulic test facility can be utilised or a benign outdoor site. Each option offers its own particular technical and financial advantages therefore the decision of which to take should only be taken during the later stages of Phase 2 testing. Correctly scaled wave conditions are an important consideration of the outdoor locations and may restrict safe testing of a device to specific seasons of the year. Extended bench testing of the power take-off and generating unit should be considered. Mathematical prediction of the performance should move into time domain modelling.

Phase 4: Prototype Device; by this time realistic performance data should be available, together with accurate manufacturing and constructions costs. If these are favourable to a device having economic production potential, a large to full-scale prototype of the selected device specification can be considered. Scales of 1:1-3, are expected, depending on the individual device (i.e. power output) and sea area in which it will be deployed. This is still part of the design and development work, so the actual power station park or array site is not essential. All operation components must be scaled units of the projected final components. Grid connection is not essential in the initial stages of operation so the deployment site may be selected to facilitate accurate, extensive testing rather than the electrical distribution network. Monitoring of the quality of supply, however, is paramount so connection to a network is to be expected at some stage before completion of the device evaluation.

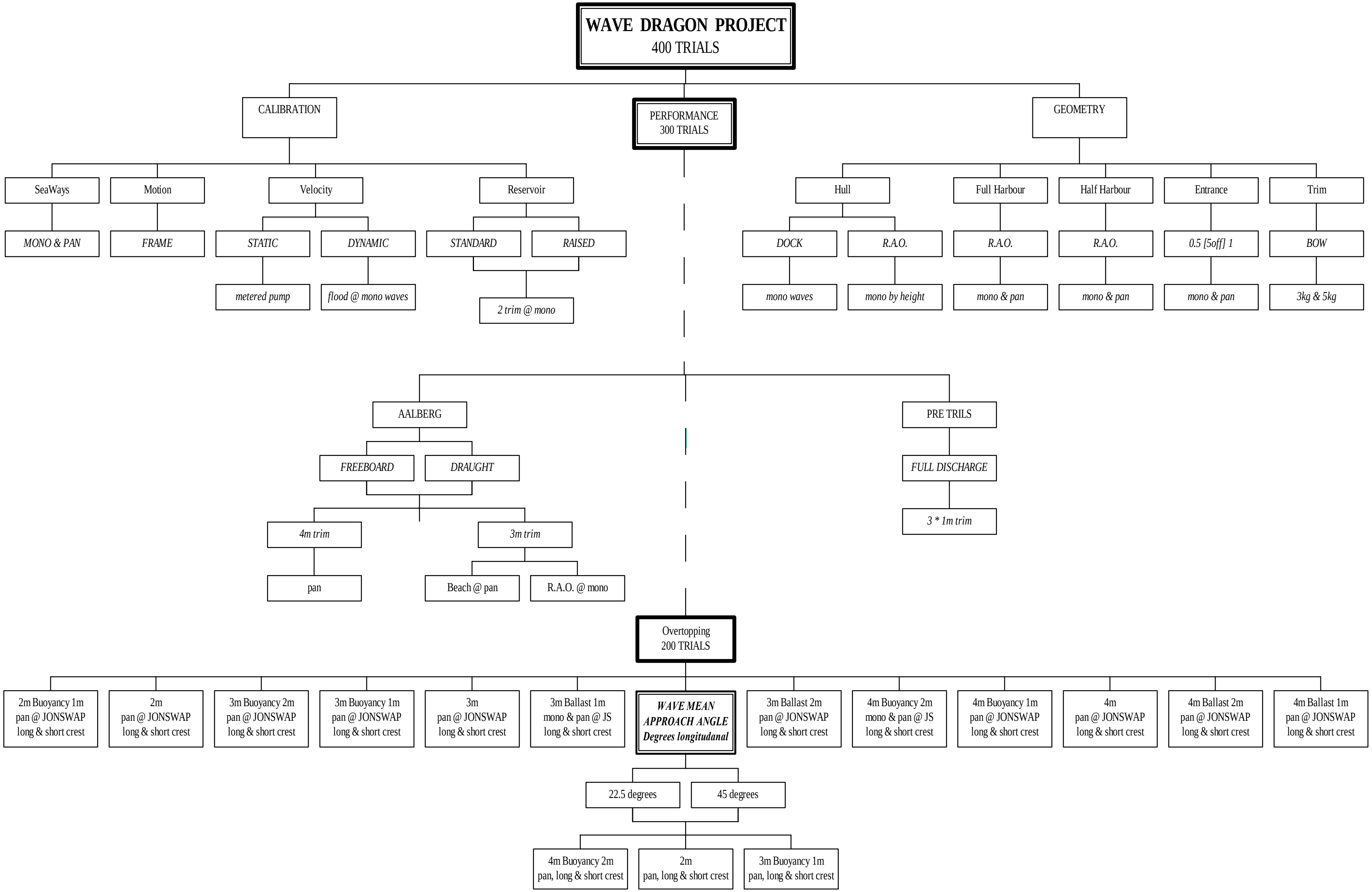
Phase 5: Demonstration Device; (Final Phase, details of which are outside the scope of this document) depending on the scale selected to complete the prototype sea trials this section may require a full scale WEC to be built or the re-location of the prototype. Essentially, the device performance should have been optimised and proven that a fully operational unit can safely and confidentially be located at, or in, the projected WEC Park. Initially a solo unit could be considered but grid connection and electricity sale must be part of the package at this time. However, confidence should exist that at least a small array of devices can be considered for this phase since the infrastructure and power production of an isolated unit would probably never be economic. The full power station, however, is not initially required.

The whole programme is tabulated in the following diagram which lists the main objectives, parameters and evaluation criteria at each Phase. Also shown are (a) a typical flow chart of the criteria to be investigated during the device development. (b) a full test schedule for the initial evaluation of a wave energy converter.

DEVELOPMENT	**PHASE 1:** *Validation Model (lab)*			**PHASE: 2** *Design Model (lab)*	**PHASE: 3** *Process Model*		**PHASE: 4** *Prototype*	**PHASE: 5** *Demonstration*
	Concept	**Performance**	**Optimisation**		**Lab. Tests**	**Sea Trials**		
Objectives / Investigations	Op. Verification Design Variables Physical Process Validate/Calibrate Maths Model Damping Effect Signal Phase	Real Generic Seas Design variables Damping PTO Natural Periods Power Absorption Wave to Devise Response Phase	Hull Geometry Components Configurations Power Take-Off Characteristics Design Eng. (Naval Architects)	Final Design Accurate PTO [Active Control] Mooring system Survival Options Power Production Added mass	Scale effects of Overall Performance PTO Method Options & Control Environmental Influences & Factors Inst. Power Absorption Characteristics Electricity Production & Quality Mooring & Anchorage Security		Ops Procedures Electrical Quality Grid Supply PTO Performance Control Strategy Survival	Grid Connection Array Interaction Maintenance Service Schedules Component Life Economics
Output/ Measurement	Vessel Motion Response Amplitude Operators & Stability Pressure / Force, Velocity RAOs with Phase Diagrams Power Conversion Characteristic Time Histories Hull Seaworthiness; Excessive Rotations or Submergence Water Surface Elevation Abeam of Devices			Motion RAOs Phase Diagrams Power *v* Time Wave Climates @ *head,beam,follow*	Incident Wave Field 6 D of F Body Motion & Phase PTO Forces & Power Conversion Seaworthiness of Hull & Mooring [Survival Strategies]		Full On-Board Monitoring Kit for Extended Physical Parameters	Service, Maintanance & Production Monitor, Telemetry for Periodic checks & Evaluation
Primary Scale (λ)	$\lambda = 1 : 25 - 100$ ($\therefore \lambda_t = 1 : 5 - 10$)			$\lambda = 1 : 10 - 25$	$\lambda = 1 : 10 - 15$	$\lambda = 1 : 3 - 10$	$\lambda = 1 : 1 - 2$	λ = Full size
Tank	2 D Flume or 3 d Basin			3 –d Basin	3 – D Basin	Benign Site	Exposed Site	Open Location
Duration –inc Analysis	1-3months	1-3months	1 3 months	6 – 12 months	3 – 6 months	6 – 18 months	12 – 36 months	1 – 5 years
Typical No. Tests	250 - 750	250 - 500	100 - 250	100 - 250	50 - 100	50 - 250	Continuous	Statistical Sample
Budget (€000)	1 – 5	25-75	25-50	50 - 250	500 – 1,000	1,000 – 2,500	5,000 – 10,000	2,500 – 7,500
Model	Idealised with Quick Change Options Simulated PTO (0-∞ Damping Range) Std Mooring & Mass Distribution		Distributed Mass Minimal Drag Design Dynamics	Final design (internal view) Mooring Layout	Advanced PTO Simulation Special Materials	Full Fabrication True PTO & Elec Generator	Grid Control Electronis Emergency Res	First Fully Operational Device
Excitation / Waves	Monochromatic Linear (10-25Δf) (25-100 waves)	Panchromatic Waves (20min scale) +ve 15 Classical Seaways Spectra Long crested Head Seas		Deployment -Pilot Site Sea Spectra Long, Short Crested Classical Seas Select Mean wave Approach Angle		Extended Test Period to Ensure all Seaways inc.	Full Scatter Diagram for initial Evaluation Continuous Thereafter	
Specials	DofF (heave only) 2-Dimentional Solo & Multi Hull	Short Crest Seas Angled Waves As Required	Storm Seas (3hr) Finite Regular As required	Power Take-Off Bench Test PTO & Generator	Device Output Repeatability Survival Forces	Salt Corrosion Marine Growth Permissions	Quick Release Connections Service Ops	Solo or Small Array (Up-grade to Generating Station)?
Maths Methods (Computer)	Hydrodynamic, Numerical Frequency Domain to Solve the Model Undamped Linear Equations of Motion		Finite Waves Applied Damping Multi Freq Inputs	Time Domain Response Model & Control Strategy Naval Architects Design Codes for Hull, Mooring & Anchorage System. Economic & Business Plan			Array Interaction Economic Model Electrical Stab.	Int Market Projection for Devise Sales
EVALUATION								
Absorbed **Power**								
Converted (kW)								
Weight, (tonnes)								
Manufacturing Cost (€)								
Capture (kW/tonne) or [kW/m^3])	[200 – 50 m^3]							
Production (c/kW)	< 25 €c / kW			≤ 15 €c / kW			≤ 10 €c / kW	≤ 5 €c / kW



Typical Flow Chart of Device Performance Variables



Example of Initial Phase Test Schedule

1.0 Rationale

Because of the uncertainty of supply and the ephemeral nature of oil prices, countries with limited or no crude reserves have always taken an interest in more secure, alternative energy sources. This is especially true for the production of electricity. The replacement market has inevitably been driven by price, which initially limited many options. However, the uncertainty is intensifying with time as the known global reservoirs are inevitably decreasing and irreplaceably used up. Conversely international power demand is increasing annually, although at a reducing rate. This growth continues even today despite dramatic energy conservation improvements in both the commercial and domestic markets. A recent European review estimated 200B€ would have to be invested in electricity generation to fulfil demand by 2010. The anticipated decline in the offshore oil, manufacturing and services industries is also already being felt in many countries and they are now seriously searching for replacement activities for the labour and machinery investment that has occurred in these companies over the years.

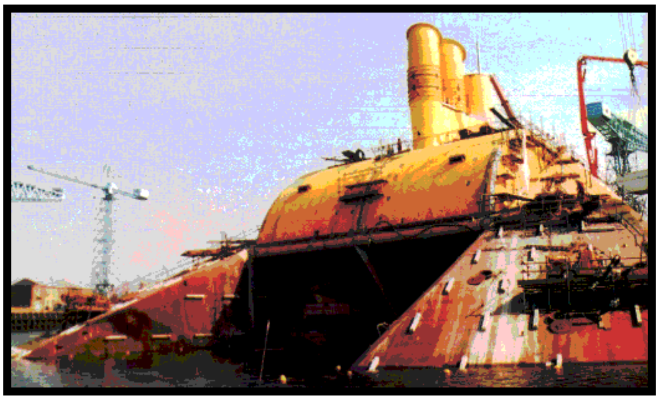
Running in parallel with the requirement for a secure, inexpensive energy supply and future marine sector job creation schemes is the growing awareness of the atmospheric pollution being caused by past national power policy which relied primarily on the use of oil and other fossil fuels to feed the economies and industries. Climate change, mainly in the form of global warming, is now universally perceived as a real threat to the planet and its inhabitants, if not today then certainly in the not too distant future. Renewable, sustainable energy alternatives are included in most industrialised states electricity supply programmes and international emission reduction agreements have been signed, notable Kyoto. Without serious effort at the highest government levels, these pollution targets may yet prove illusory and difficult to achieve without relying on nuclear power.

Atmospheric pollution problems continue to be of global concern.

These community concerns, combined with its estimated resource size, have generated a re-newed interest in utilizing ocean energy, in the form of both surface gravity waves and tidal flow. Each could become a considerable contributing source to national power generating plans. Whilst the success of such schemes could obviously prove beneficial on a state, European and international level, the technical difficulties have proved considerable. Consequently the budget levels required to advance the technology have also been high. Failures on the other hand will benefit no one and may even result in detrimental environmental impacts in themselves.

1.1 Design Groups

As is the current economic and political doctrine converter development has tended to be left to private sector supported, at least in part, under different mechanisms by proportional public funds. However, there has not really ever been an agreed policy or strategy for this support and individual projects have been dealt with on an ad hoc basis, even at the European Union level. Because the utilization of ocean energy has not yet gathered the interest of large, resource rich companies these developments have remained the preserve of small, enthusiastic groups, either within institutes or, more recently, SMEs. Neither of these bodies could possibly contain the depth of knowledge or manpower to cover all the requirements of this multi-disciplined subject which, combined with the inevitable budget restraints, has often led to calculated risk having to be taken since offshore engineering experience, expertise or assistance is expensive. Often excellent engineers are left to work in isolation when consultation is required. Because the industry is so small at present any failures, or even past failures, tend to stand out disproportionably to the technical effect they will have on overall and long-term progress. A team's success will primarily enhance its own business plans but a failure will affect everyone.



Development protocols of this type should reduce expensive large scale risk.

The differing interest levels and commitments to ocean energy development between nations, particularly visible in the EU member states, has often resulted in these enthusiastic device teams having to chase funds across borders. Once again this has not necessarily lead to the best use of limited resources, either in knowledge, funds, personnel or equipment. A traditional business aphorism is that export markets can not be developed unless there exists a strong home market for a company's product. These forced device emigrations, therefore, may prove a poor approach to establishing an independent wave energy industry. Finance has often arrived piece meal, largely to solve a particular difficulty being encountered. This situation will obviously be exacerbated during expensive sea trials more than the model testing, as they increasingly become the priority and interest. Analysis of past projects shows how the famine-feast funding adversely effect overall progress, particularly in the loss of important team members during the lean times. If groups had known the investment levels of support they could have expected prior to sea trial scheduling it seems clear a more efficient use could have been made of the resources. Errors and missed opportunities always cost more to rectify at a later date.

1.2 Investors and Backers

As stated above most of the ocean energy utilization companies are still based around the compact device development teams. Few, if indeed any, of these have sufficient capital resources to bring the devices to market and so must search out funds for the various stages of development, either in the public or private domain. This process has sometimes proven to be more difficult than it need be for two reasons. Firstly, most private capital is usually nervous of ventures involving the sea and especially those away from the coast. They are perceived, rightly or wrongly, as either very costly exercises or too technically challenging for the expected rates of return involved. This has usually meant that at least some support has been necessary from the public purse to advance the projects timetable under the public good category. A concern often expressed by those charged with spending pubic money wisely is that it can be unclear precisely how much of an investment requirement they are becoming involved in or how the stake can be protected or evaluated during the development. This situation has intensified the stop-start funding of many projects and the limits placed on the amount of capital made available to individual designs at any one time. Since there have been few successful deployments of large scale prototypes, companies have not yet been able to establish reputations of their ability to achieve the overall objectives. Indeed the rather unsuccessful history to date has no doubt had the opposite effect in financer's minds. A couple of device teams have been able to overcome these confidence and accountability problems by moving their products along sensible development schedules but others are perhaps more due to the sales and marketing expertise of those concerns. In general there has not been long established mechanisms in place that, from a public good standpoint, would aid developers along an agreed and accepted path of development and evaluation of their designs.

Although it is a hostile, harsh environment the maritime and offshore industries operate there safely.

It should be remembered however that navigation and weather recording buoys, of various sizes, are routinely deployed for extended periods in exposed oceanic locations with acceptable success rates.

1.3 Protocol

The primary aim of a standardised (though flexible) ***Development and Evaluation Protocol*** for use with ocean energy devices is to facilitate a quicker, closer, clearer communication between design team/inventors and funding agencies. The structured model test programme is based on past experience of device teams and includes the soon to be published International Energy Agency/Ocean Energy Systems (**IEA/OEA**) sea condition criteria together with reference to the UK's Orkney test site demonstration scale sea trial proposals. At each specific Phase of development, evaluation criteria can be produced on which project continuation decisions can be made. Robust physical parameters are recommended, e.g. average values rather than maxima, and response sensitivity trials at different wave conditions are important. If any tested parameter is difficult to quantify, specific investigations should be conducted to qualify the effect, e.g. vortex shedding, air compressibility, etc. Typical budgets (at 2004 values) for each section are suggested together with the physical properties that should be investigated at each stage. The existing national laboratory and marine infrastructure capable of servicing these requirements is also highlighted.

Reviews of past projects show that the longest delays in the development timetables are caused by groups having to wait for financing decisions before the work can continue, even when results up to that time have been favourable and encouraging. This documented structured approach should reduce, if not eliminate, these hold-ups whilst at the same time providing the designers with a valuable information tool to progress the device development. The **Protocol** should not, therefore, be seen as yet another bureaucratic hurdle that must be cleared but a method of fast tracking funding options if the device performance warrants progress to the next Phase.

Care has been taken that the **Protocol** will be a mobile standard rather than requiring accredited facilities to conduct the work. Experiences with similar studies are, however, beneficial since there is inevitably specialist knowledge used which requires a considerable learning time curve. The consequence of this, and the random funding source possibilities, means the knowledge base and experience gained by the industry will be somewhat diverse rather than concentrated within a small group of service providers. However, this also means that new ideas and approaches will not be stifled by limiting input. The balance between diversification for originality and concentration for experience has always been a difficult contradiction. The situation is compounded by the decentralised development strategies and open market approach adopted by the countries pursuing wave energy research. Unfortunately this inevitably leads to considerable commercial sensitivity of much of the data produced by the design teams so only a limited exchange of results can be expected since IPR must be guaranteed.. This confidentiality, however, need not and should not be total secrecy and should not apply to the improving expertise in model testing techniques and sea trial skills around which the **Protocol** is based. This might particularly apply to the latter Phases when real seaways provide the excitation forces and for which the **IEA** document was produced. Mathematical models also would benefit from common development themes, at least until the control strategy requirement has been defined.

Wave basins and flumes can both be useful development tools.

Analysis techniques are as important as the scaled physical testing methodologies since even when data are acquired by an established approach they can be manipulated to reveal different accounts, or possibly and more importantly, cross-referenced to validate test results. As a basic principal the approach recommended in the **IEA/OES** is adopted. Diagrams illustrating data analysis and presentation methods are included throughout the following text.

2.0 Development and Evaluation Standards

The **Protocol** is based in 5 main **Phases**, which in turn are dictated, by the different type of scaled physical and/or mathematical model required for each section. The schedule detailed below is based on an attempt to maximise limited resources (especially budgets) and as such should be regarded as the minimum standard required to logically and effectively develop a product from the initial idea to market (or in this case the economic demonstration phase of the machine). Divisions between Phase*s* are not sharp and stages may overlap to differing degrees, but should never fully merge or combine. It should also be noted that different types of devices, such as the over-topping units, will require specific mathematical approaches based more on probabilistic than deterministic theory to predict the run-up characteristics. However, for the floating variants even of this class the equally important body motions can be investigated by standard approaches recommended in this document.

2.1 Validation Model : Phase 1

Scale (λ); 1 : 25 - 100

Following a theoretical evaluation of concept by a reputable reviewer most devices will probably progress to the first empirical phase of model testing. Design teams may feel more comfortable if this initial assessment is supplemented by a very basic set of physical tests in a wave facility. This approach is not recommended or encouraged since crude, unrepresentative models can produce misleading results or too much is made from very limited data. However, if a model is available the operating principal can be observed and used for future development.

The basis of this phase is to include all the physical variables that could influence the overall performance for at least one geometry of the device. It is important to change only one at each test stage to identify its contribution to the power absorption. An idealised model that can be easily and quickly converted to the next configuration will be sufficient together with a simplified, but effective, applied damping (energy dissipater) unit that will simulate the power take-off system. It is preferable if the system can be set for both infinite and zero damping during early trials. The final power take-off unit's operating characteristics will not initially be known so damping sensitivity trials may be required to ensure the appropriateness in later results.

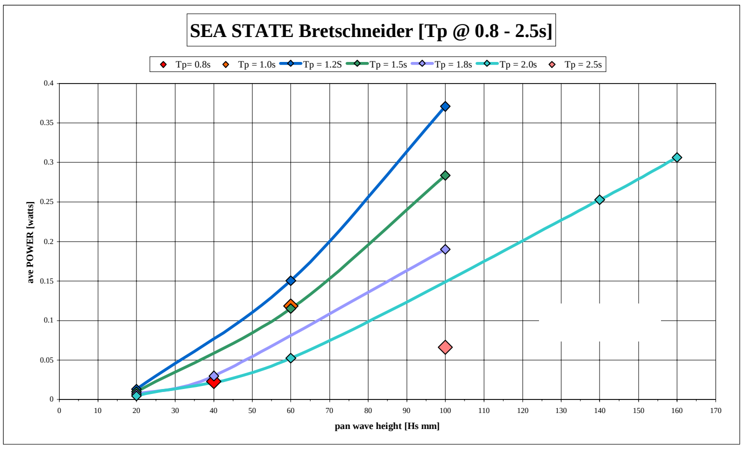
The following might be regarded as a list of criteria to be included in the various parts of this Phase.

1. ***Linear monochromatic waves to validate or calibrate numerical models of the system (25 – 100 waves).***
2. ***Finite monochromatic waves to include higher order effects (25 – 100 waves)***
3. ***Hull(s) sea worthiness in real seas (scaled duration at 3 hours).***
4. ***Restricted degrees of freedom (DofF) if required by the early mathematical models.***
5. ***Provide the empirical hydrodynamic co-efficient associated with the device (also mathematical modelling).***
6. ***Investigate physical process governing device response. May not be well defined theoretically or numerically solvable.***
7. ***Real seaway productivity (scaled duration at 20-30 minutes)***
8. ***Initially 2-D (flume) test programme***
9. ***Short crested seas need only be run at this early stage if the devices anticipated performance would be significantly affected by them.***

To achieve, or investigate, the extensive objectives Phase 1 should be sub-divided in 3 distinct sections:

1. ***Concept verification (monochromatic waves)***
2. ***Performance and response (panchromatic waves)***
3. ***Device optimisation (panchromatic waves)***

Comparison, via analyses of the results, should be performed after each sub-set against the projected, or mathematical model predicted, figures. At this early stage the acceptance parameter can be based on a measure of the absorbed power. A set of physical properties must be measured which will be specific to the device, or generic type of device, under investigation. Ideally the sensors will monitor robust performance criteria that are reasonably insensitive to subtle changes, especially in the wave field or scale effects. The large number of tests conducted will enable a clear, unambiguous comparisons to be made. Discontinuities in the trends indicate points of low confidence. By this extensive testing approach both extrapolation and interpretation to untested settings can be confidently estimated: If conditions are sensibly selected even a limited data graph can reveal intermediate readings. In the following illustration the plot shows power output as a function of significant wave height for a device in difference seaways. The trends are clear and individual point can be estimated at the intermediate temporal settings.



A well constructed test sequence can reveal more information than just at the selected points.

For slack moored, floating bodies a mobile wave gauge should be adapted such that the water surface elevation abeam of the test station can be measure. This procedure helps compensate for the inevitable downstream reflected waves that occur in most enclosed testing tanks (flumes and basins) and re-appear at the measuring station. A judgement call regarding the influence of reflected waves must be made prior to the test schedule commencement.

The monochromatic wave periods required will be a function of the device under investigation balanced against the timetable. Conventional practice would be to run a standard set of frequencies across a wide range, adopting a coarse step. Based on the results from these and the visual observations during the tests a finer set of frequencies around resonance can reveal the details and response characteristics, usually important for mathematical model verification. A fixed wave height is used together with a statistical sample of higher amplitudes to evaluate second order non-linear (finite) effects.

Typical Physical properties to monitor are:

1. *Vessel motion*
2. *Wave induced operating forces*
3. *Wave induced operating pressures*
4. *Water surface elevation (waves)*
5. *Mooring forces*
6. *PTO output (torque, motion (translatory or rotational), voltage etc).*
7. *Overtopping rates*

From these basic parameters performance characteristics can be produced, which in the case of energy extraction devices, is often the absorbed POWER. Whilst other measured or derived values assist in an understanding of the working principals of the unit and the level of environmental induced loads on the main components (i.e. hulls and moorings), this primary calculation provides a single result on which the device performance can be evaluated and compared to threshold criteria or other reported WECs.

Schedule and Budget

SECTION	TIMETABLE (Including Analysis)	BUDGET (€000)
Idea	1 – 5 Days	1 - 5
Concept	1 – 3 Months	25 - 75
Performance	1 – 3 Months	
Optimisation	1 – 3 Months	25 - 50

National Facilities

ACTIVITY	ESTABLISHMENT
Physical Model Testing	HMRC, UCC
	Queens University Limerick University
Air Turbine Development	
Mathematical Methods	Applied Maths, UCC CleanPower Technology
Device Dynamics	Harland & Wolfe HMRC, UCC
Model Construction	
Initial Economic Model	WEC Design Team

It is not practical to establish an exact standard for testing ocean energy extraction/conversion devices since each one will have significantly different tailored requirements. Test programmes must, by necessity, be bespoke but the requirements can be expected to follow a set of established principals. The development programme should be based along the following lines to minimise time and maximise resource utilisation, including funds.

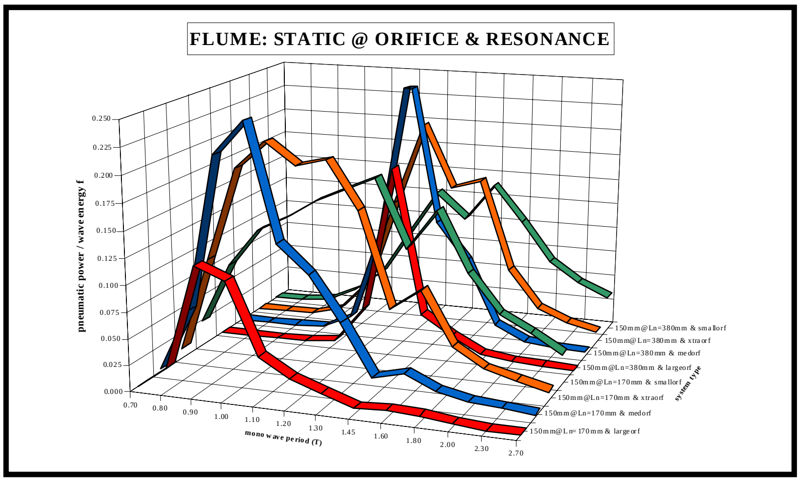
2.1.1 Concept Verification

As stated above a simplified, idealised model can be used for the early validation trials. Care should be taken to minimise scale and laboratory effects, such as sharp corners that introduce vortices. This is especially noticeable since viscosity is a parameter poorly represented by Froude similitude. If the device is a complex structure, such as multi hulled, components can be initially evaluated separately. The number of degrees of freedom of the body(s) may also initially be limited. Response characteristics are the principal criteria investigated, including any interactions or interference between the independent bodies.

Data should be in a form that can validate and/or calibrate the numerical models being produced in parallel with the physical modelling. A worthwhile sophistication that can be introduced at this stage is the measurement of the hydrodynamic coefficients, particularly, damping, added mass, radiated wave damping, forces on the static bodies, (diffractions forces) etc. However to be conducted accurately these tests require rather more attention than wave excitation response monitoring so add to both allocated time and budget. Special and specific equipment is usually required though sensors and drive mechanisms can be incorporated in the PTO for these procedures. Alternatively the forced oscillation measurements can be postponed until Phase 2 trials, when a full understanding and accurate absolute records are required for the numerical models. Free oscillation trials can be used to determine added mass and damping values at the natural period which can be used to check the theory.

All the primary design variables should be evaluated during this phase so results are principally used for comparative purposes rather than to produce absolute values. Once again this provides the testing with a robustness in the results that increases confidence levels. These are not exclusively incompatible requirements, however, and the absolute values should be reasonably accurate (<10% error). Scale effects are more difficult to quantify and may result in slightly greater discrepancies, perhaps due to fluid flow patterns around the models. This will be of particular importance to the theoretical models, which will not include drag losses. Dye tracing visualisation can be used to observe this phenomenon but this procedure can be difficult to conduct and especially repeat.

Tests are conducted in single frequency, regular wave fields of small to moderate amplitude (steepness) to remain in the linear regime. Sample higher, finite waves should be randomly included to establish higher order differences in the response characteristics. Magnification Response Amplitude Operators **(RAOs)** can differ considerably depending on the wave amplitude selected.



The effect of changing design variables can be observed on a single graph.

Basic applied damping settings should be used to establish the power conversion characteristics across the wave excitation frequency range and should include a zero setting for free motion and an infinite or locked option for excitation evaluation.

2.1.2 *Performance Validation*

If satisfactory results are achieved in the concept verification the same model can be employed for trials in irregular wave excitation. The range of options for the model configuration and PTO damping settings can be specified from the former trial results. Seaways should cover a conventional bi-variate scatter diagram from the anticipated sea area of choice. A strategic selection of the summary sea state statistics is made based on occurrence, extremes and resource turning options. Spectral shape, however, can be of a classical form such as *Pierson-Moskowitz, Bretschneider, JONSWAP etc.*

Tz **Hs**	< 4 sec	5 sec	6 sec	7 sec	8 sec	9 sec	10 sec	12 sec	14 sec	>14 sec
0-1 m					B3		B6	B10	B14	
1-2 m		B1						B11		
2-3 m				B2	B4		B7		B15	
3-4 m										
4-5 m					B5		B8	B12		B18

5-6 m									B16	
6-7 m							B9			
7-8 m								B13	B17	
> 8 m										

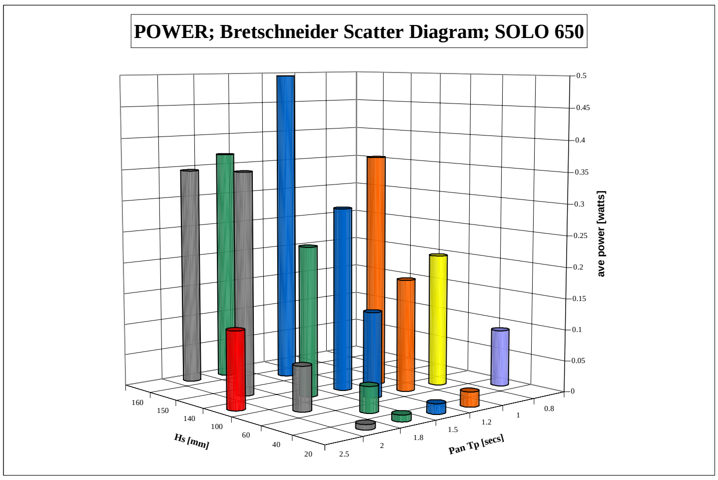
A typical sea state scatter diagram showing 18 selected conditions for testing

The duration of a single test can vary but must not be less than the temporal scaling equivalent to the industrially established 20 - minute full scale measuring period over which a seaway is regarded as stationary. For storm extremes an equivalent 3-hour duration should be selected to ensure a realistic H_{max} is produced within the water surface elevation time series. If the test facility wave generator signal is produced by *Fourier* techniques the data acquisition rate and overall time can be adjusted to suit later FFT analysis. In other words, a 2^n integer to avoid a numerical bias. Wave height will be **Rayleigh** distributed unless the location is in shallow water when adjustments are required. This probability should be verified.

As in the monochromatic wave tests the basic requirement is to consider and include all relevant device variables and monitor their influence on overall response and performance characteristics, but in this instance by panchromatic excitation. The full schedule can be based on the previous regular wave test results.

2.1.3 Device Optimisation

Although it is recommended that as many device variables as practicably possible are investigated in the first two test sequences, i.e. response and performance in regular and irregular waves, it may not be possible to quickly and conveniently change certain fundamental dimensions. These might be overall size, mass, shape and possibly even the governing dynamic characteristics. Initially these should have been agreed with the aid of theoretical matching to sea states or adjusted by experience from similar studies. Before passing on sketches to the naval architects for full design feasibility and working drawing to progress on to detailed measurements on an enhanced model an optimisation procedure should be conducted. (NB. The border between Design Optimisation and Design Model is blurred such that if shipbuilding requirements demand fundamental changes these may be better checked in this phase rather than after constructing a new model).



Performance figures from the selected seaways allow comparison between device options and with other wave energy

If the numerical model has proved reliable when compared with the empirical RAO results thus far obtained it is acceptable to perform this sub-phase analytically and incorporate changes into the Phase 2 model. Alternatively, if the model construction allows change, such as different diameter buoys, various draft setting, optional PTO characteristics, changed hull shapes etc., than limited empirical data can be produced for comparisons with the benchmark figures already established. These trials again need only concentrate on comparative data rather than absolute values and selective sea states to suit the alternatives can suffice. A full test programme is of course preferable but this may not be possible. The decision should be related to the number of imposed changes to the initial design. If a new model was to be required a small increase in scale would be recommended.

2.1.4 Mathematical Methods

Basic hydrodynamic theory is sufficiently well understood and formulated so that theoretical solutions should also always be pursued in the development programme. As with the scaled, physical modelling the degree of complexity of the analytical approach can also be staged, essentially to reflect the empirical results.

Although many simplifying assumptions and approximation methods are required the numerical models can be either validated or calibrated from the physical results (and vice versa) and early practical tests should be structured to provide the required information, such as the hydrodynamic co-efficients. These values are the most difficult to obtain mathematically but standard programs are now available that can provide them by numeric solutions (i.e. WAMIT, Aquadyne, Mavrakos, etc.) It may also be initially important to improvise with extremely small amplitude, linear waves in physical tests to compare the empirical measurement and theoretical predictions.

Drag forces may also require empirical input so care must be taken during the testing as viscous forces are not easily modelled since this physical property does not comply with **Froude's** similitude scaling. These losses can often account for differences in magnitude of the the two sets of results.

Frequency domain programs will usually be employed in the initial stages of device development.

2.2 Design Model: Phase 2

Scale (λ) ; 1: 10- 25

Following a satisfactory conclusion of the first phase the overall dimension, configurations, dynamic, response characteristics and preliminary power production should be reasonably understood. Additional data, such as forces, mooring loads and, especially, phase relationships should also have been considered by the initial results analysis, together with device specific measurements. This means the overall layout of the WEC can be established and a reputable naval architects office or engineering consultancy used to confirm the construction feasibility and establish the fabrication/manufacturing costs (i.e. mass of steel, etc). It is unfortunately too easy to envision and model components that will not be practical to manufacture. If the basic economics still seem sound and the evaluation criteria passed then the inevitable design changes imposed by the Phase 1 test programme and manufacturing practicalities (possibly checked in the previous phase) should be incorporated in a new/modified model and a second phase of larger scale physical testing undertaken. The primary aim at this stage is to establish the performance figures in realistic seaways, either of a generic nature or from a specific proposed deployment site. If the latter is the case measurements from a monitoring station close to the location are preferable but computer model predictions can be used, with caution. Some single frequency investigation may be required to confirm the effects of the changed geometry. In previous device developments, the second phase has actually been a radically re-fitted unit, but his should be the exception rather than the rule.

The specific areas under investigation are:

1. ***Accurately simulated PTO characteristics***
2. ***Performance in real seaways (long and short crested)***
3. ***Survival loading and extreme motion behaviour.***
4. ***Active damping control (may be deferred to Phase 3)***
5. ***Device design changes and modifications***
6. ***Mooring arrangements and effects on motion***
7. ***Proposed power take-off design and bench testing (Phase 3)***
8. ***Engineering Design (Prototype), feasibility and costing***
9. ***Site Review for Phase 3 and Phase 4 deployments***
10. ***Over-topping rate***

2.2.1 Model Testing

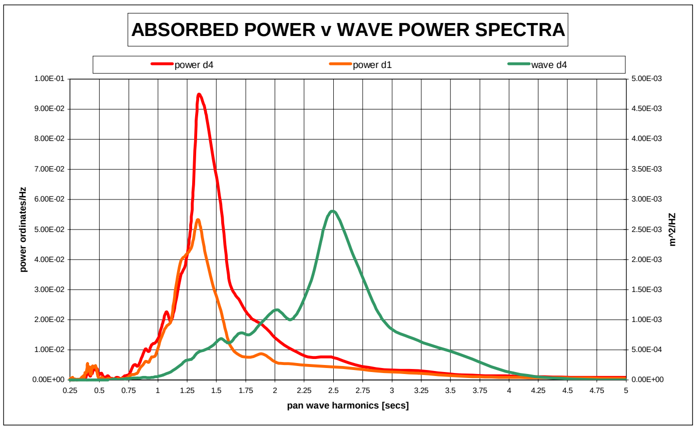
Although alternative configurations can still be introduced in Phase 2, considerable progress should have been made on all matters concerning the operation and endurance of the device(s).

Larger scale models should incorporate more representative features of the proposed device, especially PTO features.

The following main components should therefore be regarded as the minimum to have been decided and be accurately represented in Phase 2.

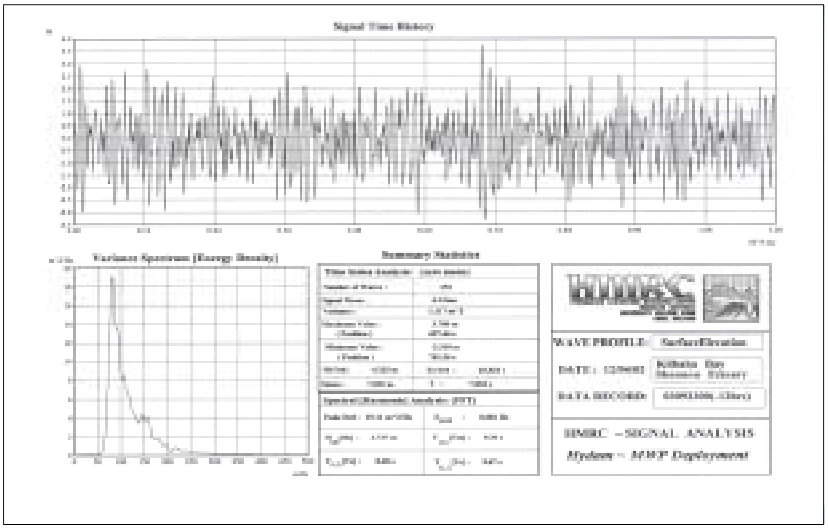
1. *Hull*
2. *Mooring*
3. *Power take-off*
4. *Active control (if required)*
5. *Run-up beach profile*

Trials would be conducted in real seas, as suggested in the **IEA/OES** document, but adjusted to the proposed deployment sea area or typical conditions found off the countries coastline. All seaways follow the same growth patterns but in more exposed locations with longer fetch the bi-variate combinations of height and period are expanded. Actual spectral shape can differ, however, which is important for resonant oscillator response since most power production is still concentrated at the device's tuned period. Both mean approach direction and spreading functions must be included at a this stage. (That is, long crested waves but at non-normal angles and short crested seas). The effect of these input parameters will be more important with devices that are not axi-symmetrical point absorbers for which all conditions are head seas. However, all devices will require investigation regarding moorings loads produced by these conditions.



Power conversion of the device is still strongly influenced by the resonant wave periods, even in multi-frequency seas.

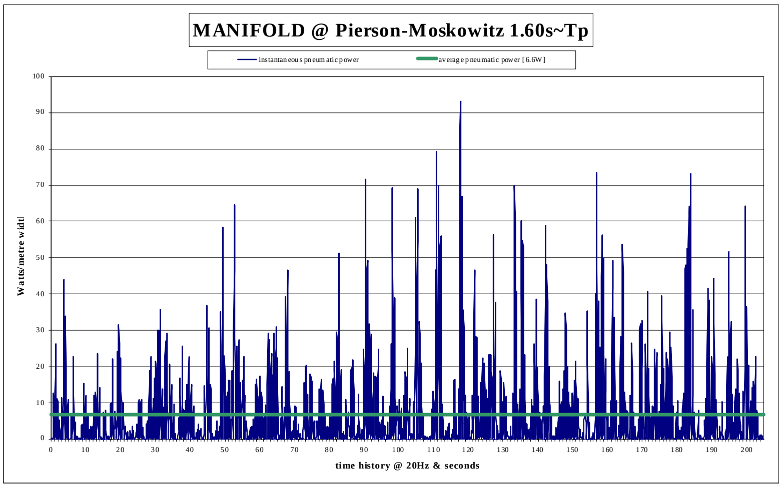
The actual elements tested may vary to suit a particular site, taking into consideration the number of occurrence and extremes present in the scatter diagram, as recommended in the **IEA** testing procedures. The spectral shape can be based on the fully adjustable ***Bretschneider*** equation (or a parametric ***Pierson-Moskowitz***) and specified by the seaway's integrated statistics, **Hs** and **Tz (Tp, Te).** It is not recommended to rely on the temporal parameter **Tp** for analysed time series since the erratic nature of the spectral curve causes it to be unstable. It is however, the usual input parameter for wave generation systems and mathematical models.



Both time & frequency domain data should be recorded.

The results from these trials can be presented in different forms that facilitate quick comparisons between the various model option performances as in Phase 1 analysis. However, the high variability of the instantaneous power absorption of the primary converter is one of the major complications of all wave energy machines and any improvements to this irregularity could produce quantum improvements in overall conversion rates. As in the First Phase the analysis should rely on robust calculations such as average, RMS or other signal processing statistics. Maxima and minima values will be required for certain evaluations, such as mooring loads, but should be treated cautiously and only as a good approximations.

The general form of the power conversion caused by irregular wave excitation is repeated in similar histories of the other measured parameters, such as hull motion (velocity, acceleration), PTO force or relative element extension etc. Others, such as mooring forces, may also contain second order components of longer periods superimposed on the wave frequency loads. Since these may often be greater than the primary forces monitoring equipment must be capable of recording them for statistical review. Analysis of the signals provides important records for the detailed design, including frequency for fatigue evaluation and the periods of calm. Methods of reducing, or smoothing, the extremes should be pursued, either as a loss in relief (pressure valves) or transfer by short-term storage (accumulators). These may be investigated either by time series analysis or Fourier techniques.



In real seas with irregular wave patterns device parameters exhibit high variability.

A reduced set of the scatter diagram elements can be used for the long crested mean approach angle and spreading seas. The actual number depends on the relationship found between these and the long crested, head sea results though beam and following seas must be included, especially is they are expected at the deployment site. If considerable discrepancies are found then a more extensive set of spectra will be required. Although there may appear considerable overlap or repetition of tests it should be remembered that the investigations at this time are still considerably quicker and easier to facilitate that in the next phase, should unexpected results present themselves. Also, as in Phase 1, the philosophy is still to use a robust procedure that is composed of relatively insensitive calculations of the physical properties, such that summary results can be evaluated with high confidence directly by the extent of the number of trials conducted. Discontinuities are not often found to occur in engineering results but single, or limited range, programmes do not quickly and securely highlight the smooth trends.

2.2.2 Mathematic Modelling

The theoretical forecasting of devise performance should have advanced to Time Domain modelling, based on the previous Frequency Domain programs results. These methods are particularly important with regard to PTO control and strategies. Such models can be extremely complex and time series solutions are not a trivial task. Close links with the physical model results are essential and may require a limited number of simplified, narrow banded, spectra to be included (beginning at single frequency response).

This work will also be closely related to the PTO development and may be based on either deterministic or stochastic probabilistic methods, or a combination of both. Depending on the level of sophistication of the strategy forward event (wave) prediction may be required. This method is often termed **Unconstrained Control**. A simpler, less demanding method is **Casual Control** whereby the transfer function is based only on past and instantaneous values. Finally a special case can also be considered, that is **Discrete Control**, also known as latching.

2.2.3 Feasibility Study

In addition to continuation of the device response and performance prediction there will be a requirement for structural and mooring modelling, together with the introduction of the feasibility and economic study of a large-scale prototype machine. Following the agreement of the secondary converter some preliminary bench testing of the proposed power take-off could be considered. Alternatively this design study alone could be undertaken and the testing postponed until Phase 3. The decision should be dictated by whether a fully operational PTO is required for the next phase.

2.2.4 Power Take-Off

Following the establishment of the primary power absorption characteristics, initial investigations and feasibility studies should be undertaken on the PTO of choice. Unless a direct drive generation system is proposed (linear generator) the whole system should be included in the feasibility study whilst for practical purposes the independent mechanical converter and electricity production unit can still be dealt with separately. Combining them, however, should not be long delayed.

Accurately representative power take-off simulation is essential in this phase of the test programme.

The timetable for this development should be scheduled relative to whether an operational product will be fitted to the WEC at the beginning or later in the Phase 3 Sea Trials, or even delayed until Phase 4 Prototype.

At present the only feasible options downstream of the pneumatic or hydraulic primary conversion are turbines or pumps, which can change the translatory motion of the wave into rotary motion to drive a conventional generator. To reduce the number of components and consequential losses, such as through a gearbox, a direct coupling is usually proposed which inevitable means a rather slow drive speed. This in turn restricts generator options. Innovative and original thinking in this field should be encouraged, especially with regard to smoothing / re-distributing the high power fluctuations that occur over short time spans. Efficiency levels in this overall conversion chain could be lower than desired so they must be accurately represented for use in the Economic Forecasting.

2.2.5 Hull and Moorings

Marine engineers, especially naval architects, should have been influencing the hull(s) design since the Optimisation section of Phase 1. They certainly should have played an important part in specifying the Design Model layout used in this Phase, particularly mass distribution to ensure the correct dynamics can be achieved. This involvement would have been fairly general until now but from this point must become more specific, focused and directed.

By the conclusion of the Phase 2 physical and mathematical modelling, the device specification should be defined sufficiently to enable a full design feasibility study to be undertaken. The results of this study will play a major role in project continuation. Combined with the power absorption characteristics it should provide the confluence of the main commercial components and economics.

Within the previous studies the mooring system and anchorage requirements should have been specified, particularly with regard to directionality of wave approach. Final design will be an evolutionary process but preliminary investigations and early designs should be introduced during Phase 2 in preparation for later Sea Trials. Reasonably accurate loads should have been produced and monitored as part of the Optimisation tests and extended during these large-scale Design Model trials.

The calculations should be based on the appropriate engineering design codes and standards required for the large to full-scale prototype device. The intermediate Phase 3 system can be a scaled version of the final product.

2.2.6 Site Selection

As stated in the introduction, resource assessment is not included as one of the components of the **D&E Protocol**, being more general in nature. Deployment options for the required Benign Site of Phase 3 and initial Sheltered Location of Phase 4 should, however, be considered at this early stage since obtaining licences and permissions can be a slow process.

The actual requirements for each type of site will be specific to the actual machine and final selected scale. In some situations more than one deployment station will be used in the Phase 4 proving trials, initially reasonably sheltered to gain operational experience and working towards a fully exposed (relative to the device scale) sea lane. There will also be a requirement for the unit to be connected to the national grid following independent performance evaluation, especially in respect of electricity supply quality. Suggested requirements for each type of site are specified in the related test Phases.

Schedule and Budget

Section	**Timetable**	**Budget (€000)**
Performance	1 –3 Months	25 - 50
Survival	1 Month	15 – 25
Mathematical Model		10 -- 20
Hull Design		15 – 25
Power Take – Off		25 – 75
Control		
Generator & Power Elecs		25 – 50
Mooring & Anchor		15 – 25
Preliminary Site Selection		10 – 25
Project Supervision	6 – 12 months	25 - 50

National Facilities

Activity	**Establishment**
Medium Scale Model Testing (< 1 : 10)	*HMRC (labour)*
Small Scale Model Testing (< 1 : 25)	HMRC Queens University
Model Construction & Instrumentation	HMRC Queens University
Mathematical Methods *(Control)*	Maynooth University Dept of Mathematics, UCC CleanPower Technology
Power Take – Off	
Air Turbine Development	Limerick University Queens University
Hydraulics	Mustekeer Engineering Hydam Technology
Linear Generators	
Electrical Machinery	Queens University University College Cork Marine Electrical Services
Hull Design	
Mooring Design	MCS Irish Lights
Preliminary Site Selection	
Wave Climate	HMRC
Licence & Permission, Environment	ESBI
Anchorage	Ocean Energy

***2.3 Process Model**: Phase 3*

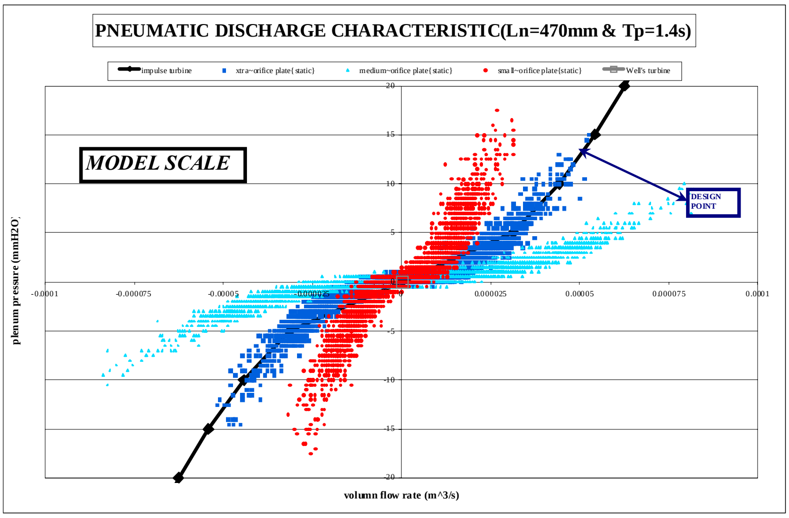
Scale (λ) ; 1 : 15 – 30

Although still principally the next stage in the engineering design procedure the true importance of Phase 3 is that it is the last step before a large to full scale prototype machine is built and installed in the open sea. As such it represents the final opportunity to quickly, reasonably easily and relatively inexpensively learn about the inevitable problems still associated with a device, its operation and deployment techniques. The importance of the possibility to gain valuable experience when combining a multi-disciplined device and team of experts should also not be missed. This will be the first time all the required components, from primary converter to electrical generators and power electronics will be assembled, albeit at reduced scale. This means that design teams can experience and develop both technical and managerial skills to bring these tasks together. It can be noted from past experience that if this step is neglected there has usually been a high price to pay later.

Difficulties at the large scale inevitably become expensive and will require heavy equipment to deal with so the fewer the snags that are exported between Phase steps the better. This approach represents the optimal use of the **Protocol** system. Also, if there is a delay at prototype phase testing that restricts measurements for any length of time, a situation unfortunately experienced more than once by pioneer design groups, it means that no results are obtained with which to convince investors of the device's eventual potential. However, it should always be possible to jury rig the Phase 3 scale test bed deployed at an external site such that valuable data can be obtained in all but the worst situations, with which to encourage backers through any difficulties. Financial support bodies will accept rectification work more readily at this time than when a productive, prototype unit is expected to be generating exportable quantities of electricity. Wave tank testing will, as always, be fully controllable but may not enable full PTO studies to be included in the schedule.

One consequence of using even large-scale test devices is that the power production is quite small. This results from the ***Froude*** similitude scaling for power, which is $\boldsymbol{\lambda}^{3.5}$ (i.e. @ ¼ scale = **128 ∴1MW ≈ 10kW**). However, these results should agree with the values forecast from smaller scale models and mathematical predictions so they can still be used to validate full size production expectation. The devices will also be at a physical size that observers can both visit and relate to more easily (i.e. **20m** diameter buoy = **5m**) so have more confidence in the measurements than might be acceptable at 1:50 or 1:100 scaling. A weakness of this approach is that although budgets can be lower the model manufacturing cost will be disproportionate to the power production. However, it is the work schedule, and in particular the rectification budget that provide the benefits of the stepped procedure.

Due to the high cost of submarine cable and strict connection requirements to a national electricity supply network it would not be expected that these units are grid linked. It should also be anticipated and budgeted that breakdown will occur so, in the absence of quick release submersible power cable connectors, this independent operation will also facilitate the removal of the device for repair and refit during the test schedule. There should be no problem in dumping the small production of electricity or simulate the network loads, another advantage over a full-scale unit which could require huge heat exchangers to accomplish the task.



Careful calibration and sensitivity trials of PTO simulators are essential.

In certain instances, such as at the smaller of the recommended scales, it may prove difficult to manufacture the actual power take-off system so that a high quality, accurate simulator will still be used instead. In such circumstances, if it was not included in the previous phase, the bench testing of the PTO and electrical production units must be undertaken at an appropriate size. This requirement applies whether the device testing is to be conducted at an indoor facility or an outdoors site where it may subsequently be fitted for on-board trials.

A secondary objective of Phase 3 is to validate and/or calibrate the earlier model results by investigating scale and laboratory effects at this increased model size. Physical scaling considerations are reduced and the full-size multipliers for force, power, and pressure etc, are much lower. The empirical hydrodynamic coefficients obtained in earlier phases should be rechecked. Percentage error on measured parameters will, of course, remain the same at all model scale testing if the similitude criterion or similarity laws are followed. The response characteristics controlling the device's efficiency and consequent power conversion costs required to be reviewed. Survival and maximum force conditions may not be achievable in the benign site scenario where full environmental loadings are reduced for safety reasons. This should not be the case at a large-scale facility depending on the wave generation limitations. If a restriction exists on size selection the Phase 3 primary requirements would suggest the largest linear scale should be chosen at the expense of storm and survival representation. Seaworthiness will still be observed, and monitored and detailed measurements in key components that enable extrapolation to all loading conditions is essential. Since strength of material is a property not easily scaled, the components will not have to be tested to destruction to obtain the worse case scenario.

If these trials lead to results showing vulnerability in structural components or the PTO then large to full scale tests should be scheduled using land based rigs capable of simulating the measured irregular, oscillating load patterns measured at sea or in the wave tank.

The larger scale Phase 3 rationale can be summarised:

- *To investigate physical properties not well scaled.*
- *To employ a realistic/actual PTO and generating system.*
- *To qualify future environmental factors.*
    - *(marine growth)*
    - *(corrosion)*
    - *(windage and current drag).*
- *To validate electrical supply quality.*
- *To quantify survival conditions*

As the results became available, the economic and business plan should be improved and fine-tuned. It is of particular importance to address the power response characteristics to the joint probability density function and occurrence in the sea state scatter diagram. This procedure enables annual energy (kWh) estimates to be produced from the standard performance indices for any sea area required.

The engineering design models should be considered for further refinement, particularly in control strategies if required and power control methods. The latter techniques will of necessity have to utilise on-board systems, which may restrict the automated options. Transmission difficulties can be temporarily ignored.

Schedule and Budget

SECTION	**TIMETABLE (including Analyses)**	**BUDGET (€000)**
Large Scale Facility	3 – 9 Months	500 – 1,000
Benign Site	6 – 18 Months	1,000 – 2,500

National Facilities

ACTIVITY	**ESTABLISHMENT**
Large Scale Facility	*HMRC (Labour*)
Sea Trials	HMRC

	Ocean Energy Hydam Technology Clearpower Technology
Model Construction	
Internal Facility	HMRC
External Benign Site (Pilot Plant)	Foynes Engineering BMD (Cohn) Arklow Ship Yard Harland & Wolfe Liffey Marine
Mooring & Anchor Deployment	Marine Institute Ocean Energy
Electrical Installation	Marine Electrical Services SDGA
Instrumentation & Telemetry	PROS-CON HMRC
Power Take-Off Testing	Limerick University Musketeer Engineering Queens University
Supply Quality	ESBI
Tugs & WorkBoats	Celtic Tugs Seahorse Marine Transport Waterford Tugs Marine Institute

Two specific and distinct approaches can be taken to completing this phase of the development. There are advantages and disadvantages to each. For both options the costs arise primarily in material, manufacture and facility hire charges, the engineering design having been completed in the previous Phases. The latter figure could vary considerably between institutes, type of contract (research or commercial) or whether the testing can qualify for inclusion in the EU backed Large Scale Facilities Programme. The two options are:

1. *An internal large-scale test facility.*
2. *An external benign sea trial site.*

The decision on which approach to take will be a combination of several technical factors and the specification of the objectives to be achieved. Results from the previous stages of development may influence the selection but fundamentally it should be made based on the questions requiring resolution and any modelling or scale factors that would affect the results. The option taken will depend to a large degree whether a fully operational power take-off and generating system is to be included in the model specification.

2.3.2 *Large Scale Tanks (Flume or Basin)*

The main advantage of this approach is that the facility is fully controllable both in terms of the actual sea states produced and the exact repeatability of conditions for test comparisons.

The primary disadvantages are the high cost of hiring such facilities and the upper limit on the size scale of the model that can be accommodated. The former consideration can be modified in EU states by the Large Scale Facility funding programme. However, acceptance of a project into this scheme cannot be guaranteed as competition is severe so full cost accounting in the planning stage must be adopted.

Models between **1 : 10 - 15** linear scale should be possible, which inevitably means they are relatively costly items. Since scale factors are considerably reduced the test programme can be written with two objectives whilst consuming the minimum tank time:

1. *Validate or calibrate, the smaller scale results.*
2. *Introduce advanced trials not possible at the smaller scale.*

The first objective is primarily a process of repeating specific and selected model set-ups and environmental conditions and comparing analysed results from all test series. If the procedure proves successful (i.e. close compatibility) then a considerably reduced test programme only is required. This is an important consideration if the full facility cost is being absorbed. A consequence is that expensive models may seem to be under utilised but this must be accepted.

There are only a limited number of large-scale test facilities, most of which are flumes. Wave generation is the principal restriction.

The second objective is based around the power take-off modelling, mooring system and survival scenarios. The excitation response of the device should be more accurately represented such that forces in vulnerable, or highly stressed, components can be measured, though the actual unit itself may not be accurately modelled, particularly in terms of material strength. Obtaining the forces for use in final design calculations is sufficient at this time. Seaworthiness of the hull can be observed and monitored.

An important feature of the machine that may have proved difficult to accurately represent in previous phases, either as a component or simulated feature, is the PTO and, if proposed, its active control. The selected scale of the hull and hence the facility hired and budget required will probably depend on this single consideration. If the fully operational power take-off system cannot be used for the model testing due to manufacturing and scale considerations a very accurate simulation substitute must be included. This essentially means the damping characteristics of the full size system have to be represented in detail, a complicated requirement if control is required. The fixed damping settings from the previous trials when analysed across the monochromatic wave frequencies will have indicated the value of incorporating a variable applied damping but a full active control system will not yet have been tested. The problem of how to obtain the wave data to produce the activity signal has not yet been resolved so this area is very much in the experimental stage. Different options exist but if full control is to be applied future event information is required on a wave- by-wave time scale. Sea state to sea state tuning remains an easier possibility with certain machines so this quasi-dynamic adjustment can be tested, if the previous results indicate improved output results.

2.3.4. Benign Site

The alternative to a large-scale hydraulic facility is an outdoor site around which the required facilities exist. This must be a wave active but partially protected location and can be either a fresh water lake or sheltered bay offering sufficient water depth and easy land access. Launch and recovery facilities must be close by, particularly if a temporary survival strategy is to remove the device from harms way in the event of extreme conditions arising. A seawater location has the advantage that waves created over a large area can propagate to the site whilst lakes can be fetch limited in most instances. Data acquisition could be on-board loggers but more typically telemetry systems can be employed. Because of the quantity of data involved this would probably be based around a radio transmitter and receiver. This means an on-shore command centre with power supply (fixed or portable, permanent or on demand) is also required which may eliminate very remote locations. Such an approach was favoured by the Danish Energy Agency who established a test centre at *Nissum Bredning*. Water depth is rather restricted, however, for floating **WEC** with deep draughts.

The primary requirement of a natural deployment site is the wave climate. This must be a safe, scaled replica of the prototype sea states.

Typical linear scale for this type of work would be **1 : 4** full size. This would result in power conversion units of **20-100kW** based on prototypes of **1-2 MW.** It should then be possible to equip any model with an operationall (scaled) power take-off mechanism, electrical generator and power electronic system. Grid connection can be simulated and the electricity production dumped into heat exchangers etc.

Of particular importance is the wave climate found at the site. Even sheltered sites will often exhibit high-energy seas from certain directions. The optimal solution, therefore, is an enclosed sea that scales the climate of the open ocean. Sections of the Mediterranean for instance are perfect **1:2 – 1:4** scale scatter diagrams of the North Atlantic, ranging from **2-7 seconds, Tz** and **0-3m Hs**. Alternatively, specific locations in the *Irish Sea* could be considered. The joint possibility diagrams do not match exactly, but the extreme swell waves that propagate through *St. Georges Channel* should not produce destructive conditions. A location of low tidal current would also be necessary.

A primary list of requirements for a benign test site could be summarised as follows:

- *acceptable wave climate*
- *sufficient wave depth*
- *local launch and recovery facilities*
- *local service harbour*
- *attitude / acceptance (by national and local inhabitants)*
- *on-shore command centre back-up*

    - *electricity*
    - *portable or fixed office*
    - *security*
- *staff accommodation*
- *convenient travel hub*
- *basic rectification and engineering maintenance shops*
- *modern communication links*

Advantages of using an external deployment sites are that there is usually only a moderate hire fee, if any, and the model scale can be larger.

The principal disadvantage is that there is no control on the input conditions so the test programmes must be well structured to achieve repeat trials and cover the extensive set of different excitation forces required. One approach is to extend the testing period, which, could be perfectly acceptable depending on the cost of monitoring the device once it is on station.

2.3.5 PTO Bench Testing

Designing and engineering of the complete power take-off unit has been undertaken in the previous Phase 2 schedule. Manufacture, assembly and dry bench testing of the scaled units required for the sea trials, however, may be deferred until the initial period of Phase 3. If major development of the system is required this work too should have been started in Phase 2 and then run in parallel with the initial trial period of Phase 3. The timing and objective should be to produce a working system for assembly on the scaled Process Model during the sea trials.

Initially the mechanical/hydraulic converter and the generator /control units can be tested independently but the complete system will require to incorporate active control strategies and to verify the algorithms. This work should be conducted prior to sea trials and may be undertaken following the satisfactory conclusion of the independent tests.

Input conditions for the bench testing will be provided by the previous test result.

*2.4 **Prototype Device:** Phase 4*

Scale (λ): 1 : 1 – 1.25

Traditionally marine engineering is a bespoke, one-off industry but a principle behind the floating type wave energy converter is that the design and construction can be modular and production automated. The renewable energy industrial benchmark for installed capacity is **€1,000-1,500/kW**. A fully fitted **1 to 2 MW WEC** coming out of the dry dock could therefore be expected to have a sale value of **M€1-2**. Initial estimates for offshore wind parks however are twice this value so relative economic vessels could have a production cost as high as **M€4.** Assuming the standard price of fabricated steel being **€3500/tonne** this economic bench mark figure should be achievable. This phase represents the first of these units, though the budgets reflect a first-off elevated price tag or it may dictate that a slightly reduced scale has to be considered. This would probably be related to power conversion rather than linear dimensions, ie half scale by de-rating, **(2MW** down to **1MW).** The actual requirements will be related to the base ratings of the device. Small machines will be full size whilst large units may be slightly down sized.

The primary objective of the prototype will be to fully verify the technical and, consequently, the economic feasibility of the wave energy converter. This will be achieved by assembling the complete machine and connecting it to the national distribution network (10-20kV). Since only a solo unit is being considered reasonable flexibility should exist on the deployment site options. Sacrificing a **1-2MW** capacity cable may prove a better option than utilising the proposed power station wave park where a **+10-20 MW** cable will be required. Cautious steps can also be followed whereby the unit is installed at a slightly sheltered site initially and not grid connected. Operational experience can therefore be gained prior to towing the device to a more exposed site. Further behaviour and performance data, and especially survival, can be analysed before the final electricity supply cable is connected and the grid activated. Some attention to methods off instantaneously dumping **1MW** of power will be required. This extensive test schedule accounts for the slightly elevated budget requirement for Phase 4, which includes full instrumentation and the control equipment (SCART) to supervise the system.

Elements of particular importance to be monitored leading up to commissioning are:

- *Hull Seaworthiness and survival strategies*
- *Mooring and cable connection issues*
- *PTO performance and reliability*
- *Electricity supply quality*
- *(Absorbed/pneumatic power-converted/electrical power)*
- *Local wave climate/conditions*
- *Service, maintenance and operational experience.*

Even at large prototype scale units may not be the final design configurations, but rather test beds for component proving.

Since even the final test location may not be the selected site for the full wave energy park it would be envisaged that the installation should be removed following completion of scheduled sea trials. An alternative strategy, however, could be to chose a secondary site for this work such that if the device remains fully functional it could remain in operation for an extended period of time. This could entail a small, inhabited island or remote community such that even the single device could provide an economic electricity supply. The device could even remain on station for publicity and promotional purposes at such a location.

2.4.1 Wave Power Parks

In preparation for the next phase of development knowledge regarding the interaction of several individual units responding in a wave excitation field should be pursued. This task is somewhat more difficult than the well documented and understood wake interference effects created in flow fields since the radiated wave of the oscillators will travel in two dimensions and expand in area rather than contract. However, the magnitude of the scattering wave will diminish quickly due to the circular spread of the energy.

The full study of the consequence of this phenomenon has not been specifically highlighted in this device development programme since it is common to most machines that will be deployed in arrays, or wave parks. As such it is expected that the topic will be generically investigated extensively outside of the individual device team budgets with solutions and recommendations to accommodate effects, if required, becoming available.

Each particular type of device, however, may have its own particular array interaction considerations, therefore, some studies, both theoretical and empirical should be included in the Phase 4 development programme.

Schedule and Budget

TIMETABLE (inc analysis)	**BUDGET (€000)**
6 – 12 Months	**2500-5000**
1 – 5 Years	**- 7500**

National Facilities

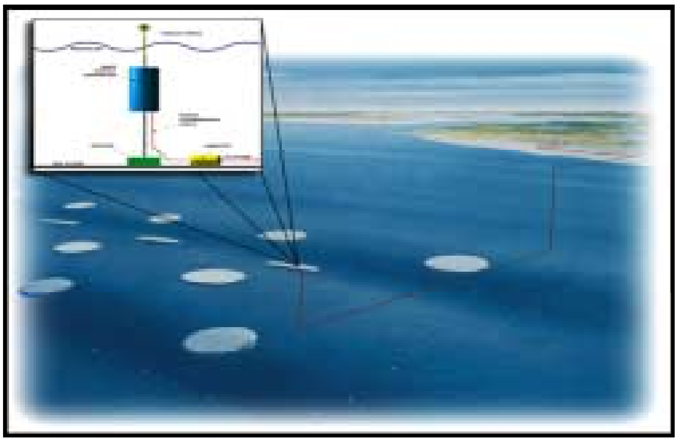
ACTIVITY	**ESTABLISHMENT**
Sea Trial Monitoring Instrumentation Telemetry	HMRC Ocean Energy Hydam Technology Cleanpower Technology ESBI PROS_CON DATAC (Irish Lights)
Vessel Design	
Vessel Construction	Harland & Wolfe Cork Dock Yard Arklow Boat Yard
Mooring Deployment	Marine Institute Marine Technology Development Services
Wave Measurements	HMRC IHD
Site Survey	IHD
Licence & Permissions	Ocean Energy ESBI
Power Take Off Module Air Turbine Hydraulics	Musketeer Engineering
Electrical Control System	Marine Electronic Services SDGA

Supply Cable	
Grid Connection	ESB

2.5 Demonstration Unit: Phase 5

Scale (λ): 1 : 1,Full Size

The device constructed for this phase of development should represent the Mk1 production unit to be deployed at the selected wave energy production park. The full rigors required for the schedule of this phase are beyond the scope of this document but some general remarks and comments are appropriate to describe this final section.



Wave power stations will comprise of arrays of solo WECs in the same style as wind farms.

Depending on the evidence and information that has been gathered prior to this time the device may still initially be installed at sea as a solo unit. Alternatively a small array of converters may be simultaneously installed and connected to make optimal use of the plant and manpower mobilisation. For floating devices it may be sufficient to deploy the anchors and moorings for future park units, which can be towed out and connected at a later date. A quick fit re-usable grid cable connector will be essential in such circumstances.

Connection to the grid would be expected to take place at, or soon after, installation but the device development work may still be continuing relative to the type of PTO system and control strategies employed. The unit will therefore require additional monitoring sensors, including transducers to monitor service and maintenance.

Acknowledgements.

The following people kindly edited this document at various stages and thereby provided an important contribution to its final production. Although most of their comments have been incorporated into the text individually they may not endorse all the points specified in copy. Pat McCULLEN, ESBI; Bob MEIR, UK; Aodhan FITZGERALD, Marine Institute; Paul BREWSTER, ClearPower Technology.