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The "ρC" WEC in "Offshore Wave and Wind Together; Afloat" – 3 Years' Progress

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ABSTRACT

Offshore wind and wave power can be remarkably complimentary. Given an extended, stable floating platform to share, important economies of renewable power production and energy storage are possible. The Pneumatically Stabilized Platform (PSP) embodies such a platform. Developed with DARPA support and proved in model scale, the PSP will achieve its at-sea motion stability and structural loads mitigation by decoupling the "hull" from ocean wave pressures through the partial use of air buoyancy. In addition to supporting an array of WTs, the PSP deploys along its seaward edge the "Rho-Cee" WEC, termed the "Impedance-Matched Terminator"; comprising a nested set of tuned OWC absorbers, resonant across a selected frequency band. By means of impedance matching, highly efficient wave energy absorption may be achieved, and has been demonstrated in tests. Procedures and results of those tests are summarized. However, attempts to optimize the design for minimum cost, per unit of delivered energy, show that the "efficiency" of absorption is largely dictated by economics, rather than physics, and is typically smaller than that attainable. Three PTO types are considered

The PSP and Rho-Cee WEC are constructed, modularly, in pre-stressed reinforced concrete, which is found degradation-free in long term exposure to sea water – and only concrete touches sea water in the platform, WEC or WT systems. All equipment subject to maintenance, replacement or inspection is "in-the-dry"– fully accessible to platform-resident personnel on foot, dry-shod. As an effective breakwater, the WEC-lined PSP ensures ready access by personnel and equipment in high sea conditions. The reduced cost and enhanced availability for such maintenance should yield significant economies. With integral foundations, WTs deployed upon such a floating platform can be located

offshore in more favorable winds (and less visibility); avoiding prohibitive foundation/installation costs, and in the greater water depths favorable to the WECs;

INTRODUCTION

The Resource

Because of a concentration on offshore wind energy, high sea states (waves) are considered an impediment, a hazard to efficient and safe ocean energy production. In fact, waves are an energy asset, an asset so large as to frequently exceed that of the available wind energy itself. This is because the available wind power varies, as is well known, as the cube of the wind velocity – whereas, as is little known, the available wave energy varies as the fifth power of that self-same wind velocity that creates and sustains it.[1] In figure 1, the uniformly spaced disc areas of regularly spaced wind turbines are converted to an equivalent uniform power capturing area per unit of lateral frontal length, so as to be directly comparable to the equivalent for the wave energy converters.

When compared on this engineering-consistent basis, as shown plotted in Figure1, the available incident power of waves will be seen to equal that of wind at about 18 kts wind speed, and to exceed it, beyond. (In the figure, "P-M" refers to the Pierson-Moskowitz wave spectrum and "JONSWAP" to that-named variant thereof.)

In addition, because waves travel global distances with little loss, it is frequently possible to harvest the energy of swells arriving from distant storms while residing in a region temporarily windless. (We have termed this "other people's wind".). The result is an increase in wave energy utilization factor.

The Platform

In order to simultaneously harvest both offshore wind and wave energy in an efficient (economical) and safe manner, it appears that the equipment should be deployed from, and commonly supported by a very large floating platform. The functions and systemic relationships supported by such a platform are described diagrammatically in Figure 2.

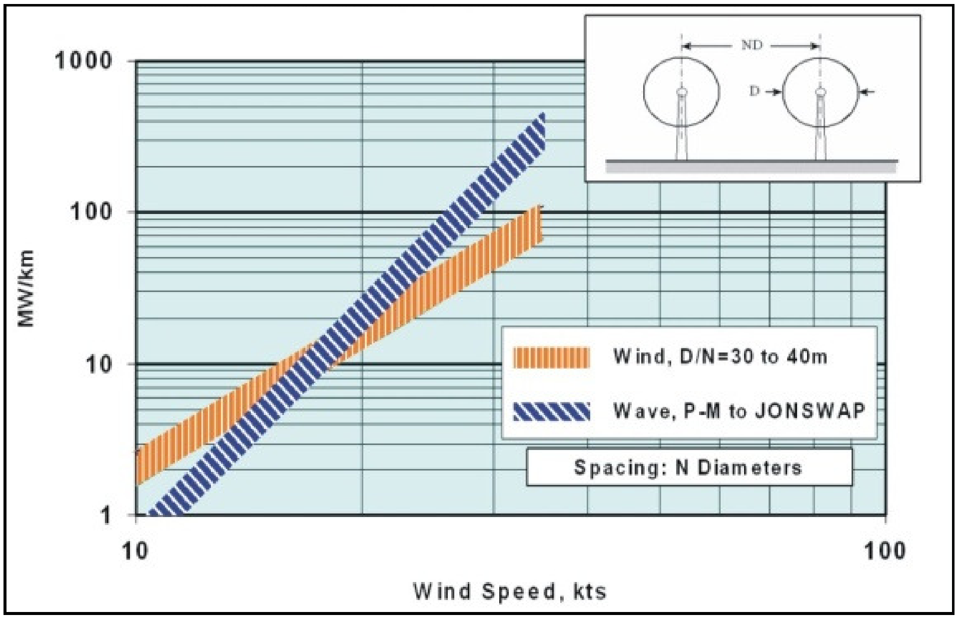


FIGURE 1. AVAILABLE POWER COMPARISON, WIND AND WAVE.

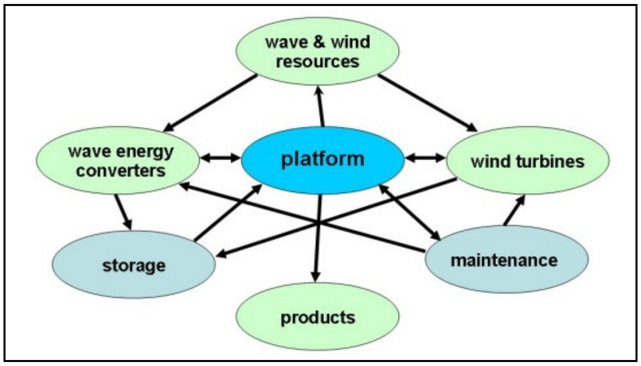


FIGURE 2. THE CENTRAL ROLE OF THE PLATFORM IN THE OFFSHORE FLOATING OCEAN ENERGY SYSTEM

First, the stable floating platform places the wind and wave energy harvesting systems offshore, adjustably moored, where those resources are largest, and without restrictions of water depth. Both systems are supported, with but little mutual interference (due, perhaps, to differing directions of incidence), by the platform whose capital and maintenance costs are shared.

The platform acts as an effective breakwater, allowing ready access by personnel and materials in any weather that allows navigation. The platform provides a dry land-like environment for maintenance. Indeed, personnel may reside there, temporarily, and work in onboard shops.

The platform provides an onboard potential energy storage system in the form of pressurized air contained in its large internal volume, and operated by the buoyancy air handling system with which the platform is inherently equipped.

Finally, power outputs of both numerous wind turbines and wave energy converters may be collected via on-board, dry cabling to a central on-board conditioning unit from whence it may be sent ashore via a single submarine cable bundle.

THE PNEUMATICALLYSTABILIZED PLATFORM (PSP)

Concepts exist for very large floating platforms, moored offshore, with superior motion stability and load capacity in challenging sea-state environments. The generic type is termed a Pneumatically Stabilized Platform (PSP).[2,8] It achieves its at-sea motion stability and structural loads mitigation by decoupling the "hull" from ocean wave pressures through the use of reduced waterplane area and partial air buoyancy, which is both compressible and mobile. The air is contained in an array of interconnected, open-bottomed, cylindrical tanks. The air is made mobile by means of ducting. The ducting arrangement is selectable in real time, to best suit the sea-state environment and platform deck loading. Local air pressure adjustments are made via Roots-type blowers, as needed.

The PSP is constructed, modularly, in pre-stressed, reinforced concrete, which, if properly formulated and applied, has been shown to be degradation-free in long term exposure to sea water. In contrast to steel hulls, a concrete PSP need never be dry-docked for inspection, and requires no significant maintenance of the basic hull. Its useful life is expected to exceed 70 years.

The PSP modules will be constructed at the largest scale feasible and will be launched fully equipped with WECs and WTs installed, ready to run. These modules will be assembled into the fully complete platform, or nearly so, in a protected water body, from which the assembly will be towed to its assigned location were it is to be connected to pre-placed moorings and power cables – ready to operate.

Most significant from a practical (that is economic) point-of-view, is that only concrete touches sea water in the platform, WEC or wind turbine systems. All equipment subject to maintenance, replacement or inspection is "in-the-dry" – fully accessible to personnel on foot, dry-shod. Maintenance personnel can comfortably live on the platform.

The platform is to be moored in deep water by means of steel chain or cable in catenary configuration, or taut-moored using synthetic lines. Anchors, subject to environmental acceptability, may be of the removable suction-pile, or the plow-types. Mooring technology is well developed in the offshore industries.

THE WAVE & WIND OFFSHORE FLOATING OCEAN ENERGY SYSTEM (OFOES)[6]

The first embodiment of an OFOES was intended as a 2.5 km-long breakwater for the port of Leixoes, in the North of Portugal. The breakwater was conceived as a means to enlarge the port's docking capacity for Atlantic shipping, in that it was limited by the configuration of the very old port with its stone breakwater. It was also intended to lend shelter to the more southerly mouth of the River Douro. With an annual average incident wave power of approximately 56 kW/m, it was expected to deliver 70 MW power to the local grid, with a somewhat lesser amount from the wind turbines.

In order to enlarge the wind turbine capacity proportion of a wind & wave offshore "farm," the generic arrangement of Figure 3 has been adopted. Here, the WEC and WT-bearing PSP is again intended to fill the "aperture" of the farm, but an attached wind turbine-bearing structure is extended and protected to leeward.[6} In contrast to the PSP portion, approximately 30 m wide in "beam", the wind turbine-only support is proposed to be constructed as a truss-like structure made of reinforced, pre-stressed concrete culvert pipe. (Figure 4) This is attractive because concrete culvert is a mass produced product with well known properties [7]. It is also relatively inexpensive!

This truss construction concept includes struts of 15 ft. inside diameter, 13.25 in. wall culvert pipe and has vertical bulkheads interspersed, which bulkhead structures reach to above the waterline. The culvert pipe struts are assumed to remain submerged at a depth (TBD) that allows for efficient structural connection to the PSP. Note that the air-filled culvert pipe has a net buoyancy of about eight tonnes per meter. The bulkheads, with freeboard, may serve as stanchions for supporting tracks and walkways for access of personnel and heavy equipment (cranes, trucks) to all parts of the farm. The bulkheads are to serve as anchor structures for the numerous pre-tensioning tendons that hold the concrete culvert pipe sections in axial compression. Any one such strut-member should provide sufficient bending strength to avoid tensile stresses under the extreme moment loading of a single wind– turbine – whereas there are typically three struts sharing the load to some extent.

The spacing of wind turbines in Fig.3 is 200m, with rotor diameters of 90m assumed. The truss triangles are equilateral. The "span" of the farm is therefore 1040 meters. There must be a trade-off performed to evaluate the output product vs. the "costs" in performance, capital and maintenance associated with both lateral and leeward spacing of the wind turbines, i.e. aerodynamic interferences. Note that each wind turbine located at the intersection of three struts is fitted with a "lily-pad" of decked PSP foundation structure that provides access for maintenance, as well as air-load moment balance, strength and buoyancy. A PSP section is fitted to one of the leeward legs to serve as a sheltered docking facility. A helicopter pad must also be fitted where air operations will not be threatened by the wind turbines; the swing-circles of the rotors may be noted.

While the costs and productivity of the new wind & wave platform concept are yet to be detailed, very

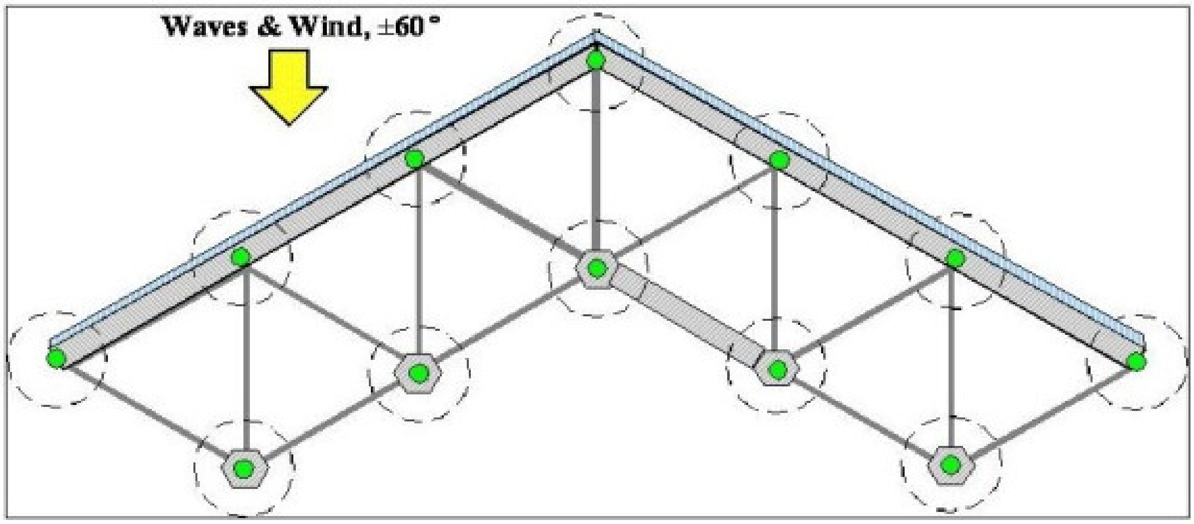


FIGURE 3. PLAN VIEW OF 1040m-SPAN "OFOES" WITH 12-90m WTs & 1200m WEC DEPLOYED FROM A PSP

preliminary estimates of platform "hull" capital costs are falling in the range of $1,400 to $1,800 per total (wave plus wind) rated kilowatt, for energetic areas. We suggest this is influenced by the prospective use of the relatively cheap concrete culvert strut structures to spread wind turbines vs. using the PSP which is priced mostly by area. On the other hand, it is a matter of current investigation to determine how the rating of a WEC should be established relative to the statistics of its production.

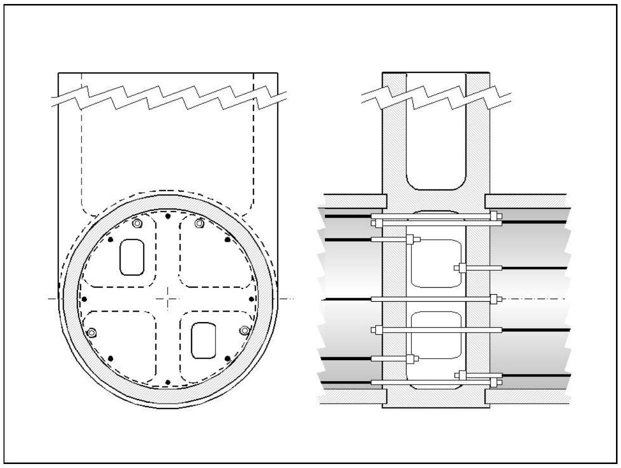


FIGURE 4. STRUT STRUCTURE. BULKHEADS TERMINATE 16 x S19-5 TENDONS PER SIDE.

ENERGY STORAGE

Finally, both wind and wave systems are uniquely capable of storing substantial amounts of potential energy in their common supporting PSP structure. That potential energy is embodied in compressed air residing in closed volumes and buoyancy cylinders of the PSP, charged and tapped by reversible motor-driven Roots blowers that are already part of the platform system. That energy can be tapped during intervals of low wave or wind activity to better match varying demands of the load infrastructure, thereby avoiding the principle objection to renewable energy sources.

With compression to three atmospheres (gauge), for example, by Roots blowers connected in series, a PSP platform of typical height may store the pressure x volume equivalent of 4 MW-hrs of potential energy per acre of deck area. As the compressed air will have cooled to ambient temperature, it will be advisable to add heat before expansion in order to increase and maximize energy output; avoiding sub-cooling of the exhaust air (unless refrigeration is a useful product). The heating may come from the combustion of a fuel, preferably Hydrogen, self-made by electrolysis with some of the excess power – or using warm seawater, in a re-heat mode.

THE WAVE ENERGY CONVERTER

The "Rho-Cee" (ρC) Wave Energy Converter (WEC) system is subtitled "The Impedance-Matched Terminator".[3] It is a large, floating Oscillating Water Column (OWC) system, to be moored in deep water. The "Rho-Cee" is integrated with the Float PSP to take advantage of the controllable stability, load capacity and deck area that it provides. The name "Rho-Cee" derives from the expression for the characteristic impedance of water gravity waves; the product of water mass density, ρ, with the length-dependent velocity of such waves, C. It is the base principle of the WEC design that its input impedance is to adjustably match the characteristic impedance of the targeted waves. Impedance matching maximizes the transfer of wave energy; with minimum reflection.

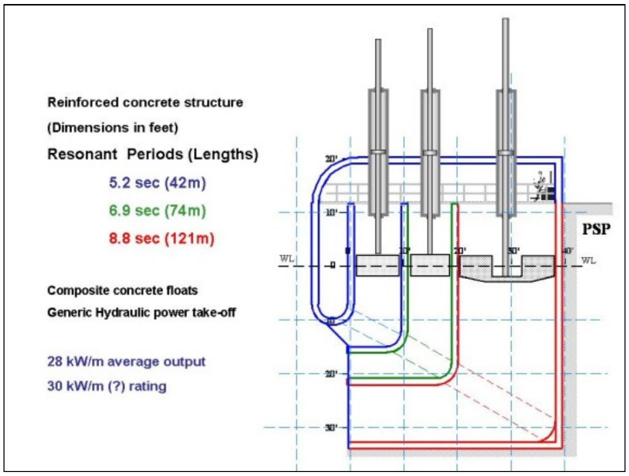


FIGURE 5. GENERIC RHO-CEE WEC - FOR PORTUGAL (DIMENSIONS IN FEET)

Several constraints dictate that the input impedances of the absorber elements be quite small and resistive. This requires resonant operation of the OWCs. Hence, several water columns are tuned to frequencies, with band-widths that span the energetic region of the yearly average incident wave power spectrum. The normalized bandwidths govern both the resistive input impedance and the output power potential of each oscillator. The successively-tuned water columns are geometrically "nested" to minimize space and weight of materials – hence cost, as may be seen in Fig. 5. The nested units are then repeated, endwise, to form a linear array of identical contiguous WECs in a two-dimensional "terminator" configuration – one that is aligned perpendicular to the usual propagation direction of incident waves.

The currently favored means to transduce OWC motion to output electric power is diagrammed in Figure 6. It is quite possible to maintain linearity in the pressure-velocity relationship; hence constancy of OWC input impedance, via hydraulic motor displacement control on a near-instantaneous basis. The impedance is also readily adjusted to account for variations in the waves' incident direction relative to the normal direction. While other means of transduction in the power take off (PTO) may be simpler, or more efficient, they may not now be procured as "commercial-off-the-shelf" (COTS) items.

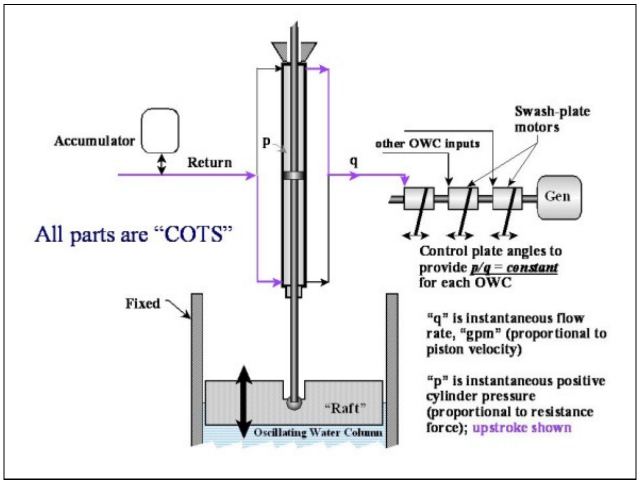


FIGURE 6. HYDRAULIC PTO: CONTROLLING INPUT IMPEDANCE VIA THE LOAD.

Alternatives for the power take-off include:

1. Electric
    - Direct linear reciprocating generator.
    - Rack & pinion or counter-weight chain driven rotary generator.
2. Pneumatic
    - Bi-directional Wells air turbine-generator.
    - Uni-directional (rectified) air flow, controllable area turbine-generator.
3. Hydraulic
    - Linear piston pump (shown), swash-plate motors-driven generators
    - Rack & pinion or counter-weight chain driven rotary pumps & swash-plate motors.

These are currently being examined by the appropriate specialists.

The "rough" power produced by the individual generators must of course be conditioned and combined for transmission to shore. This is accomplished in a platform-resident facility.

In 2009, in response to the submission of a white paper[4] describing the Rho-Cee WEC system and its proposed development, the US Minerals Management Service (now BOEM) awarded a period of wave basin testing at their large Ohmsett Facility.[5] The purpose was to verify the capture efficiency of the impedance-matching characteristic of the Rho-Cee design. For this, a simplified (two column) model was designed and built at about 1/8th scale, in four 4' modules, and subjected to waves of various heights at the two resonant periods. (Test equipment limitations, at that time, caused limits to the bandwidth.)

FIGURE 7. "RHO-CEE" MODEL BEING PREPARED FOR ABSORPTION TESTS AT OHMSETT FACILITY.

The loading impedance was selectably supplied by throttling of displaced air through calibrated, adjustable slide valves. In the best case, a maximum of 93% of face-incident wave power was found dissipated by the linear portion of the air-flow resistance (by spectral analysis). (Fig 8b) That analysis demonstrated that feared square-law response, vs. linear, cost little in impedance mismatch. Resonant column velocity (vertical) is here compared to that of the non-resonant column (horizontal) in Fig. 8a.

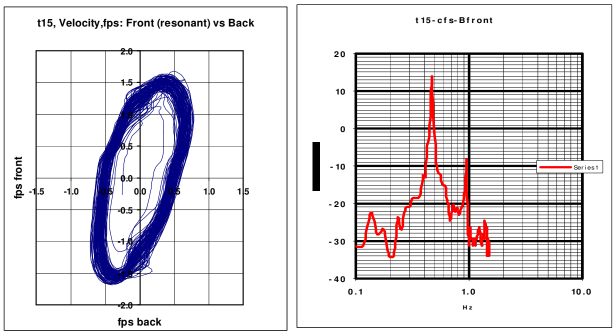


FIGURE 8a: RESONANT (Y) VS. NON-RESONANT (X) COLUMN VELOCITIES, & FIGURE 8b: FLOW RATE SPECTRUM

Recent efforts to optimize the design of the Rho-Cee make it clear that the achievable energy absorption effectiveness will be determined primarily by economics, rather than by physics. The transverse linear dimension of the WEC structure cross-section is proportional to the greatest wave length (hence squared period) of capture. Therefore, the capital cost increases rapidly with the upper limit of period-band capture.

OPTIMIZATIO OF THE WEC

A first attempt at optimization of the ρC WEC design proceeds from the assumption of a yearly incident wave energy spectrum. This one is derived from a Rayleigh distributed wind velocity via the wind-wave relationship described by Michel [1] using the Pierson-Moskowitz spectral form, Figure 9, in MW-hr/m-yr. Actual historical data for a subject site would be used in practice.

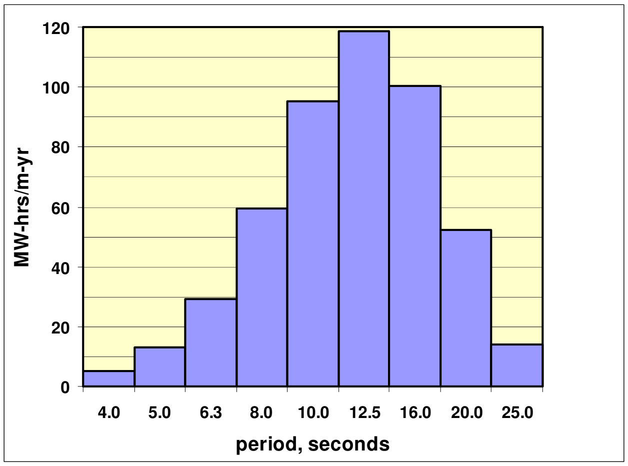


FIGURE 9. INCIDENT ENERGY SPECTRUM

The energy spectrum is here expressed, for convenience, in 1/3rd octave bands (band width, BW=23% of center period), as is common in acoustic and vibration considerations.

In the latest optimization effort, it is assumed (subject to analysis) that the available wave energy is restricted to that incident on the face of the WEC, down to its draft, allowing for a baffle plate. In the following a face draft of 8% of the wavelength of the highest intended capture band period is postulated. Energy from non-resonant, out-of-capture bands is ignored. The fraction of full deep-water energy that is presumed available to the restricted face depths is shown in Figure 10.

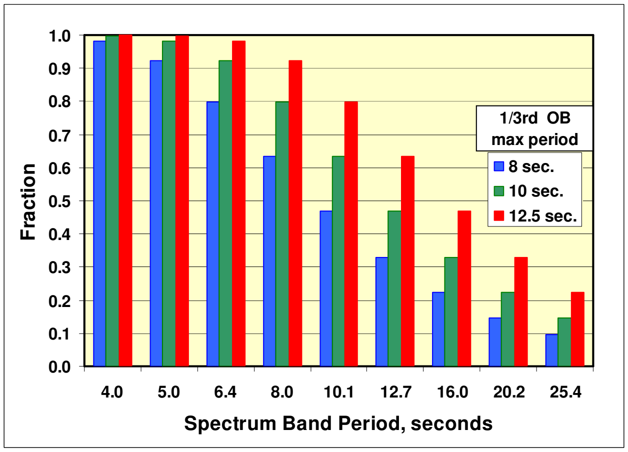
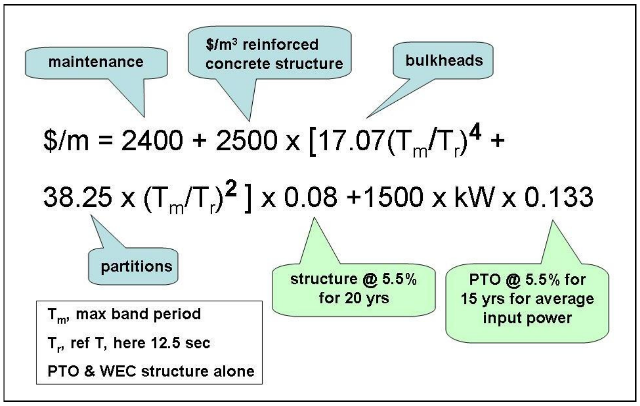


FIGURE 10. AVAILABLE INCIDENT ENERGY FRACTION WITH AN 8%-OF-WAVELENGTH FACE DEPTH.

As the linear dimensions of a scalable, generic, three-column OWC WEC vary as the wave length, hence as the square of the period, the upper terminal band period is the major variable. A (preliminary) cost model is diagrammed in Figure 11. The yearly cost in $US per meter of wave-incident "aperture" is shown heavily dependent on the levelized cost of reinforced concrete structure – here in terms of transverse bulkheads and inter-column partitions. Other levelized costs of the power take-off equipment, based on average incident power handled, and of all maintenance are shown, as assumed.



$$\$/m = 2400 + 2500 \times [17.07(T_m/T_r)^4 + 38.25 \times (T_m/T_r)^2] \times 0.08 + 1500 \times kW \times 0.133$$

FIGURE 11. COST MODEL (PRELIMINARY)

The results of exercising this model with the assumed available energy inputs are shown in Figure 12, where a pronounced and consistent minimum is found in the predicted levelized cost of energy.

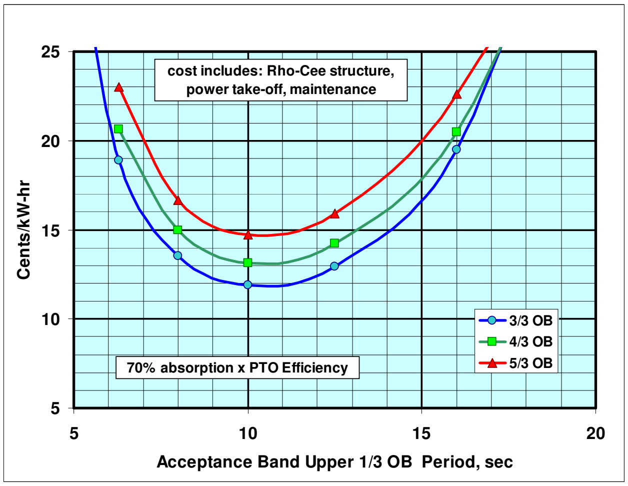


FIGURE 12. MINIMA ARE FOUND IN THE LEVELIZED COST OF ENERGY.

It appears that attempting to capture the high energy of the longer waves is uneconomic as the size and cost of the required structures become increasingly large. Fortunately, the cost minima are found in a range of periods that are obtainable in reasonably sized OWCs.

In these results, it has been assumed that the products of absorption and PTO efficiencies are uniformly 70%. The resulting levelized costs are inversely proportional to that compound efficiency value.

Not included in the indicated costs are those of the platform that are assigned to the WEC system. If those costs are split equally between wave and wind systems, they are expected to add about 1 to 1.5 cents per kW-hr to the WECs' levelized cost; assuming a 50 year term at 2.5%. Further, no provision has as yet been made for non-linear "clipping" of column oscillations for overload protection.

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