

UNITED KINGDOM WAVE ENERGY PROGRAMME

**BELFAST DEVICE**

DEPARTMENT OF CIVIL ENGINEERING,  
QUEENS UNIVERSITY



TWO-FREQUENCY  
OSCILLATING WATER COLUMN

REFERENCE DESIGN AUGUST 1983

## SUMMARY

This report describes the optimisation of the power conversion chain and the engineering design considerations of a two-frequency oscillating water column wave power device which would form part of a 2 GW power station. Novel features of the principal device described include the multi resonant concept, which considerably widens the frequency bandwidth response, and the use of the simple efficient Wells self rectifying air turbine in the secondary power conversion stage. It is concluded that using established technology wave power stations comprising sea bed mounted reinforced concrete structures could be constructed to produce power for 8p per kilowatt-hour during the first 25 years and for as little as 1.3p per kilowatt-hour thereafter.

## NOTATION

|           |   |   |
|-----------|---|---|
| b         | - | Duct breadth (perpendicular to wave direction)                    |
| Ba        | - | Applied damping (relating power extraction from the water column) |
| Br        | - | Radiation damping $Br_0$ - (value at resonant frequency)          |
| C         | - | Damping ratio   |
| e         | - | Mathematical constant   |
| Fs        | - | Scattered wave force $F_{s_0}$ - (amplitude of force)             |
| Fr        | - | Radiated wave force $F_{r_0}$ - (amplitude of force)              |
| $\bar{h}$ | - | Mean duct entrance depth  |
| i         | - | $\sqrt{-1}$   |
| kd        | - | Pressure modification factor                                      |
| Ms        | - | Mass of water in duct   |
| Ma        | - | Added mass  |
| n         | - | Horizontal duct entrance width/wavelength ratio                   |
| W         | - | Duct width (parallel to wave direction)                           |
| x         | - | Water column displacement   |
| $\theta$  | - | Duct entrance angle   |
| $\lambda$ | - | Wavelength  |
| $\omega$  | - | Angular frequency $\omega_0$ (resonant frequency)                 |

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## APPENDIX A

Kirk, McClure & Morton and Taywood  
Engineering Limited; "Two frequency  
Oscillating Water Column - Reference  
Design 1982"; Report to Department  
of Civil Engineering, Queen's University.

APPENDIX B Davidson and Co. Limited; "Design Analysis  
of 2.65 m diameter Wells Turbine for Queen's  
University, Belfast Wave Energy Device".

AND

Harland and Wolff Limited; "Generation  
Equipment for new 800 kW Turbine".

APPENDIX C Q.U.B. Memorandum; "Wave Energy: Power  
Conversion Costing".

## 1. INTRODUCTION

As one of the many wave energy extraction systems proposed in recent years, the oscillating water column device provides the simplest and possibly the most reliable means of converting slow irregular wave motion into the high speed rotational movement required for electrical power generation. It is also a proven system as it has been successfully used to power navigation buoys during the past twenty years. In principle both the kinetic and potential energy of ocean waves are converted into piston like motions of one or more water columns in ducts within a structure. The air trapped in the plenum chamber above the water surface is vented to the atmosphere through a turbo-alternator unit which converts the cyclically reversing air flow initially to rotary motion and then to an electrical output.

During the past seven years a research team based in The Department of Civil Engineering, Queen's University, Belfast, has been examining the parameters which govern the performance of the three power conversion stages. The most significant contribution to hydro-pneumatic device technology has been the development of a novel self rectifying air turbine, invented by Wells\*, which maintains unidirectional rotation in cyclic flow. The Wells Turbine combines high average efficiency with simplicity as there is no requirement for control valves and ducting to rectify the airflow.

Recently, as part of the U.K. wave energy programme, two reference designs have been prepared for a 2 GW power station located off South Uist; a Scottish Island in the North Atlantic.

Much of the information gleaned from these studies is presented in this report and the various design aspects of a wave power station are discussed with due emphasis being placed on the cost of power produced.

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## 2. EVOLUTION OF THE Q.U.B. TWO-FREQUENCY OSCILLATING WATER COLUMN WAVE ENERGY CONVERTOR

The wave power station initially envisaged at Queen's University comprised a single line array of 20 m diameter buoys each with a single downward facing water column. Inertial restraint in the heave mode was provided by water ballast in the base of the buoy whilst the moorings provided restraint in surge. Performance was poor and the high capture efficiency predicted by Budal et al (1) for heaving axi-symmetric point absorbing bodies was not realised. These observations were attributed to weak coupling between the wave and the water column, phase variation of the wave force around the single large diameter duct and significant power dissipation around the entrance lip.

The subsequent wave energy convertor designs were developed from the findings of an extensive hydrodynamic research programme initially conducted by Whittaker (2) and later by Robinson (3). The water column was divided into six equal segments using radial fin walls and the base structure profiled to create water columns shaped like the letter 'J'.

Extensive model testing in both the wave flume at Queen's and the wide tank facility at Edinburgh University revealed the difficulty of restraining the device in the surge mode. The potential power extraction efficiency of both the heave and pitch modes was not fully realised as a consequence of the excessive horizontal excursions.

A floating, six column axi-symmetric device was designed and costed (4) but it became apparent that the provision of moorings, at full-scale, involved non-developed technology thus resulting in a very high predicted cost element. It was therefore decided to rigidly fix the structure to the sea bed.

## 2.1 SIX COLUMN AXI-SYMMETRIC DEVICE

The first detailed reference design (5) for a 2 GW power station was an array of bottom standing, six column axi-symmetric structures, 18 m in diameter at the water line, shown in Figure 1. Excitation of the landward facing water column was primarily due to the wave diffracting around the structure. As there was close agreement between the results produced by a single model in both the narrow and wide tanks, it was concluded that array interaction had little effect particularly in random seas. However the devices had to be spaced at least 2.5 diameters apart to enable the diffraction of the wave around the device.

## 2.2 TWO-FREQUENCY DEVICE

The second design which included the multi resonant concept was developed from the six column axi-symmetric device. An oscillating water column is a tuned system with a resonant frequency determined by the mass and stiffness of the column. The frequency bandwidth response of a device can be widened by incorporating columns of varying length within the one structure. Figure 2 shows the two frequency device with two sets of water columns tuned to 7 and 12 seconds respectively.

## 3. DEVICE PRODUCTIVITY

The productivity of a wave power device is assessed as shown in Figure 3 using a computer program, 'Power', which has been developed to calculate the pneumatic power output of an oscillating water column device operating in waves of various spectral forms. The program is composed of two principal segments which calculate the hydrodynamic response of the water column and the spectral characteristics of the sea state respectively.

The two parts of the computer program will be considered separately to show how the design of the multi resonant device has been matched to the prevailing sea state at South Uist.

### 3.1 WATER COLUMN RESPONSE AND DUCT GEOMETRY

The dynamic response of a water column in a fixed structure can be described by the equation of motion for a single degree of freedom:

$$F_{s_0} e^{i\omega t} = M_s \ddot{x} + B_a \dot{x} + k_s x + F_{r_0} \quad (i)$$

The interaction between the wave and the water column is described in terms of the scattered and radiated wave forces ( $F_s$ ) and ( $F_r$ ) respectively. ( $F_s$ ) is the product of the hydrodynamic pressure acting on a stationary column at the centroid of the entrance ( $F_i$ ) and a pressure modification factor ( $k_d$ ), which allows for phase variation of the force across the entrance and for wave scattering due to the presence of the duct. ( $F_r$ ) is the force required to oscillate the column in still water, assuming no losses, and is the vector sum of the inertia and damping terms ( $M_a \ddot{x}$ ) and ( $B_r \dot{x}$ ). The forces are frequency dependent in harmonic motion.

The mass of the column ( $M_s$ ) and stiffness ( $k_s$ ) are determined simply by the internal geometry of the duct. Robinson (3) produced a set of semi-empirical equations which defined the values of ( $k_d$ ) and ( $M_a$ ) in terms of wavelength ( $\lambda$ ), duct width ( $W$ ), mean depth of the duct entrance ( $\bar{h}$ ) and entrance orientation angle relative to the internal water surface ( $\theta$ ). These semi-empirical relationships are simpler to use when solving the equation of motion than the fully interactive analytic solutions developed by Lighthill (6).

The interrelation between the ratio of the undisturbed waveforce at mean water level to the effective force acting on the duct entrance

( $Kde \frac{-2\pi\bar{h}}{\lambda}$ ) and the geometric wave field variables for two ranges of values of  $(\theta)$  is shown in Figure 4. Although Robinson's original equations were developed for a duct, rectangular in plan, facing the incident wave, subroutines in 'Power' modify the coefficients to accommodate ducts of different shape, variable cross section along the length of the duct and different wave headings. In essence the shape, position and orientation of the duct entrance in the wavefield determines the Froude-Kyrlov wave force ( $F_i$ ) while the internal geometry of the duct determines the dynamic response. 'Power' calculates the geometry of each duct and by considering the wave diffraction around the structure calculates the Froude-Kyrlov wave force ( $F_i$ ) for each duct heading. The wave forces acting on columns with a range of headings, as calculated by the diffraction model based on the work of MacCamy et al (7), are compared with the values measured from experiment in Figure 5.

'Power' solves the equation of motion for  $x$  and calculates the pneumatic power output relative to the wave power incident on the column frontage, capture factor, (CF) time averaged over a cycle:

$$CF = \frac{4\pi f Ba (\dot{x})^2}{\rho g^2 a b} \quad \text{where } (\dot{x}) = \frac{\omega^2 |F_{so}|^2}{|K_s - \omega^2(M_s + M_a)|^2 + (Ba + Br)^2 \omega^2} \quad (ii)$$

The peak capture factor occurs at the resonant frequency ( $\omega_0$ ) when  $k_s - \omega^2 (M_s + M_a) = 0$  and  $Ba = Br_0$  i.e. applied damping equals the radiation damping at the frequency determined by the mass/stiffness ratio. The influence of entrance angle ( $\theta$ ) and damping ratio ( $C$ ) is shown in Figures 6 and 7 respectively; ( $C$ ) is defined by the ratio  $Ba/Br_0$ . The effect of damping ratio on frequency bandwidth response is discussed later in relation to the turbine design. From Figure 4 it is evident that the maximum wave column interaction occurs when the entrance is close to the surface (small  $\frac{\bar{h}}{\lambda}$ ), the duct width wave length ratio ( $n$ ) is minimised and the entrance orientation angle ( $\theta$ ) is greater than  $\frac{\pi}{2}$ . Figure 6 shows a

significant increase in the frequency bandwidth response when the radiated wave is directionalised for duct orientation angles greater than  $90^{\circ}$ . Optimisation of these parameters maximises both the forcing function ( $kd$ ) and the radiation damping ( $Br$ ) producing a device which is a good wave generator.

Theoretically an upward facing duct is best but experiment has shown that the proximity of the free surface due to the shallow immersion depth of the entrance curtails the flow with correspondingly large losses. Entrance angles of between  $120^{\circ}$  and  $150^{\circ}$  have been shown to give the best overall performance and have been used in the two reference designs.

### 3.2 SEA RESOURCE

The prevailing sea state is described by a scatter diagram which shows the number of occurrences of Pierson Moskowitz type spectra characterised by their significant waveheight  $H_s$  and energy period  $T_e$ . A better representation of each spectra as described by Crabb (8) was produced, by identifying principal components such as swell and wind sea. The latter was sometimes subdivided into old and new wind seas. Each sea component was assigned a spectral form with due consideration being given to directionality and modification of the spectral shape as a result of limited water depth. With each spectral shape subdivided into 20 frequency elements and knowledge of the capture efficiency of the device in each frequency bandwidth it is possible to calculate the pneumatic power conversion for the spectrum. When this procedure is repeated for the full set of spectra the annual power output can be calculated for a typical year. The calculated values of capture factor for the axi-symmetric device are compared with the experimental values shown in Figure 8. A correction factor has been applied to the experimental results as non linear duct losses are proportionally larger at model scale than at full scale particularly in Pierson Moskowitz' spectra with higher energy periods.

### 3.3 MATCHING THE DEVICE TO THE RESOURCE

Analysis of the 46 representative spectra and their three characteristic components revealed that the wind seas with an average  $T_e$  of 8.5 sec. were the most commonly occurring while the  $T_e$  for the annual average spectra was 11 sec. Clearly the less commonly occurring swell seas produced a large proportion of the annual power. In addition the swell sea had a predominant heading of  $270^{\circ}$  while the wind seas had a much wider distribution between  $180^{\circ}$  and  $360^{\circ}$ .

The two frequency device developed from the six column axisymmetric structure was designed to fully utilise the sea resource with the total working area of the device being divided into two parts. The original 3 seaward facing columns with headings of  $210^{\circ}$ ,  $270^{\circ}$  and  $330^{\circ}$  are virtually unchanged while the remaining columns were taken forward beneath the front columns as shown in Figure 2. The resultant increase in duct length produced a resonant period of 12 sec. compared to the 7 sec. period of the top columns. Thus part of the device would respond to the shorter wavelength of the more commonly occurring wind seas while the remainder of the device would tap the larger powers of the swell seas. In addition the directional spread of the wind seas and the directionality of the swell seas was also accommodated.

It is interesting to note that the duct depth-wavelength ratio  $(\frac{\bar{h}}{\lambda})$  is the same for the two sets of columns at their respective resonant periods. Flow interaction due to phase variations between the motions of the two sets of columns was considered. However, it was argued that this would be minimal as only the central top column has the same heading as the bottom columns and both were separated by a well defined boundary segregating the radiated wave forces at the structure. Experiment had shown that interaction did not occur between adjacent columns of the axisymmetric structure due to directionalisation of the radiated waveforce.

The capture factor for the complete device and its distribution between the two sets of columns calculated by 'Power' is shown as a function of energy period ( $T_e$ ) for P.M. seas in Figure 9. Comparison of Figures 8 and 9 shows that by using the two frequency system it has been possible to considerably widen the frequency bandwidth response of the O.W.C. device. The multi resonant concept can provide an alternative to 'Phase Latching' systems; a technique which widens the frequency bandwidth response by producing pseudo resonant conditions over a wide range of wave frequencies.

#### 3.4 TURBINE AND ALTERNATOR CHARACTERISTICS

Following the primary power conversion stage the pneumatic power in the plenum chamber must be efficiently converted by the turbo-alternator unit to an electrical output. Before discussing the interaction between the power conversion stages the principle of operation of the Wells turbine and its principal design variables will be briefly described.

The Wells turbine, shown in Figure 10 consists simply of a rotor with a hub carrying a number of radially disposed blades of symmetric aerofoil section, set at zero incidence angle to the plane of rotation. The turbine operates by the principle of a lifting aerofoil and thus has an operational speed range in which the angle of incidence of the airflow is sufficiently small to prevent stall. Raghunathan et al (9) has shown that the performance and self starting characteristics of the turbine are determined by the geometry of the rotor and the profile of the blades. A wide range of rotor configurations have been tested and computer programs have been developed to predict turbine performance.

The turbine is designed to provide the optimum level of damping to the water column to maximise the frequency bandwidth response associated with damping ratios of between 2 and 4 as shown in Figure 7 which determines

the pressure differential between the plenum chamber and the atmosphere and the air flow rate available to drive the turbine. The turbine in the Q.U.B. device is designed to maintain nearly constant velocity throughout the wave cycle and is consequently a linear damper in the time domain. From Figure 11, which shows turbine efficiency as a function of flow coefficient ( $\phi$ ), it can be seen that for constant turbine speed ( $U_t$ ) there is an optimum value of ( $\phi$ ) for peak cyclic efficiency. This optimum value of ( $\phi$ ) is maintained in the frequency domain if the load imposed by the alternator is regulated so as to achieve variable speed operation (as the sea states vary but not in each cycle). Consequently applied damping varies with wave frequency as it is proportional to turbine speed.

As applied damping increases with decreasing wave frequency, which is associated with greater wave power, increasing pressure drop, flow rate and turbine speed, the frequency bandwidth response of the water column is widened as shown in Figure 7. Increased damping also provides a larger resistance to the water column motion and limits peak velocities at the duct entrance minimising losses and reducing the probability of water ingestion through the turbine. It should also be noted that the high inertia of the system prevents a rapid response to the extreme levels of input in a random sea and as a consequence the power output is much smoother.

### 3.5 POWER STATION OUTPUT

As the turbine can vary speed to match the pneumatic input it can operate at a nearly constant efficiency of up to 80%. However, as losses occur in the bearings, alternator and transmission lines, a secondary power conversion efficiency of 67% has been assumed. On this basis each multi resonant device would have an installed capacity of 4.6 MW and 720 devices would be required to meet the 2 GW power output for 5% of the

year. This may appear to be oversized but when calculating the annual average power output of the station it is also necessary to consider a threshold power level below which the turbo-alternator set would not be activated. In the context of the Q.U.B. device the installation of 3 turbo-alternator sets on the large rear column introduces the possibility of shutting down one or more during the less energetic sea states. This form of load sharing does not incur the high manifold losses observed in other devices but still enables the machines to operate at high load factors.

#### 4. ENGINEERING DESIGN OF A WAVE POWER STATION

It is essential that the first generation wave power stations should be designed to be constructed and emplaced at sea using current technology in order to establish credibility and to provide a reliable basis for costing. Construction and installation methods will be influenced, mainly, by the number of devices required and the time allocated for the establishment and commissioning of a wave power station.

##### 4.1 STRUCTURAL DESIGN AND CONSTRUCTION

A detailed report of the design of the structure including construction, installation, maintenance and cost is contained in Appendix A.

Reinforced concrete was chosen for the structure because it is economical, is readily cast into complex geometric shapes, has a long life expectancy (minimum 50 years), and requires little maintenance, even in a marine environment. Preliminary analysis of the structure indicated low stress levels with the section thicknesses being determined by durability and handling considerations. The outer caisson wall was scalloped and counterforts and radial fin walls added internally to provide stiffness and to limit deflections.

A one in 50 year design wave with a height of 23 m was chosen as the design for the structure and foundations. Structural loadings were determined using a computer program which idealised the structure into cylindrical sections and took wave diffraction into account. Since the front face of the device is compliant due to the water columns, the calculated peak horizontal wave force and overturning moments were reduced by an attenuation factor of 10% to give values of 180 MN and 3150 MNm respectively.

The final shape of the device was determined not only by the optimum shape of the water columns but also from considerations of stability, during float-out, emplacement and operation. Construction is envisaged as a three stage operation with the logistics of producing 720 devices in a 7½ year period necessitating three construction yards. The 56 m diameter base unit will be constructed ashore in a casting bay and when complete, launched using a ship lift. The 30 m diameter cylindrical superstructure will be constructed at a wet berth alongside a jetty, with a minimum of 14 m water depth. Temporary steel closures will be placed over the water column entrances to ensure floatation and the mechanical-electrical plant ancillaries will be installed prior to the device being towed to temporary storage.

The foundations are designed to both locate and support the device while accommodating the geology and topography of the sea bed at South Uist. In its final state the device is a "gravity structure"; therefore foundations are never subjected to uplift force. 4.6 m diameter concrete plinths set in predrilled holes approximately 5 m deep, each with a projecting steel core to provide a shear key, will be installed; six equally-spaced around the periphery of the base structure and one located at the centre. Sea bed preparation is minimal but may require the removal of local high spots, on the sea bed, using explosives. Foundation

installation represents the most difficult element in the whole construction sequence and requires the only specialist vessel used; a jack up platform with three drilling rigs to provide all seven foundation plinths from one station. Final tow and installation of the devices will require a cycle of five days. On site each plinth will be marked by a buoy supporting a heavy steel connecting cable which will be attached to winches on board each device. These in conjunction with the tugs will locate the structure during the sinking operation. Finally the temporary closures will be removed, the shear connectors grouted and the base structure filled with gravel ballast to complete the installation. It is envisaged that 2 m is the maximum significant wave height in which this operation could be undertaken.

#### 4.2 DESIGN OF THE TURBO-ALTERNATOR UNITS

A detailed report on the design analysis of the turbine including construction, maintenance and costs and a design summary of the alternator including costs are contained in Appendix B.

The turbo-alternator units are the only mechanical components in the power conversion cycle and in terms of machine size, speed, configuration and working fluid are similar to industrial fans. Construction technology, therefore is well established. A six blade Wells turbine with an overall diameter of 2.65 m and an operational speed range up to 1000 r.p.m. provides the level of applied damping necessary to optimise the hydrodynamic performance of the water columns. The rotor will be coupled to a 800 kW alternator with an automatic voltage regulator and will operate at constant current. The main rotor bearings, alternator and drive shaft will be mounted horizontally in a pod located in the cylindrical duct which houses the rotor as shown in Figure 12.

The oil lubricated bearings are designed to accommodate the rotational speeds, sustain the cyclically reversing axial thrust and have an expected 100,000 hour life. As the remaining mechanical electrical plant is designed for 25 years of operation the bearings will be replaced once in this period. Annual maintenance will be required to generally inspect, clean, lubricate and replace damaged surface coatings. It is envisaged that the entire mechanical plant will be replaced after 25 years.

#### 4.3 ELECTRICAL TRANSMISSION

In the preferred transmission scheme proposed by McIlhagger (10) it is envisaged that the station would be sub-divided into groups of devices with their alternators connected in series. As the power source is intermittent and the rotor speed variable, the alternator output is inverted and the D.C. output transmitted to shore via submarine cables. After reinversion to A.C. at the frequency of the grid system the power can be supplied to the consumer in the normal manner.

A summary of the transmission scheme, including component costings and a schematic layout diagram is included in Appendix C.

#### 5. COST OF WAVEPOWER

Figure 13 shows the breakdown of the total cost of energy produced expressed as pence/kW hr. To obtain these figures, the annual average power output from the station has been calculated as 5.22 TW hr. and an allowance has been made for an average loss of generating capacity of 5% due to maintenance or breakdown. The cost of the station which includes the construction facility and the cost of electrical transmission has been discounted at 5% over a period of 25 years. When the maintenance is

included the total average cost of energy during the first 25 year period, when the capital is being repaid, is 8p/kW hr. This cost is for South Uist where the foundation conditions are extremely difficult. It is envisaged that a device located on a flatter sea bed with softer rock could produce energy at less than 6p/kW hr.; the primary savings being in the foundations and the base of the structure. If, after 25 years the entire mechanical electrical plant is replaced and maintenance is continued, energy will cost as little as 1.3p/kW hr. for the remaining design life of the structure.

The economics of sea bed mounted reinforced concrete O.W.C. devices are, therefore, very similar to those of hydroelectric stations. In much the same way as hydroelectric power was developed earlier this century, wave power is an investment for the future and should have a value to society which is greater than simply the cost of fossil fuel it has saved during the life of the station.

In addition the Q.U.B. device provides the ideal opportunity to combine wind and wave power as its cylindrical structure provides a compact base on which a large offshore wind generator could be mounted. With a dual purpose installation of this type the initial energy costs would be consequently reduced significantly.

Although only the large scale generation of electrical power has been considered in the context of this report, the technology is applicable to a wide range of device sizes including 100 W units for navigation buoys and 100 kW to 1 MW units for offshore island communities. The electrical output does not necessarily need to be frequency controlled to suit national grids but could be used for either offshore or coastal based industrial processes in its raw state.

## 5.1 COST COMPARISON BETWEEN AXI-SYMMETRIC AND TWO-FREQUENCY DEVICES

The conceptual change from the six-cell axi-symmetric device to the current two-frequency device has produced a saving in the cost of energy of about 1.3p/kW hr. (based on the previous figure of 9.3p/kW hr.). An examination of the relative cost elements of both devices reveals that the cost of the structure, mechanical and electric plant and annual maintenance are similar and that variations occur in the cost of the construction facilities, installation and transmission.

The parity in structural costs is understandable since the basic total quantities remain similar. The turbine was redesigned as a single-stage larger machine resulting in an increased unit cost. Although the total number of turbo-alternator units has been reduced from 9000 to 4320 the installed capacity has been increased. Consequently the overall total cost for the scheme was only slightly greater than for the axi-symmetric device even with the additional capacity. Maintenance costs virtually doubled for each device, because the re-design of the turbo-alternator unit resulted in a shorter bearing life, but the overall effect remained the same.

The variations for the other cost elements need to be considered in more detail.

### a) Construction Facility

Construction facility costs have increased by about 200% thus representing a cost element of 1.04p/kW hr. Although the number of required devices has been reduced from 1500 (six-celled device) to 720 the weight of each device has been significantly increased from 10800 t to 25000 t. Consequently each construction site must be provided with two-stage construction facilities comprising dry casting and wet berths adjacent to jetties. Larger ship-lifts are also necessary.

Logistics determine that three sites are now required whereas previously two would have been sufficient.

The additional facilities required for each site together with the increase in the number of sites account, therefore, for the increase in the overall cost. The cost element for the construction facility now represents 12.9% of the total cost (compared with 3.7% for the axi-symmetric Reference Design).

b) Installation

The cost of installation, including the provision of foundations and device emplacement, has been reduced by nearly 60%. It has been established that the dominant factor affecting installation costs is the purchase cost of the drilling platform and associated equipment. The large reduction in the number of devices has accordingly reduced the number of platforms required thus effecting a considerable saving. Since the device is now a gravity-type structure a secondary saving has also been achieved by the requirement to provide foundation plinths instead of tension piles as previously envisaged.

It is very significant that the installation cost element, at 1.67p/kW hr., now represents only 20.7% of the total cost (compared with 42.3% for the axi-symmetric device).

c) Transmission

Transmission costs show an apparent increase of 26%. This is a consequence of:

- (i) an increase in installed capacity from the previous 2700 MW to 3400 MW, each alternator now having a 800 kW rating.

- (ii) the inclusion, in this cost analysis, of additional transmission costs from Skye to Craighroyston, amounting to £103.75 M. The cost analysis for the axi-symmetric Reference Design made use of transmission costs as included in the Consultants' computer cost model which only considered transmission to Skye.

Accordingly, transmission at 1.15p/kW hr. now accounts for 14.3% of the total cost (compared with 9.8% for the axi-symmetric device). If however, the additional Skye - Craighroyston costs are not included here the transmission costs reduce to 0.97p/kW hr. which represents an increase of only 6.5%.

Consequently, the cost of power would drop from 8.06p/kW hr. to 7.88p/kW hr. (compared with 9.3p/kW hr. previously).

## 6. CONCLUSIONS

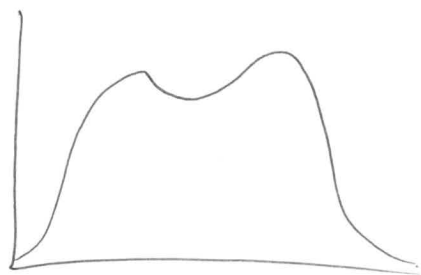
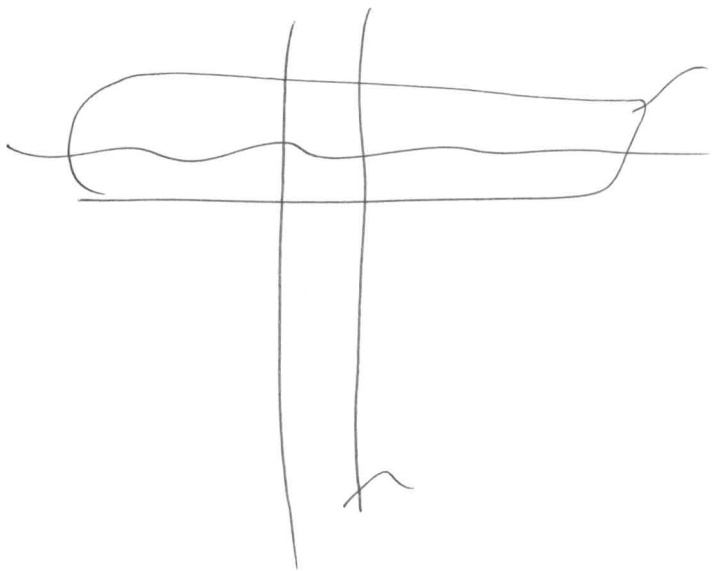
As a result of this research and engineering design it has been concluded that:

1. The Multi Resonant O.W.C. device can efficiently extract power from a wave spectrum with a wide frequency distribution and a high degree of spreading. The concept provides an economic alternative to 'Phase Latching' systems and non-resonant devices.
2. A Wells turbine coupled to an alternator can be designed with damping characteristics to match those of the hydropneumatic power conversion stage. Simplicity and high cyclic efficiency makes the Wells turbine the ideal secondary power conversion system for all hydropneumatic devices.
3. With the computer software developed, it is possible to predict the performance of oscillating water column devices with a wide range of duct geometrics operating in seas of various spectral forms.
4. Since the Q.U.B. device can be constructed using established technology the costings are realistic and power could be produced for 6 to 8p/kW hr. during the initial 25 year capital pay pack period depending on the sea bed conditions.
5. The reliability and long life of the structure enables the production of energy for as little as 1.3p/kW hr. for the remaining life of the structure even with the complete mechanical plant replacement after the initial 25 years.

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FIGURES



Wells Turbine  
Generator

J tube  
Water  
Columns

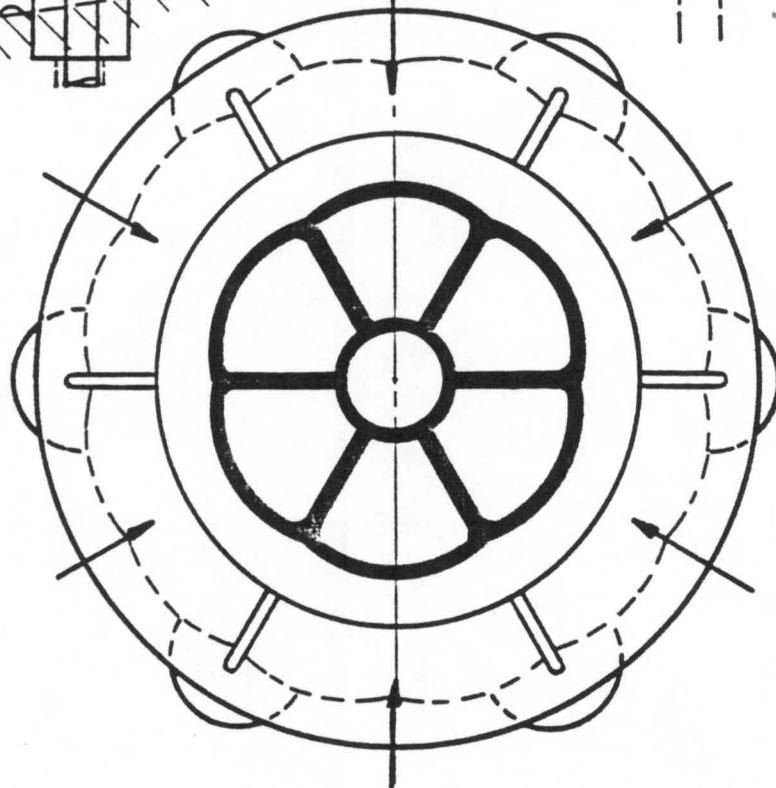
22m dia  
Super -  
Structure

150°

Base  
Caisson

Ballast

Tension  
Piles



Waterline Plan

Fig. 1. Axi - Symmetric Device.

Wells Turbine  
Generators

Upper and  
Lower  
Columns

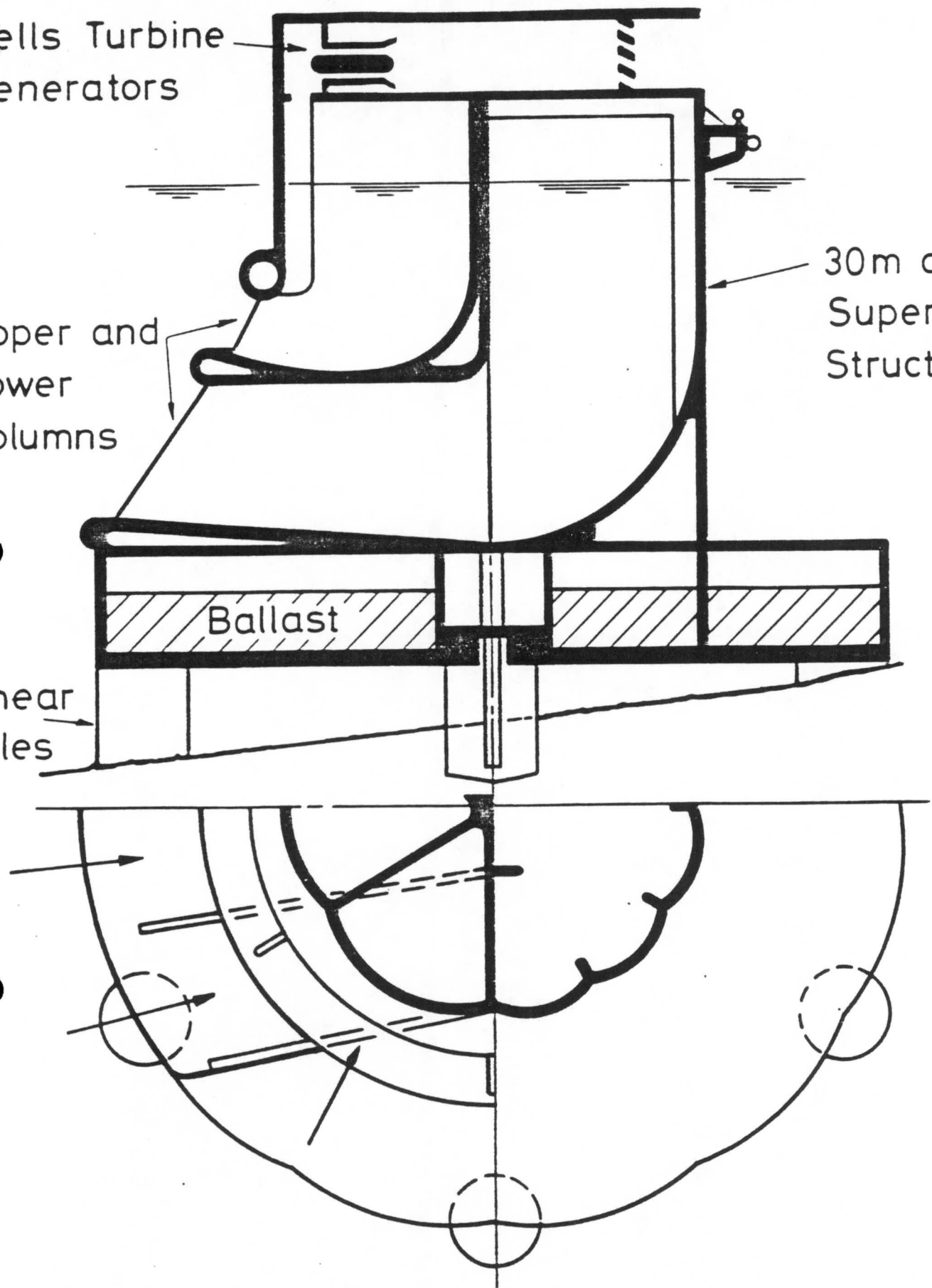
30m dia  
Super -  
Structure

Ballast

Shear  
Piles

1/2 Waterline Plan

Fig. 2. Two Frequency Device.



# Economic Equation

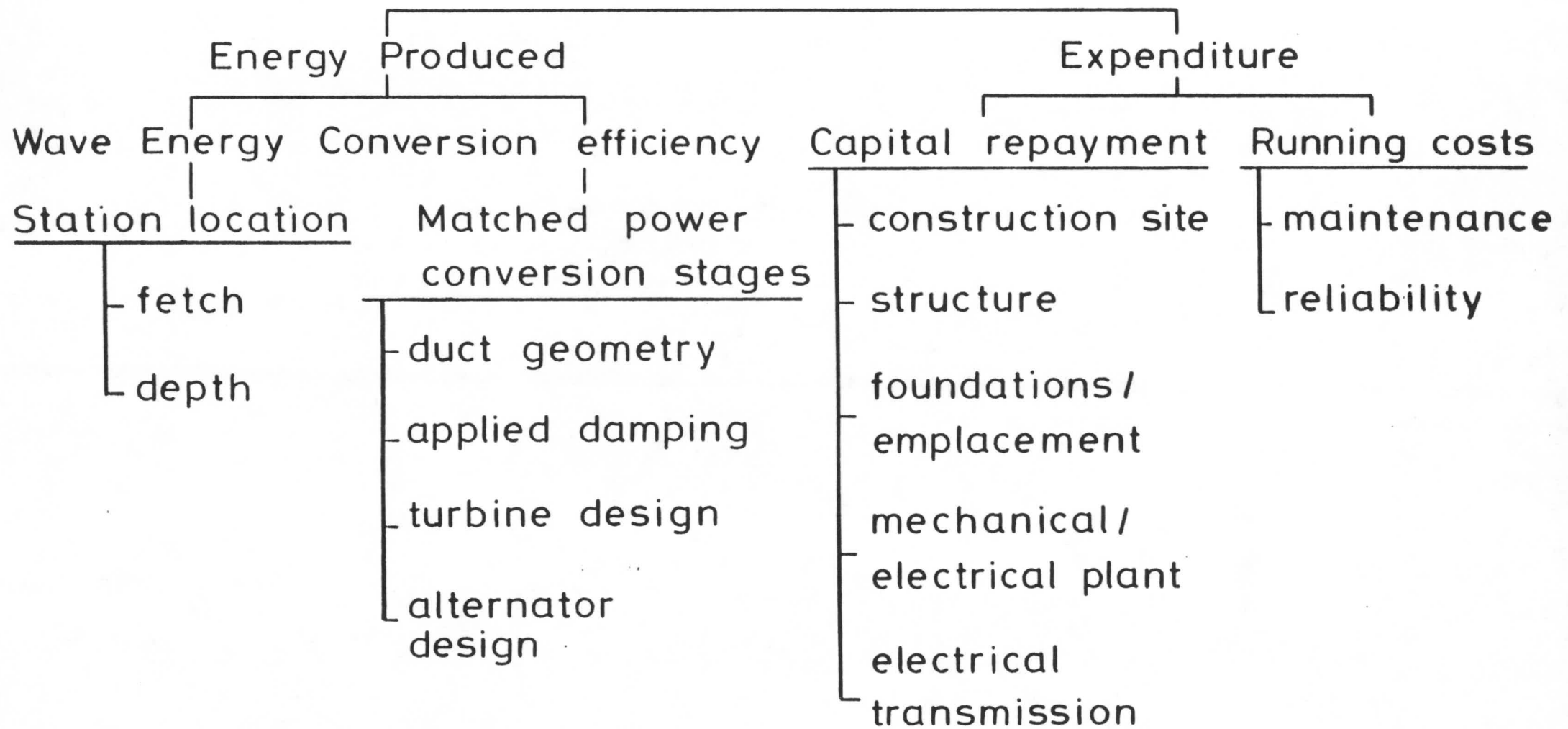


Fig. 3. Parameters Governing the Cost of Wave Energy.

Wave Force  $\propto kd \times e^{-\frac{2\pi\bar{h}}{\lambda}}$

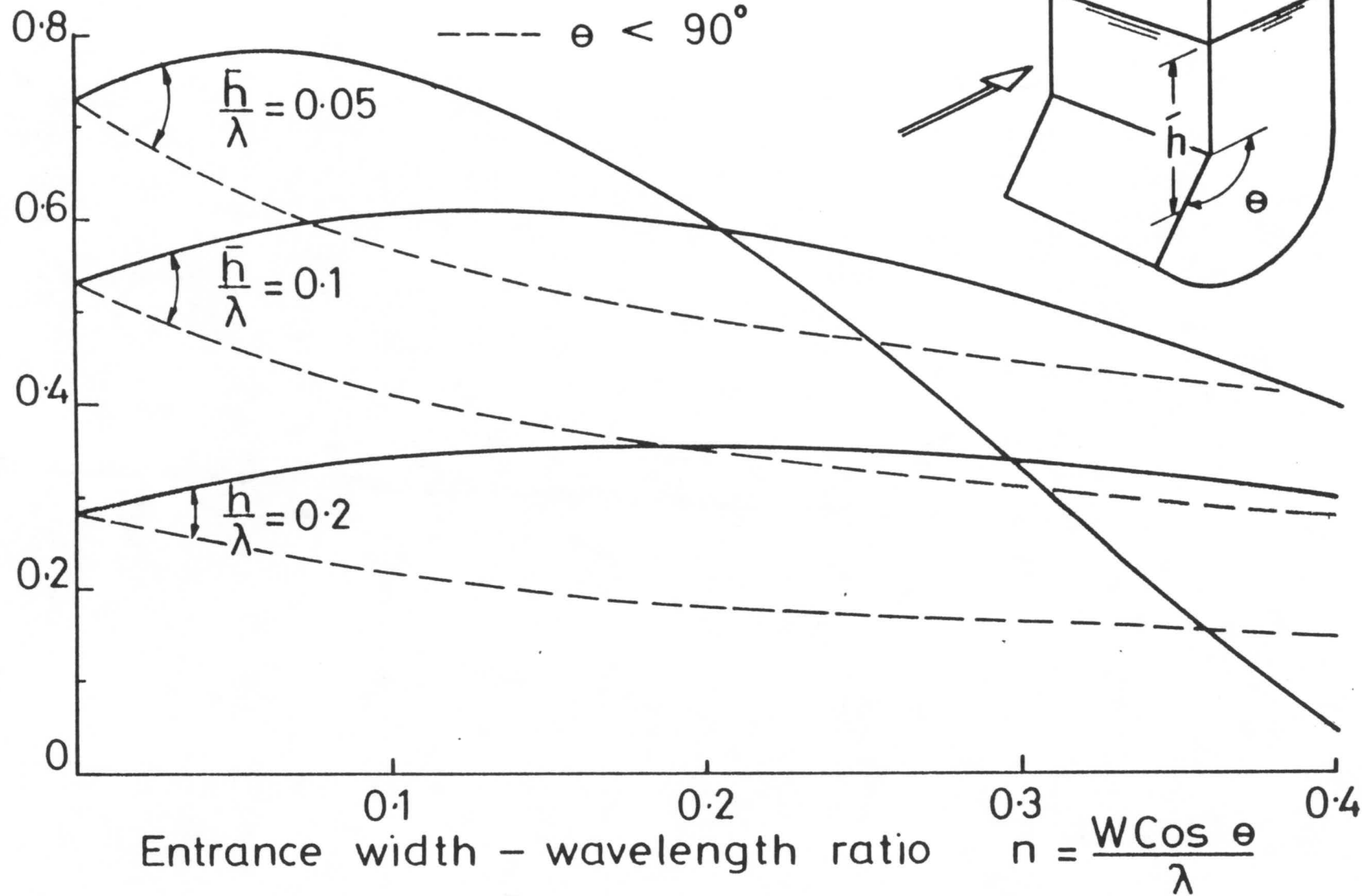


Fig. 4. Wave Force Duct Geometry Relationship.

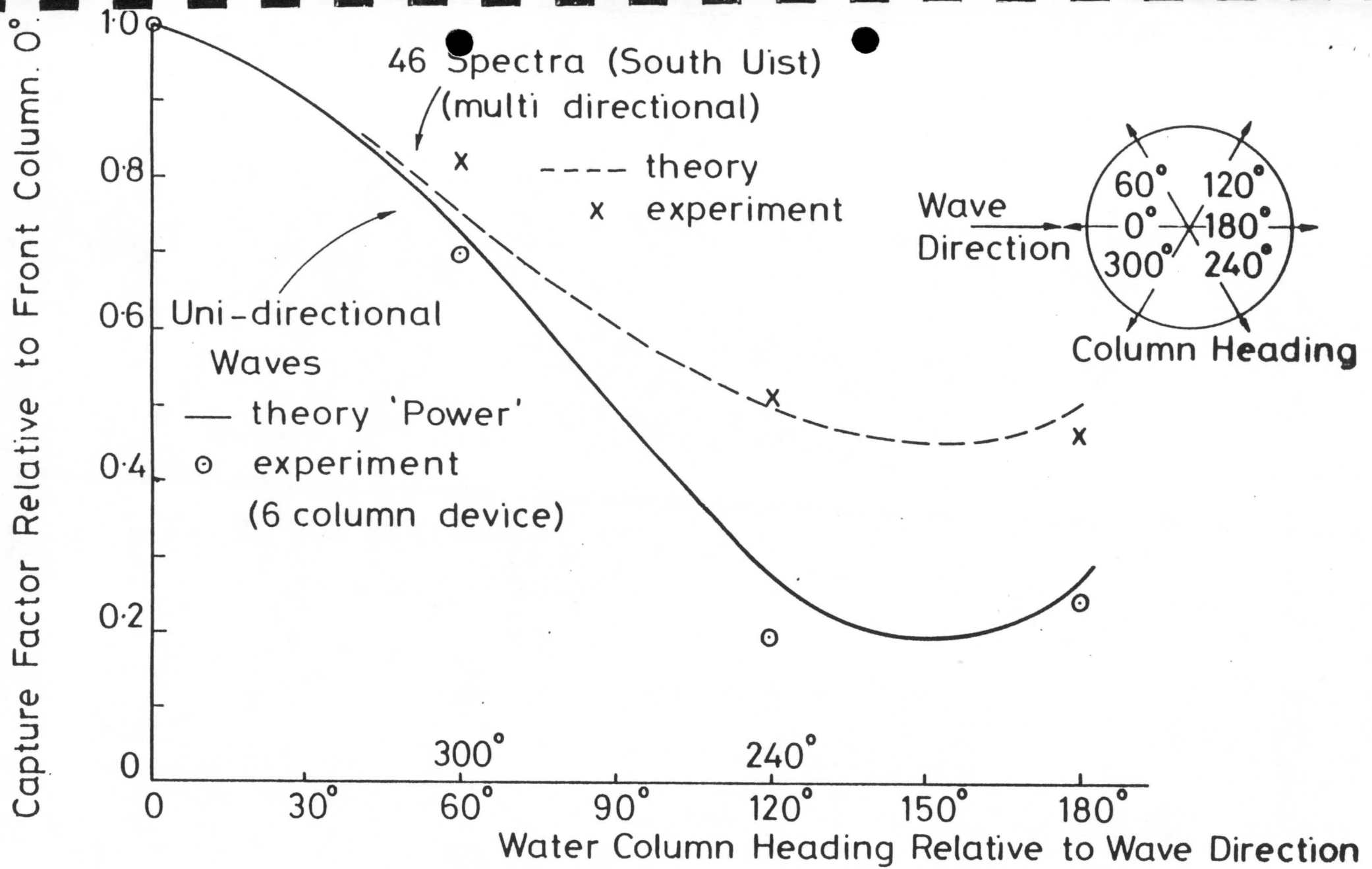


Fig.5. Relative Water Column Performance of Axi-Symmetric Device.

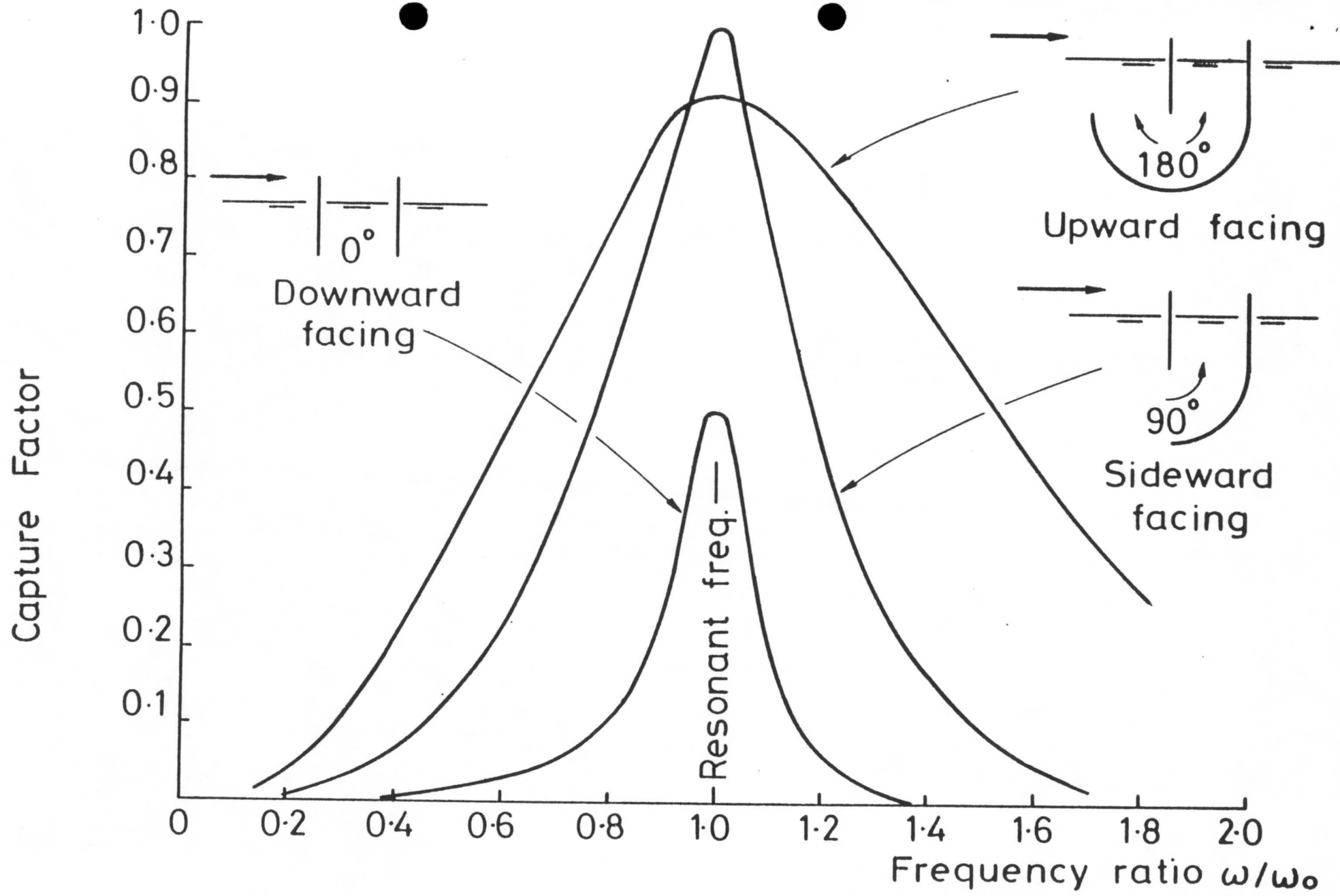


Fig. 6. Duct Entrance Angle / Frequency Bandwidth Response.

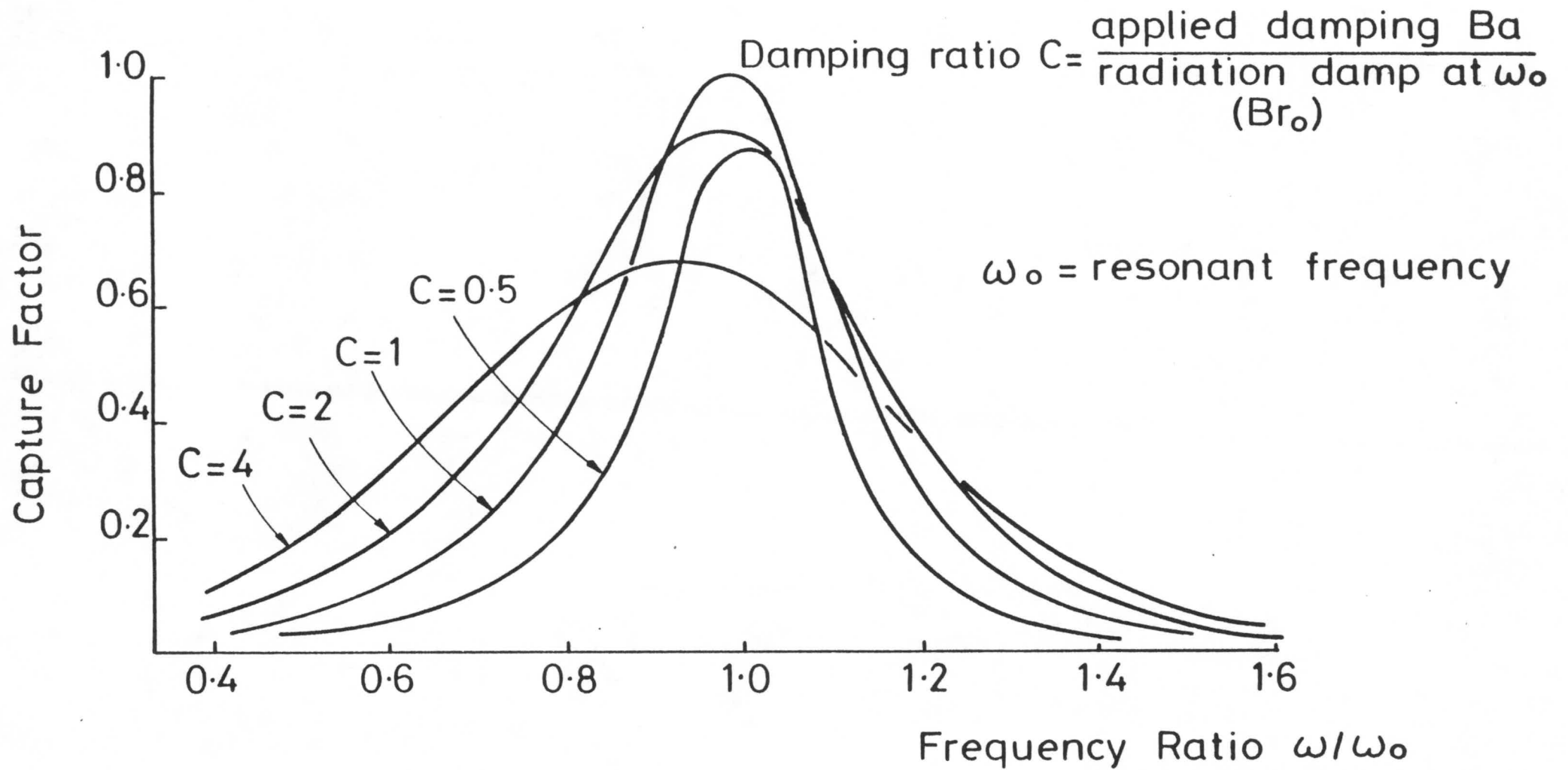


Fig. 7. Frequency Bandwidth Response (Variable Damping Ratio)

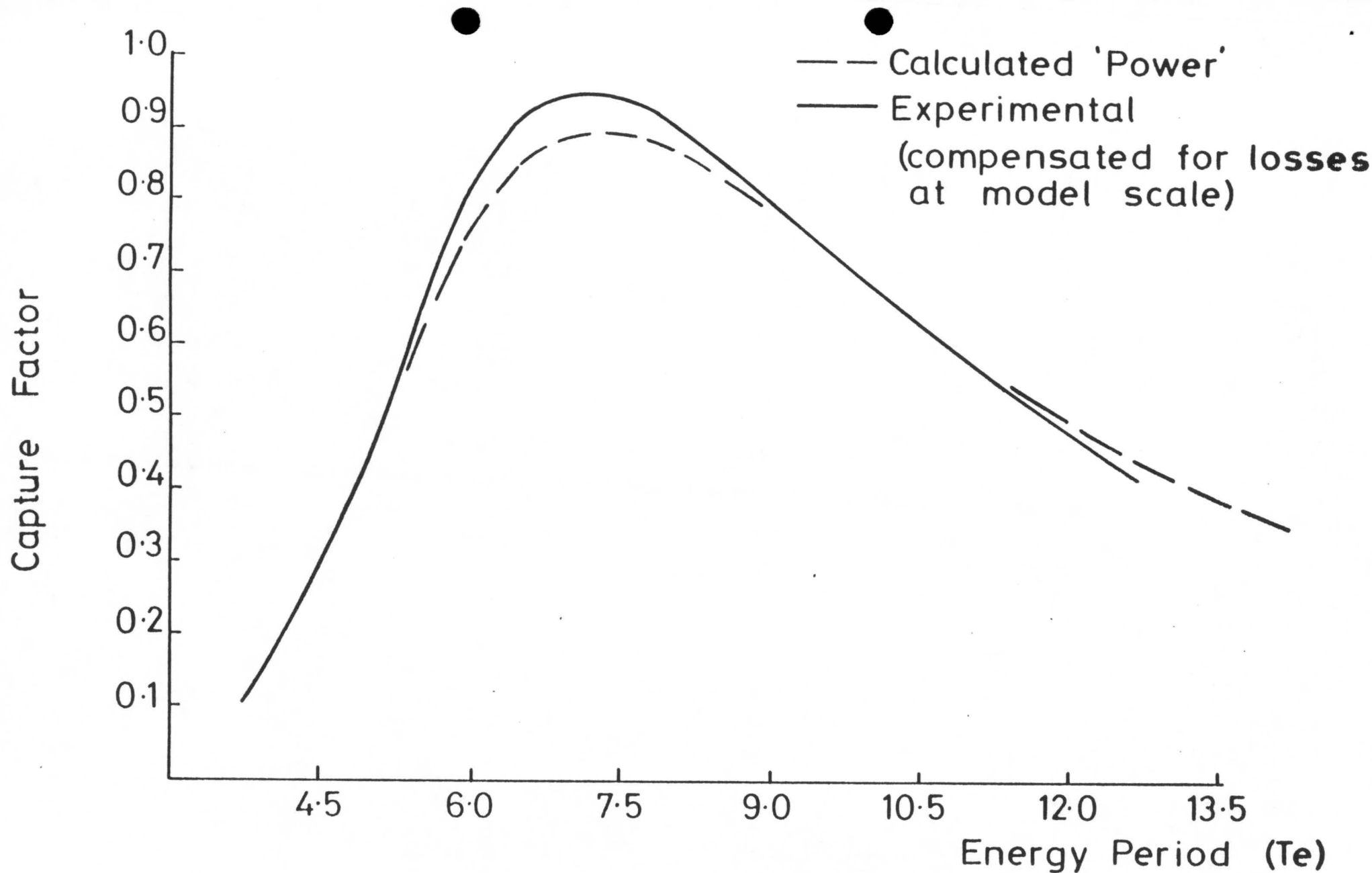


Fig. 8 Performance of 6 Column Axis - Symmetric Device.

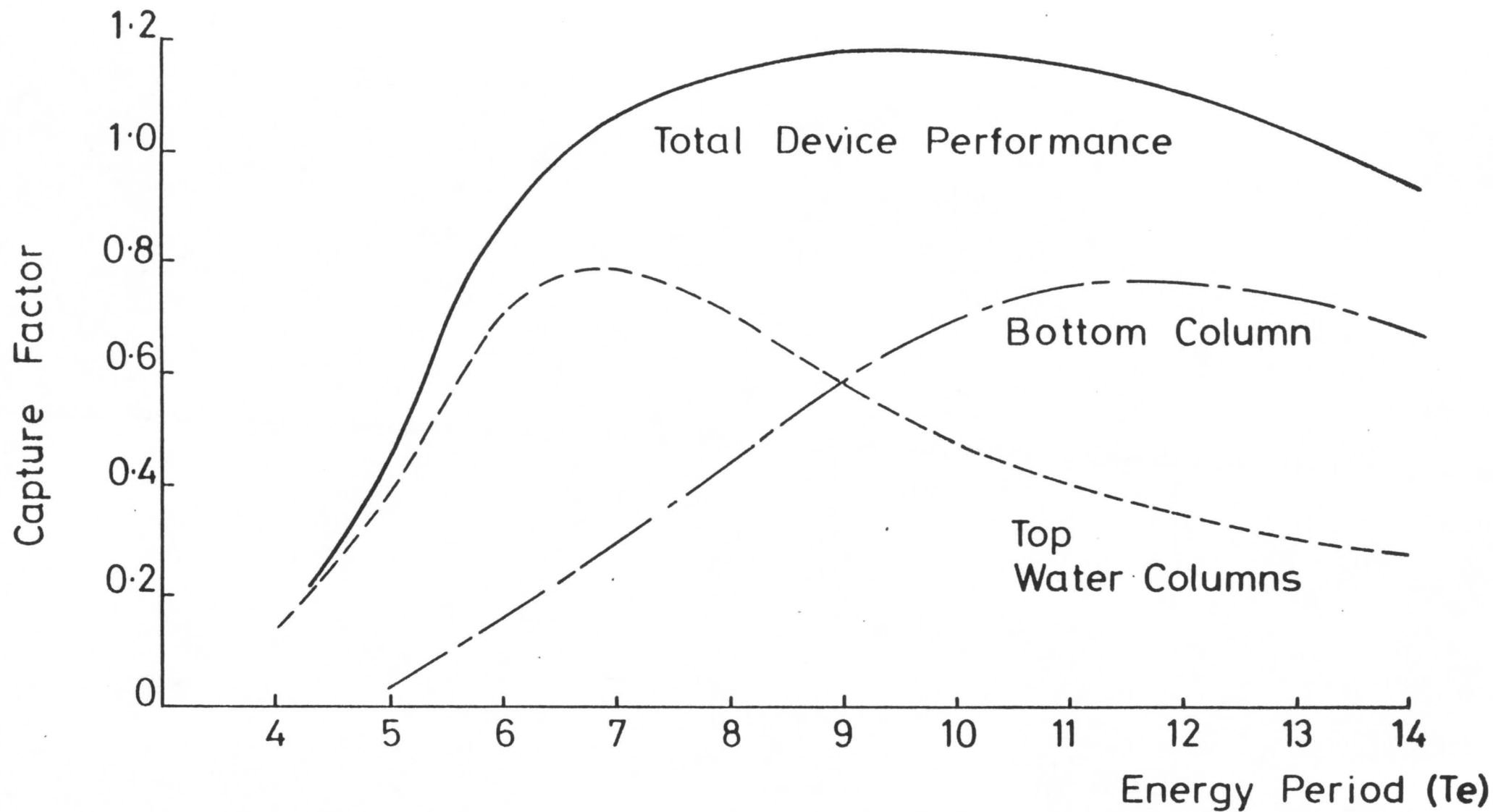


Fig.9. Performance of Two Frequency Device.

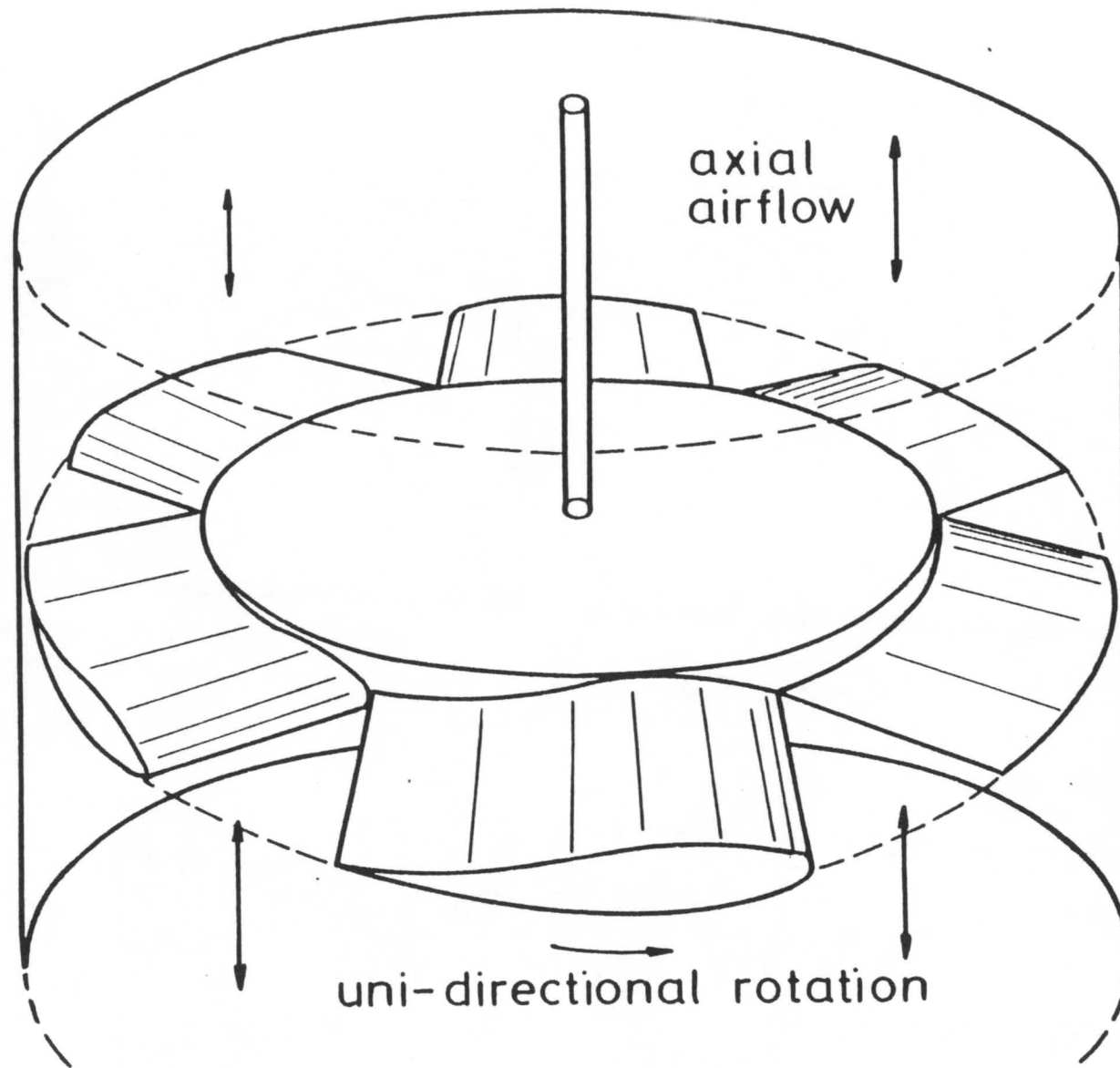


Fig. 10. The Wells Turbine.

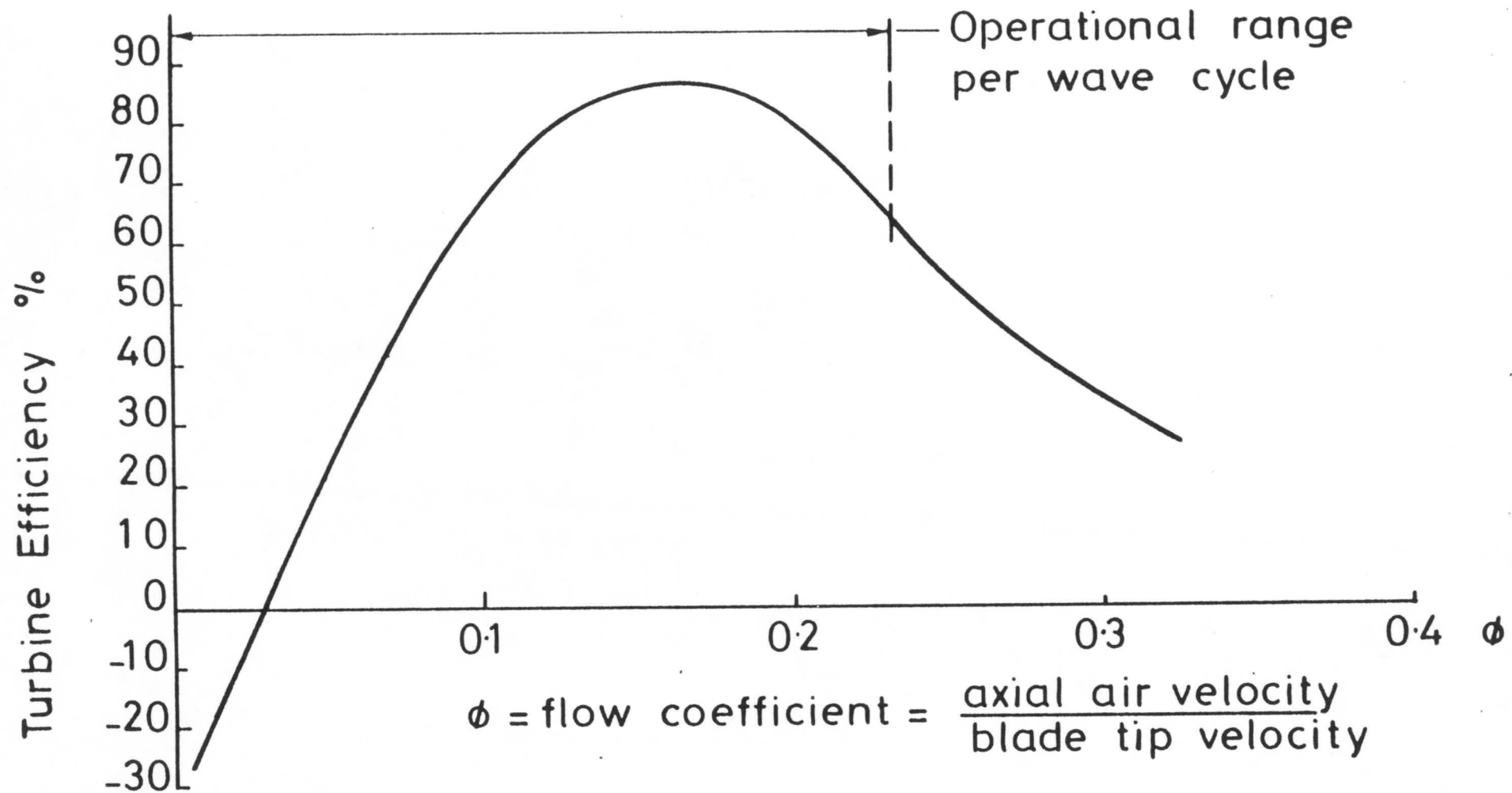


Fig. 11. Wells Turbine Efficiency.

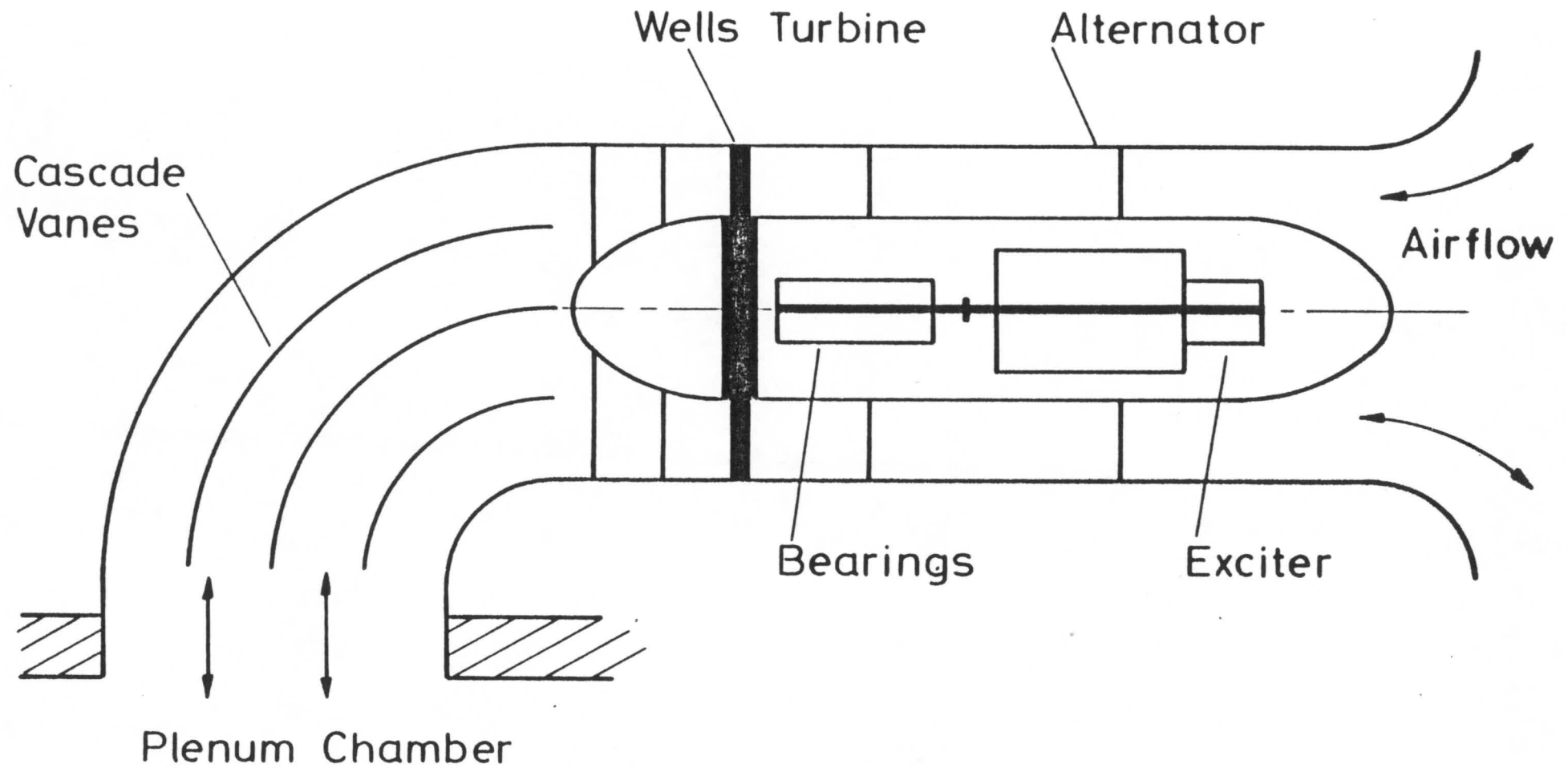


Fig. 12. Wells Turbine - Generator Module.

Cost per Unit of Energy Produced  
pence / kWhr.

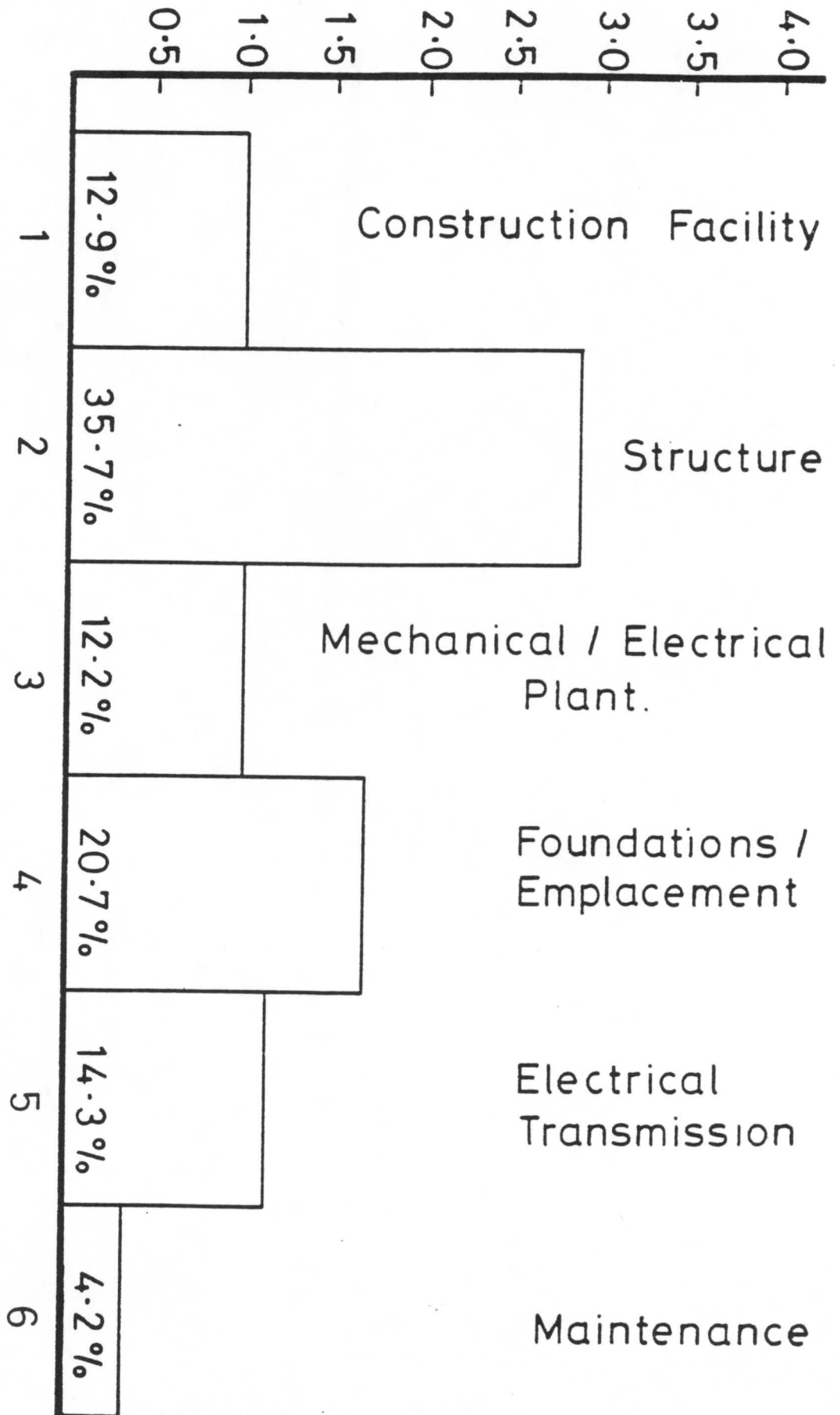


Fig. 13. Cost Distribution for 2GW. Wave Power Station.

APPENDIX A