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DEPARTMENT OF ENERGY

WAVE ENERGY STEERING COMMITTEE

UNITED KINGDOM WAVE ENERGY PROGRAMME

CONSULTANTS INTERIM REPORT

N.E.L. OSCILLATING WATER COLUMN (Bottom Standing Device)

NOVEMBER 1979

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The cover illustration is a computer simulation of a Random Sea - Pierson-Moskowitz Spectrum with $\cos^4 \theta$ spreading function

WAVE ENERGY

CONSULTANTS' INTERIM REPORT 1979

NEL - OWC

BREAKWATER TYPE DEVICE

22nd November 1979

Draft Versions of the Consultant's 1979 Interim Reports

Notwithstanding that the Device Teams were working to the same reporting date as the Consultants, it was hoped that satisfactory final Consultant's reports agreed to by the Device Teams could be produced for 1 December 1979. In the event, the Consultants are still receiving a continuing flow of reports and new information, and there is no possibility that the reports now being submitted to W.E.S.C. can be final presentations of the positions of devices and Device Teams at 30 November. In particular information relating to costing for some devices has only been made available in the second half of November, and the assimilation and reporting on this is having to be done in less time than is properly required. The reports are therefore submitted as drafts with the intention that continuing discussion should lead to final versions early in 1980.

E.T.S.U. will be informed immediately of any significant changes of content or emphasis that may have a bearing on programme related recommendations due to be made by E.T.S.U. and W.E.S.C.

30 November 1979

N.E.L. BOTTOM STANDING DEVICE

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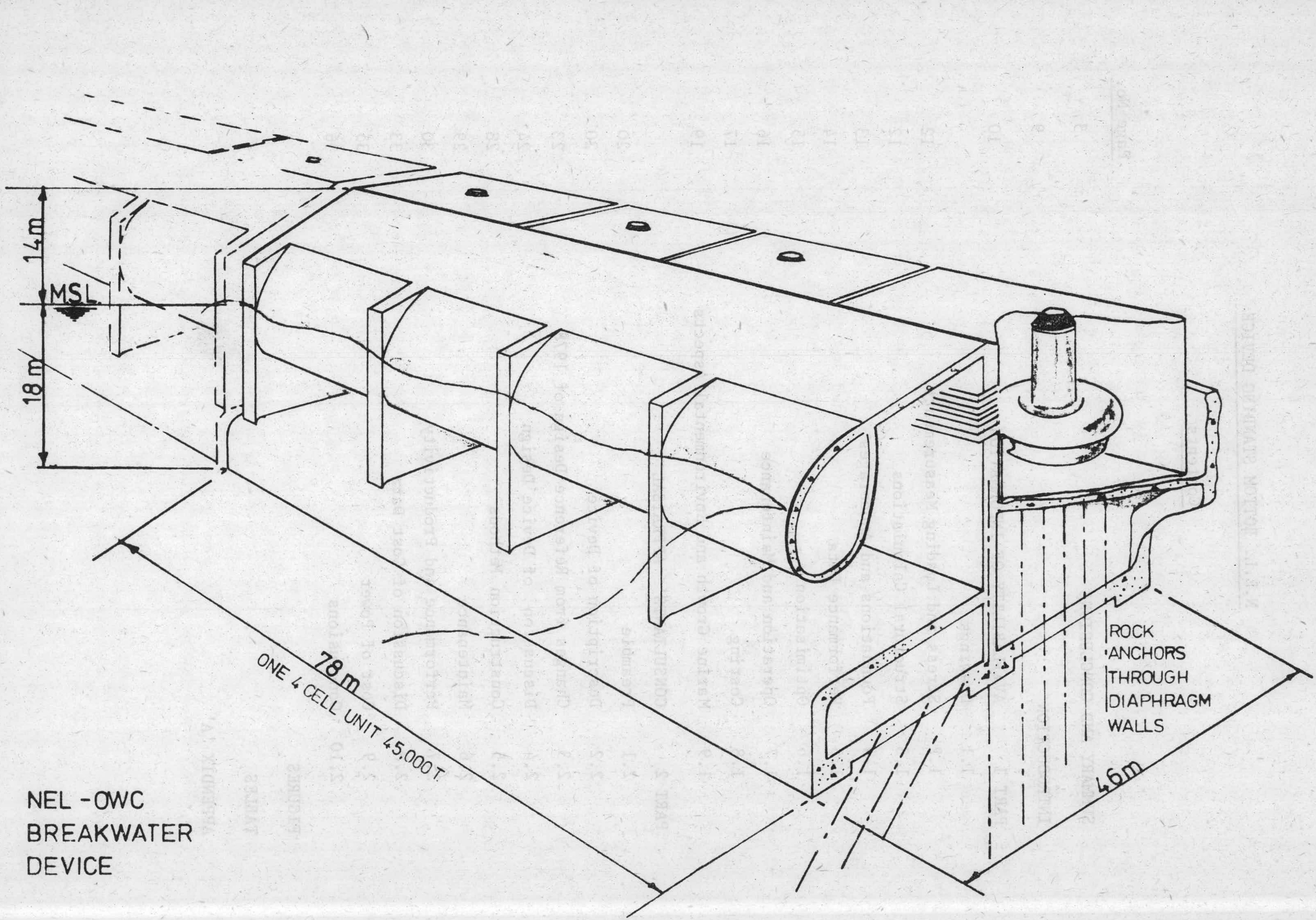


NEL -OWC
BREAKWATER
DEVICE

SUMMARY AND CONCLUSIONS

Direction of activity during 1979

At the end of 1978 the N.E.L. oscillating water column was identified as a device with the virtues of a simple monolithic structure, a good power take-off, reliability and reliance wholly on current technology. It was, however, a large structure with an inertial reference frame attracting high mooring forces and expensive to build. Activity during 1979 to improve the device followed three directions.

a) Alternative O.W.C.configurations were tested in the wide tank including a model Kaimei device and an N.E.L. attenuator. Results on the attenuator encouraged the Device Team to favour the long attenuator as an alternative configuration worthy of further study.

b) A sensitivity study was carried out on the 1978 Reference Design to identify the main cost centres. Moorings and plant were found to offer the most potential for cost reduction.

c) A breakwater type structure was designed and tank tested. This use of the seabed as a reference frame appears to give more economic power than the 1978 Reference Design. However, a report by the Consultants on sites for bottom standing devices confirmed that the available inshore sites to exploit the resource are limited.

Very recently tests using a new system of active valve control on the O.W.C. have been shown to promise large improvements. This is of greater relevance to the floating O.W.C. than to the fixed O.W.C.

Developments over the year

The Device Team recognised the high cost of power from the 1978 Reference Design and although improvements in the electrical conversion gave some benefit to the device, the Team decided to concentrate its efforts on the testing of alternative configurations and on breakwater type structures.

The Team worked to develop a reference design for a bottom standing device in 15m to 20m of water. Essentially this uses the power 'cell' and power offtake of the floating device, mounted on the front of a gravity caisson rock bolted to the sea bed. Economy is achieved by removing the inertial reference frame and taking advantage of the broad band efficiency resulting from the fixed reference frame.

The resulting device shows a reduction in the quantity of structural concrete per linear metre of device, compared to the 1978 floating design of some 5% on top of which there will be the saving of the concrete ballast.

This fixed bottom device is still considered to be at an early stage of development.

A recent experiment by the Device Team successfully demonstrated that a system of active valve control could increase the amount of energy extracted by an oscillating water column device. This will be of more relevance to the floating than to the fixed O.W.C. Nothing of this work has yet been passed into the device design.

Work on devising a method of placing these caissons is still at a very early stage.

Device Team Costing

The Device Team has costed the fixed bottom device primarily by using established rates and inhouse costing experience together with the cost from the Consultants' 1978 Report as a yardstick. The Team considered that their breakwater design was not yet developed sufficiently to warrant approaching a Contractor for independent costing and have chosen to ignore any possible benefits of extensive mass production at this time.

There is considerable uncertainty regarding the available power in the sea at the depth considered, so that the power output side of the cost equation is correspondingly uncertain.

In line with the Consultants' approach in the 1978 Report on costing, the Device Team is quoting a range of costs.

The Team's predicted cost is 10-20 pence/kwh. Their predicted total contribution to the grid from the west and north of Scotland is 3-4 GW mean annual. This prediction was made on the basis of 29 kW/m being available over the whole length of coastline where these devices could be installed. On the same basis, but corrected to a figure for available power of 17 kW/m and allowing for the increased productivity factors derived by the Consultants, these figures become:

Cost of power = 14 - 28 p/kW h.

Predicted total power = 2 - 3 GW mean annual

The above figures have been based upon the Device Team's range of device costs and a range of results for mean annual power. The Consultants have derived figures for the cost of power of 17 - 22 p/kWh based upon the Device Team's range costings but only using the mean value of the power.

Reasons for the changed costs of the breakwater structure compared to the floating structure.

The breakwater device is so different from the 1978 floating O.W.C. that only the most general comparisons can be made.

1. The inertial reference frame of the floating device was large to meet hydrodynamic requirements. It required to be buoyant, so that its walls were resisting a hydrostatic pressure head of up to 35 m of water. Its final draught (25m) required expensive two-stage construction, with the first stage in a deep dry dock and the second after launching.

The current design of the fixed bottom device still requires two-stage construction and, although optimisation of the structure size is in hand, has not at this stage significantly reduced the volume of structural concrete. The present design incorporates a large gravity caisson to provide stability during construction and towing to site.

During installation temporary stability is provided by an emplacement barge until permanent stability is provided by ballast in the caisson and rock anchors.

2. Very expensive moorings are eliminated and separation is minimised such that there are virtually no gaps between units.

3. Maintenance and transmission to shore are both simplified by the fixed inshore location.

4. The broad band efficiency of the fixed device leads to improved efficiency for a given size.

5. The benefits of a cheaper structure have to be offset against the greatly reduced power at the inshore location (17 kW/m is the latest TAG 2 estimate).

Utilisation of Natural Resource

Based upon the Consultants' (and Device Team's where applicable) productivity calculations, the number of devices required to deliver 0.5 GW mean annual power to the grid is 1115.

Excluding any allownace for special gaps between devices to permit the passage of shipping,(the devices are otherwise contiguous) the length of coastline required to deploy this number of devices is 90 Km.

Rated power is a less satisfactory criterion since it is a measure of plant installed and not of power delivered. At present rated power, the number of devices required for a power station of 2 GW rated capacity is 1382. This would utilize 113 Km. of coastline.

It should be noted that the above figures relate to a station centred on South Uist and that they would not necessarily apply to a station sited elsewhere.

Conclusions

1. The breakwater alternative was conceived as a potentially more cost effective version of the O.W.C. Its attractiveness has been significantly eroded however by two factors anticipated last year but proving to be possibly rather more adverse than expected these are:

The available power in the sea in 15 m depth is estimated to be 17 kW/m compared with 47.5 kW/m for floating devices in deeper water.

The estimated net length of sites available off the West and North costs of Scotland with 15 m depth of water is only 230 km.

The device can thus never make a significant contribution to the power needs of the UK.

2. Justification for the device does not at present appear to lie in its cheapness compared to other devices, although the current scheme might well be redesigned to a lower cost. The current design incorporates a large gravity caisson which is not fundamental to the design concept. We do not yet know where the cost floor is.

3. The device could be built tomorrow and could be an intermediate step to a floating O.W.C. The operation of placing of caissons to the present design could prove so expensive as to make this intermediate step option unattractive, but this position can probably be very much improved in a redesign which the Device Team intend to carry out.

4. The environmental impact of a breakwater would be more significant than for devices further offshore. Air noise would need to be investigated. Visually, the device protrudes up to 14 m above sea level.

INTRODUCTION

Last year, due to the lack of time for many of the Device Teams to advance their work to an adequate stage, it was necessary for the Consultants themselves to generate much of the information required for their report. The basic work included the development of reference designs from information supplied by the Teams to a degree of detail sufficient for quantities to be taken off and for productivity to be assessed and the cost of power to be calculated.

This year the Device Teams are responsible for the reference designs, with the Consultants commenting upon the schemes and the data presented.

The stage of development reached by the various Device Teams differs widely due to the varying starting dates and resources. In addition, the philosophy adopted by the Device Teams in their approach to presentation leads to differing emphases or degrees of optimism when considering the data available to them. The Consultants feel that it is an important part of their task to comment on devices from a common standpoint and in particular to differentiate between facts established by the Teams and the ideas and hypotheses which they introduce to complete their presentation.

In view of this, it was considered essential to establish the scope and degree of development of the various key aspects related to each device.

The first section of this report sets out to present the full range of information available to the Consultants, together with its status as judged by its suitability and degree of completeness for incorporation in the development of a reference design which can be assessed and costed.

The second part of this report contains the Consultants' appraisal of the information, discussed under the most significant headings.

In order to avoid contention, this report in draft form has been discussed with the Device Team. There is no disagreement as regards the extent and status of the information made available to the Consultants and, except where specifically noted, the Consultants' appraisal has been generally accepted.

NOTE: THIS REPORT IS TO BE READ IN CONJUNCTION WITH THE DEVICE TEAM'S REPORTS. THE CONSULTANTS HAVE NOT REPRODUCED THE DEVICE TEAM'S DRAWINGS IN THIS REPORT.

PART 1 AVAILABILITY OF INFORMATION

1.1 Drawings

The drawings prepared by the Device Team are in various stages of development and the table overleaf indicates the status of the drawings received. It relates to the major elements of the device.

The drawings have been categorised in accordance with the following definitions.

Preliminary Sketches

Devices which are at an early stage of development may only be at the stage where small-scale rudimentary sketches are practicable due to the fact that ideas are rapidly changing and sizes are not finally determined.

Conceptual Drawings

Drawings indicating in broad outline the Device Team's proposals for the device as a whole or for specific elements, features, plant, fittings, systems, etc., where the Team has not yet developed its ideas to the extent that the subject can be costed in a conventional way.

Outline Drawings

Drawings of a general or specific nature not fully documented or detailed but providing adequate information to enable costs to be assessed with a reasonable degree of reliability.

1.1.1 Subjects covered by Drawings

Subject or Title	Preliminary Sketches	Conceptual	Outline
General Layout of Breakwater Type O.W.C. Device indicating:-			
1. General Arrangement of Device;	Yes		
2. Foundations and sea bed preparation;	Yes		
3. Power Take Off:			
a) Rectifying Valves (As Floating Device)		Yes	
b) General Arrangement of Plant	Yes		
c) Details of plant (As Floating Device)		Yes	
4. Method of Construction	Yes		

1.1.2 Subjects not covered by Drawings

Method of Installation*

Details of Rock Anchors≠

Structural Details

* Various methods of installation are discussed in an Interim Report by a specialist commissioned by the Device Team.

≠ Rock Anchors are discussed in an Interim Report by a specialist commissioned by the Device Team.

1.2 Stress and Loading Measurements

Since last year the Device Team has carried out some model tests in a narrow tank on a 1/175 scale model of the breakwater type structure. The purpose of the tests was to assess the overall forces on the structure. The results of these tests were forwarded to the Consultants for information.

Part of Element of Structure	Load measurements available	Stress measurement
One cell of bottom mounted O.W.C. device (¼ of one device unit)	Vertical heave force and the horizontal surge force as a function of wave amplitude and period	NIL

1.3 Structural Calculations

The Device Team has forwarded to the Consultants calculations for the overall stability of the structure when subjected to standing wave forces and referred the Consultants to calculations submitted for last year's floating device Reference Design as indicative of the order of size of structural members required for the Bottom Mounted Device.

(The structural calculations for the 1978 Reference Design include design calculations for the main slabs, walls and roof members of the floating device).

1.4 Foundations and Anchorages

The data provided by the Device Team are set out below:-

General	Information Available
Preferred range of water depths	Yes
Preferred foundation type	Yes
Preferred means of fixing to sea bed	Yes
Preferred number of rock anchors per device	Yes
Required ultimate capacity of and force in each anchor	Yes
Foundations	
Probabable Seabed conditions	Yes
Type of seabed preparation	Yes
Material to be used for foundations	Some data
Scour protection details	Some data
Maintenance procedure	Some data
Rock Anchors	
Force (working) in each anchor	Yes
Number of anchors each device	Yes
Anticipated angle of inclination of anchors	Yes
Material content of rock anchorage system	Yes
Method statement inclusive of installation time required	Some data
Estimated life of rock anchors	Some data
Maintenance procedure	Some data

1.5 Performance Data

Summarised below are the data available to the Consultants together with an indication as to whether the data have been obtained since last year's report and whether they relate to the Device Team's most recent development of their Device.

	New data since 1978 Report	Data as available for 1978 report	No data	Are data related to latest device?
Monochromatic sea efficiencies	Yes	Some model tests applicable to new device	N/A	Yes
Variation of efficiency with wave direction	Variation less significant as wave directionality better inshore	N/A	N/A	N/A
Relationship of model tests to actual device behaviour	Model tests relevant to device concept now envisaged	Some model tests relevant to new device	N/A	Yes
Plant Efficiency				
a. Turbine efficiency	Revision of data available for 1978 report	Yes	N/A	Yes
o. Generator efficiency	"	Yes	N/A	Yes
c. Transmission	"	Yes	N/A	Yes
Active Valve Control	Preliminary Results	No	N/A	Yes

1.6 Optimisation

This section summarises the extent to which the Device Team has optimised the size, performance, power take off and other aspects of the Device.

Parameter of Device	Optimisation Undertaken Yes/No/In hand
Shape of Water Column	Yes
Shape of Device	In Hand
Size of Device	In Hand
Fixing Details of Device	In Hand
Depth of Installation	In Hand
Separation	N/A
Power Off Take	In Hand
Power Plant Layout	In Hand
Damping	N/A

1.7 Operation and Maintenance

This section sets out the extent to which the Device Team has considered and priced the cost of operation and maintenance of each major component e.g. foundations, power off take etc.

Component of Device	Operation		Maintenance	
	Considered	Costed	Considered	Costed
Device as a whole only; including foundations, anchors, structure, power take off and M&E plant	Yes	No	Estimated annual cost	Yes
			Estimated Capital Cost of Maintenance Base	Yes

1.8 Costing

In a report dated June 1979 the Device Team presented a summary of their preliminary cost estimates for their device. In this report they adopted similar broad headlines to those used in Volume 3 of the Consultants' report of 1978.

The Device Team's report also presented for comparison purposes, similar cost estimates made by them for the 1978 floating device.

These costings do not indicate the labour, plant and material requirements and have not been expressed in the format of a bill of quantities.

The Device Team has also presented certain costings of rock anchors prepared by Messrs Colcrete Ltd., and of device installation prepared by London Offshore Consultants Ltd.

In addition to the above information the Device Team has supplied updated costing data on the latest arrangement of the breakwater device using established rates and inhouse costing experience. The Device Team considered that their breakwater design was not yet developed sufficiently to warrant approaching a Contractor for independent costing. The possible benefits of extensive mass production have not been included in the costing analysis at this time.

1.8.1 Unit Costs

The following table summarises the costing information provided by the Device Team.

Element of structure, equipment, plant or operation	Build up of costs provided	Rates quoted
Rock Anchorage installation	Cost estimate from specialist Contractor (Colcrete Ltd)	
	Mobilisation	Yes
	Provide, install and stress rock anchor	Yes
Installation of device on prepared foundation	Broad cost estimates from specialist (London Offshore Cons. Ltd.)	
	Rock Foundation Transportation & Placing	
	i) by Marine operation (cost per 100 units)	Yes
	ii) by Platform Operators (Capital + Running Cost)	Yes
	Installation Costs	
	i) Towing (Cost per 100 units)	Yes
	ii) Manoeuvring (per 100 units)	Yes
Capital Cost Estimate:		
Body of Structure	No build up	Yes
M&E Plant	"	Yes
Tow & Install	"	Yes
Foundations & Rock Anchors	"	Yes
Power Take Off	"	Yes
Contingencies	"	Yes

In addition to the above information the Device Team's Quantity Surveyor agreed certain basic cost centres at a meeting with the Consultants.

1.9 Marine Growth and Environmental Aspects

The Device Team has provided an Interim Report by a specialist containing the following data regarding the environmental aspects possible as a result of siting devices off the West Coast of Scotland:

General	Information Available
Marine Fouling	Yes
Changes imposed on inshore environment	Limited
Impact on fisheries	Limited

PART 2. CONSULTANTS' APPRAISAL

2.1 Preamble

The Device Team, whilst maintaining its broad study objective, has adopted as current "front runner" the breakwater type OWC.

Different methods of installing the breakwater device are being investigated and the optimum depth of water in which it should be sited is under consideration.

Alternative layout schemes for the power take off equipment are being studied and work is continuing on the development of the Francis type turbine currently favoured by the Device Team for use with the oscillating water column for primary power conversion.

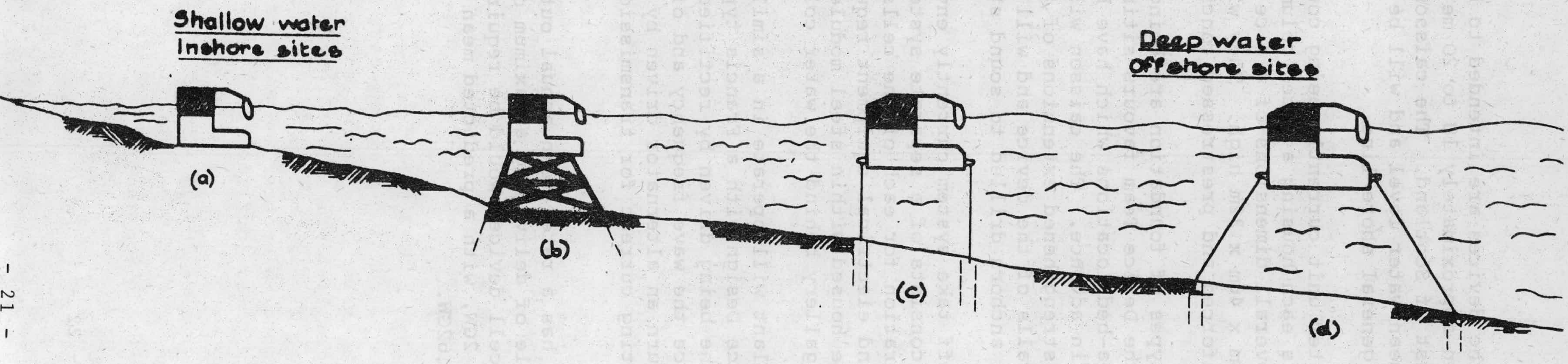
2.2 Description of Device

The emphasis of the work undertaken by the Device Team over the last year has been towards reducing the total unit cost of power produced by their device. As a result of this work it has been determined that a breakwater device fixed to the sea bed offers good prospects for cost reduction. This is the broad concept which evolved during the development of the Second Interim Reference Design proposed by the Team in 1978 and was included in a list of possible variants worthy of further investigation in the 1978 Consultants' Second Report.

Although the Team's efforts are now concentrated on a bottom mounted device this is now being considered by them as the first in a "family" of oscillating water columns which they envisaged as possible developments as technology expands and experience is gained in their construction and deployment.

This stepping stone philosophy can be considered as starting with the construction of Breakwater Type Structures close to shore; then progressing into deeper locations using Fixed Platform Structures and Tethered Buoyant Structures; finally Moored Floating Structures of the type of the Second Reference Design would be used at deep water offshore sites (outlined in Diagram No. 1).

A significant proportion of the studies for the Breakwater Device are generic and as such will be equally valid for any of the intermediate stages of the oscillating water column development.



(a) Deep breakwater structures (1980 Reference design)

(b) Fixed platform structures

(c) Tethered buoyant structures

(d) Moored floating structures (1980 Reference design)

DIAGRAM 1 THE FAMILY OF O.W.C. STRUCTURES

Initially the devices are intended to be sited some 2-3km offshore in approximately 18 to 20 metres of water off the West Coast of Scotland. The caissons will project some 14m above mean water level and will be aligned parallel to the general shore line.

The breakwater unit currently being considered comprises 4 cells each housing a water column 18m long by 14m wide. The overall dimensions of a 4 cell unit are approximately 78m x 46m x 32m high. They will be constructed in reinforced and prestressed concrete.

Different types of foundation are being considered but at present the Device Team favours siting the caisson directly onto sea-bed locations which have been dredged or cut to level in advance. The caisson will bear onto the sea bed via strengthened extensions of the longitudinal and transverse walls of the device and will be fixed to the bottom with rock anchors drilled to sound strata.

The power off take system currently envisaged by the Device Team consists of a separate system of power capture and generation for each of the cells in the unit. The mechanical and electrical equipment required for each cell will be housed within steel modules which will be located on a gallery behind the water column.

The power plant will operate in a similar manner to the 1978 Reference Design with a Francis type radial inflow air turbine being driven by rectified air flows pulsating at twice the wave frequency and of random magnitude. In turn an alternator driven by the turbine provides alternating current for transmission to the Grid.

Each device has a rated mean annual output of 446.4kW with plant capable of delivering a maximum of 1447.2kW. Hence 1382 four-cell devices would be required to form a power station of 2GW, with a predicted mean annual output to the grid of 0.62GW.

2.3 Changes from Reference Design of 1978

The Device Team has retained the basic shape of the oscillating water column and also the method of power conversion proposed in the Second Interim Reference Design. The principal changes from the previous design can be summarised as follows:

(a) The current design is not a moored device floating in deep water offshore but is now a bottom mounted design anchored to the sea bed with prestressed rock anchors. It will be sited closer to shore in water of from 15m to 20m depth.

(b) The power plant is no longer within the body of the structure but is housed in works assembled steel modules, the mechanical and electrical plant being fully tested on installation. The power take-off modules would be lifted into position when the device has been successfully fixed to the sea bottom. They should be capable of replacement in situ.

(c) The hydraulic power collection link introduced into the 1978 design has been eliminated.

(d) The set of six flexible a.c. cables otherwise required by last year's reference design (in place of the hydraulic link) are this year superseded by the provision of rectification plant for each generator, power collection being achieved by series d.c. connections between the four device generators and others on adjacent units. Single core d.c. cables are now used and the flexibility necessary for floating devices is no longer essential.

(e) The seaward face of the device (nose) has been modified to provide a smoother flow path for water entering or leaving the water column.

2.4 Discussion of Device Design

The member sizes and internal structural layout of the device have not yet been finalised by the Device Team and further work to identify these particulars is dependent on the results of three separate sub-studies commissioned by the Team from specialists.

The subjects being covered by the sub-studies are:

1. Biological growth and seabed conditions;
2. Logistics and installation;
3. Rock anchors.

Unfortunately, due to administrative problems, the issue of contracts for the specialist sub-studies was delayed some 3 to 4 months. As a result these contracts for the sub-studies were let in September and October 1979 instead of June 1979 as originally planned and the progress on the design of the bottom mounted device has suffered in consequence.

A complete costed reference design for the Breakwater structure is now programmed to be available in March 1980.

As mentioned above the Device Team has sought specialist advice on each of the following topics: seabed conditions; marine growth; installation techniques; rock anchorages. Until reports on these sub-studies are received by the Device Team and utilised by them to produce the 1980 Reference Design, then the information details and drawings provided by the Team are necessarily of a preliminary nature.

Consequently it is not possible at this stage to comment on the details of the Device other than in broad terms.

2.4.1 Foundations

Calculations of the stability of an early design for a four-cell breakwater type unit subjected to standing wave forces have been made available to the Consultants.

Information available to date indicates that the bedrock at the chosen site would probably be Lewisian gneiss with some sandy pockets and the possibility of granitic intrusions. Surveys of the sea bed indicate that the surface of the bedrock is uneven and undulating. More detailed surveys would be required to confirm the optimum alignment for the devices and the founding level for each unit.

To provide adequate factors of safety against sliding and overturning whilst minimising the gross volume of the device, the Device Team favours utilising rock anchors to resist the major part of the standing wave forces. For the early design of a four cell unit the Team found that the caisson could resist waves of only 3m height without rock anchors being used.

Because the breakwater type structures are to be founded in the exposed, hostile environment of the West Coast of Scotland, it is the Consultants' opinion that each operation should be limited by the constraint that the structure must be capable of surviving the 10-year seasonal storm by the end of the weather window forecast at the start of that operation and the Device Team's Report implies concurrance with this requirement. At present accurate weather forecasts can be made for about 72 hours.

Although the design of the breakwater unit has now been made heavier and wider, a large number of rock anchors are still necessary. The length of time required to drill, fix, grout, and prestress these anchors may conflict seriously with the constraints imposed by the weather. The Device Team is considering utilising a special emplacement barge to provide additional ballast to hold the units in place against the wave loading until such time as sufficient anchors are installed to stabilise the device.

2.4.2 Installation

To exploit to the full the limited resource available inshore the caissons will require to be closely spaced and the Device Team propose to have no effective separation between the device units. Thus to prevent serious structural damage which would result from inter-caisson collision or from impact of the caisson with the sea bed during placing, due account must be made of the heave and surge forces imposed by the waves when deciding on the method of placing the caissons.

Analysis of the limited wave records available from the inshore buoy suggests that conventional caisson placing techniques will not be suitable for use in this location because the required sea state will not be achieved either frequently enough or for long enough periods to permit the deployment of the large number of units required for a 2GW station.

The number and size of the compartments provided in each unit are of insufficient capacity for use as a ballasting system to sink the caissons onto prepared foundations by conventional means.

Some ingenuity may therefore be required in order to develop satisfactory methods of lowering units into position and securing them within the limitations of predictable weather windows.

The Device Team is at present considering the use of a special catamaran type installation barge to provide extra ballasting capacity and to reduce the response of the caisson to the incident waves. The installation barge would be used to provide additional buoyancy initially until the breakwater unit is on station above the prepared foundation, then the structure would be ballasted down onto the sea bed. Additional ballast would then be taken on by the barge to hold the unit in place whilst the rock anchors are installed.

2.4.3 Structural

The back i.e. shoreward side of the caisson is shaped to provide a gallery to accommodate the power take off equipment and to satisfy draught, freeboard and underkeel clearance requirements of the structure afloat. The base of the caisson is envisaged as being cellular to provide strength during installation and to facilitate ballasting and trimming, while the unit is afloat.

The roof of the water column is steeply angled from front to back to minimise freeboard and hence reduce the area exposed to extreme waves.

With the exception of calculations for overall stability no new detail structural calculations have been made available to the Consultants since last year.

The device, in its present form, is at an early stage of development and sizes of individual members have not yet been fully detailed. This detail design depends in a large part on the procedures still to be established for founding the caisson units. However, the long term survival of the bottom mounted units will depend on their ability to resist breaking wave forces.

By referring to certain calculations supplied in relation to the 1978 Reference Design for the floating oscillating water column a first approximation can be made of the required member sizes. However, the Consultants are of the opinion that the bottom mounted device will be more liable to experience breaking wave forces than the floating device. Although the height of the breaking waves at the fixed device will be depth limited, it is anticipated that breaking wave forces will be a critical environmental loading.

2.4.4 Primary Conversion System

The bottom mounted device extracts energy from the waves in a similar manner to that of the moored floating device, utilising a column of water induced to oscillate by the action of the waves to pump air through the secondary system. By fixing the structure to the sea bed the efficiency band width of the water column extracting energy is increased.

2.4.5 Secondary Conversion System

NEL have retained virtually the same power conversion design as in the 1978 floating device. The pulsating air flows produced by water column oscillation are rectified by sets of flap valves and supplied through a short duct to a radial inflow Francis type reactor turbine. There would be one air turbine alternator set for each cell producing an output of 350kW maximum from a turbine developing about 520 h.p. The turbine would be relatively large, operating a medium speed and provided with controllable inlet guide vanes.

In order to optimise conversion efficiency the turbine speed will have to be varied to match the secondary power delivery rate. Inertia of the rotating parts would preclude significant speed variation during a wave cycle. but sensitive control equipment would adjust the mean turbine speed to suit the prevailing wave energy level. In this way turbine runner velocity would be kept closer to that of the inlet air and the requirements of best plant efficiency.

The air valves in the 1979 reference design are intended to be self actuated aerofoil flaps of which there would be as many 81 in each valve unit. When in the open position the net flow area should be about $8m^2$. It is understood that consideration will be given later to the desirability of adding servo operation of the air valves under somewhat advanced logic control. There are grounds to believe that proper timing of valve operation might lead to an improvement in the band-width of wave frequency response and the gaining of some incremental energy.

The air duct connections have been shortened but further design would include aerodynamic modelling. Particular attention will be necessary to the axial discharge geometry.

The interposed hydraulic power link in the energy conversion chain, previously provided to overcome a multiple submarine cabling problem, is no longer required. Random generation output can be assimilated electrically.

The four individual OWC generators could follow conventional maritime practice; be provided with brushless excitation of the required response capacity, and have adequate thermal rating for six pulse rectifier duty. Interconnection of the four outputs is achieved electrically by the addition of generator isolating transformers and diode rectifiers, the direct current outputs of which are connected in series, not only across all four cells of a device but including 30 or so of its neighbours. The 40 MW output of the group of 30-32 devices would be transmitted ashore to the Outer Hebrides, a distance of 3 or 4 km, using cables only to the first and last device.

This improved method of power collection not only permits freedom of variation of individual generator output and thereby matching the pneumatic damping to the column motion but with the additional advantage of being close inshore, will offer considerable cost savings compared with the previous year's design.

The power take-off air turbines and the various air chambers will all be subject to corrosion and contamination by sea water droplets carried in the reversing air stream. It will therefore be essential to choose fabrication materials which will withstand long-term marine exposure. In particular, the air turbine runners could be fabricated in stainless steel alloy plate, and the air flow rectification flap valves will need particularly careful design if they are to perform efficiently and without excessive leakage losses over a long period of time.

The electrical plant in particular must not be exposed to the air flow so that the generator will require indirect cooling. Thought should also be given to what may happen during the suction cycle when under winter conditions drop in pressure below atmospheric could produce fog and possibly ice formation. These, however are matters to be resolved in any on-going research.

2.5 Construction Methods

Full details of the sequence of construction have not been finalised.

The units will be constructed in two stages. The first stage of construction will take place in a large dry dock of the type used forthe manufacture of large North Sea Oil Production platforms. Depending on the size of the dock, two or three of the devices might be constructed simultaneously.

The base slab and then the vertical walls will be constructed using fixed and slipform shuttering to a height sufficient to allow float out from the basin. Temporary bulkheads will be installed across the mouths of the water columns, the basin will be flooded and the units floated out to be towed to a sheltered site. At the sheltered site construction will continue on the floating body, completing walls and placing the precast floor and roof slabs.

The units are then towed to the operating site, and fixed in location using rock anchors.

The air ducts are installed in the mechanical plant modules placed in position and the mechanical and electrical installation work completed.

The Consultants have estimatedthat to construct a 2GW rated power station in 10 years would require approximately 100 yards similar to Hunterston Dry Dock each producing 2 units per 14 month cycle. The annual resource requirement is shown in Table 5.1.

2.6 Maintenance

For the following reasons the Device Team anticipates that the bottom mounted oscillating water column device will have relatively low maintenance costs:

- the breakwater unit is monolothic;
- the power off take is reasonably conventional;
- the major items of plant are in modular form and can be removed for repair or maintenance;
- there are no moorings;
- there is no flexible power distribution cable;
- the device is fixed to the sea bed and is relatively close to the shore;
- the water column chamber may be sealed off using steel stop logs which would be located in guides on the front wall of the structure. The chamber could then be dewatered to provide dry access for cleaning and inspection.

As already noted elsewhere, the Device Team has initiated a study of the marine growth likely at the device sites.

The Interim Report by the Scottish Marine Biological Association indicates that marine growth and fouling are not expected to present any serious problems. Although standing crops may possibly colonise the water chamber the sizes of the crops concerned are estimated to be between 100mm and 700mm maximum height and vary in density from a standing crop of 0.8 kg/m^2 at the entrance of the chamber, to 0.1 kg/m^2 at the rear of the chamber. It is anticipated that these standing crops will be removable by scraping and water jetting.

2.7 Performance and Productivity

As was the case last year, the Consultants have been responsible for the assessment of productivity of the Device. It is, therefore, appropriate to set out in some detail the manner in which that has been done and any differences between the present approach and that adopted last year.

The Consultants' assessment of productivity is intended to represent the total electrical power delivered to a 2GW rated station at Perth during a typical year from a long string of devices located off the west coast of the Outer Hebrides. A water depth of 18m was assumed for the NEL Bottom Standing Device.

The procedure for calculating productivity remains essentially the same (see Appendix A). It should be re-emphasized however, that the upper and lower limits on estimates of the various factors are extremely subjective. The interpretation given to these ranges, therefore, should be the limited one of estimating errors, not the full long-term probability distribution about each estimate.

Minor modifications to the productivity calculations are listed below together with changes in wave climate and device data:

2.7.1 Shallow Water Correction

In this report the shallow water correction has been made by dividing the variance of each frequency component of the recorded wave spectra by the appropriate shoaling coefficient. The mean annual power of the 399 Selected Offshore Spectra modified in this way is 47.5 kw/m. For details see Appendix A.

2.7.2 Wave Climate Data

Since the last report new wave data have become available for the South Uist offshore and inshore buoys (reference WESC (79) DA89). Thenew wave recordings made at the offshore buoy during the year '77-'78 confirm that the '76-'77 South Uist Selected Spectra are representative of the climate during a typical year. Fig 7.1 shows the scatter diagram of the selected offshore spectra after modification using shoaling coefficients.

The wave spectra recorded at the inshore buoy during the year '78-'79 are incomplete as data are missing for two winter months. To compensate for this IOS have selected 1259 spectra, for which simultaneous recordings were taken at both the inshore and offshore buoys. The annual mean power calculated from these selected spectra is 11.31 kw/m for the inshore buoy and 31.69 kw/m for the offshore buoy. To get the mean annual power at the inshore buoy for a typical complete year the figure of 11.31 kw/m has been multiplied by the ratio 47.5/31.69 = 1.50, which gives a mean annual power of 17.0 kw/m. Fig 7.2 shows the scatter diagram of the selected inshore spectra after modification to allow for the shallow water effects.

The offshore scatter diagram was used in the computer analyses to calculate productivity of devices located in depths of 50 to 100 metres. For the shallow water devices the inshore scatter diagram was used and the calculated power delivered to Perth was then multiplied by the factor 1.50. This procedure of compensating for the missing winter data could result in an overestimation of the harnessed power, as the missing winter months probably contain a high proportion of powers too large for the Device to capture.

2.7.3 MET Office Computer Model

New data on wave directions and mean annual power levels have been derived using the MET Office computer model (reference WESC (79) DA84). Values of mean power levels and directionality factors of 4 grid points off the west coast of South Uist with associated depths of between 50 and 100m are shown below.

Grid Point No.	Depth (m)	Mean power (kw/m)	Directionality Factor
30	55	54	0.78
39	91	52	0.78
47	91	65	0.77
48	55	47	0.82

The wave power rose grid point No. 39 is shown in Figure 7.3.

2.7.4 Directionality Factor

In this report the directionality factor has been calculated using the wave power rose given in Figure 7.3 and has been included in the first stage of the computer analysis rather than in the second. This approach results in the same annual power chain efficiency as that calculated by applying the direction correction factor in the second stage, but it does produce lower optimum plant ratings. Details are shown in Appendix A.

2.7.5 Site Correction Factor

Figure 7.4 shows an assumed relationship between mean sea power and water depth. This graph is based partly on the wave power recordings at the inshore and offshore buoys and partly on the MET Office computer model predictions. A site correction factor of 1.1 has been used for devices located in 50 to 100m of water: this value corresponds to depth of 75m in Fig 7.4. For shallow water devices, the site correction factor was determined by linear interpolation between the mean powers at the inshore and offshore buoys.

2.7.6 Reliability

New assessments of failure rates and repair times are currently being made by Consultants to TAG 6. Until these results are available, reliability factors have been left largely unchanged from last year's report. The "high" estimate has been modified to 0.95 for all devices, representing the maximum achievable, although this probably infers considerable costs in plant and cable redundancy, monitoring systems and extensive repair facilities.

Devices not included in last year's report have been grouped with similar devices from the point of view of accessibility and type of plant.

2.7.7 Device Efficiency Data

Tank testing by the Device Team with monochromatic waves has shown that the bottom standing device captures power over a much larger frequency range than the floating device. Fig. 7.5 shows the efficiency curve. Computer calculations show that the bottom standing device will be able to capture about 75% of the mean annual energy incident on the device. This is substantially more efficient than any of the wave energy devices reported last year and approximately double that of the floating oscillating water column device.

2.7.8 Power Chain Data

This device has a similar power take-off scheme to that of the floater. This data is shwon in Figure 7.6.

2.7.9 Productivity

As for the NEL floating device, the results from the model tests have been applied to a wide range of full size devices using Froude scaling. Figure 7.7 shows the results of this exercise, which indicate that a device with a 10m wide air column would capture just as much power as the proposed 14m wide device.

The effect of varying the plant rating to establish the optimum plant rating has been analysed. The results are plotted in Figure 7.8.

A breakdown of the factors affecting the device productivity is shown in Figure 7.9. Using this information the mean annual power delivered to Perth is predicted to be 6.2 kw/M With plant rated at 27.0 kw/m. For a 2GW rated power station 1382 four-cell devices will be required. The mean annual power produced by the 2GW station (housing 5528 water columns) is predicted to be 0.62GW.

It should be noted that in the above assessment of productivity no allowance was made for variation in mean sea level. This could have a serious effect on the device productivity, but it is difficult to see how this could be investigated without carrying out experiments to determine how the device efficiency varies with mean water level.

2,8 Discussion of Cost Data

2.8.1 Capital Costs

The Device Team has used inhouse costing experience and established rates together with costing data supplied by specialist sub-contractors to obtain an estimate of the capital cost of the breakwater structural units. The capital cost of plant and power take-off equipment has also been estimated using the plant costs contained in the Consultants' 1978 Report on the cost of the floating device,as a yardstick where appropriate.

Although the Consultants' 1978 costing analysis was based on the costing exercise submitted by three independent Contractors, the Device Team is of the opinion that the breakwater device has not yet reached the stage in its development where it would warrant detailed costing by an independant contractor. For similar reasons the Device Team has chosen to ignore, for the meantime, any possible benefits which might be forthcoming from extensive mass production techniques.

Where rates and costs used in the estimates have been based on earlier assessments, an inflation allowance has been applied by the Device Team to update the figures to represent current, November 1979, prices.

Certain areas of costs i.e. moorings, towing and dredging, have been repriced by the Device Team as a result of subcontracts received for these items.

In line with the procedure adopted in the 1978 Consultants' Report, the Device Team has presented basic rates in the form of a short bill of quantities and have included estimating tolerances in the summary of costs to indicate the confidence level of the values obtained.

2.8.2 Maintenance Costs

The Device Team has allowed for the establishment of a maintenance base from which to service the breakwater units and has estimated the capital cost of the base to be £20 x 10^6.

In addition the Team has estimated the annual running costs per breakwater unit to be £1 x 10^5.

2.8.3 Analysis of Costing

The costs as submitted and the Consultants' comments are given on Table 8.0/1. In this table a maximum and a minimum basic cost is given.

TABLE 8.0/1

Item	Cost/Device Min. (£)	 Basic (£)	 Max. (£)	Comments
Provision of facility	585,000	650,000	780,000	- very reasonable based on 1979 Constructing costs and methods
Structural cost including Rock Anchor	4,860,000	5,400,000	6,480,000	- probably slightly overpriced due to current market prices not reflecting NEDO indices
Plant including enclosures	1,350,000	1,500,000	1,800,000	- again alightly pessimistic. Further study should reduce this
Float out tow to site, install and prepare foundations	765,000	850,000	1.020,000	- reasonable
Power take-off	270,000	300,000	360,000	- reasonable
TOTAL	£7,830,000	£8,700,000	£10,440,000	

No transmission costs or indications of quantity were given by the Device Team. These have, however, been supplied by the Consultants.

The level of pricing for this device as submitted is generally slightly high. The rates used, up-rated from the NEDO indices from 1978, give an duly pessimistic cost when applied to the Civil Engineering industry and instead of the 20%-25% increase (since 1978) used, a figure of about 16% would be more realistic when applied to large Civil Engineering Projects. This device, due to its massive size, does not, however, lend itself to the total adoption of large scale man production techniques and the Consultants' opinion is that this device is perhaps 5%-10% overpriced.

2.9 Cost of Power

The costs of power produced by the wave power schemes investigated in the Consultants' 1978 Report were presented in terms of cost/kW mean annual output. While this is a meaningful parameter in itself, a more comprehensive presentation is in terms of a power cost in pence/kWhr, in which account is taken of initial capital and maintenance costs.

The objective of this section of the report is to present the total costs (capital and running costs) for the NEL bottom standing device as an annual equivalent which may then be measured against the return, in terms of mean annual power output.

In section 2.8 the Consultants have presented the costs of a single device, as built up by the Device Team. These figures have been used to build up the cost of a 2GW rated power station based upon the appropriate number of devices and including the cost of electrical transmission, which has been prepared by the Consultants.

In section 2.7 the Consultants have developed figures for the productivity of a 2GW power station i.e. the figures indicate the mean annual output of a 2GW power station to the grid.

In assessing the power, the Consultants have in the first place derived an annual cost of the station. For this, it has been assumed that the capital cost of the station would be recovered over a period of 25 years, allowing interest at a rate of 5% compound. This agrees with the manner in which ETSU perform their own costing calculations and is equivalent to repaying 7.1% of the capital cost each year. In addition to this, an allowance has been made for the cost of maintenance. This has been taken from the figures supplied by the Device Team.

The annual cost derived as above is thus divided by the number of hours in a year, 8760, and the mean annual output of the station, in order to obtain the cost per kilowatt-hour.

The costs can be worked out as follows:

	Min.	Max.
Cost of each device	£ 7,830,000	£ 10,440,000
No. of devices per 2GW Station	1382	1382
Hence:		
Cost of devices required	10,821M	14,428M
Cost of transmission	412M	412M
Cost of maintenance base	20M	20M
Total Capital Cost	£ 11,253M	£ 14,860M
Annual Cost at 7.1% of capital cost	787M	1,055M
Annual maintenance cost	138M	138M
Total annual cost	£ 925M	£ 1,193M
Mean annual power	0.62GW	0.62GW
Cost of power	17.0 p/kWhr	22.0 p/kWhr

7.1% = capital recovery factor

19.5

2.10 Conclusions

2.10.1 By persuing a breakwater type O.W.C. located inshore in shallow water between 15m and 20m depth, the Device Team is utilising a smaller energy resource than that available off shore.

Based on the latest information available to date, the power available in the sea at 15m depth is 17 kW/m compared with 47.5 kW/m for floating devices in deep water.

2.10.2 The total potential for the inshore breakwater devices is limited by the availability of suitable shallow water sites.

The estimated net length of seabed required to house a 2GW rated breakwater power station is 113 km. The Consultant's assessment of the net length of suitable sites available off the West and North Coast of Scotland is 230 km in 15m depth and 310 km in 25m depth of water (Consultants' Working Paper No.6).

2.10.3 Optimisation of the breakwater devices will be more site specific and depth dependent than for offshore floating devices.

Seabed conditions and proximity of islands and headlands are more significant factors and will vary from site to site. Tidal effects are relatively more important at the inshore sites.

2.10.4 Certain features of the fixed breakwater device make it more attractive than the 1978 Reference Device floating device:

- the power capture efficiency has been doubled by fixing the water column to the seabed;
- the costly moorings have been eliminated and replaced by cheaper seabed preparation, foundations and rock anchors;
- maintenance and transmission to shore are both simplified by the fixed inshore location.

2.10.5 The fixed bottom device shows encouraging costs. The present structure is however still of the same order of size as the 1978 floating device.

During the development of the breakwater device the Device Team and the Consultants have discussed in detail the progress of the device and are in agreement that the potential advantages of a fixed device have not yet been fully realised and the present structural layout should be considered as an intermediate stage in the design.

The Consultants would agree that there are other configurations to be explored and lower civil engineering costs might well result.

2.10.6 Further work has to be done on the problems of installation (weather windows and seabed conditions). This is recognised by the Device Team to be critical to the cost of the device.

2.10.7 Consideration must be given to the visual impact of the device protruding some 14m above sea level 2 to 3km offshore and to the noise which will be generated by the devices.

Some attempt will be made by the Device Team to quantify these as they may prove limiting.

	N.E.L. BREAKWATER DEVICE (1382 No)	
	Resources per unit	Resources/Annum for 10 year programme
CONCRETE	16,000 m^3	
Cement	6,500 T	900,000 T
Aggregate	26,000 T	3,600,000 T
FORMWORK	29,200 m^2	4,050,000 m^2
REINFORCEMENT	3,200 T	450,000 T
STRUCTURAL STEEL	-	-
ROCK ANCHORS (19/18 Dyform Tendon)	(250 T) 7,000 m	1,000,000 m

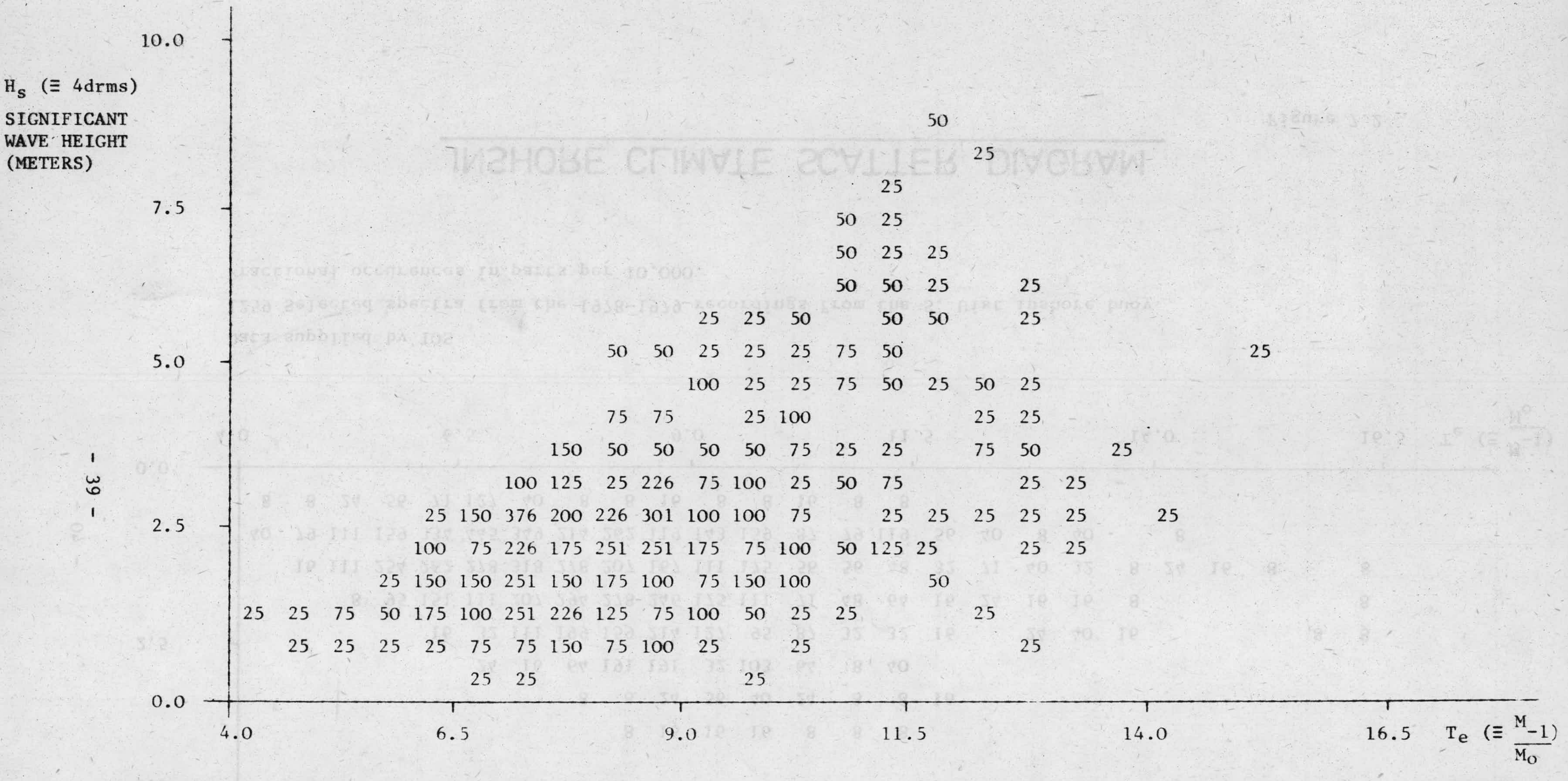
UNITED KINGDOM WAVE ENERGY PROGRAMME

OPTIMUM PROGRAMME FOR PRODUCTION OF UNITS FOR ONE CONSTRUCTION FACILITY IN 10 YEARS

N.E.L. BREAKWATER DEVICE

Description of facility	Hunterston single basin	Brent type basin (x 2)
No of units/cycle	2 No.	3 No. (x 2)
Construct in dock	13 months	9½ months
Float out	1 month	1½ months
Complete at deep berth	12 months	4 months
Cycle time	14 months .	11 months
Production/10 years	28 units from 2 No. Hunterston basins	57 No. from 2 No. Brent type basins

TABLE 5.1



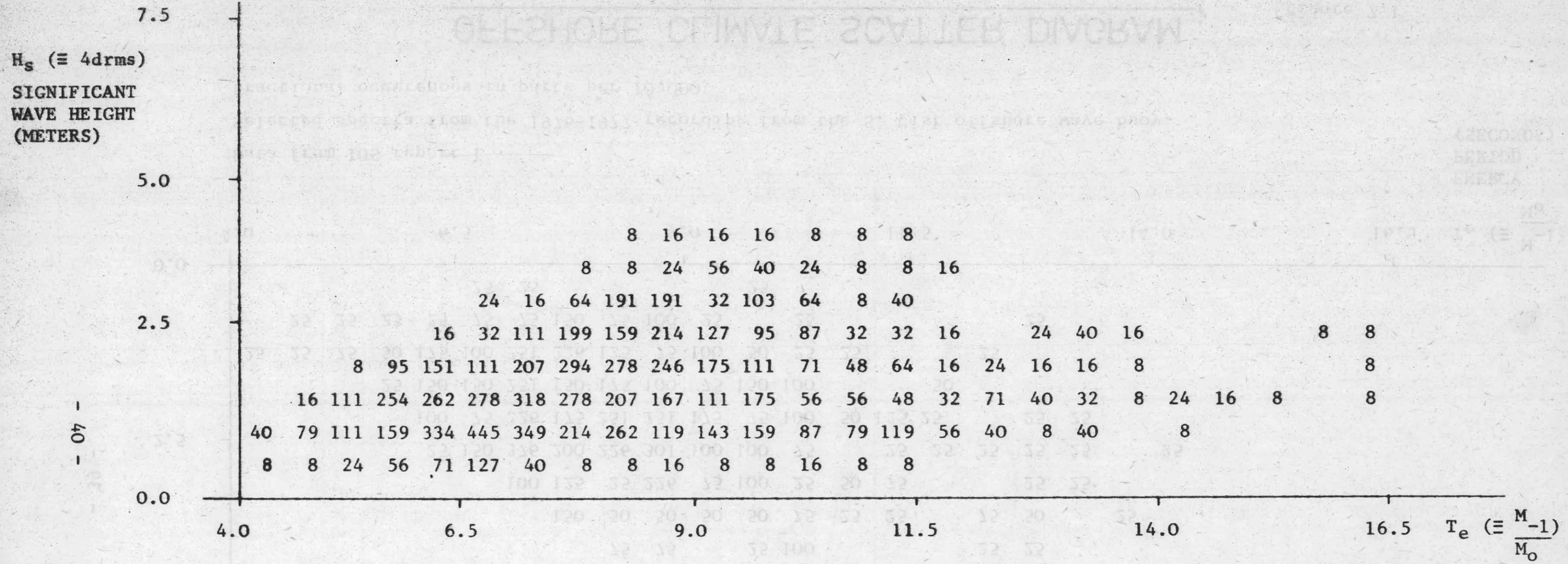
Data from IOS report 1.

Selected spectra from the 1976-1977 recording from the S. Uist offshore wave buoy.

Fractional occurences in parts per 10,000.

OFFSHORE CLIMATE SCATTER DIAGRAM

Figure 7.1



								8	16	16	16	8	8	8										
							8	8	24	56	40	24	8	8	16									
					24	16	64	191	191	32	103	64	8	40										
				16	32	111	199	159	214	127	95	87	32	32	16		24	40	16				8	8
		8	95	151	111	207	294	278	246	175	111	71	48	64	16	24	16	16	8					8
	16	111	254	262	278	318	278	207	167	111	175	56	56	48	32	71	40	32	8	24	16	8		8
40	79	111	159	334	445	349	214	262	119	143	159	87	79	119	56	40	8	40		8				
8	8	24	56	71	127	40	8	8	16	8	8	16	8	8										

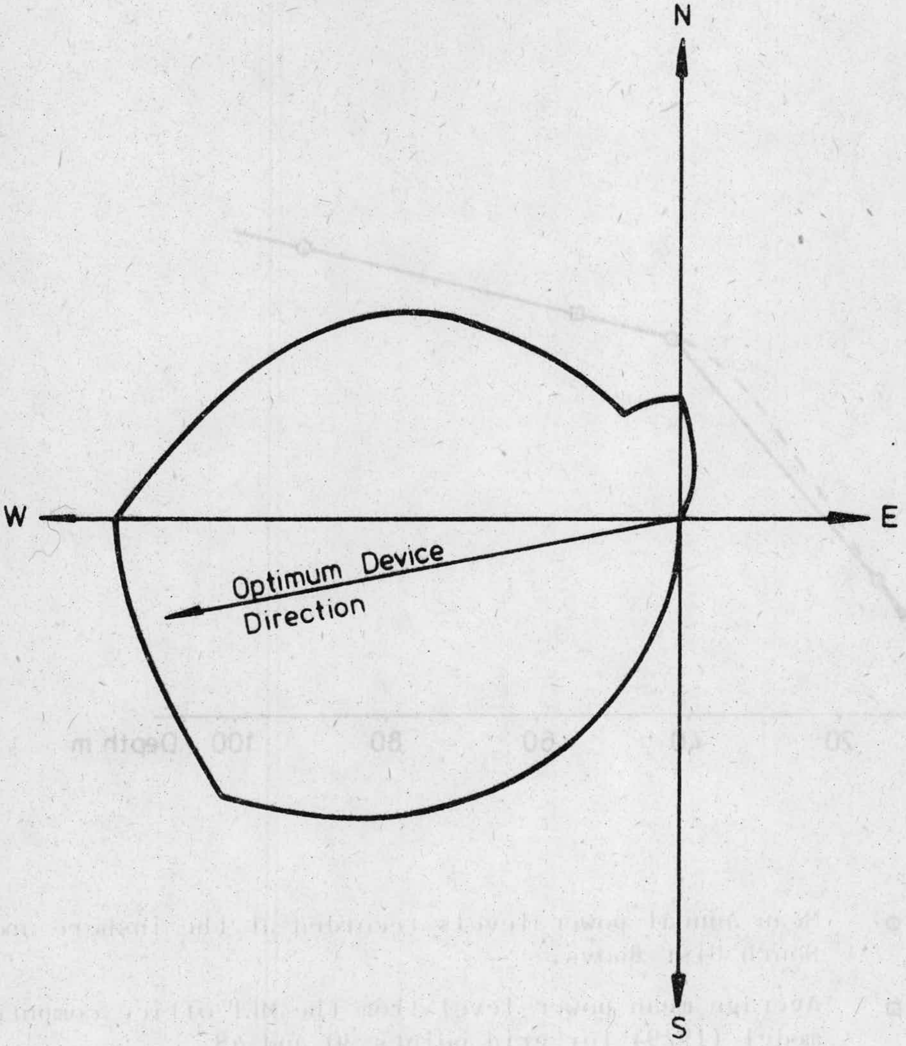
Data supplied by IOS

1259 Selected spectra from the 1978-1979 recordings from the S. Uist inshore buoy.

Fractional occurences in parts per 10,000.

INSHORE CLIMATE SCATTER DIAGRAM

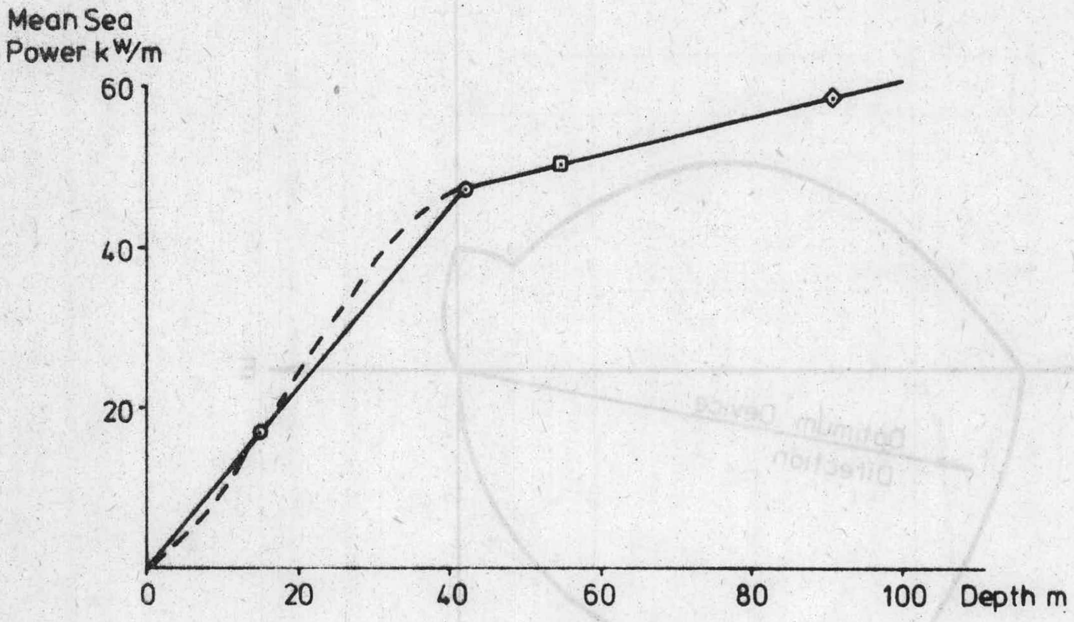
Figure 7.2



WAVE POWER AS A FUNCTION OF DIRECTION – MET OFFICE COMPUTER SIMULATION 1979 (GRID POINT No.39)

Figure 7.3

ASSUMED RELATIONSHIP BETWEEN THE MEAN SEA POWER AND DEPTH

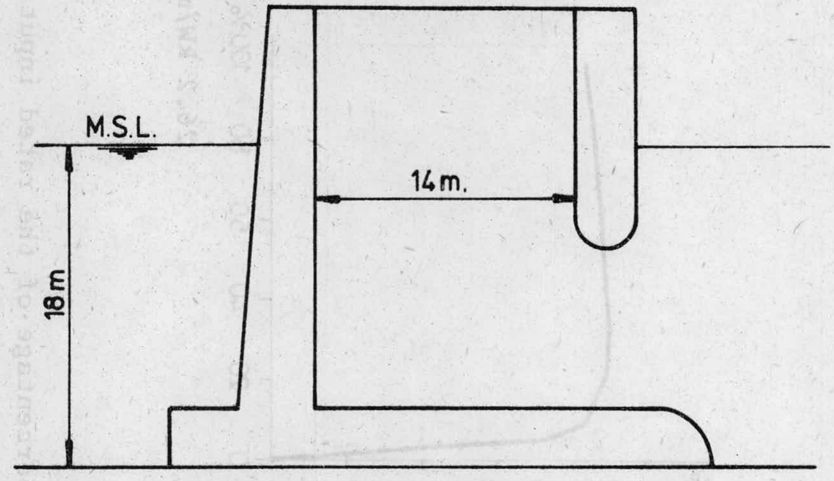


◎ Mean annual power levels recorded at the inshore and offshore South Uist Buoys.

▣ Average mean power level from the MET office computer model (1979) for grid points 30 and 48.

◇ Average mean power level from the MET office computer model (1979) for grid points 39 and 47.

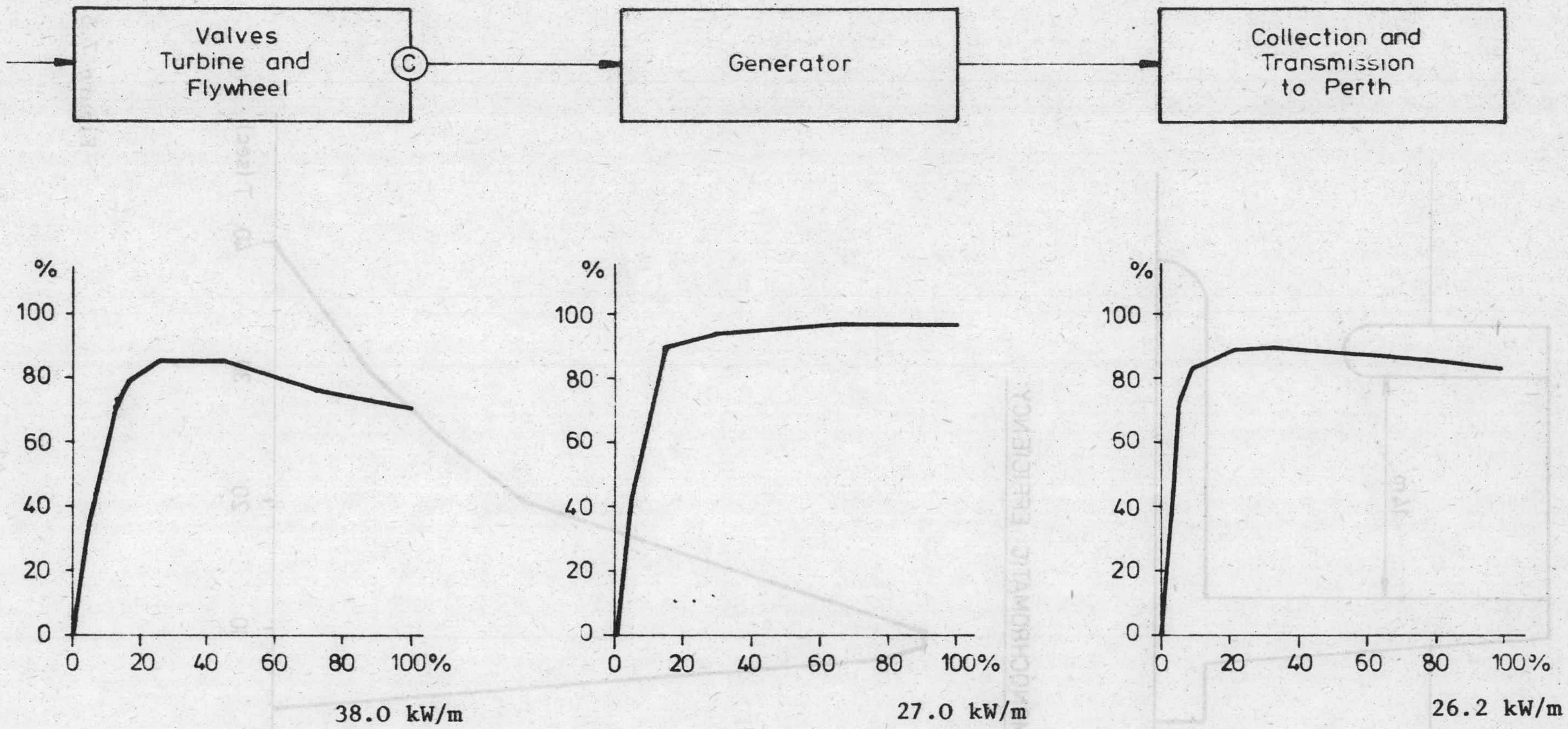
Figure 7.4



MONOCHROMATIC EFFICIENCY

Figure 7.5

POWER CHAIN

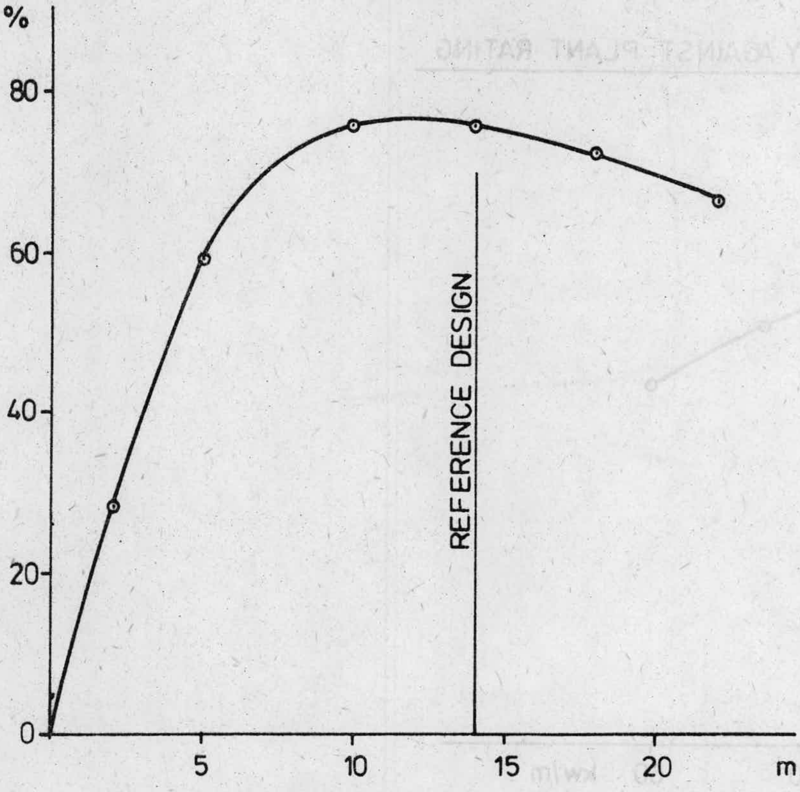


Ⓒ Cut off on Mean Hourly Output = 27.0 kW/m

The graph show power chain efficiencies plotted against input power as a percentage of the rated input power.

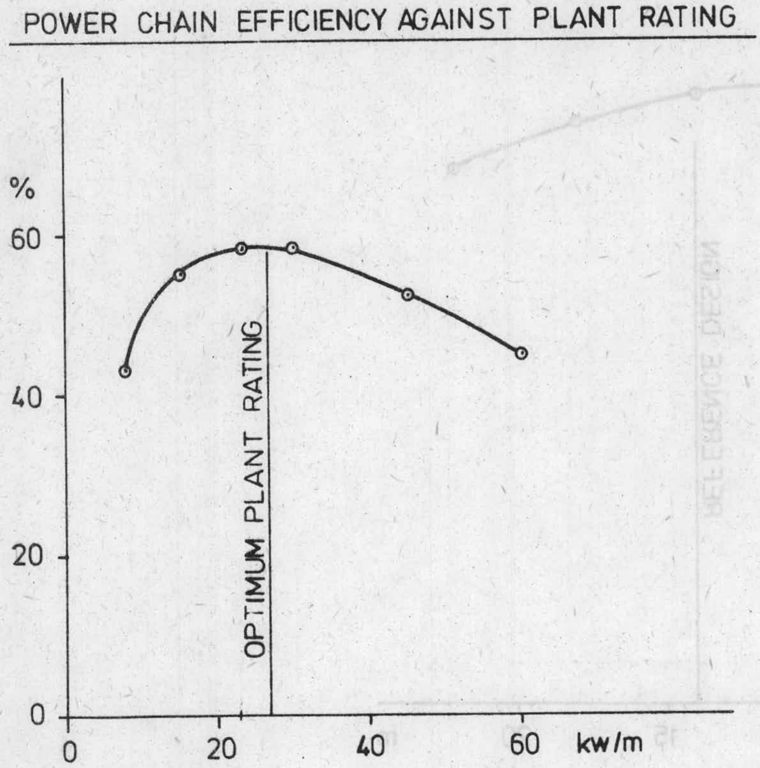
Figure 7.6

CAPTURE EFFICIENCY AGAINST CHARACTERISTIC DIMENSION



Capture efficiency = (Mean annual captured power) ÷ (Mean annual incident power)

Figure 7.7



Power chain efficiency = (Mean annual power delivered to Perth) ÷ (Mean annual captured power)

Figure 7.8

	MEAN POWER AT S.UIST INSHORE BUOY (KW/m)	SITE CORRECTION FACTOR	DIRECTIONALITY FACTOR		INCIDENT POWER
HIGH ESTIMATE	18.0	1.26	0.88		18.2
MOST PROBABLE	17.0	1.18	0.83		16.9
LOW ESTIMATE	16.0	1.15	0.78		15.6

	INCIDENT POWER	DEVICE CAPTURE EFFICIENCY		POWER CHAIN			POWER DELIVERED TO PERTH PER METRE OF DEVICE
		BASED ON PM SPECTRUM	DIGITAL SPECTRUM CORRECTION	EFFICIENCY	RELIABILITY		
HIGH ESTIMATE		0.81	1.00	0.63	0.95		7.3
MOST PROBABLE		0.76	0.95	0.58	0.92		6.2
LOW ESTIMATE		0.71	0.90	0.48	0.83		5.1

8.82
8.5
3.97

PREDICTED ANNUAL MEAN POWER DELIVERED TO PERTH	PER M WORKING FACE OF DEVICE	PER 2GW RATED INSTALLATION
UPPER BOUND 95% CONFIDENCE	7.3	0.73
MEAN	6.2	0.62
LOWER BOUND 95% CONFIDENCE	5.1	0.51

100,000m +
19,550

Figure 7.9

APPENDIX A

CONSULTANTS PRODUCTIVITY ANALYSES

1. SHALLOW WATER CORRECTION

As the inshore and offshore buoys are located in transitional water depths the power associated with each wave is a function of both the wave height - period and depth. To take depth into account the variance of each frequency component of the recorded spectra has been divided by the appropriate shoaling coefficient. The proceedures used for both the inshore and offshore spectra are described briefly below:

a) Offshore Buoy:-

Available data - 399 digital spectra.

Divide the amplitude of each frequency component of each digital spectrum by the shoaling coefficient given by the formula

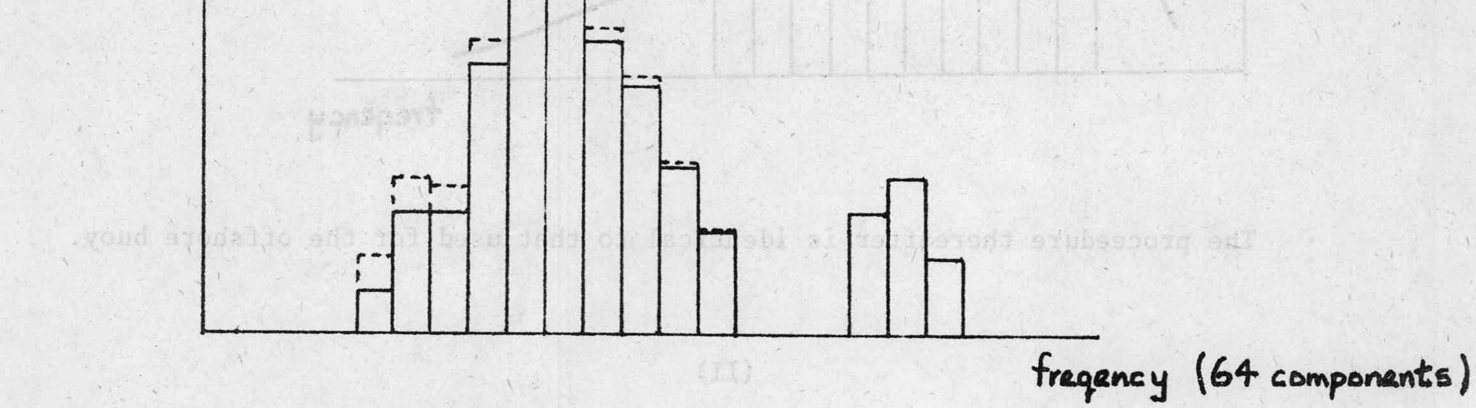
$$K = \left[\frac{1}{\tanh(2\pi d/L)} \times \frac{1}{\left(1 + \frac{4\pi d/L}{\sinh(2\pi d/L)}\right)} \right]^{1/2}$$

Where d is the depth at the buoy

L is the wavelength $= g/(2\pi f^2)\tanh(2\pi d/L)$

g is the acceleration due to gravity

f is the wave frequency



The significant wave height and energy period are then derived for each spectrum using the following formulae:

$$H_s = 4\left(\sum_{i=1}^{64} S_i \times \Delta f\right)^{1/2} \quad , \quad T_e = \frac{\sum_{i=1}^{64} S_i / f_i}{\sum_{i=1}^{64} S_i}$$

where S_i is the modified variance

f_i is frequency

Δf is the frequency increment

b) Inshore Buoy:-

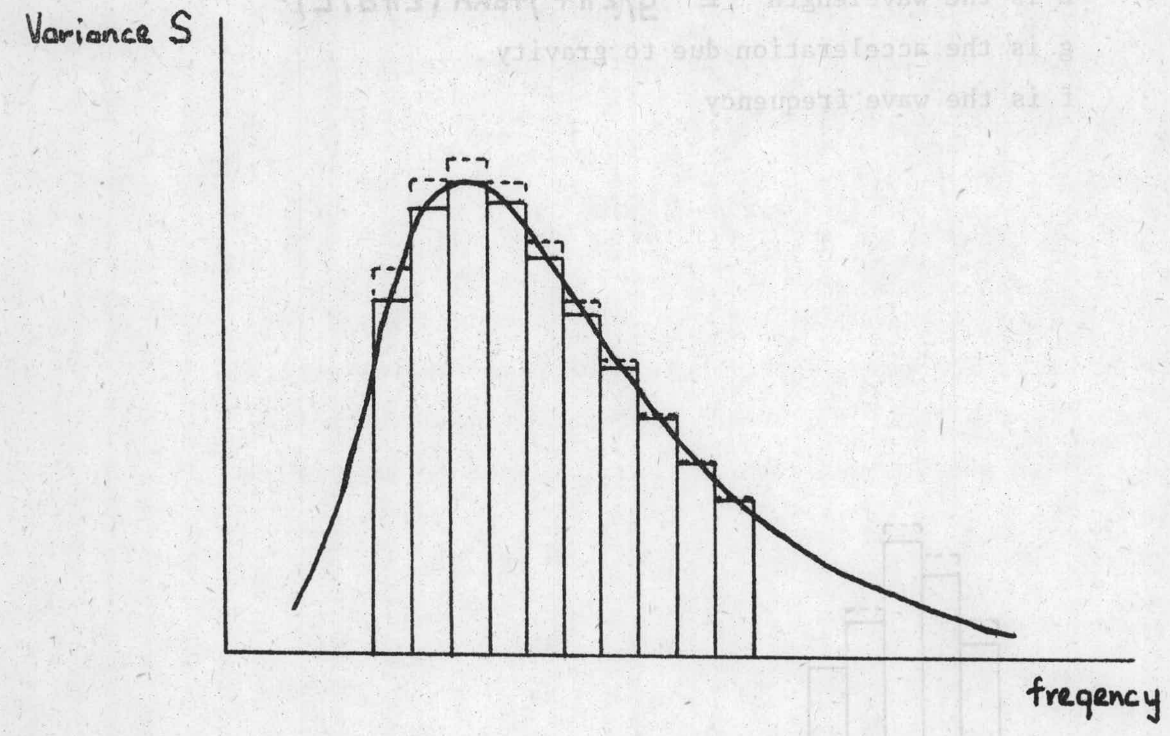
Available data - 1259 pairs of H_s, T_e calculated directly from the recorded spectra without modification to allow for depth.

For each pair of H_s, T_e values reconstruct the Pierson - Moskowitz curve using the formula:

$$S = 0.16875\, H_s^2 / (T_e^4 . f^5)\, \mathrm{axp}\left(-\frac{0.6750}{T_e^4 . f^4}\right)$$

where f is frequency

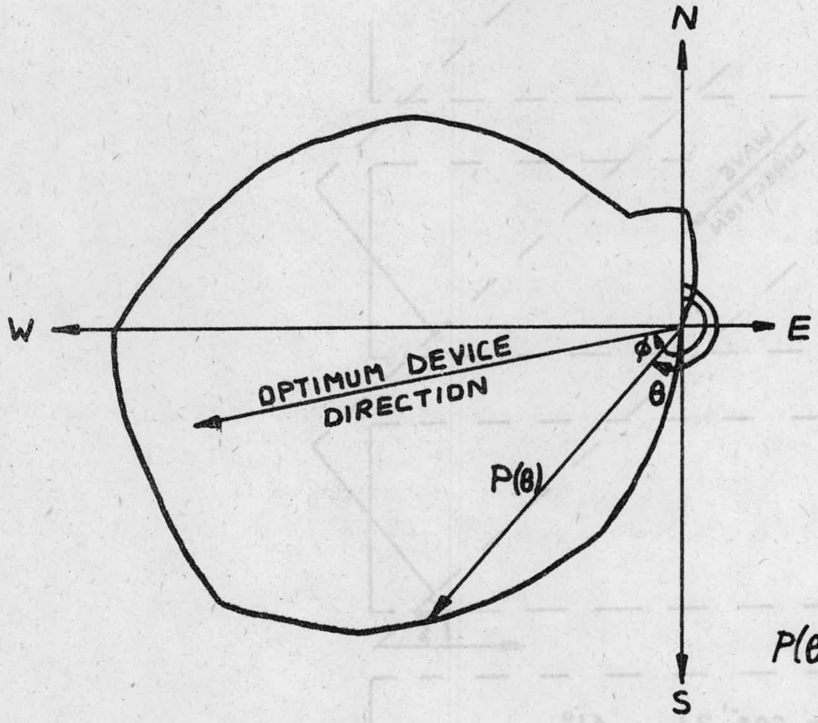
and divide the curve into 64 frequency components.



The proceedure thereafter is identical to that used for the offshore buoy.

2. DIRECTIONALITY FACTOR

Using the wave power rose given in the productivity section two values of the directionality factor have been determined.



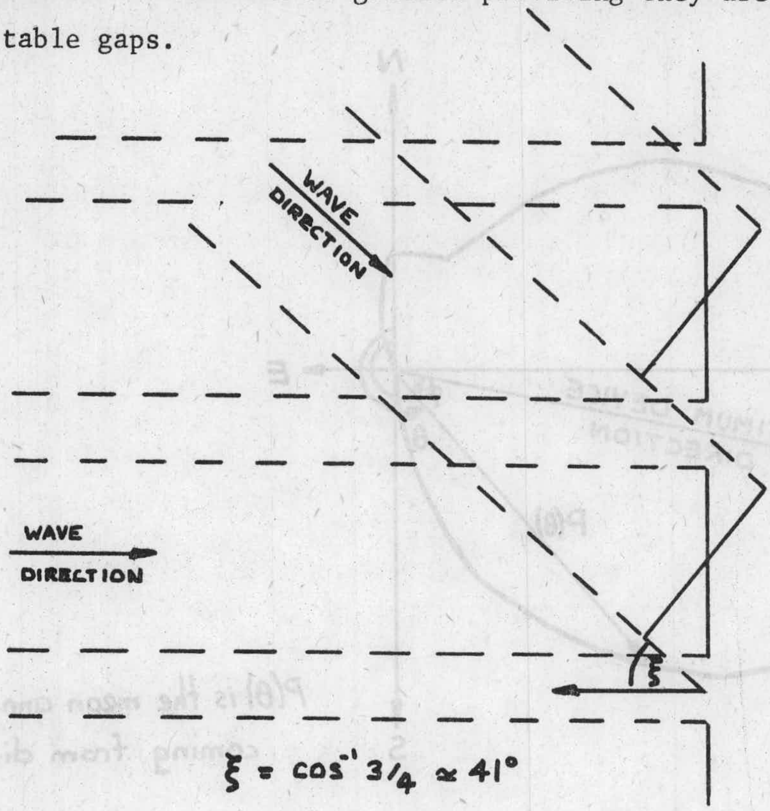
P(θ) is the mean annual power coming from direction θ

The directionality factor for a fixed device facing the optimum direction is 0.78 and has been determined using the formula

$$\int_{\phi-\pi/2}^{\phi+\pi/2} P(\theta)\cos(\phi-\theta)\,d\theta$$

A directionality factor of 0.83 has been assumed for shallow water devices, as the above wave rose applies strictly to water depths of 55 - 100m and some narrowing down of the wave rose in shallow water can be expected due to retraction.

For devices resembling point absorbers and for devices which can swing round to face the direction of the waves the energy available to them can be greater providing they are separated by suitable gaps.



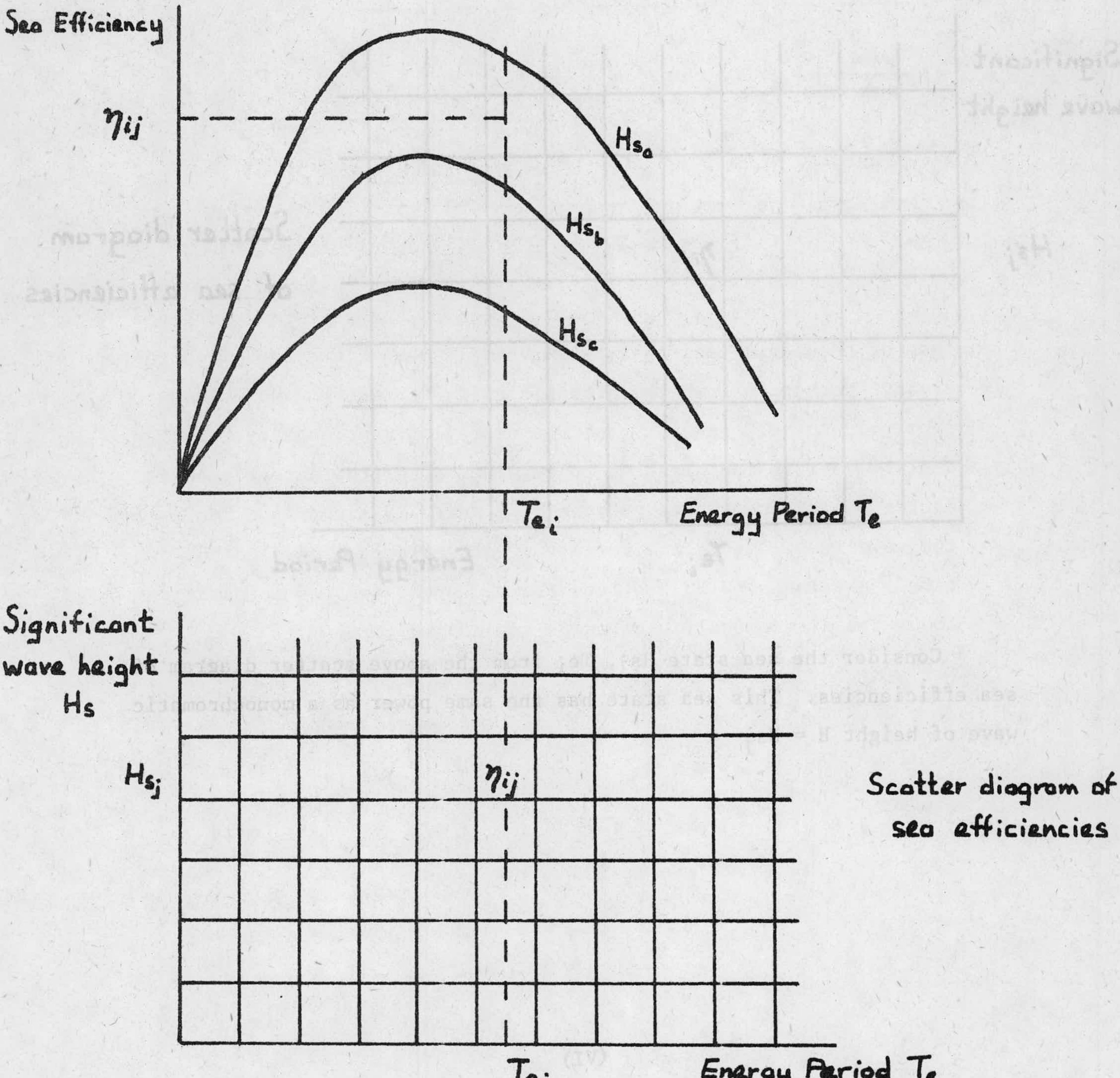
If we assume a gap equal to 1/3 of the effective working face of the device and that the waves all come from the same direction at any instant in time, the directionality factor for angles ranging from -41° to +41° is unity and the overall directionality for the whole wave rose can be shown to be 0.88. The true directionality factor will be somewhere between 0.78 and 0.88 since in a real sea the waves may come from a variety of directions at any instant in time. A value of 0.83 has been assumed until further information about the directionality of waves is acquired.

3. CALCULATION OF SEA EFFICIENCY BASED ON PIERSON-MOSKOWITZ SPECTRA

Depending on the type of data available, this was done as follows:-

a) From sea efficiency data

This data is directly applicable provided an appropriate wave spectra type was used during testing. The sea efficienty curves are stored by the computer program in the form of a sea efficiency scatter diagram, derived in the following way:-

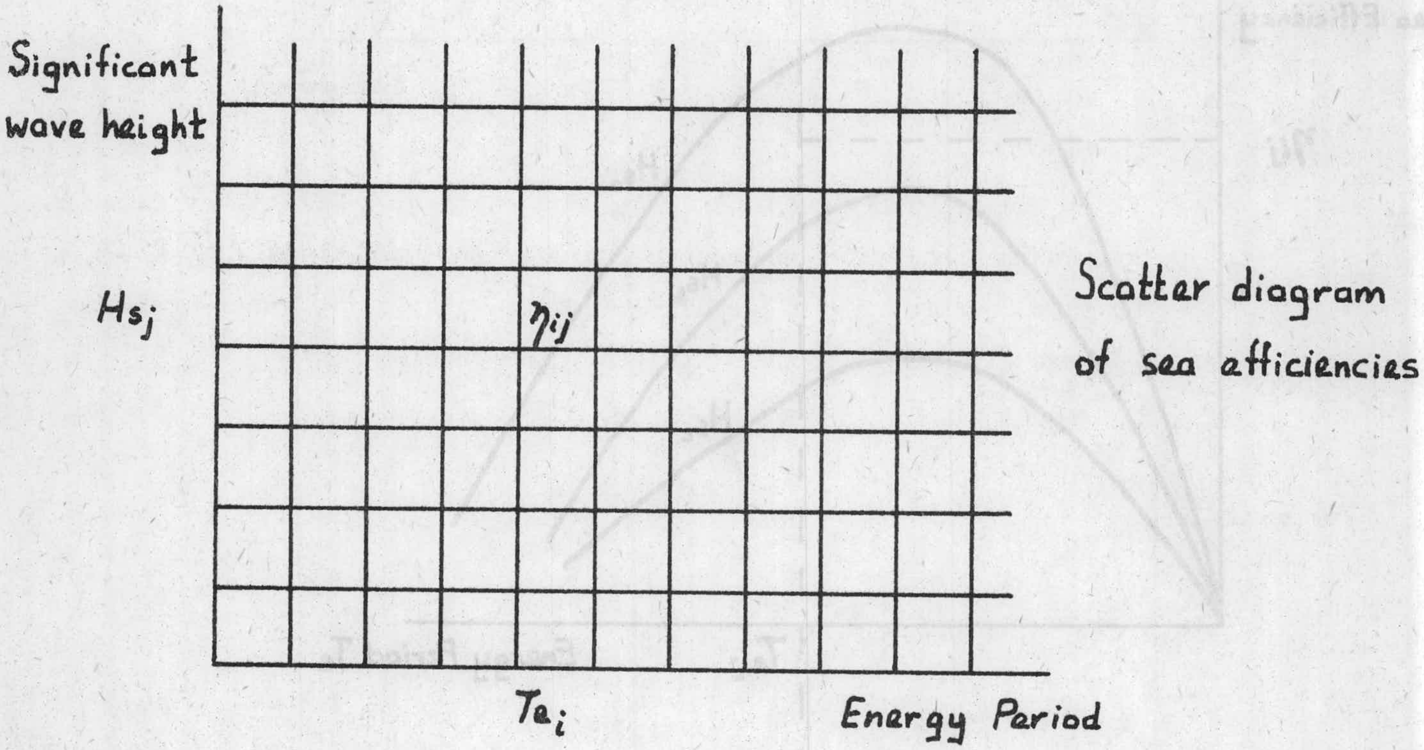


To determine the efficiency for the sea state Hs_j, Te_i the program finds the position of Te_i along the abscissa of the sea efficiency curve and then determines the efficiency η_{ij} by linear interpolation between the curves for $Hs_a < Hs_j < Hs_b$.

This process is repeated for all the sea boxes.

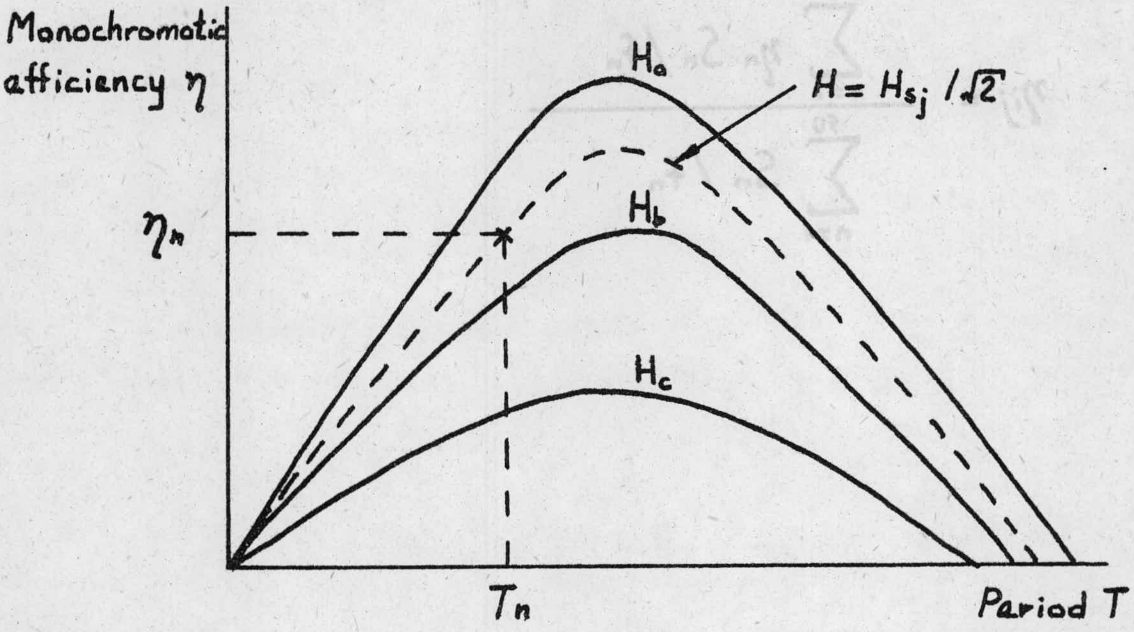
b) From monochramatic efficiency data

Random sea efficiencies are calculated from the monochromatic efficiency curve by numerical integration. The procedure is described below.

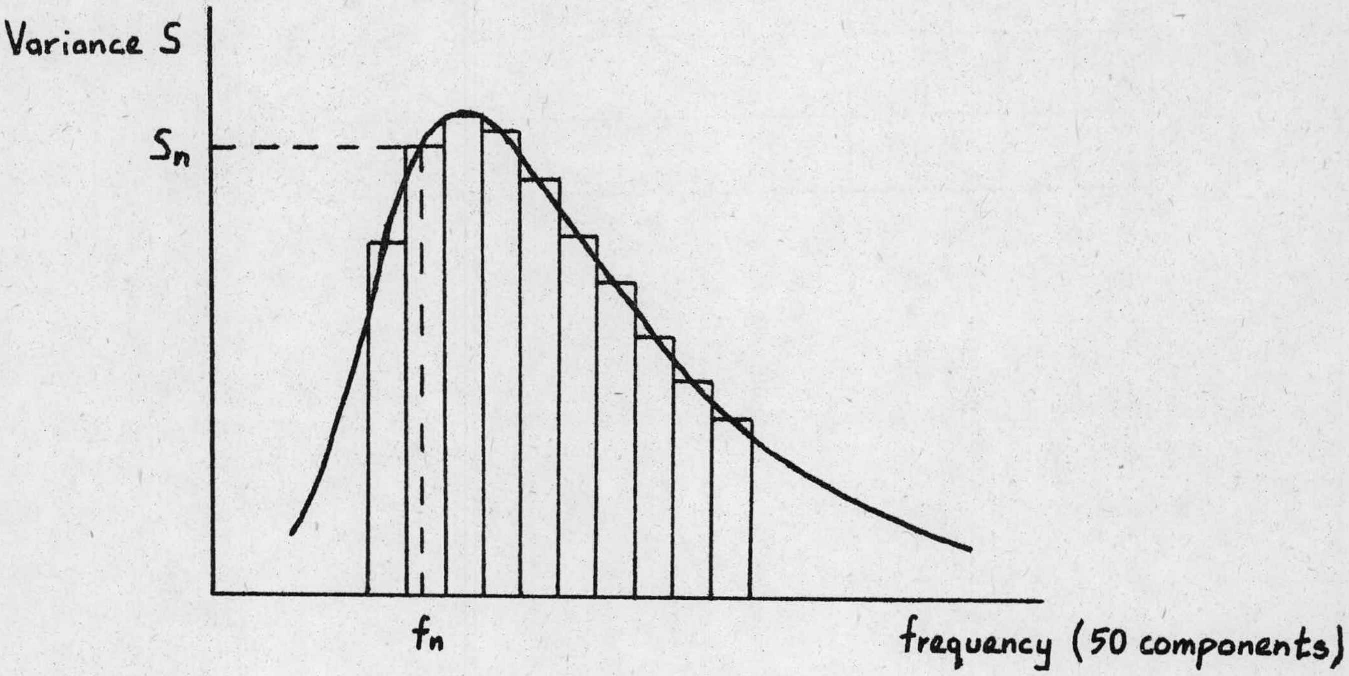


Consider the sea state Hs_j, Te_i from the above scatter diagram of sea efficiencies. This sea state has the same power as a monochromatic wave of height $H = Hs_j$

A typical monochromatic efficiency curve is shown below



The program constructs a new monochromatic efficiency curve by linear interpolation between the curves for $H_a < H_{sj}/\sqrt{2} < H_b$
It then constructs the Pierson-Moskowitz curve for the sea state Hsj, Tei and divides it into 50 frequency components.



Let $T_n = 1/f_n$
η_n is the monochromatic efficiency for the frequency component f_n.

The sea efficiency for the sea state Hs_j, Te_i is then derived using the formula

$$\eta_{ij} = \frac{\sum_{n=1}^{50} \eta_n S_n / f_n}{\sum_{n=1}^{50} S_n / f_n}$$

4. CALCULATION OF SEA EFFICIENCY BASED ON DIGITAL SPECTRA

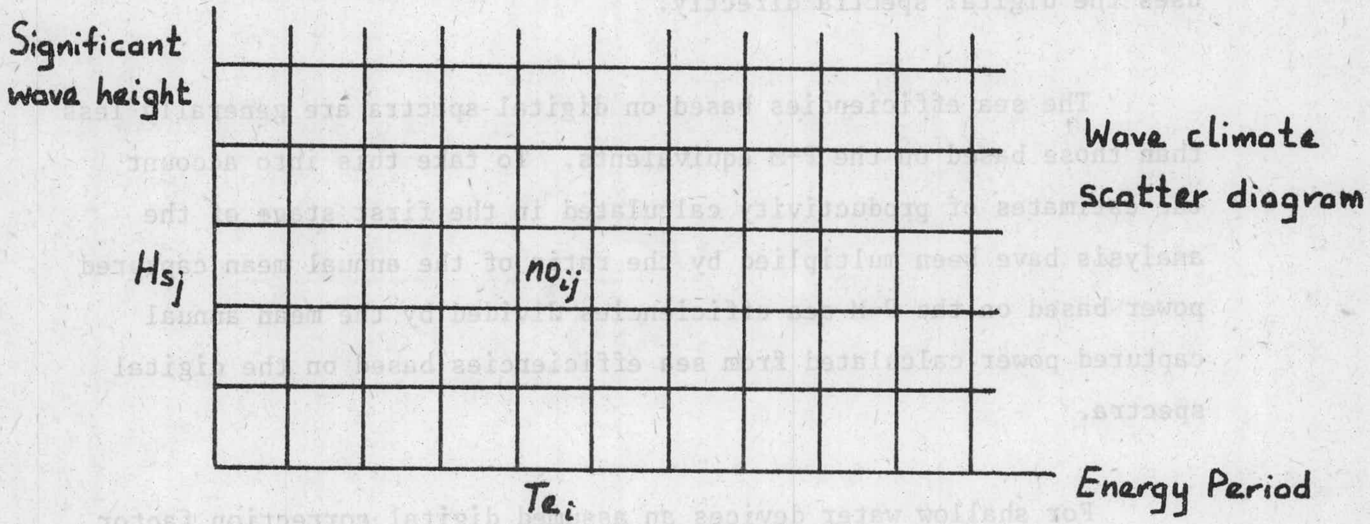
These are derived in much the same way as the sea efficiencies based on P-M spectra, but instead of using the Pierson-Moskowitz equivalents of the 399 recorded offshore digital spectra the program uses the digital spectra directly.

The sea efficiencies based on digital spectra are generally less than those based on the P-M equivalents. To take this into account the estimates of productivity calculated in the first stage of the analysis have been multiplied by the ratio of the annual mean captured power based on the P-M sea efficiencies divided by the mean annual captured power calculated from sea efficiencies based on the digital spectra.

For shallow water devices an assumed digital correction factor of 0.95 has been used, as the digital spectra recorded at the inshore buoy have not yet been made available to the Consultant.

5. CAPTURE EFFICIENCY

The annual capture efficiency of a device is defined as the mean annual captured power divided by the mean annual incident power and is derived in the following way.



In the above wave climate scatter diagram no_{ij} represents the fractional occurence of the sea state Hs_j, Te_i.

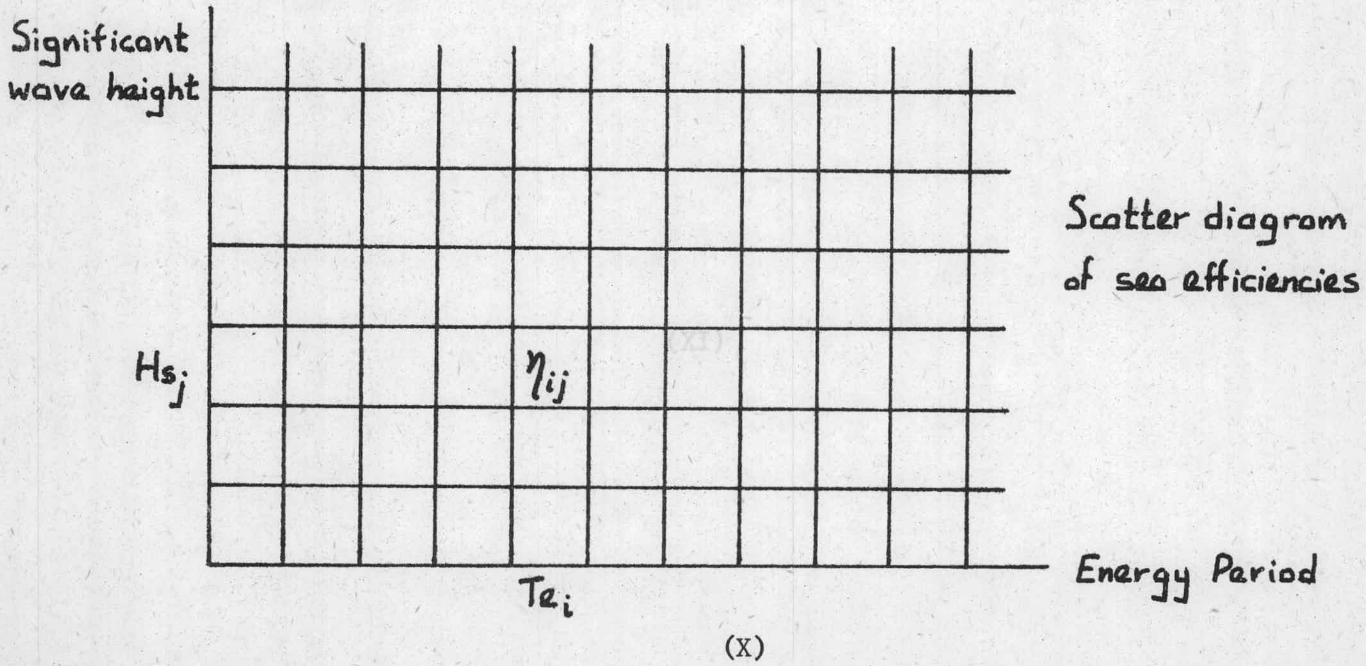
The average power available in the sea box Hs_j, Te_i is given by the expression

$$P_{sea_{ij}} \qquad no_{ij}\, \rho g^2/(64\pi)\; Hs_j^2\, Te_i$$

and the average incident power

$$P_{inc_{ij}} = P_{sea_{ij}} \,.\, \overline{\cos\theta}$$

where $\overline{\cos\theta}$ is the directionality factor



The captured power for the sea state Hs_j, Te_i is then given by

$$P_{cap_{ij}} = P_{sea_{ij}} \,.\, \overline{\cos\theta} \,.\, \eta_{ij}$$

where η_{ij} is the sea efficiency associated with Hs_j, Te_i.

The annual capture efficiency is then given by the ratio of the mean captured power over a whole year divided by the mean incident power during that year.

$$\text{Capture efficiency} = \frac{\cancel{\overline{\cos\theta}} \displaystyle\sum_{i=1}^{25} \sum_{j=1}^{25} P_{sea_{ij}} \,.\, \eta_{ij}}{\cancel{\overline{\cos\theta}} \displaystyle\sum_{i=1}^{25} \sum_{j=1}^{25} P_{sea_{ij}}}$$

6. POWER CHAIN EFFICIENCY

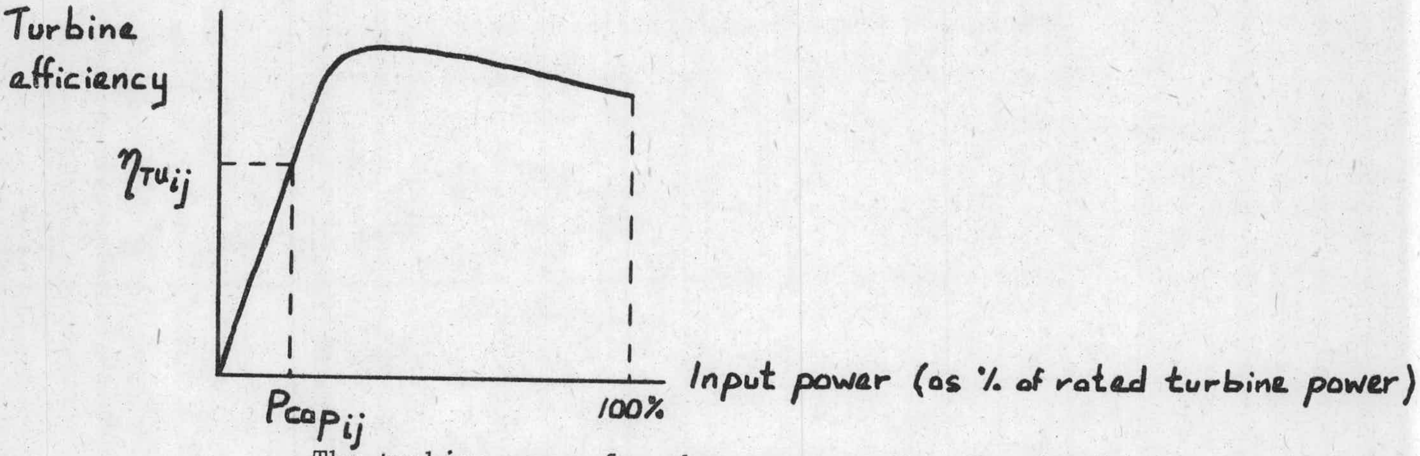
The annual power chain efficiency is defined as the mean annual power delivered to Perth divided by the mean captured power. It is derived as follows.

The average captured power for the sea state Hs_j, Te_i is given by the expression

$$P_{cap_{ij}} = P_{sea_{ij}} \cdot \overline{\cos\theta} \cdot \eta_{ij}$$

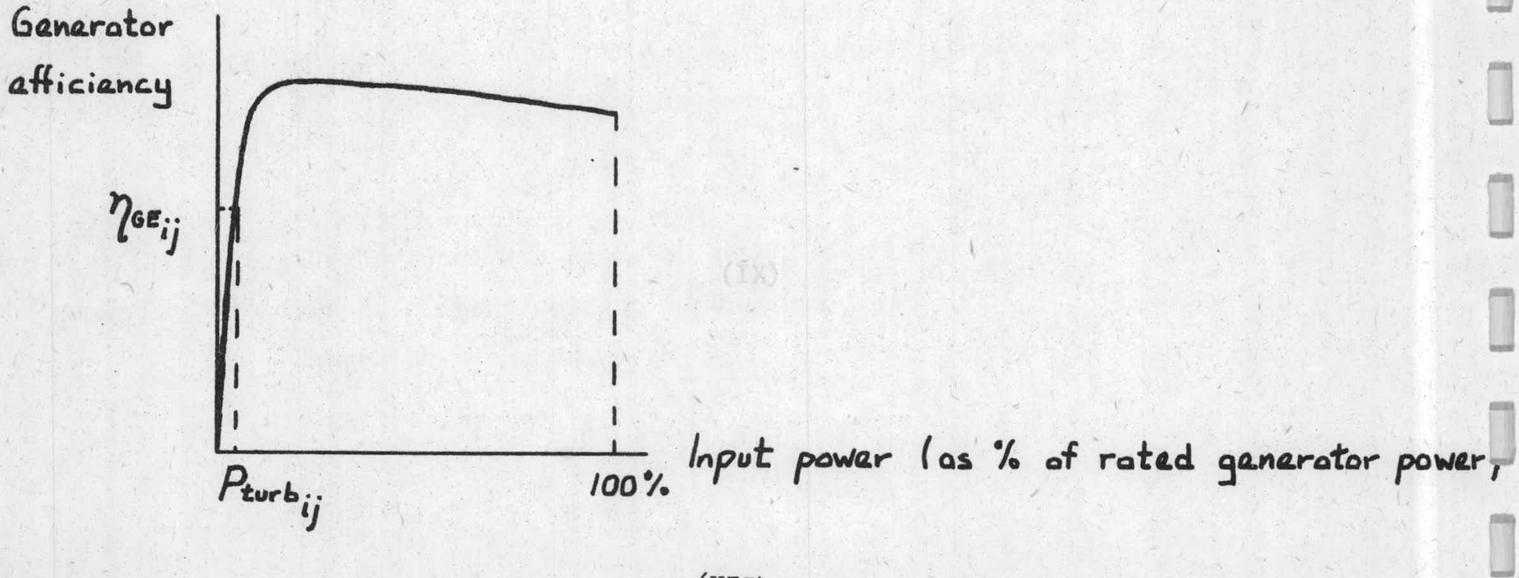
and is assumed to be constant.

Typical steady state efficiency curves of the power chain components are shown below.

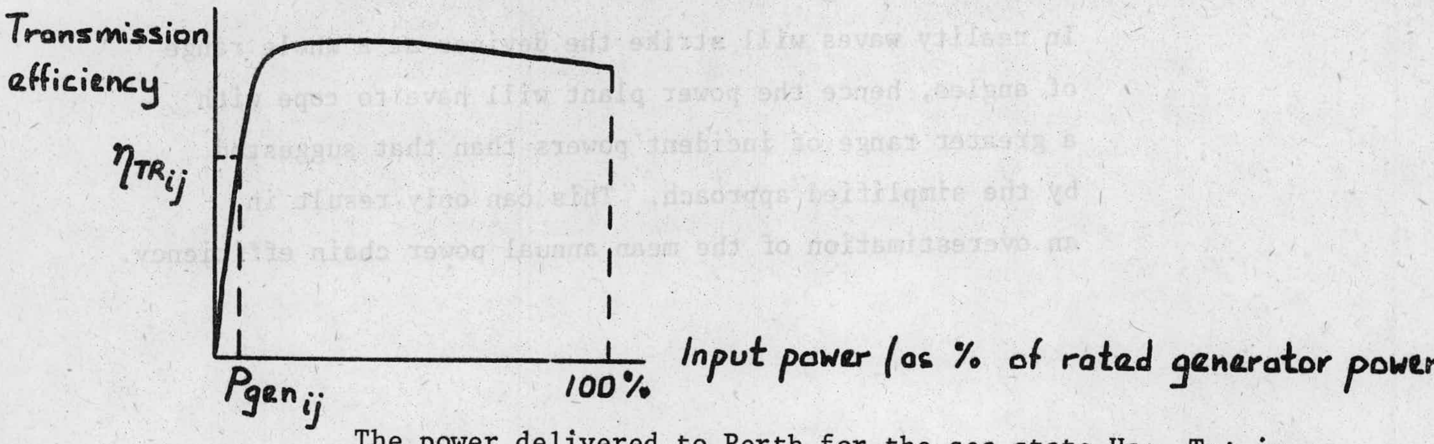


The turbine power for the sea state Hs_j, Te_i is given by

$$P_{turb_{ij}} = P_{cap_{ij}} \cdot \eta_{TU_{ij}}$$



The generator power is given by $P_{gen_{ij}} = P_{turb_{ij}} \, . \eta_{GE_{ij}}$



The power delivered to Perth for the sea state Hs_j, Te_i is

$$P_{Perth_{ij}} = P_{gen_{ij}} \, . \, \eta_{TR_{ij}} = P_{sea_{ij}} \, . \, \overline{\cos\theta} \, . \, \eta_{ij} \, . \, \eta_{TU_{ij}} \, . \, \eta_{GE_{ij}} \, . \, \eta_{TR_{ij}}$$

The annual power chain efficiency is then given by the ratio of the mean power delivered to Perth over a whole year divided by the captured power.

$$\text{Power chain efficiency} = \frac{\cancel{\overline{\cos\theta}} \displaystyle\sum_{i=1}^{25} \sum_{j=1}^{25} P_{sea_{ij}} . \eta_{ij} . \eta_{TU_{ij}} . \eta_{GE_{ij}} . \eta_{TR_{ij}}}{\cancel{\overline{\cos\theta}} \displaystyle\sum_{i=1}^{25} \sum_{j=1}^{25} P_{sea_{ij}} \, \eta_{ij}}$$

The above calculations are repeated for several values of plant rating in order to determine the size of plant which gives the optimum mean annual power chain efficiency.

Two simplifications made in the above analysis could lead to an overestimation of the harnessed power.

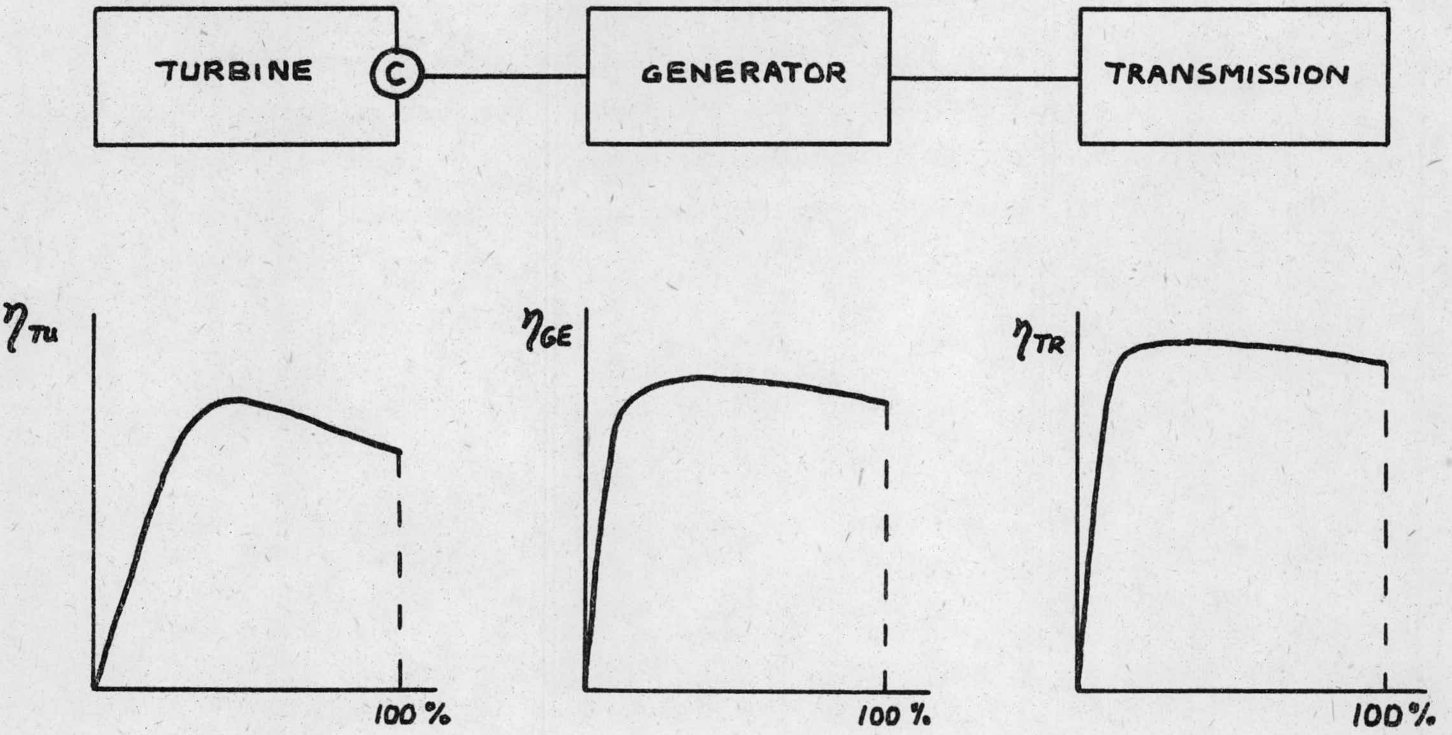
These are:

1) The power associated with each sea state Hs_j, Te_i has been assumed constant and no account of the random nature of the sea power has been taken.

2) The incident powers are all assumed to arrive at the device at an angle $\cos^{-1} 0.78$ or $\cos^{-1} 0.83$ In reality waves will strike the devices at a whole range of angles, hence the power plant will have to cope with a greater range of incident powers than that suggested by the simplified approach. This can only result in an overestimation of the mean annual power chain efficiency.

7. NUMBER OF DEVICES

The number of devices required for a 2 GW rated station has been calculated as follows:-



The above diagram shows a typical power take off scheme. The curves represent steady state efficiencies for each component plotted against input load expressed as a percentage of the rated load.

For optimum design the generator rating should be equal to the turbine rating multiplied by the turbine efficiency at 100% load, the transmission rating should be equal to the generator rating multiplied by the generator efficiency at full load, and finally the power station rating per metre length of device should be equal to the transmission rating multiplied by the transmission efficiency at full load.

As an example let us assume that the optimum plant rating (i.e. generator rating) for a 200 m long device is 100 kw/m and that the generator and transmission efficiencies at full load are 85% and 90%. The transmission rating should then be equal to 100 x 85 kw/m and the power station rating should be equal to 85 x 0.9 = 76.5 kw/m and hence the number of devices required for a 2 GW rated station is equal to 2000000/(200 x 76.5) = 130