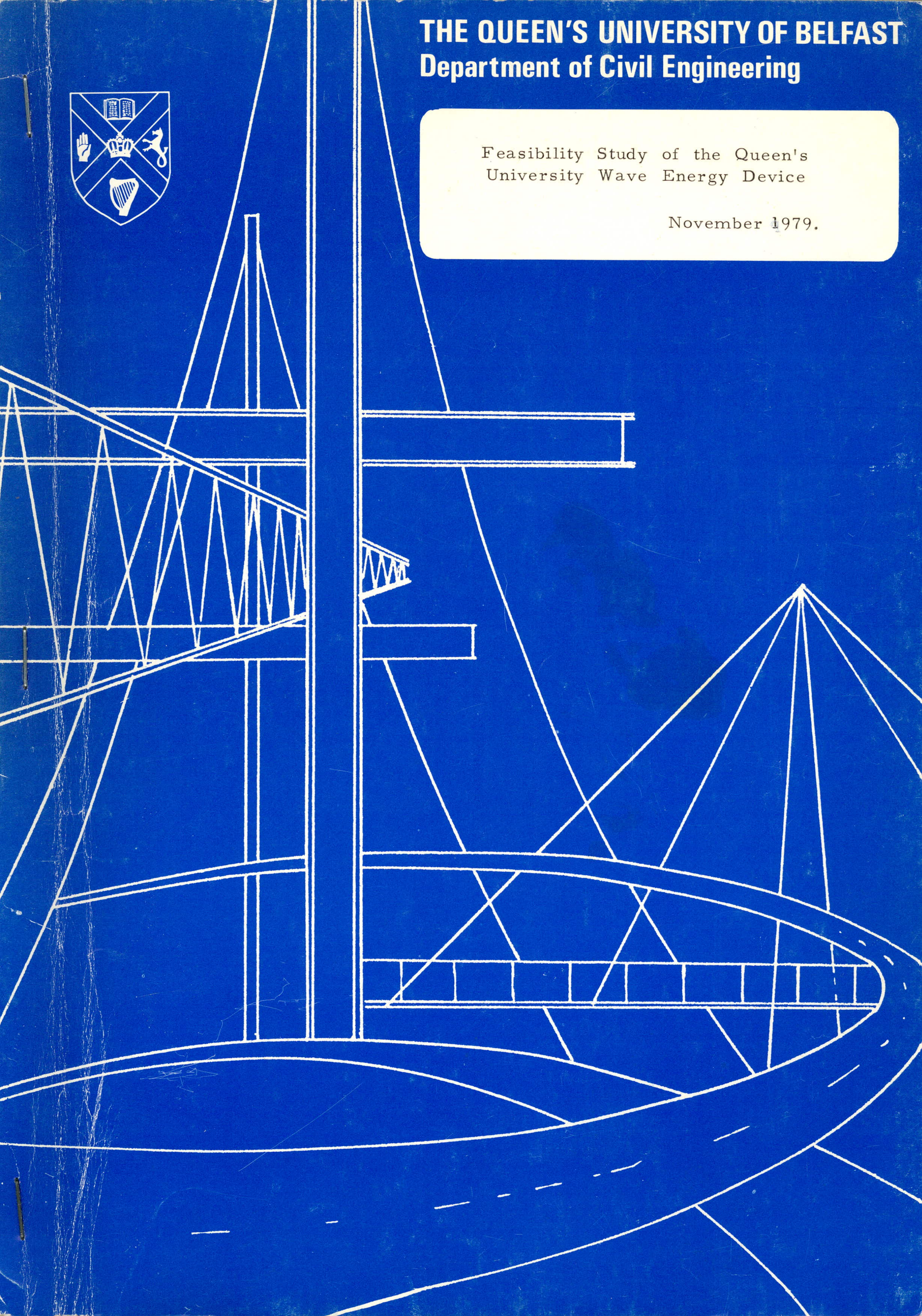
THE QUEEN'S UNIVERSITY OF BELFAST
Department of Civil Engineering

Feasibility Study of the Queen's University Wave Energy Device

November 1979.



Bob Robinson

Revised Feasibility study of the Queen's University Wave Energy Device

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1. INTRODUCTION

1.1 General

In order to assess the Queen's University device on a more realistic basis than in 1978 it has been found expedient to adopt a point absorbing device which is directly moored to the sea bed via a rigid tension leg system (shown schematically in Fig. 1). This type of mooring effectively restricts the heave motion of the device and as a consequence it corresponds closely with the fixed canopy tests which have been carried out in our upgraded test facility over the past 2 months. These tests have shown excellent repeatability and the extraction efficiencies have been found to be considerably greater than those for the 1978 device. It was therefore considered logical at this time to concentrate our efforts on this system especially as it was estimated that the costs of moorings and overall structures would not be appreciably altered from those for a less restrained device.

The other alternative of assessing a device based on the estimated drop-off in extraction efficiency, which would occur if the canopy was not fully fixed against heave motion was abandoned for this feasibility study as it would have been based on too many uncertainties. In the near future when the appropriate series of model tests on the flexible mooring system have been carried out it is intended that a comparative feasibility study will be made.

At this time it is important to emphasise that the hydrodynamic model studies have not as yet yielded the optimum configuration for the form of device being considered this year and as a consequence the overall costs are still likely to be pessimistic. It is in this context and on the understanding that the consultants will attempt to take these considerations into account that the team embarked on this further feasibility study.

The main objectives of this study were to:

(1) obtain an approximate overall estimate of the cost of the latest form of the QUB device for use in comparison with other wave energy devices and with conventional thermal power systems.

and

(2) assess the relative contributions of moorings, structures, electrical and turbine to the cost of the overall system.

As in 1978 the device team does not consider that a comprehensive submission can be made at this time. However, attempts have been made to produce more realistic general arrangement drawings of the proposed structure and a more detailed appraisal has been made of possible mooring arrangements and the generation and transmission system.

1.2 Advantages over 1978 device

Whilst the proposed system may differ in many aspects from the optimum form of a point absorbing device it does have a number of advantages over that considered in the 1978 submission. The more important advantages are:-

(1) The extracted efficiencies are considerably higher than those utilised in 1978 and in addition the drop off in efficiency for larger waves is much less marked.

(2) The single leg mooring system means that problems associated with the interference of conventional chain moorings is eliminated. As a consequence devices can be located in an array at approximately 100m centres which coincides with the spacing used in the model tests.

(3) The demands on the single core flexible submarine cables would be much less than previously because relative movements would be greatly reduced.

(4) The most vulnerable part of the structure, the canopy, could be replaced without having to replace the overall structure including the moorings as the concrete chamber can now be made buoyant and a stable unit in its own right.

The advantages have however to be balanced against the possible disadvantages of the more rigid system having to sustain much more severe wave slamming forces. In addition it may be conceivable in the future that a more flexible moored device can be arrived at which has comparable extraction efficiency.

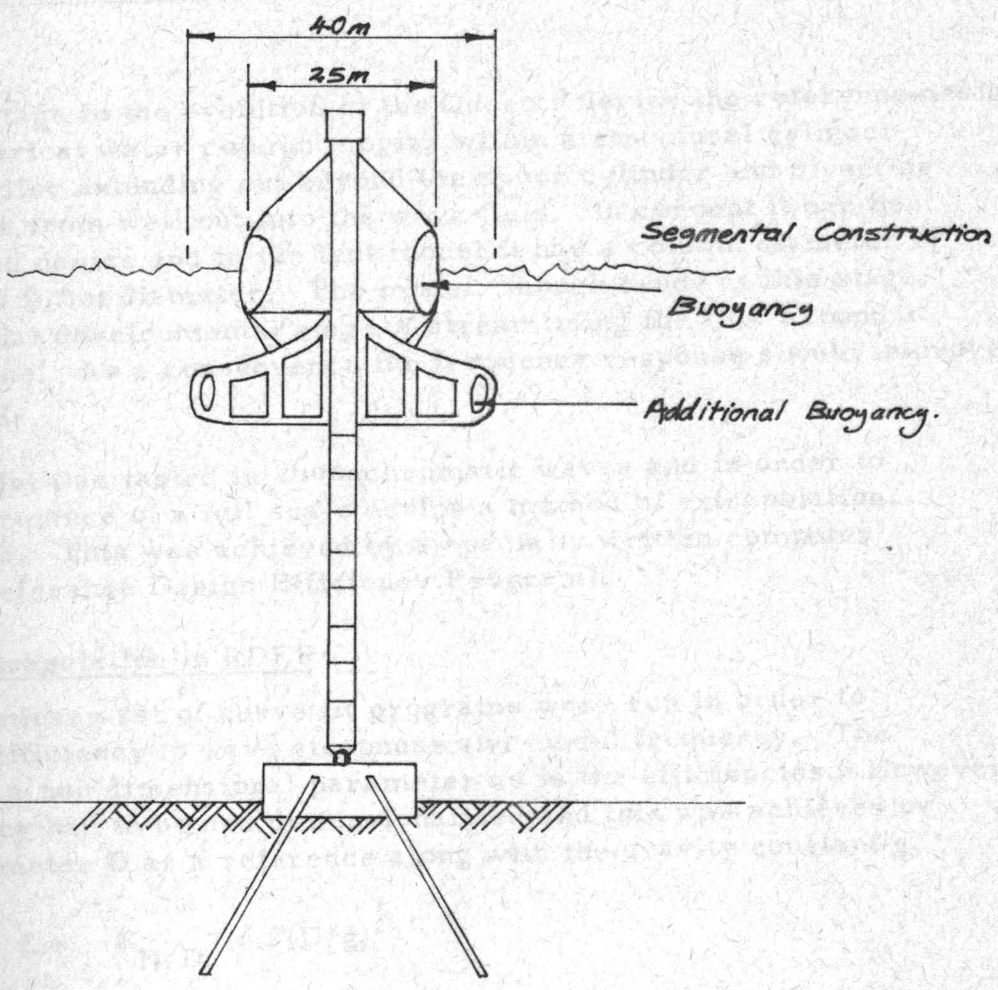


FIG 1.

Buoyancy must not be too high so that lateral movements are not restricted unduly which will enable surge motions to contribute to the Power absorbed.

This system is much less compliant vertically than the previous system but this should greatly improve energy extraction capabilities.

Scale 1:1000.

Department of Civil Engineering
The Queen's University of Belfast

2. SELECTION OF DEVICE DIAMETER AND ESTIMATION OF MEAN POWER GENERATED.

2.1 Introduction

At this stage in the evolution of the Queen's device the reference design for 1979 is a cylindrical water column moving within a structural cylinder attached to a base disc extending out beyond the upper cylinder and directing flow into the device from well out into the wave field. In concept it can be described as a fixed device and in the test model it had a column diameter of 0.4m with a disc of 0.6m diameter. The model, though crude at this stage, represents the initial developmental stage of streamlining the flow around a wave energy device. As a consequence the frequency response should improve with further testing.

The model was tested in monochromatic waves and in order to estimate the performance of a full scale device a method of extrapolation had to be conceived. This was achieved by a specially written computer program RDEP (Reference Design Efficiency Program).

2.2 Method of Extrapolation in RDEP

(i) A preliminary set of curve fit programs were run in order to relate the device efficiency to wave steepness and model frequency. The wave steepness is a non dimensional parameter as is the efficiencies. However, the model frequency had to be non dimensionalised and this was achieved by using the buoy diameter D as a reference along with the gravity constant g.

$$\text{i.e} \quad F_{N.D.} = F(D/g)^{\frac{1}{2}}$$

(ii) The model used for the North Atlantic is the pure wind sea model devised by Pierson Moskowitz to describe a random sea. This is a weighting envelope for adjusting amplitudes for the different frequency components in a random sea and was written into the program as a function which weighted the ten frequency intervals on either side of the average energy frequency. This was considered sufficient as the amplitudes at each end of the envelope approached zero. The average conditional parameters for each sea state were stored in an array along with the percentage occurrence per annum.

(iii) The power contained in each element of the P.M. sea for each sea state was calculated knowing the amplitude and frequency. This value was then multiplied by the efficiency corresponding to that frequency for a specific buoy diameter using the response curve fits and summed up over the total envelope. Hence, the pneumatic power converted was estimated for each sea state.

(iv) The pneumatic power was then multiplied by a further efficiency factor to cover the turbine, electrical and directional losses. This consisted of a combination of a figure of 0.65 for the turbine and 0.75 for the electrical and directional components to give an overall efficiency of 0.5 to bring the pneumatic power ashore. The program allowed a generation plant rating to be set and for each buoy diameter this was optimised until the maximum output was just obtained (see Table 1). This prevented over-rating the generation plant.

(iv) The final matrix of power produced for each possible sea state was multiplied by the percentage occurrence values of that sea state and the total power summed up to give the mean annual device productivity (see Table 2). Thus for each buoy diameter an annual productivity figure can be predicted. This is the mean annual power received ashore from a wave energy convertor.

2.3 Costing

The 1978 reference design used a costing unit base on the cube of the buoy diameter. Rendel Palmer and Tritton in their costing came up with an optimised diameter based on the diameter to the power of approximately 2.75. In this years submission it is proposed that the costing should be based on the square of the diameter, since

(1) The device is essentially a shell structure which has a volume closer to the square rather than the cube. (Assuming that the thickness is largely controlled by corrosion resistance requirements).

(ii) The mooring costs were shown to be significant to the costing. Since approximately 50% of these costs are associated with the device placement then it is not unreasonable to assume that the cost of moorings is related to the device diameter raised to the power of between 1 and 2. This is because the number of moorings laid is proportional to the number of devices and the forces and material costs are dependent on the device area.

2.4 Final device size

The chosen costing unit this year is to be the mean annual production over the diameter squared (kW/m^2). However, it was noted that the response curves of the device predicted a slightly larger device (from considering the power matrices) and an optimum diameter of 24m was chosen with a generation plant rating of 1250kW.

Table 1

Plant optimisation results for 24m diameter device

Plant rating	Total Mean Power generated	Max. power to turbine
1000	206.9	1369
1250	211.7	1369
1500	212.6	1369

optimised rating

Table 2

Buoy Diameter (m)	Optimised plant rating (kW)	Total mean power generated (kW)	Max. power to turbine (kW)	Device output (kW/m)*	Device output (kW(m²)*
5	10	3	12	0.61	0.12
10	100	28	121	2.81	0.28
12	200	46	209	3.80	0.32
14	250	68	357	4.85	0.35
16	300	91	504	5.65	0.35
18	500	121	698	6.74	0.37
20	750	152	983	7.53	0.38
22	1000	182	1173	8.26	0.37
24	1250	212	1333	8.82	0.37
26	1500	238	1940	9.14	0.35
28	1750	262	2091	9.36	0.33
30	2000	289	2782	9.64	0.32
35	3000	343	3524	9.80	0.28
40	4000	384	4532	9.59	0.24

* The output being divided by the diameter and the diameter squared respectively.

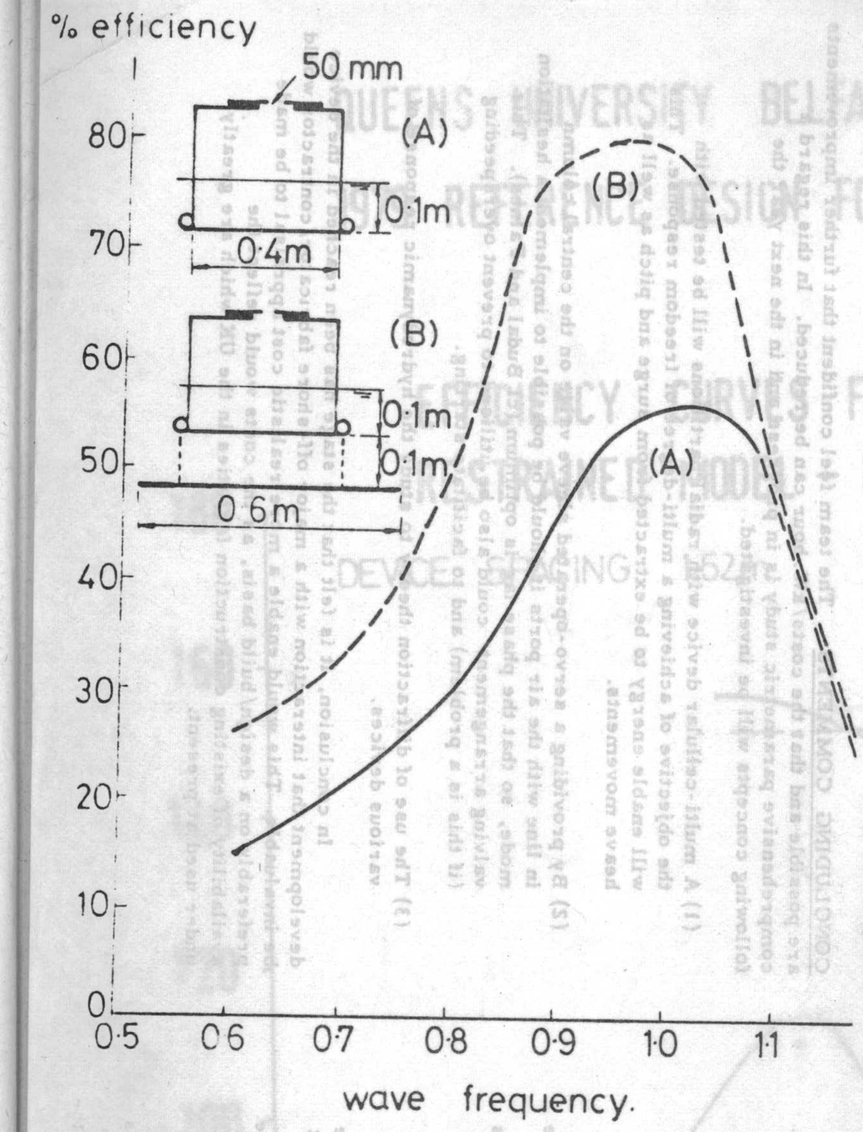


Fig. 1

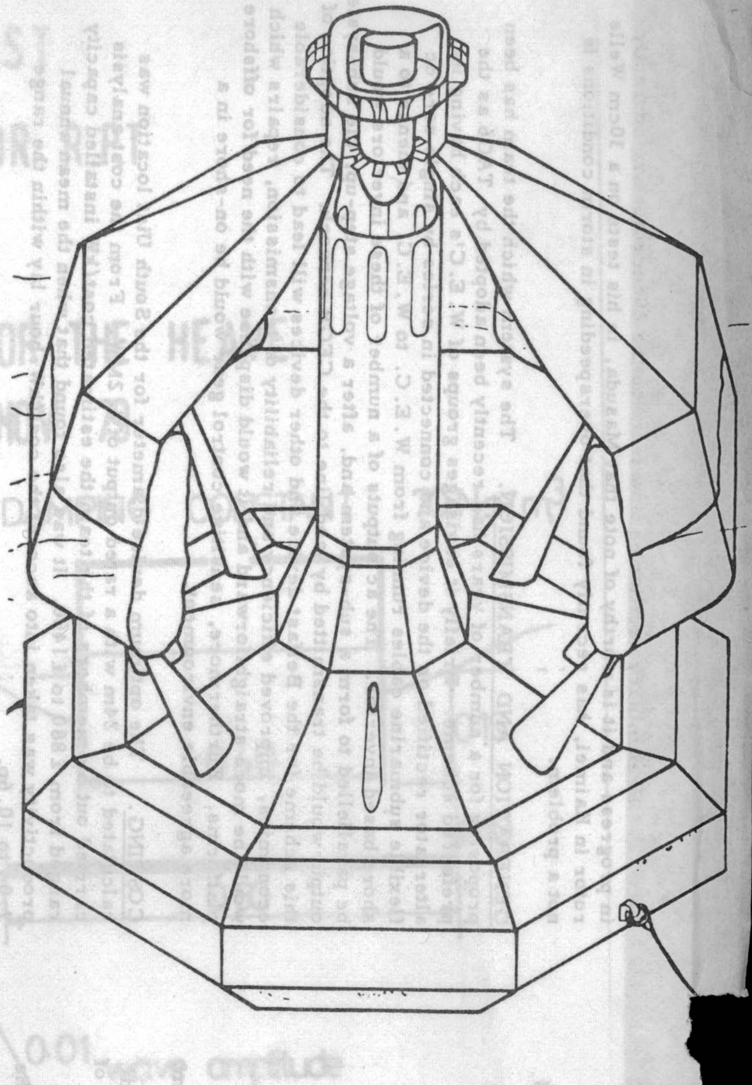


Fig. 2

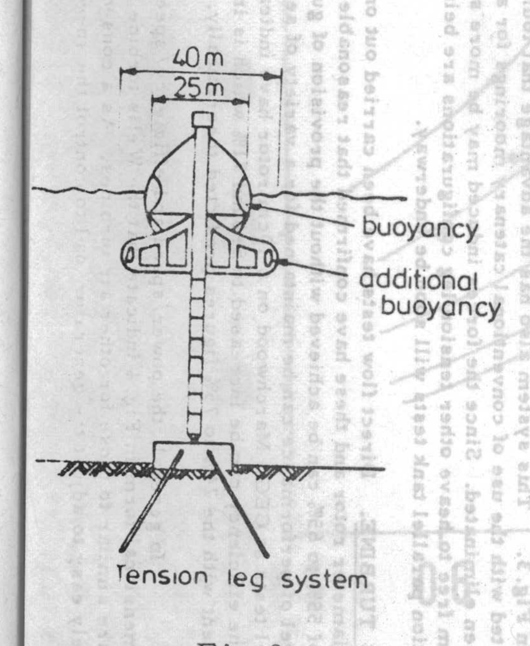


Fig. 3

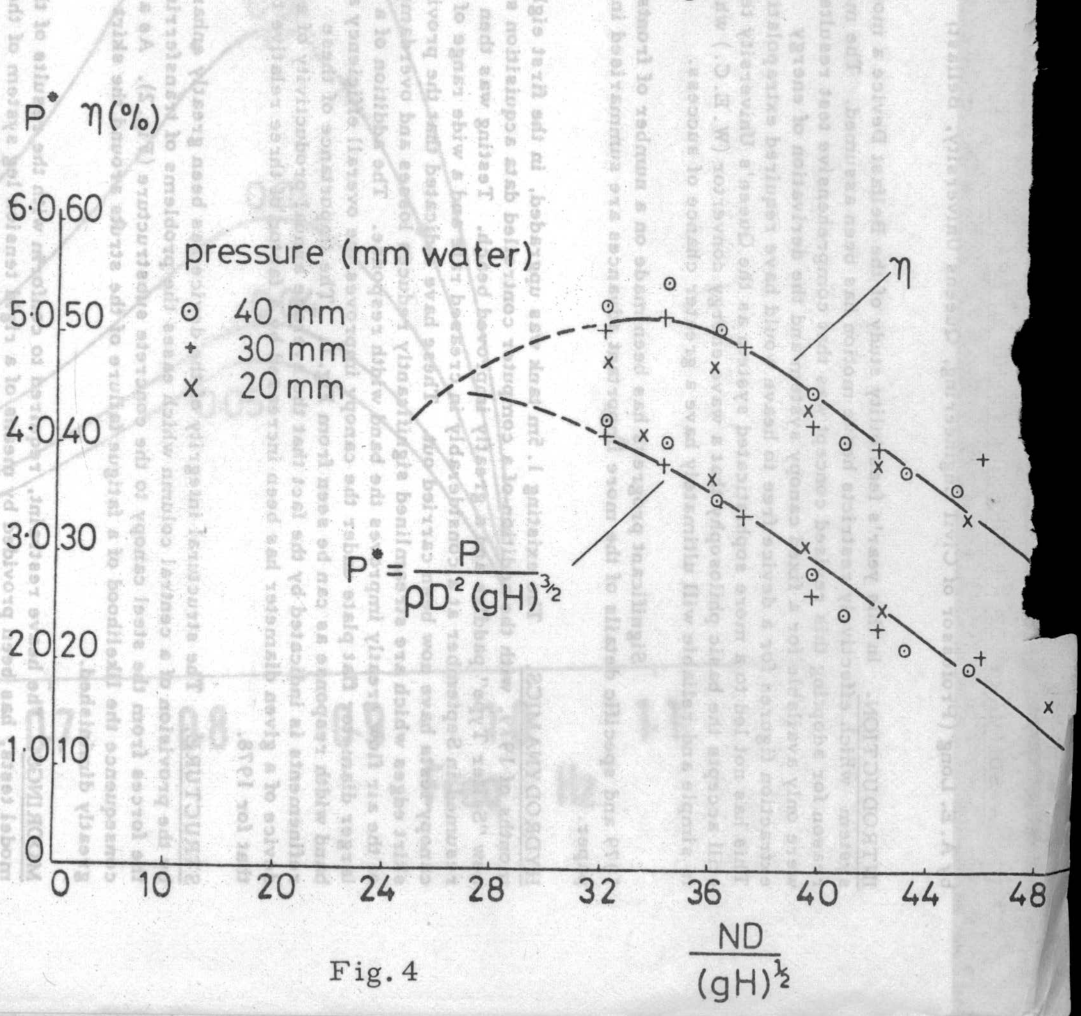


Fig. 4

A SUMMARY OF PROGRESS ON THE BELFAST DEVICE

by A. E. Long (Professor of Civil Engineering, Queens University, Belfast)

INTRODUCTION. In this year's feasibility study of the Belfast Device a mooring system which effectively restricts heave motion has been assumed. The main reason for adopting this revised concept was that comprehensive test results were only available for a fixed canopy system and the derivation of energy extraction figures for a device free to heave would have required extrapolation. This has not led to a more sophisticated system as the Queen's University team still accepts the basic philosophy that a wave energy convertor (W. E. C.) which is simple and reliable will ultimately have a greater chance of success.

Significant progress has been made on a number of fronts in 1979 and specific details of the more important advances are summarised in this paper.

HYDRODYNAMICS. The existing 1.5m tank was upgraded, in the first eight months of 1979, with the addition of a computer controlled data acquisition system, new "Salter Type" paddles and a greatly improved beach. Testing was then resumed in September at a considerably increased rate and a wide range of fixed canopy tests have now been carried out. These have indicated that the provision of skirt edges which are streamlined significantly reduces losses and overdamping of the air flow greatly improves the band width response. The addition of a larger diameter flat plate under the canopy improves the overall efficiency and the band width response as can be seen from Fig. 1. The importance of these refinements is indicated by the fact that the average annual productivity of a device of a given diameter has been increased by a factor of three relative to that for 1978.

STRUCTURE. The structural integrity of the device has been greatly enhanced by the provision of a central column which eases the problems of transferring the forces from the steel canopy to the concrete substructure (Fig. 2). As a consequence the likelihood of a fatigue failure of the struts around the skirt is greatly diminished.

MOORINGS. The heave restraint, required to conform with the results of the model tests, has been provided by means of a rigid tension leg system of the type shown in Fig. 3. This system also has the advantage that fouling problems associated with the use of conventional catenary moorings for an array of devices have been eliminated. Since the forces induced may be more severe than for a system free to heave other tension leg configurations are being considered and in addition parallel tank tests will soon be underway.

WELLS TURBINE. Direct flow tests have been carried out on a single stage 20cm diameter rotor and these have confirmed that reasonable efficiencies of the order of 55% to 65% can be achieved without the provision of guide vanes and that this level of performance can be maintained for a variety of sea states.
Parallel tests at CEGB Marchwood on a 40cm rotor have indicated that with guide vanes the efficiency can be increased to around 71% which is in reasonable agreement with the 74% to 75% figures predicted theoretically.

In general, the power/speed and efficiency/speed curves shown in non-dimensional form in Fig. 4 indicate that the Wells turbine has characteristics which are similar to those for other air turbines. As a consequence it should be relatively easy to adjust the generator load to control the speed and so optimise the output.

Preliminary oscillating flow tests on the 20cm rotor are currently in progress and it is worthy of note that Masuda, in his tests on a 30cm Wells rotor in Kaimei, has recently found that overspeeding in storm conditions is not a problem.

GENERATION AND TRANSMISSION. The system which the team has been proposing for a number of years has recently been adopted by TAG6 as the preferred scheme. Briefly it envisages groups of W. E. C's each having its alternator rectified on the device and connected in series by single core dc flexible submarine cables running from W. E. C. to W. E. C. and thence to a shore based invertor. The ac outputs of a number of these invertors would be parallelled to form a sub-system and, after a voltage step-up, the sub-system output would be transmitted by land line to the CEGB network. The adoption of this scheme for the Belfast device and other devices will lead to considerable economies, improved efficiency and reliability of transmission, repairs which would be more straightforward and it would dispense with the need for offshore platforms. Furthermore, sensitive control gear would be on-shore in a more agreeable environment.

COSTING. The optimum device diameter for the South Uist location was calculated to be 24m with a rated output of 1.2MW. From the cost analysis carried out by members of the team the estimated cost/kW installed capacity ranged from £880 to £1460. It was also found that when the mean annual productivity was taken into account the cost/kW. hour lay within the range 7.0p to 10.6p.

CONCLUDING COMMENTS. The team feel confident that further improvements are possible and that the costs/kW. hour can be reduced. In this regard a comprehensive parametric study is in progress and in the next year the following concepts will be investigated.

(1) A multi-cellular device with radial partitions will be tested with the objective of achieving a multi-degree of freedom response. This will enable energy to be extracted from surge and pitch as well as heave movements.

(2) By providing a servo-operated sleeve valve on the central column in line with the air ports it should be possible to implement a hesitation mode, so that the phase lag is optimum (cf Budal and Falnes). This valving arrangement could also be utilised to prevent overspeeding (if this is a problem) and to facilitate starting.

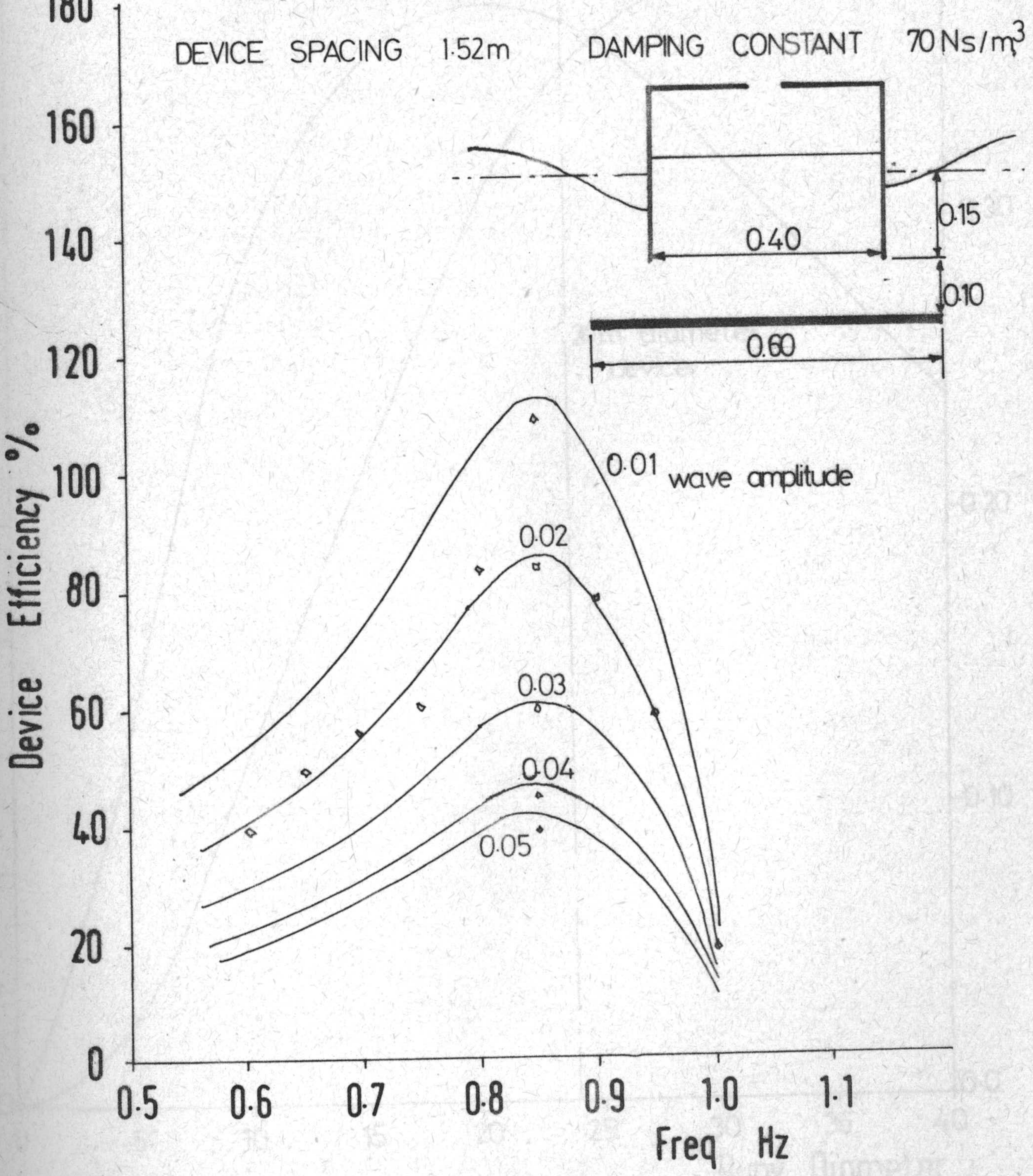
(3) The use of diffraction theory to study the hydrodynamic response of various devices.

In conclusion, it is felt that the stage has been reached in the device development that interaction with a major off-shore fabricator/contractor would be invaluable. This would enable a more realistic cost appraisal to be made preferably on a design/build basis, as the costs would reflect the availability of existing construction facilities in the UK which are greatly under used at present.

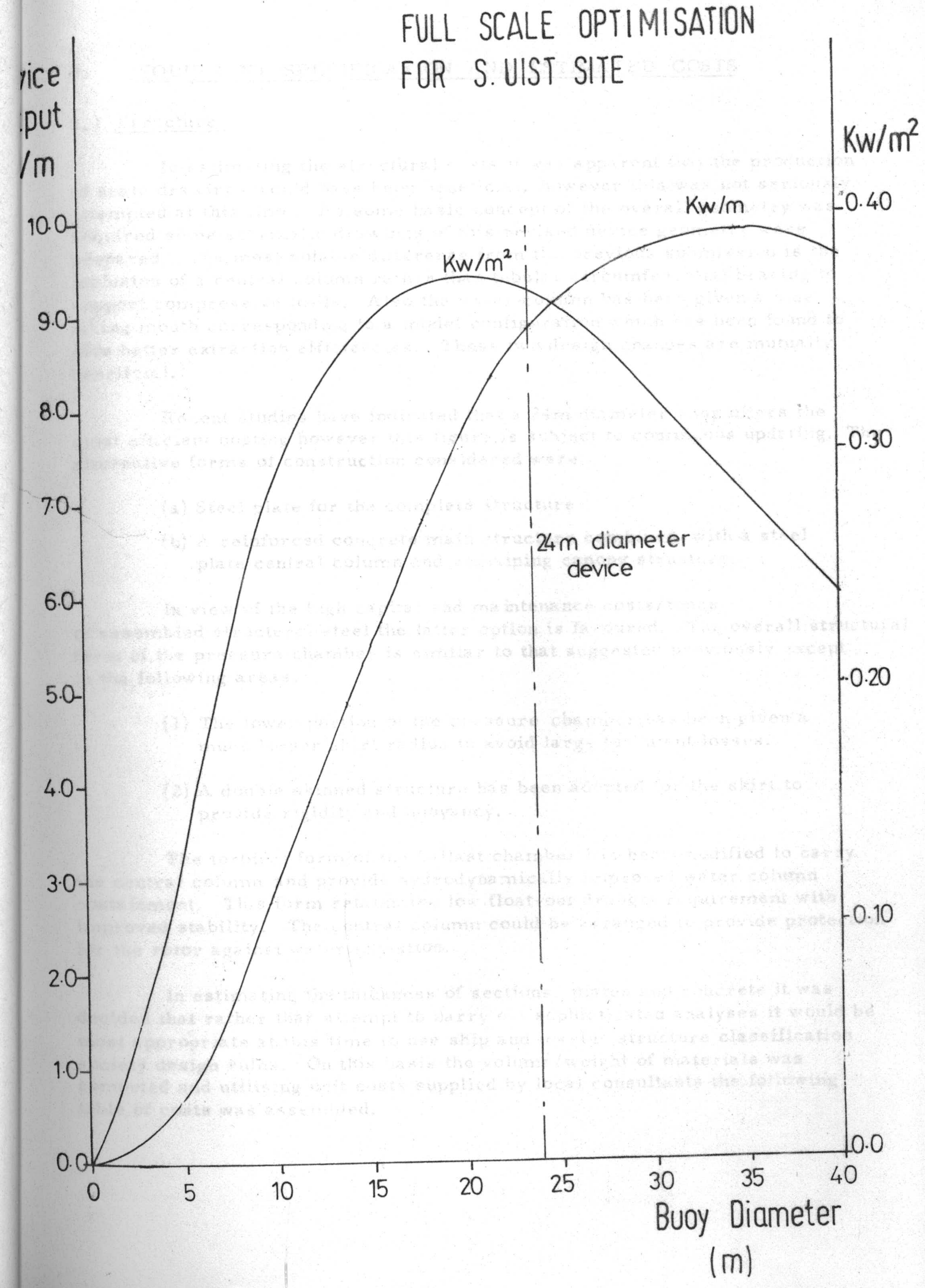
QUEENS UNIVERSITY BELFAST

1979 REFERENCE DESIGN FOR R.P.T

EFFICIENCY CURVES FOR THE HEAVE RESTRAINED MODEL - NOV 79



FULL SCALE OPTIMISATION FOR S. UIST SITE



3. EQUIPMENT SPECIFICATION AND ESTIMATED COSTS

3.1 Structure

In estimating the structural costs it was apparent that the production of scale drawings would have been beneficial, however this was not seriously attempted at this time. As some basic concept of the overall geometry was required some schematic drawings of this revised device geometry were prepared. The most notable difference from the previous submission is the inclusion of a central column rather than tubular circumferential bracing to support compressive loads. Also the water column has been given a side facing mouth corresponding to a model configuration which has been found to give better extraction efficiencies. These two design changes are mutually beneficial.

Recent studies have indicated that a 24m diameter buoy offers the most efficient costing however this figure is subject to continuous updating. The alternative forms of construction considered were:

(a) Steel plate for the complete structure

(b) A reinforced concrete main structure combined with a steel plate central column and remaining canopy structure.

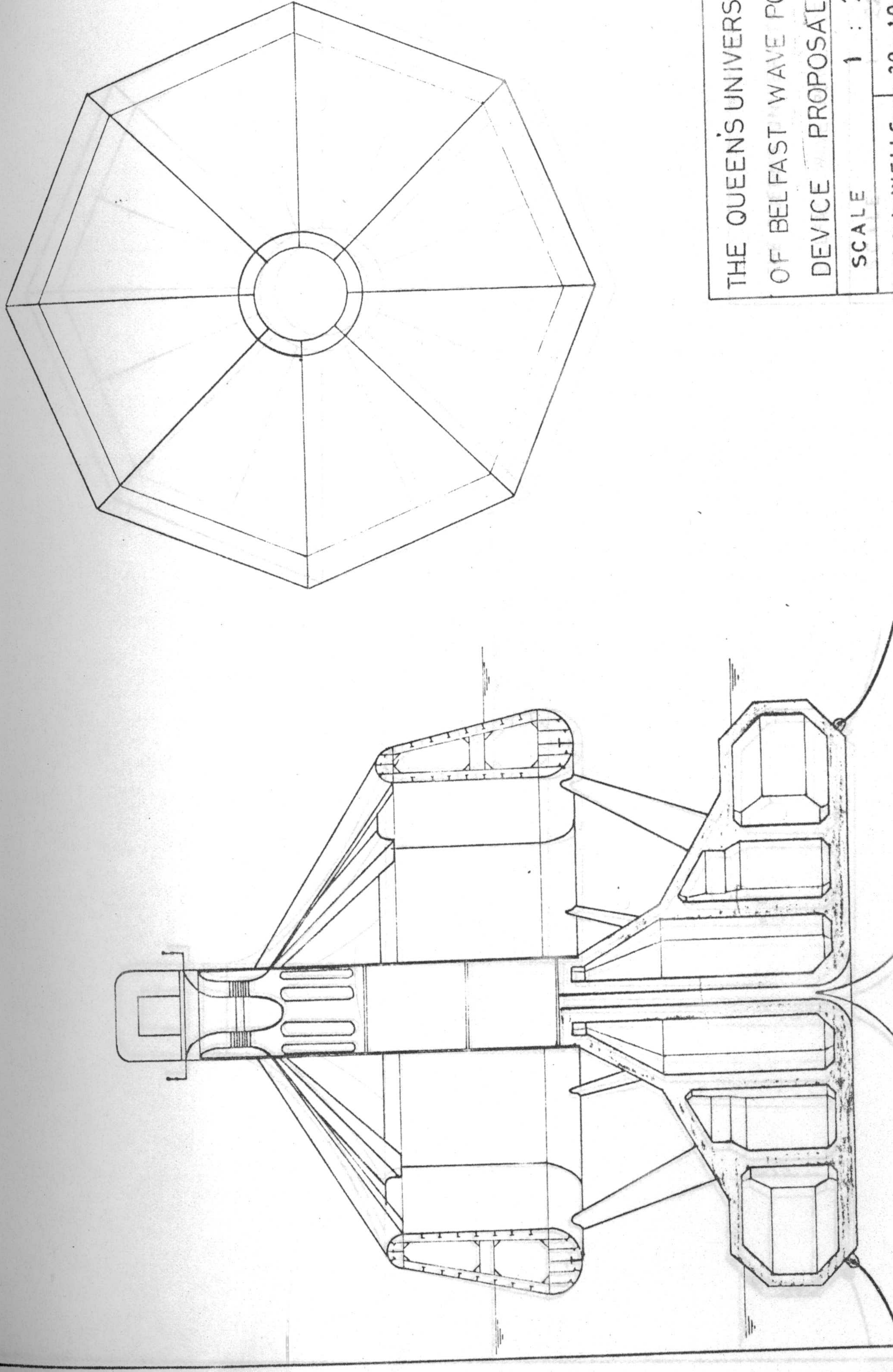
In view of the high capital and maintenance costs/tonne of assembled structural steel the latter option is favoured. The overall structural form of the pressure chamber is similar to that suggested previously except in the following areas.

(1) The lower portion of the pressure chamber has been given a much larger skirt radius to avoid large turbulent losses.

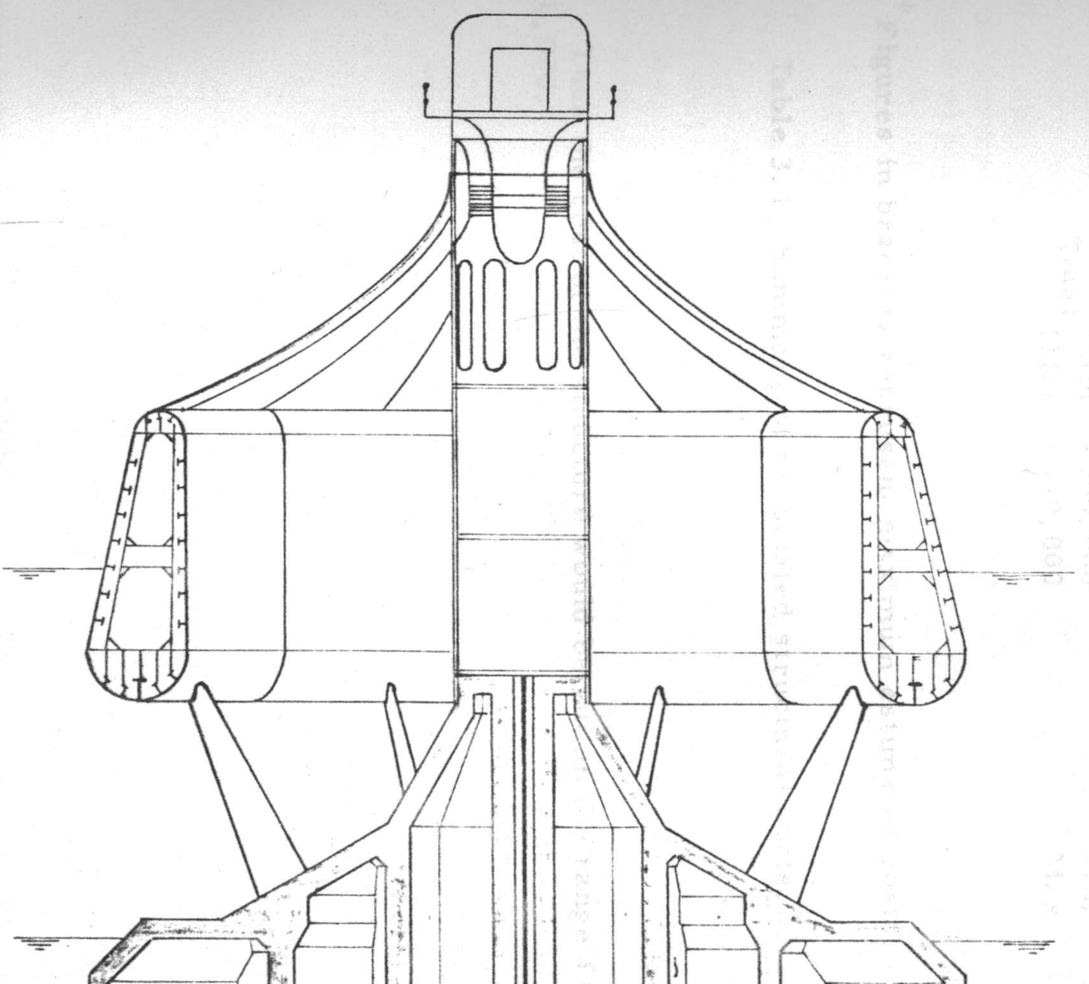
(2) A double skinned structure has been adopted for the skirt to provide rigidity and buoyancy.

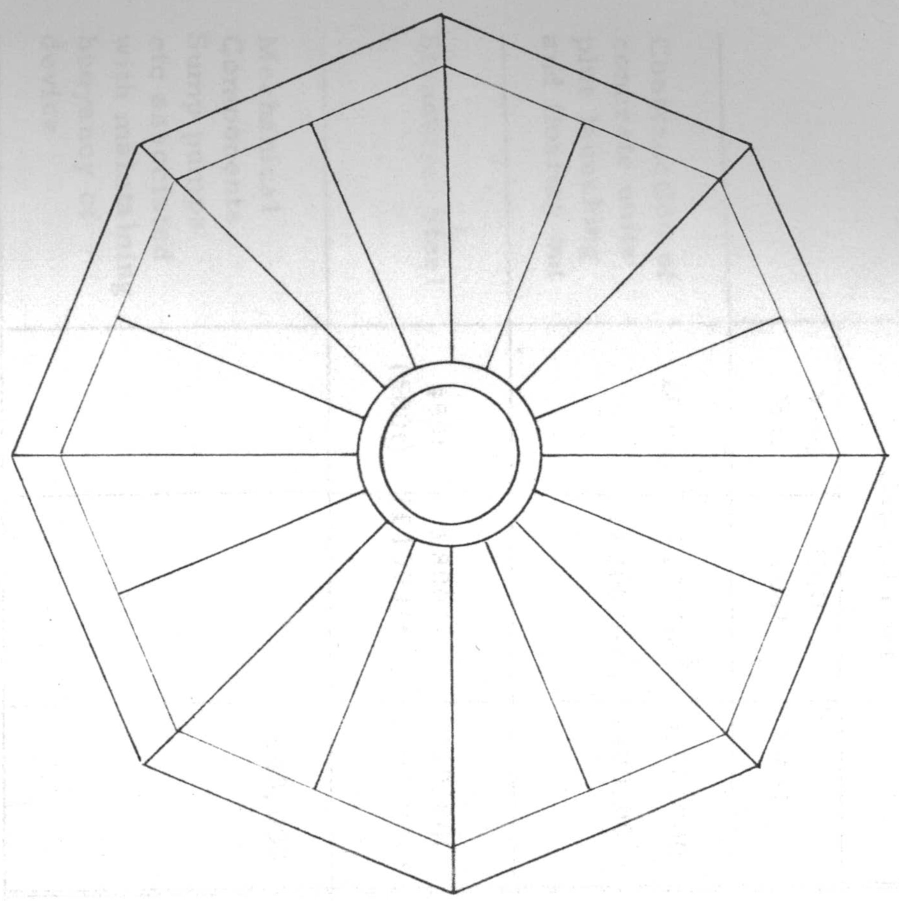
The toroidal form of the ballast chamber has been modified to carry the central column and provide hydrodynamically improved water column containment. This form retains the low float-out draught requirement with improved stability. The central column could be arranged to provide protection for the rotor against water ingestion.

In estimating the thickness of sections, plates and concrete it was decided that rather than attempt to carry out sophisticated analyses it would be most appropriate at this time to use ship and marine structure classification society design rules. On this basis the volume/weight of materials was computed and utilising unit costs supplied by local consultants the following table of costs was assembled.



THE QUEEN'S UNIVERSITY
OF BELFAST WAVE POWER
DEVICE PROPOSAL
SCALE 1 : 220
N A J WELLS
20 10 1979





THE QUEEN'S UNIVERSITY OF
BELFAST WAVE POWER DEVICE.

SCALE	1 : 220
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	Capital cost			Maintenance cost	
	Vol/ Wt.	Unit cost	Cost	% of Capital cost	Annual Cost
Construction of concrete units plus launching and floating out	$2000m^3$	£100/m^3 (£200/m^3)*	£200,000 (400,000)	1% 1%	£2000 (£4000)
Structural Steel	450t (500t)	£800/t (£1000/t)	£360,000 (500,000)	4%	£14,000 (£20,000)
Mechanical Components. Sump pumps etc associated with maintaining buoyancy of device			£40,000	3.5%	£1,200
Total		(Min (Max	£600,000 £940,000	Min Max	£17,600 £25,200

*Figures in brackets represent maximum estimated costs.

Table 3.1 Summary of associated structural costs.

Thus the cost of the structure would be within the range £600,000 to £940,000.

3.2 Moorings

The provision of adequate moorings for a wave power device involves a number of inter-related factors chief of which are the experimental forms and the hydrodynamic performance of the device. Water depth, composition of the sea bed and horizontal buoy movement (excursion), inasmuch as it interferes with other buoys in an array, are also important. It seems likely that in view of the, as yet uncertain environmental loading on the device, preliminary mooring configuration costings will contain a large margin of error.

In the previous feasibility study the cost of a conventional chain catenary system, determined by the empirical guidelines of a classification Society's rules, was estimated to be £130,000. This estimate tried to take account of the fact that the chains and anchors required for a wave energy device on an exposed site would be much more substantial than those for mooring a ship of the same deadweight tonnage in sheltered water. Allowing for inflation the present cost of such a system would be in the region of £150,000. A difficulty with such a system arises when buoys are placed in close array since the chain lengths are quite substantial.

An alternative mooring system, which is explained in the introductory section permits the current experimental hydrodynamic extraction efficiencies to be used, consists of the articulated tension leg shown in Fig. 1. This form of restraint inhibits heave motion although it permits some surging action to add to the power absorbed. The buoyancy required to provide the necessary restoring force is located circumferentially on the concrete main structure and is sized to limit angular movement of the articulated joint to ± 6m. The maximum excursion in a water depth of 70m is thus ±6m. The articulated joint proposed is similar to that in wide usage on SBM's where angular rotation of $\pm 15^{c}$ can be safely accommodated.

The joint is affixed to a simple honeycombed concrete base unit which can be floated into position prior to sinking. It is envisaged that the honeycomb cells would be filled with rock debris from the adjacent sea bed or alternatively filled with sand and 'capped' with precast concrete slabs. The tension leg and caisson would be precast and the following costings are made with this in mind. The tension leg is assumed to be hollow, 60m long with an outside diameter 4m and wall thickness 300mm.

Thus a realistic estimate of the cost of such a system would be as follows:

<u>Tension Leg</u>

Volume of concrete = $60 \times 4\pi \times 0.3\ m^3$
= $225m^3$

$225m^3$ @ £200/m^3 = £45,000

<u>Base Unit</u> (Caisson)

Volume of concrete = $600m^3$
$600m^3$ @ £200/m^3 = £120,000

<u>Swivel Joint</u>

SBM articulated joint in stainless steel = £55,000

Sub Total = £220,000

In order to lay the moorings, dredge the rock or sandfill a special vessel would have to be chartered and its estimated costs is as follows:-

Mobilisation fee	£4,000
10 day hire	£20,000
De-mobilisation fee	£4,000
Insurance	£4,000
Sub total	£32,000
Total cost	£252,000

Maintenance estimated at 12% per annum would cost £30,000/yr. A maximum estimate cost would be £400,000 involving a maintenance allowance of £48,000/yr. It should be noted that the 12% maintenance cost is likely to be too high for this type of system which is expected to require less maintenance than a conventional system.

Some alternative mooring arrangements which are currently being investigated are depicted in schematic form in Figs 2 and 3.

The first figure illustrates variations on the proposed tension leg scheme to permit heave movement, allow for tidal variations and with the inclined arrangement to reduce the buoyancy restoring force while allowing enhanced surge and pitching movement. The second figure depicts a scheme which relies on pretensioned mooring lines that are sufficiently compliant as to allow the device heave, surge and pitch body freedoms. It is suggested that since devices once in position are unlikely to be relocated chains or wires have no particular advantage over solid bars and it may well prove possible to achieve the necessary compliance using 150-200m length of 50m diameter high strength steel bars enclosed in protection sheaths.

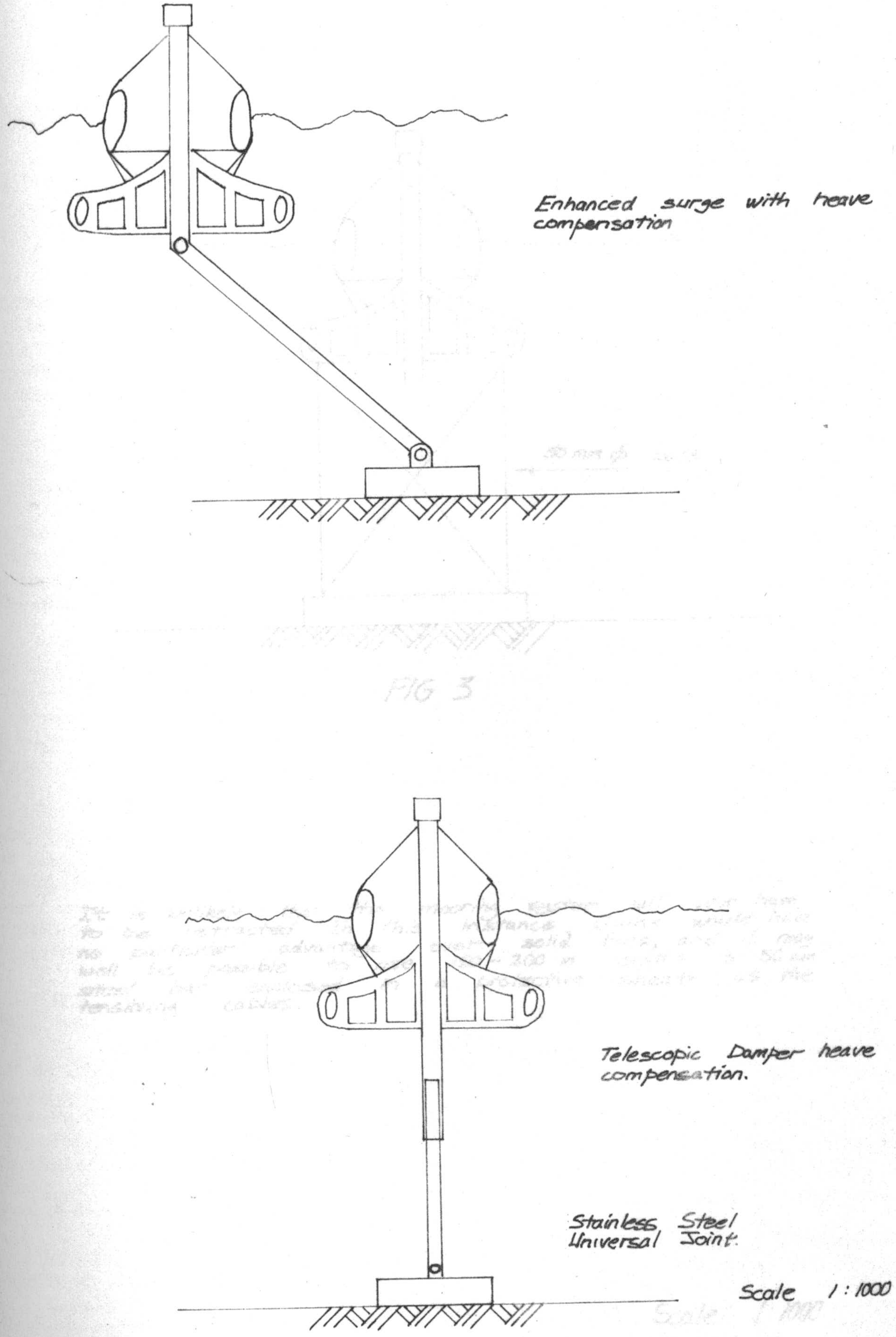

FIG 2

DEPARTMENT OF CIVIL ENGINEERING
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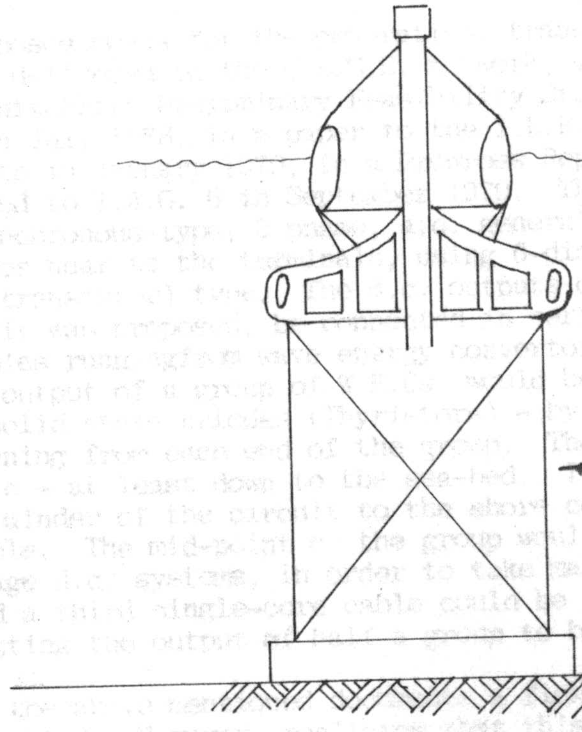

FIG 3

It is unlikely that the mooring system will ever have to be retracted. In this instance, chains would have no particular advantage over solid bars, and it may well be possible to use 150 - 200 m lengths of 50 mm steel bar enclosed in a protective sheath as the tensioning cables.

Scale 1:1000

3.3 ELECTRIC POWER GENERATION AND TRANSMISSION

INTRODUCTION

The proposed means for the generation, transmission and control of electrical energy, to be delivered to the C.E.G.B. network, is essentially as described in the Queen's University Preliminary Feasibility Study presented to Rendel, Palmer and Tritton in July 1978, in a paper to the I.E.E. International Conference on New Energy Concepts in January 1979, in a Progress Report to Mr. L. Bedford in August 1979 and to T.A.G. 6 in September 1979. The scheme involved the use of brushless, synchronous-type, 3-phase, a.c. generators, having their outputs rectified at or near to the terminals, using 6-diode, bridge rectifiers of the solid state (transistor) type. The d.c. outputs of a group of generator/rectifier units would, it was proposed, be connected in series by single-core, flexible, submarine cables runningfrom wave energy convertor (W.E.C.) to wave energy convertor. The output of a group of W.E.Cs. would be brought ashore to an invertor-a bridge of solid state triodes (Thyristors) - by two single-core submarine cables, one cable running from each end of the group. These latter cables would require to be flexible - at least down to the sea-bed. If a suitable connector was available, the remainder of the circuit to the shore could be by single-core inflexible submarine cable. The mid-point of the group would be earthed, as is customary in high-voltage d.c. systems, in order to take maximum advantage of the cable insulation; and a third single-core cable could be taken from the mid-point to the shore, permitting the output of half a group to be utilized under fault conditions.

In all the above mentioned documents a flexible cable insulation limit of 22 kV was accepted. However, realizing that this was an artificial limit imposed by the complex electric-fields in a 3- or 4-core a.c. cable, very much higher values were claimed by us to be perfectly feasible for single-core d.c. cables. This view was accepted without reservation by T.A.G. 6 at its September 1979 meeting.

In the July 1978 Feasibility Study to R.P.T. and in the I.E.E. Conference paper, permanent magnet fields in the generators were postulated; but, in later presentations, it was recognized that this could impose unacceptable constraints on terminal voltage control - an essential feature of our power optimization scheme, described below. For this reason we now propose using standard brushless alternators, with the possibility of two permanent poles (or pole inserts) in the exciter field system.

Also, in earlier presentations, to avoid proliferation of devices of similar ratings to the generator on the W.E.C., we suggested that generator armature windings should be insulated to withstand 22kV (the voltage on full output between the end-of-group generator stator windings and the frame). It would require a cost/benefit analysis to determine whether this deviation from the design requirements of a standard machine, the 'podding' of the generator in an insulating capsule or the insertion of a double wound transformer with enhanced insulation between its secondary winding and the frame should be used. As already stated above, however, an insulation level of 22kV is an artificial one, and, as this has now been accepted by T.A.G. 6 a new level of 33kV will be assumed.

It will be taken, therefore, as a working hypothesis, that a double wound transformer will be used to insulate the generator from transmission voltages, if cable insulation levels as great as or greater than 33kV are to be available. (It should, perhaps, be emphasised here that there would appear to be little technical difficulty in designing single-core flexible cables, using modern polymeric insulation, for d.c. transmission, with insulation levels of 50kV and higher). The use of higher voltages permits of higher group power outputs being transmitted to the shore, the reduction in the number of shorebased invertors and many other consequential advantages - all envisaged in our presentation to R.P. and T in July 1978.

The a.c. outputs of a number of group invertors would conveniently be parallelled to form a sub-system. It would depend on the configuration of the adjacent coast line whether parallelling should take place at a single station or whether a 'bus-bar cable or line lying parallel to the shore should be used. With the ragged coastlines of the Outer Hebrides the first arrangement has many advantages, with the parallelling stations sited at appropriate points on the islands. (A serious disadvantage of this arrangement is the convergence of many submarine cables towards the parallelling station, with the difficulties inevitable in locating, grappling raising and repairing a faulty cable. It is common practice to separate submarine cables by spacing of 100 metre or more). The power from each sub-system could be transmitted, at enhanced voltage, by inflexible cables to the Island of Skye and thence to the mainland or direct to the mainland. From the point of arrival on the mainland to the point of connection to the C.E.G.B. system transmission would be by U.H.V. overhead lines. Although a.c. transmission is proposed here, whether a.c., d.c. or hybrid transmission should be used would be determined by economic considerations; but this is an area where the C.E.G.B. and its advisers should have ample experience. Since, however, for economical transmission, twin-circuit six conductor lines are preferred for a.c. transmission and triple-circuit six-conductor lines for d.c. transmission, the total number of sub-systems should preferably be matched with the transmission system. Thus, in a 2000-MW wave energy system, three 667-MW sub-systems would be compatible with d.c. transmission, four 500-MW sub-systems with a.c. transmission and six 333-MW sub-systems with either.

SYSTEM ELEMENTS

Generating units

An annual average turbo-alternator power output of 400 kW is assumed and a generator continuous rating of 1.2MW, allowing adequate acceptance of power under high sea conditions. (It is assumed that if the self-governing properties of the Wells turbine are not sufficient to prevent overload then restriction of air-flow and/or braking will be used for protection.) Standard 8-pole, brushless type synchronous generators would be used, arranged for self excitation. (A fraction of the generator output voltage would be rectified and used to excite the field windings of the exciter. In order to ensure self excitation from re-starting permanent magnet inserts might be required in two or more of the exciter poles). Such generators could be regarded as virtually 'off the shelf' models. As a double wound transformer is to be used between the generator and the rectifier bridge any commonly available line voltage can be chosen. Also, since the Wells turbine maximum speed is determined by its rotor diameter the generator speed can again be of any freely available value. Respective values of 1.1 kV and 750 r.p.m. are suggested.

Isolating transformers

For a group maximum power output of 40MW (An artifically low value it is suggested) 34 generator/transformer/rectifier units will form a group. Thus, assuming a cable insulation level of 33kV, the rectified output voltage of each unit will be 2.0 kV and the a.c. input to the rectifier will be approx. 1.5kV (line value). Thus the transformer line voltage ratio may be (say) 1.1 to 1.5kV but the insulation level from the secondary windings to the primary windings and to the frame must be 33kV (peak value), at least. Transformer rating will be 1.2MW (Continuous).

Rectifier bridges

Six-diode transistor bridges would be used, rated at 1.2MW with input voltage of approximately 1.5kV (rms value) and output voltage of 2.0kV. No smoothing of the output would be required as the choppy voltages of the several units would be continuously out of phase with one another so that the total group voltage should be practically smooth and equal to the sum of the several average voltages. Reactive power demand will be negligible.

Flexible interconnecting submarine cables

These, it is proposed, should be of circular cross-section with stranded cadmium copper conductors (although a case could be made for steel conductors). The insulation level, for a 66kV group voltage, would require to be 33kV (peak value, since the current is uni-directional). Full-load current loading would be 600 ampere, and, for a current density of 150 A.cm^{-2}, the conductor cross-sectional-area will be 4 cm^2 or 400 mm^2, with outside conductor diameter of about 2.2 cm and outer polymeric insulation diameter of about 4 cm. It is suggested that cable sections will be suspended in catenaries from buoy to buoy so that the insulation will be subjected to minimum abrasions. Thus protective armouring may be dispensed with. With this proviso the weight (in air) of a buoy-to-buoy section should not exceed 500 kg. (Weight in sea water should be about 150kg less).

It is recognized that single direct current submarine cables will affect the magnetic compasses of ships passing over them. The effects can be considerably reduced if cables carrying currents in opposite directions can be laid comparatively close together. It is recommended therefore that the cables from each group to the shore should be so laid. Fig. 1 shows how stray magnetic fields can be minimized without resorting to two-core concentric cables or other expensive options.

Invertors and invertor station

Each pair of cables from a group would be delivered to an invertor. This would be of the thyrstor bridge type having 6 or 12 triodes or series of triodes per group. Alternatively, two such invertor bridges could be used per group giving the following advantages:-

(a) They could be used in series with high voltage inputs and with one only for low voltage inputs, thus reducing the MVAR demand on the a.c. system.

(b) In conjunction with an earth return, or using a third single core cable from the mid point of the group of generator/transformer/rectifier units, one half of the group output would be available in the event of a fault.

For an input voltage of 66kV or less to the invertor the output voltage on the a.c. side would be fixed at 66/1.35 or 50kV at the system frequency. Current and, incirectly, voltage received by the invertor would be determined by control of the firing delay angle of the thyristors.

Reactive MVA demand by the invertors would be quite considerable when the input direct voltages were low. This would be supplied partially by the capacitive susceptance of the a.c. cable connecting the sub-system output to the shore and partially by the shore-based power system. However a synchronous condenser per sub-system, based in its island parallelling station, might more economically supply a part of the reactive MVA demand.

From the proposed location of a line of W.E.Cs. about 20km off the Outer Hebrides it is convenient to consider four sub-systems of 500MW full power output each. From the choice available of many islands, the outputs of the groups comprising the four sub-systems could converge on four parallelling points as shown in Fig. 2., with two such points on N.Uist, one on S.Uist and one on Barra. With no knowledge of the terrain the points shown on Fig. 2 are purely to indicate a principle, as are the routes of cables etc. Each parallelling point would be located in a station comprising 'bus bars to parallel 25 groups, a step-up transformer of 500 MVA rating and termination arrangements for the incoming medium voltage d.c. cables from the groups and the outgoing U.H.V. cable to the island of Skye and/or the mainland. Invertor control gear and protective and switchgear would also be located here.

Step-up transformers

Because of the increased flexibility of operation and control which it offers, the employment of one transformer per sub-system is proposed to raise the voltage from the 50kV line value on the a.c. side of the group invertors to the U.H.V. transmission value of (say) 400kV. These transformers would be standard power type, using oil cooling and natural convection for normal operation with forced convection for temporary overload operation. The full-load rating would be 500MVA.

U.H.V. Transmission to C.E.G.B. system

Unless d.c. transmission was envisaged from each group of W.E.Cs. to parallelling positions on the Scottish mainland (and this would possibly be an economical proposition at the group voltage of 66kV, and it would merit very serious consideration if the group voltages were higher) the U.H.V. transmissions from the sub-system terminals will begin somehwere on the West coasts of the islands chosen. Thereafter, it will be in two stages, first by cable, partially or completely sub-marine, from the points of parallelling of groups into sub-systems to the island of Skye and thence to the mainland, or direct to the mainland*. A transmission voltage of 400kV should be adequate.

From the point of arrival on the Scottish mainland, transmission of power to the point of connection with the C.E.G.B. system (A distance vide Mr. Stansfield of 380km) would be by overhead transmission lines. For four sub-systems the options available for a.c. transmission are:-
(a) Two 400kV, 3-phase, twin circuit lines having $400m^2$ duplex conductors;
(b) Four 275kV, 3-phase, twin circuit lines having $175m^2$ duplex conductors;
For three or six sub-systems and d.c. transmission the options include:-
(c) One ± 550kV, triple circuit line using $400mm^2$ duplex conductors;
(d) One ± 550kV, triple circuit line using $175mm^2$ duplex conductors;
(e) Two ± 550kV, triple circuit lines using $175mm^2$ duplex conductors.
For the above a.c. schemes (a and b), thermal limits and costs per km route length would be respectively
(a) 660MVA and £75,000 per km per 500MW sub-system
(b) 575MVA and £100,000 per km per 500MW sub-system

POWER OPTIMIZATION

The proposed method of power optimization for each W.E.C. in an interconnected group is based on the assumption that:-

(a) For any sea state, the power output rises from zero at standstill to a maximum value at some intermediate speed, falling off to zero at no-load (This is the case with the Wells turbine operating under uni-directional airflow).

(b) For diminishing sea states (as for diminishing airflows) the above characteristic would be foreshortened, so that maximum speed at no-load, maximum power output and speed at maximum power all fall progressively.

On these bases a maximum-power/speed locus will be a curve starting from double zero with zero slope and with slope increasing with speed. There is some evidence that this locus is a cubic relationship.

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*Alternatively, overhead line transmission may be possible on the Outer Hebreddean Islands and Skye, with submarine cable links for sea crossings only.

If therefore load current is kept constant at the invertor end of a group and the output voltage of each W.E.C. is controlled to give a voltage/speed characteristic of the same form as the max. power/speed locus each W.E.C. will be working at maximum power output irrespective of the sea state in which it finds itself.

The above scheme was set out in some detail in the Q.U.B. Progress Report to Mr. Bedford in August 1979 and to T.A.G. 6 in September 1979. A paper on a more sophisticated scheme is under preparation.

CONCLUSIONS

In assessing the costs of electrical generation, transmission and control, it was clear that the costs of transmitting power from the West coasts of the Hebridean Islands to the Scottish mainland were the major item. It must be stated that, unless the reasons for siting the string of W.E.Cs. to the West of the Outer Hebrides are overwhelmning, immense savings could be made if, instead, the string was sited off the mainland without islands intervening.

SPECIFIC COSTS OF SYSTEM ELEMENTS

Component	Average load	Continuous Rating	Cost/kW out (RATED)	Effic. (p.u.)	Cost/kW in (RATED)
Generator	400kW	1.2MW	£40	0.93	£37.2
Isolating transfr.	400kW	1.2MW	£6	0.97	£5.9
Rectifier bridge	400kW	1.2MW	£5	0.97	£4.85
Flexible 33kV cable between buoys	600 A at 11kV	600 A at 33kV	£1.4	0.99	£1.38
D.c. cable to Outer Hebridean Island shore	ditto	ditto	£14	0.96	£13.4
Invertor & Control gear (per group of 34 W.E.Cs.	13.3MW	40MW	£25	0.97	£24.3
Parallelling equipment & Switchgear (for 13 Groups)	167MW	500MW	£5	1.00	£5.0
Step-up Transformer 50kV/400kV	167MW	500MW	£2	0.98	£1.96
3-phase, 400kV submarine cable to Scottish mainland	167MW	500MW	£100	0.97	£97
OR					
O/h.line transmission on islands with submarine cable for sea crossings only.	ditto	ditto	£75	0.96	£72
Two 400kV twin circuit o/h. lines having 400mm^2 duplex conductors	ditto	ditto	£57	0.94	£53.6

SUMMARIZING ELECTRICAL COSTS	Cost/kW out	Cost per buoy
Total equipment on buoy	£51	£61,200
Interconnection between buoys in a Group and d.c. cable to Outer Hebridean island with invertor and control gear on island	£40.4	£48,480
Parallelling equipment and Step-up transformer and cable to mainland	£107 (or alt.£82)	£128,400 (£98,400)
Transmission line to C.E.G.B. system	£57	£68,400

×capacity

Q.U.B. GENERATION & TRANSMISSION SCHEME

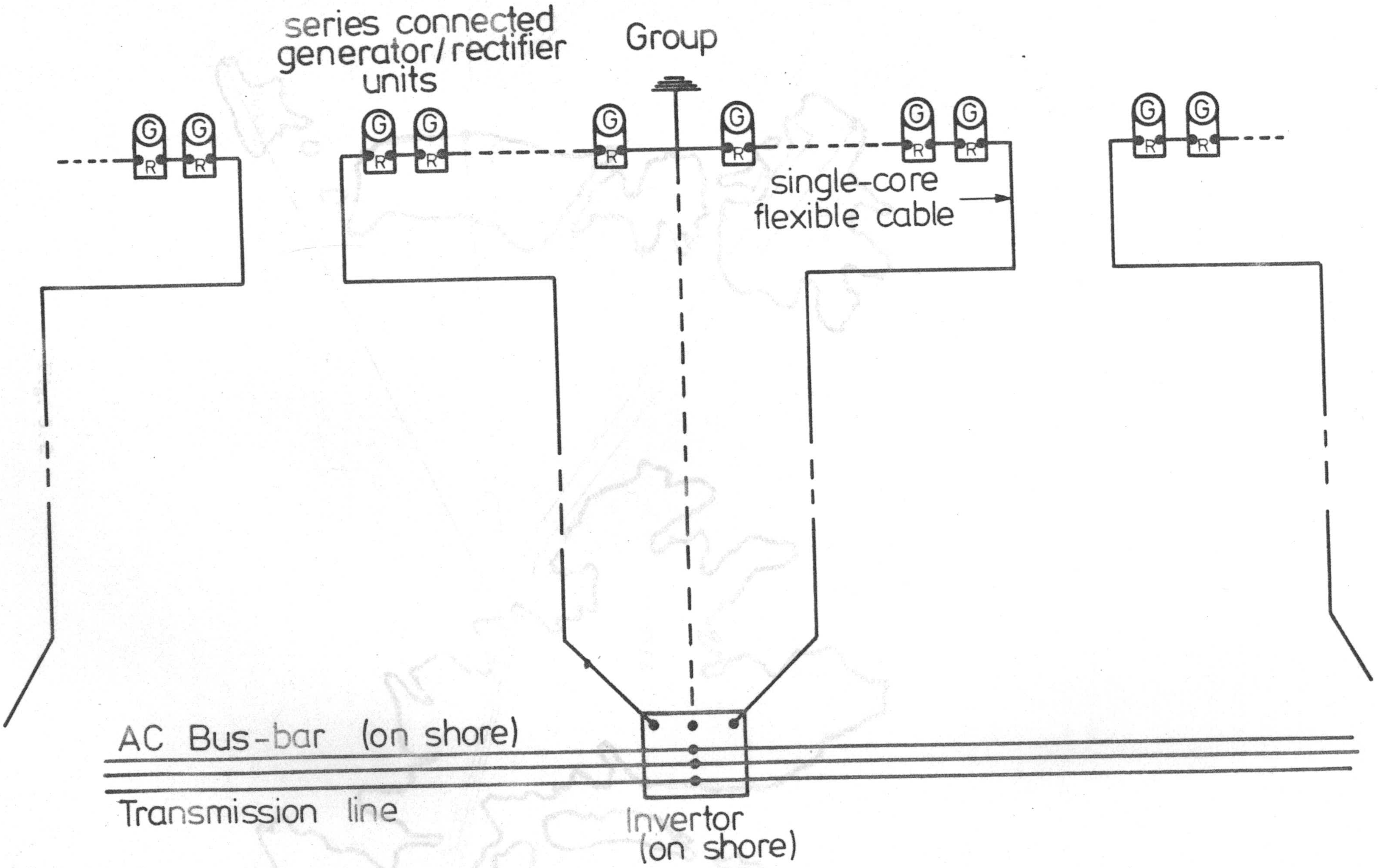

Fig. 3.1

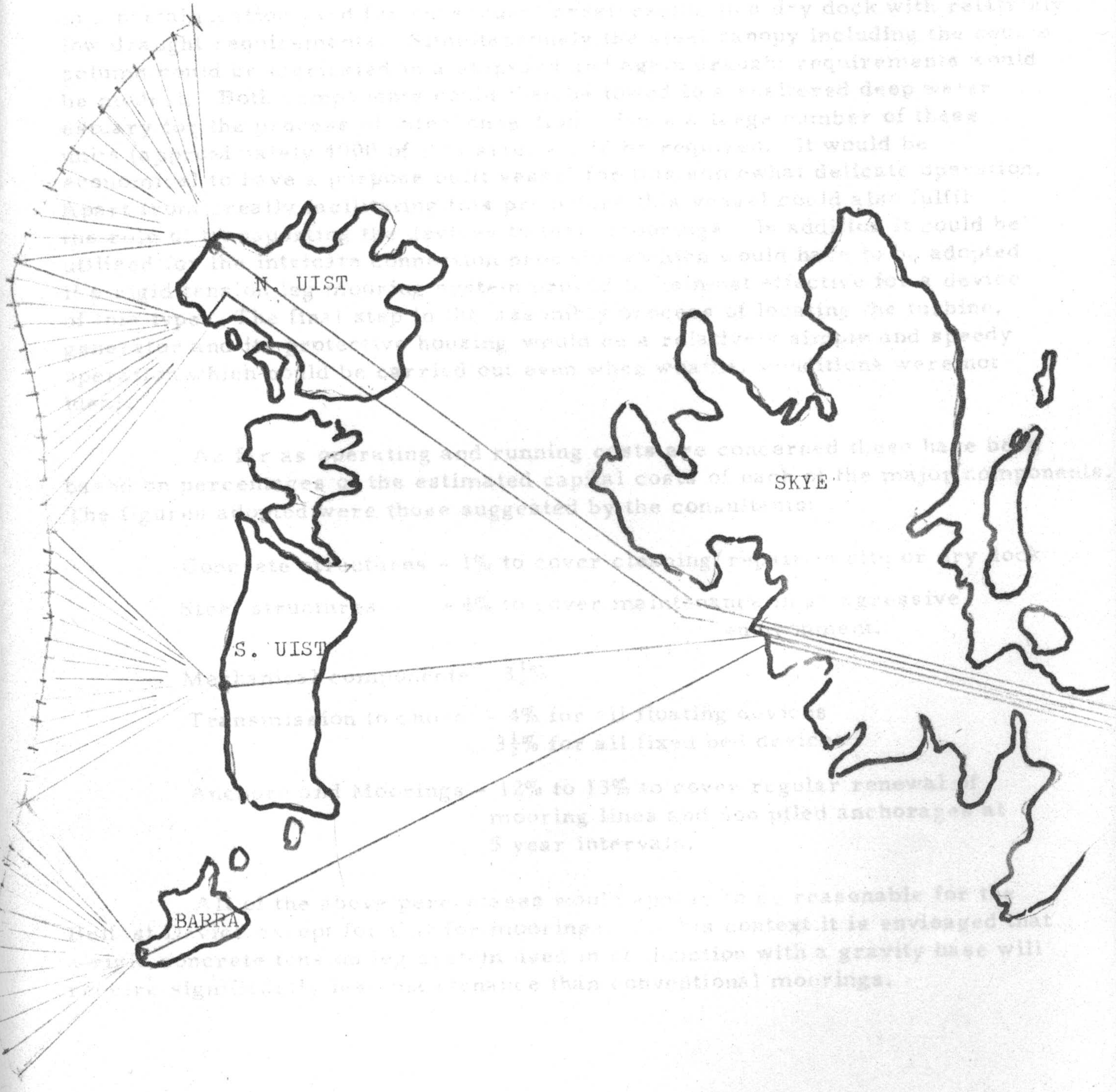

Fig. 3.2

system length approx 120 km

3.4 Miscellaneous

At this early stage in the development of the Belfast Device little or no attempt has been made to consider how the concrete sub-structure and the steel superstructure would be combined. It is considered however that the present form of the device should present little difficulty to a major civil engineering contractor with facilities suitable for the construction of North Sea oil platforms.

The sub-structure could be precast in segmental elements in a prefabrication yard for subsequent prestressing in a dry dock with relatively low draught requirements. Simultaneously the steel canopy including the centre column could be fabricated in a shipyard and again draught requirements would be modest. Both components could then be towed to a sheltered deep water estuary for the process of interconnection. Since a large number of these units (approximately 4000 of this size) would be required. It would be economical to have a purpose built vessel for this somewhat delicate operation. Apart from greatly facilitating this procedure this vessel could also fulfil the role of transporting the devices to their moorings. In addition it could be utilised for the intricate connection procedure which would have to be adopted if a rigid tension leg mooring system proved to be most effective for a device of this type. The final step in the assembly process of locating the turbine, generator and its protective housing would be a relatively simple and speedy operation which could be carried out even when weather conditions were not ideal.

As far as operating and running costs are concerned these have been based on percentages of the estimated capital costs of each of the major components. The figures adopted were those suggested by the consultants:

Concrete structures - 1% to cover cleaning/repair in situ or dry dock

Steel structures - 4% to cover maintenance in an agressive environment.

Mechanical components - $3\frac{1}{2}\%$

Transmission to shore - 4% for all floating devices
$3\frac{1}{2}\%$ for all fixed bed devices

Anchors and Moorings - 12% to 13% to cover regular renewal of mooring lines and non piled anchorages at 5 year intervals.

All of the above percentages would appear to be reasonable for the Belfast Device except for that for moorings. In this context it is envisaged that a rigid concrete tension leg system used in conjunction with a gravity base will require significantly less maintenance than conventional moorings.

4. SUMMARY OF COSTS

As in 1978, the emphasis was placed on establishing the upper and lower bounds to the cost/kW of installed capacity and the cost/kW. hour. Thus, for the 1.2 MW installed capacity system which is appropriate for the 24m diameter device the following estimates are of relevance:

		Minimum	Maximum
	Structure	£600,000	£940,000
	Moorings	£250,000	£400,000
Electrical	To first landfall	£110,000	£120,000
	To mainland	(£240,000)	(£260,000)
	Wells Turbine	£100,000	£150,000
	Total cost to 1st Landfall	£1,060,000 (£1,190,000)	£1,610,000 (£1,750,000)

Thus, the estimated cost/kW installed capacity ranges from £880 to £1460.

Using the figure of an annual mean output of 212kW (see Section 2) then total kW/hr/annum = 365 x 24 x 212 = 1,857,000 kWhr.

The costs per annum estimated for maintenance are:

	Minimum	Maximum
Structure	£17,600	£25,200
Moorings	£30,000	£48,000
Turbine/Electrical	£9,500	£11,500
Total	£57,100	£84,720

If each unit has an average anticipated life of 25 years then the capital depreciation/annum ranges from £74,000 to £112,700. Thus, the minimum estimated cost per unit generated would be of the order of

$$\frac{(57,100 + 74,000) \times 100}{1,857,000} = 7.06\text{p/kW.hr.}$$

and the maximum estimated cost around:

$$\frac{(84,700 + 112,700) \times 100}{1,857,000} = 10.62\text{p/kW.hr.}$$

5. CONCLUDING COMMENTARY

In comparison to our previous feasibility study which was submitted in July 1978 considerable progress has been made. This has not led to a more sophisticated design concept as the Queen's University team still accepts the basic philosophy that a wave energy converter which is simple and reliable will ultimately have a much greater chance of success. The following improvements which have been realised are summarised below:

(1) Hydrodynamic Performance

The installation in August/September of the computer controlled data acquisition system coupled to new wave paddles (Salter type) and a greatly improved beach has meant that a much more scientific approach can be adopted to this multivariate problem. Over the last 2 months the peak extraction efficiency has been improved but more significantly a greater proportion of the energy can be absorbed from the more energy intensive waves. In addition the effective band width has been increased. These improvements can readily be seen from a comparison of the curves in Fig. 5.1 and from the fact that the average annual productivity of a device of a given size has increased by a factor of three.

It should be emphasised that some of these advances have been achieved as a result of restraining the device against heave and this may be counterproductive in terms of the intensity of forces to which the canopy will be subjected during storms. However it is felt that in the future with the team's improved understanding of the modus operandi of oscillating water column devices that comparable efficiencies can be achieved with a flexibly moored system.

(2) Structure

The structural integrity of the device has been greatly enhanced by the provision of a central column which eases the problems of transferring the forces from the canopy to the concrete substructure. As a consequence the likelihood of a fatigue failure of the struts around the skirt is greatly diminished.

(3) Moorings

The fouling problems associated with the use of conventional catenary moorings for arrays of devices of this type have been eliminated by the adoption of a tension leg system. Since the forces induced on such systems are difficult to define preliminary tank tests are already in progress.

Apart from the above advantage it is likely that maintenance costs will also be substantially reduced and the overall reliability improved.

(4) Wells Turbine

The tests carried out on the 20cm diameter rotor have confirmed that reasonable efficiencies of the order of 55% to 65% can be achieved even without the use of guide vanes and that this level of performance can be maintained for a variety of sea states. In addition preliminary tests of CEGB Marchwood have indicated that with guide vanes the efficiency can be increased to around 71% (vs 74-75% in theory).

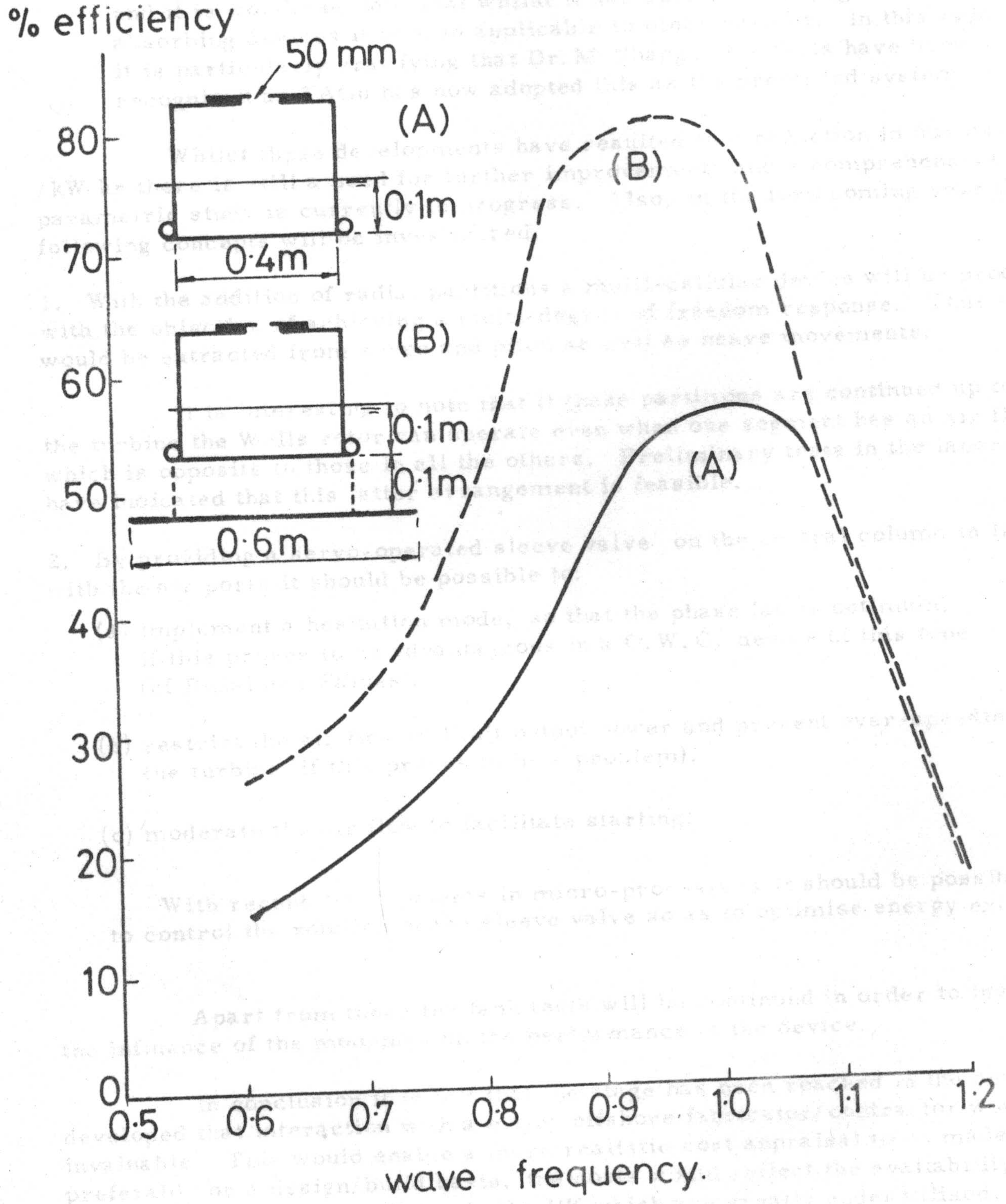
% efficiency
50 mm
(A)
0·1m
0·4m
(B)
0·1m
0·1m
0·6m
(B)
(A)
80
70
60
50
40
30
20
10
0
0·5
0·6
0·7
0·8
0·9
1·0
1·1
1·2
wave frequency

Fig. 5.1

The power/speed and efficiency/speed curves indicate that the Wells turbine has characteristics which are similar to those for other air turbines. As a consequence it should be relatively easy to adjust the generator load to control the speed and so optimise the output. It is also worthy of note that Masuda, in his tests on a Wells rotor in Kamei, has found that overspeeding is not a problem.

(5) Generation and Transmission System

The system described in last year's report has been further refined and it is worthy of note that whilst it has special advantages for point absorbing devices it is also applicable to other devices. In this regard it is particularly gratifying that Dr. McIlhagger's efforts have been recognised as TAG6 has now adopted this as the preferred system.

Whilst these developments have resulted in a reduction in our costs /kW hr there is still a need for further improvements and a comprehensive parametric study is currently in progress. Also, in the forthcoming year the following concepts will be investigated.

1. With the addition of radial partitions a multi-cellular device will be produced with the objective of achieving a multi-degree of freedom response. Thus energy would be extracted from surge and pitch as well as heave movements.

It is interesting to note that if these partitions are continued up to the turbine the Wells rotor can operate even when one segment has an air flow which is opposite to those in all the others. Preliminary tests in the laboratory have indicated that this latter arrangement is feasible.

2. By providing a servo-operated sleeve valve on the central column in line with the air ports it should be possible to:

(a) implement a hesitation mode, so that the phase lag is optimum, if this proves to be advantageous in a O. W. C. device of this type (cf Budal and Falnes).

(b) restrict the air flow to limit output power and prevent over-speeding of the turbine (if this proves to be a problem).

(c) moderate the air flow to facilitate starting.

With recent developments in micro-processors it should be possible to control the rotation of the sleeve valve so as to optimise energy extraction.

Apart from these the tank tests will be continued in order to investigate the influence of the moorings on the performance of the device.

In conclusion it is felt that the stage has been reached in the device developed that interaction with a major offshore fabricator/contractor would be invaluable. This would enable a more realistic cost appraisal to be made, preferably on a design/build basis, the costs would reflect the availability of existing construction facilities in the UK which are greatly underutilised at present.

Adrian E. Long

November 1979