COMMERCIAL IN CONFIDENCE

DEPARTMENT OF ENERGY

WAVE ENERGY STEERING COMMITTEE

UNITED KINGDOM WAVE ENERGY PROGRAMME

CONSULTANTS' 1981 ASSESSMENT

PRELIMINARY INFORMATION

MARCH 1982

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1. STATUS OF DOCUMENT

AND

2. SOME PRELIMINARY CONCLUSIONS

1. STATUS OF THE DOCUMENT

Data Base

At 30th November the information from Device Teams was incomplete in many areas, and changing almost from day to day. This was in part because lessons learned from tank testing, or costing of designs were being applied to produce revised designs very late in the programme. In other cases late or incomplete testing and designing simply had not produced the data needed. Numbers produced for E.T.S.U. at that date were totally unreliable and declared to be so by R.P.T.

In the case of some Teams, interaction with R.P.T. early in December and the results of the first costing exercise stimulated significant and urgent redesign to improve cost effectiveness, so that up to the present date 3.2.82, new data is still being presented to the Consultants, and in the absence of calculations, this has had to be validated by experience and extrapolation.

However, advantage has been taken by R.P.T. of the areas of similarity between devices to fill in missing numbers, and to correct obvious anomolies, so that the overall picture is more reliable than would otherwise be the case. During the period since November 1981 the opportunity has also been taken to cross fertilise between devices and to credit all devices of a type with any particularly cost effective solution that can be of general benefit.

An important result of late design development has been that for some devices (NEL, Bristol) the design offered for assessment is different in some measure from the design tested in the tank. Alternatively, for other devices, time and resources have not allowed adequate testing.

In these instances the production of reliable productivity data has been impossible, and important questions remain to be answered in further testing.

Productivity is crucially dependent on the power flux in the sea, and this is perhaps equally uncertain in deep and shallow water. The main problem is the uncertainty surrounding the directionality of the energy in the sea. A short paper is included on this topic.(See Section 7)

There has not yet been enough data, or enough time for analysis to produce the cost distributions which are the ultimate requirement from the assessment. Fig. 3 uses a star rating to identify broadly the security of data.

Compared to previous assessments, there is greater certainty concerning the predicted costs of the civil structure. Other very important areas, such as availability were dealt with globally in previous years and are now the subject of proper analysis, albeit from a weak data base.

In summary, across all devices, the following broadly applies. In rough order of certainty we would list

Civil Engineering Structure	(well defined)
Transmission Costs	(based on recent tenders)
*Moorings and gravity Anchors	(unit pricing well defined)

M&E plant	(incompletely specified undesigned, novel)
Installation of Bottom Mounted Devices	(many uncertainties)
Productivity	(many assumptions)
Availability Maintenance	(no very helpful (experience for data (base

Interpretation from the data base

Overall the Consultants have the sense that they are seeking to place firm numbers on to devices which are in some cases still evolving by step changes. Combined with the weakness of the data base itself, the result can not be other than unsatisfactory, and there is the strongest feeling that more time is needed to study and analyse the data so recently presented.

This said, a number of trends can be discerned, and some conclusions can be drawn which are unlikely to be overturned by the six month's work which most teams still have ahead of them.

2. SOME PRELIMINARY CONCLUSIONS

1. Two devices are clearly internally uneconomic, or less good than other similar devices and can be dismissed from further consideration. These are :-

   Belfast
   N.E.L. floating attenuator

2. The Lanchester Clam has a combination of identifiable good features which satisfactorily explain its present position as the most economic air device, but closer examination is needed to determine just how good it is - and if it could be made even better.

3. The relatively close grouping of the air devices in overall economic terms conceals a key difference between them. See Fig. 6 and Fig. 10. The fixed NEL Terminator combines <u>high</u> cost of structure and installation with <u>high</u> efficiency because of its fixed reference frame. Conversely the compliant spine of the Clam confers low structure cost and lower efficiency. The submerged Vickers devices see less power and have to survive lower forces.

   A very careful comparative study and analysis of these designs is required to determine where, in the spectrum of compliance and productivity, lies the optimum pneumatic device. This must precede any decisions to go forward with or to reject specific pneumatic devices.

4. The very high forces attracted by fixed devices, and the potential cost of locating them on a rocky bottom in shallow water is a key factor in pushing up their cost. Typically a breakwater is resisting 100 to 300 times the

force resisted by the compliant mooring of a floating device of the same length.

5. Pneumatic devices are predicted to have high availability on the basis of current technology, (in contrast to hydraulic power take offs).

6. Consideration of Fig. 8 shows the somewhat surprising fact that it costs as much to get the power out of the air, to Skye as it does to get the power out of the sea into the air. Much more work has been done on the latter, and instinctively one might expect that the greatest scope for cost savings probably lies with the M&E side.......

7. .....Transmission is seen to be an almost crippling on-cost to all schemes. There is a factor of almost five dividing the conceptual costing of Merz McLellan for a future scheme and the hard contract price for a current project in the English Channel, which K&D have used for the Consultants' assessment.

The key raw material of the copper is less than 2% of the final cost of the cable as laid. This is an unusual ratio, which seems to offer the prospect for a possible technical breakthrough in the future.

8. The Duck is a device which is conceptually almost perfect as a power absorber and converter, but requires a level of reliability in hydraulic components one to two orders above that allocated by YARD. Should this prove to be achieveable, then the device could realise its target availability, and the conceptual cost of power would become a reality and the device would be a winner.

It is important to appreciate that the fine matching of the power take off to the incident waves is made possible by the hydraulics and is not available to other devices, although 'latching' can give useful benefits to pneumatics.

The Consultants believe that there is not evidence enough to conclude at this time that the performance specified by the Duck team will not be available in the future, and a considered view must be taken of this device for the medium to long term.

9. The Bristol Cylinder has not yet fulfilled the high expectations which were engendered two years ago by its elegant hydrodynamics. The high costs of installation and power take-off have led to disappointing high cost of power, even allowing for a degree of tuning and an optimised cylinder design which have still to be proved in tank testing.

It is interesting to note that this device is in fact conceptually the non symmetrical, terminator, version of the TI device which has been studied for TAG 1. TI is a point absorber with power extracted from the heave motion, but no power extracted from the surge. The cylinder extracts from the surge also, thereby doubling the theoretical efficiency . TI has been costed out cheaper than the cylinder. A careful comparison needs to be made to establish if there are lessons to be learned that can improve the cylinder significantly.

Answers to this question can probably be obtained within the remaining period of the McAlpine Contract.

The potential benefits of tube pumps have already been admitted to the current costing exercise.

3. COMPARATIVE CHARTS & TABLES

KEY SUMMARY

	BRISTOL CYLINDER	LANCASTER FLEXIBLE BAG	NEL BOTTOM STANDING TERMINAT'R	VICKERS TERMINAT'R	VICKERS ATTENUAT'R	BELFAST	NEL FLOATING TERMINAT'R	NEL FLOATING ATTENUAT'R	EDINBURGH DUCK	LANCHESTER CLAM
NOM ANNUAL COST OF OWNERS'P (£M/YR)	346	437	331	464	368	648	426	733	292	354
MEAN ANNUAL POWER (MW)	387	480	406	504	520	477	389	465	595	603
TOTAL ANNUAL OUTPUT (TWh)	3.39	4.20	3.56	4.42	4.56	4.18	3.41	4.07	5.21	5.28
COST OF POWER (P/kWh)	10.2	10.4	9.3	10.7	8.1	15.5	12.5	18.0	5.6	6.7

No. OF DEVICES	444	356	589	1100	756	1900	185	1444	956	341
AVAILABILITY	0.80	0.84	0.89	0.91	0.87	0.88	0.86	0.86	0.80 (↑ TARGET SPECIFIED)	0.83

NOTE: NOMINAL ANNUAL COST OF OWNERSHIP ABOVE WAS CALCULATED BY MULTIPLYING COST OF POWER BY TOTAL ANNUAL OUTPUT.

FIG. 1.

ENERGY COST MAKE-UP SHEET (P/kWh)

	BRISTOL CYLINDER	LANCASTER FLEXIBLE BAG	NELBOTTOM STANDING TERMINAT'R	VICKERS TERMINAT'R	VICKERS ATTENUAT'R	BELFAST	NEL FLOATING TERMINAT'R	NEL FLOATING ATTENUAT'R	EDINBURGH DUCK	LANCHESTER CLAM
CONST. FACILITY	0.3 ***	0.7 ***	0.6 ***	0.9 ***	0.9 ***	1.2 ***	0.8 ***	1.3 ***	0.4 ***	0.5 ***
STRUCTURE	0.8 ***	3.6 ***	2.3 ***	3.1 ****	2.2 ****	3.6 ***	2.3 ***	3.6 ***	1.8 ***	2.1 ***
M & E	2.5 **	1.6 **	1.6 **	0.9 **	0.8 **	2.6 **	2.1 **	3.2 *	1.1 **	1.1 **
INST/MOORINGS	4.0 **	1.6 **	2.3 ***	3.1 ***	1.7 ***	3.8 **	1.5 **	3.1 *	0.3 **	0.4 **
TRANSM.	1.5 **	1.7 **	1.2 **	1.4 **	1.3 **	1.5 **	3.7 **	4.1 **	0.7 **	1.4 **
MAINT.	1.1 **	1.2 **	1.3 **	1.3 **	1.2 **	2.7 **	2.1 **	2.7 **	1.3 **	1.2**
TOTAL	10.2 **	10.4 **	9.3 **	10.7 **	8.1 **	15.5 **	12.5 **	18.0 *	5.6 **	6.7 **
No. OF DEVICES	444	356	589	1100	756	1900	185	1444	956	341

* = VERY UNRELIABLE ** = UNRELIABLE *** = NOT BAD **** = CHECKED AND AGREED WITH TEAM

All energy costs are discounted values

FIG. 2

FIG. 2.

UNDISCOUNTED CAPITAL COST 2GW SCHEME £M : COST PER DEVICE SHOWN ( ) ‡										
—	BRISTOL CYLINDER	LANCASTER FLEXIBLE BAG	NEL BOTTOM STANDING TERMINAT'R	VICKERS TERMINAT'R	VICKERS ATTENUAT'R	BELFAST	NEL FLOATING TERMINAT'R	NEL FLOATING ATTENUAT'R	EDINBURGH DUCK	LANCHESTER CLAM
No OF DEVICES	444	356	589	1100	756	1900	185	1444	956	341
STRUCTURE	470*** (1.1)	2451*** (6.9)	1358*** (2.3)	2346*** (2.1)	1831*** (2.4)	2791*** (1.5)	1455*** (7.9)	2590*** (1.8)	1554*** (1.6)	1836*** (5.4)
M & E	1179** (2.7)	970** (2.7)	793** (1.4)	590** (0.5)	531** (0.7)	1560** (0.8)	1042** (5.6)	1805** (1.2)	843** (0.9)	849** (2.5)
INST/ MOORINGS	1778** (4.0)	779** (2.2)	1018*** (1.7)	1694*** (1.6)	1003*** (1.3)	2055** (1.1)	741** (4.0)	1692* (1.2)	211** (0.2)	287** (0.8)
TRANSMISSION	729** (1.6)	1054** (3.0)	603** (1.0)	807** (0.7)	807** (1.1)	860** (0.4)	1783** (9.7)	2186** (1.5)	460** (0.5)	1015** (3.0)
TOTAL	4156**	5254**	3772**	5437**	4172**	7266**	5021**	8272*	3068**	3986**
TOTAL/DEVICE	9.4	14.8	6.4	4.9	5.5	3.8	27.2	5.7	3.2	11.7
ANNUAL COST OF MAINTENANCE	35	47	41	52	48	104	67	94	61	61

* = VERY UNRELIABLE ** = UNRELIABLE *** = NOT BAD **** = CHECKED AND AGREED WITH TEAM

NOTE: Neglecting the relatively small fixed cost of items such as transmission and plant platforms, the cost of power is a function only of the cost of devices and their productivity. The number of devices and hence capital cost is purely a requirement of the criterion for the scheme to produce 2GW for 5% of the year, hence capital cost of scheme is not an assessment parameter.

‡ 1981 COSTS

FIG. 3.

FIG. 3

DISCOUNTED TOTAL COST OF SCHEME PER METRE OF DEVICE

(The diameter is used for the Belfast Device)

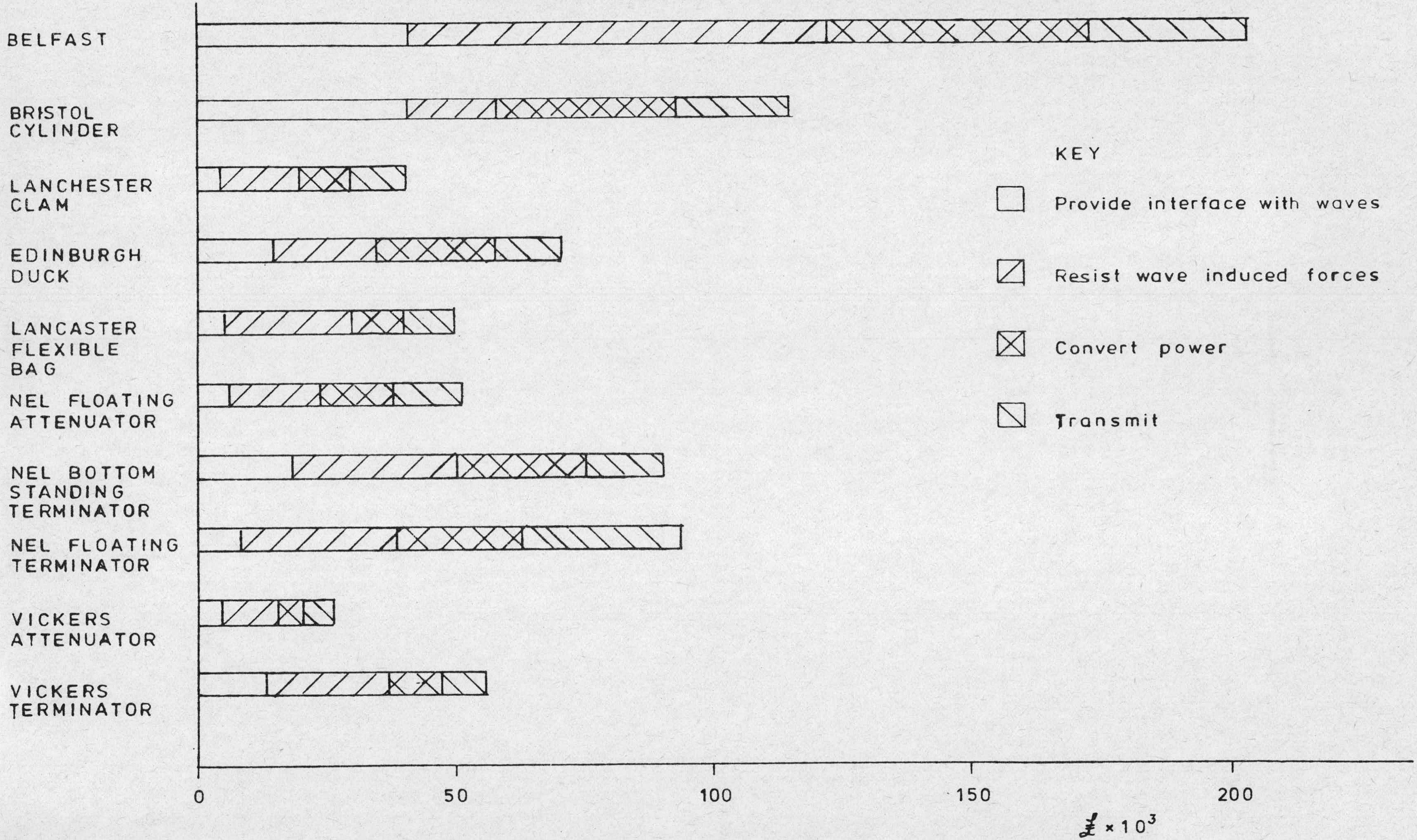


FIG. 4.

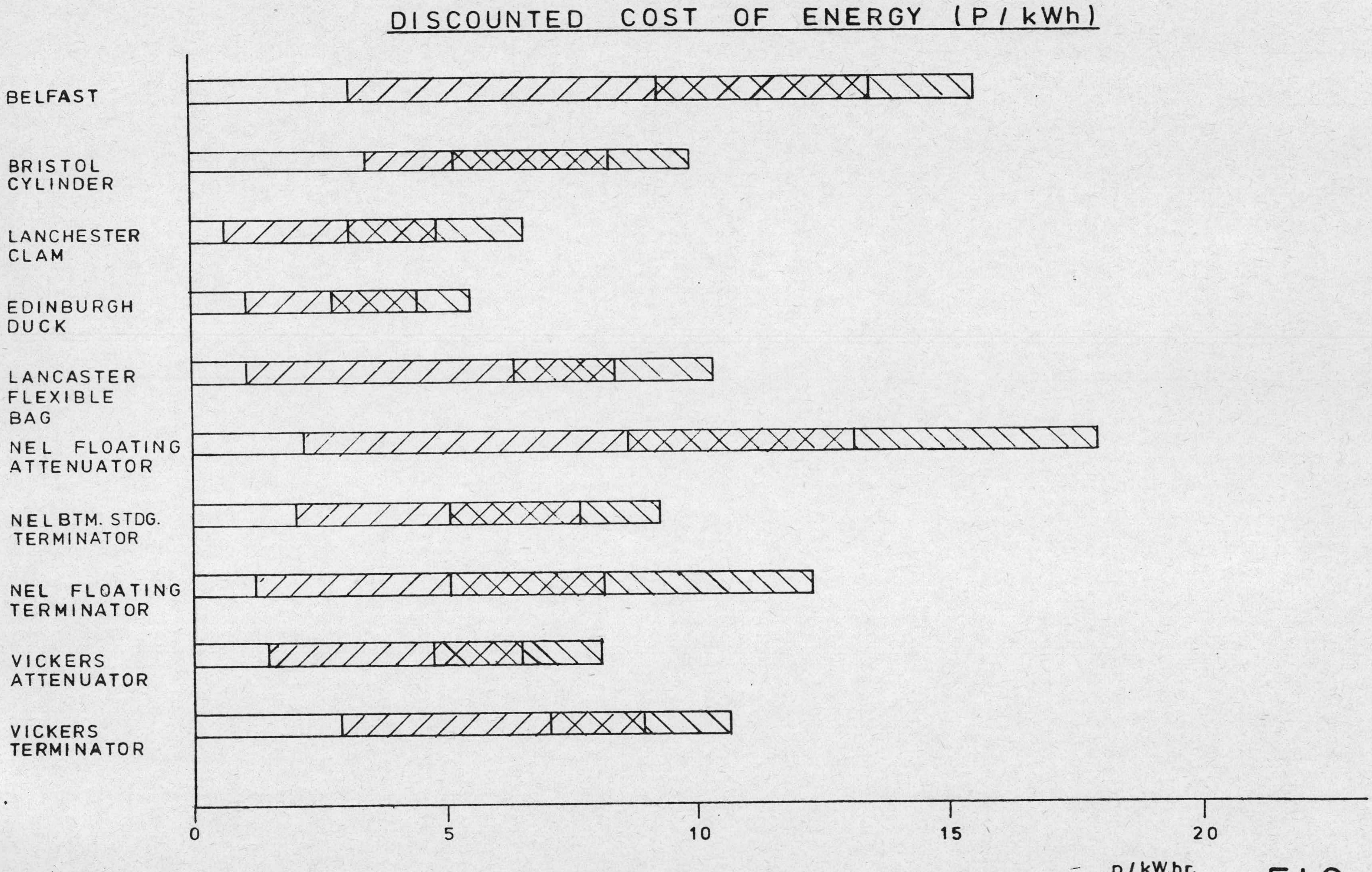
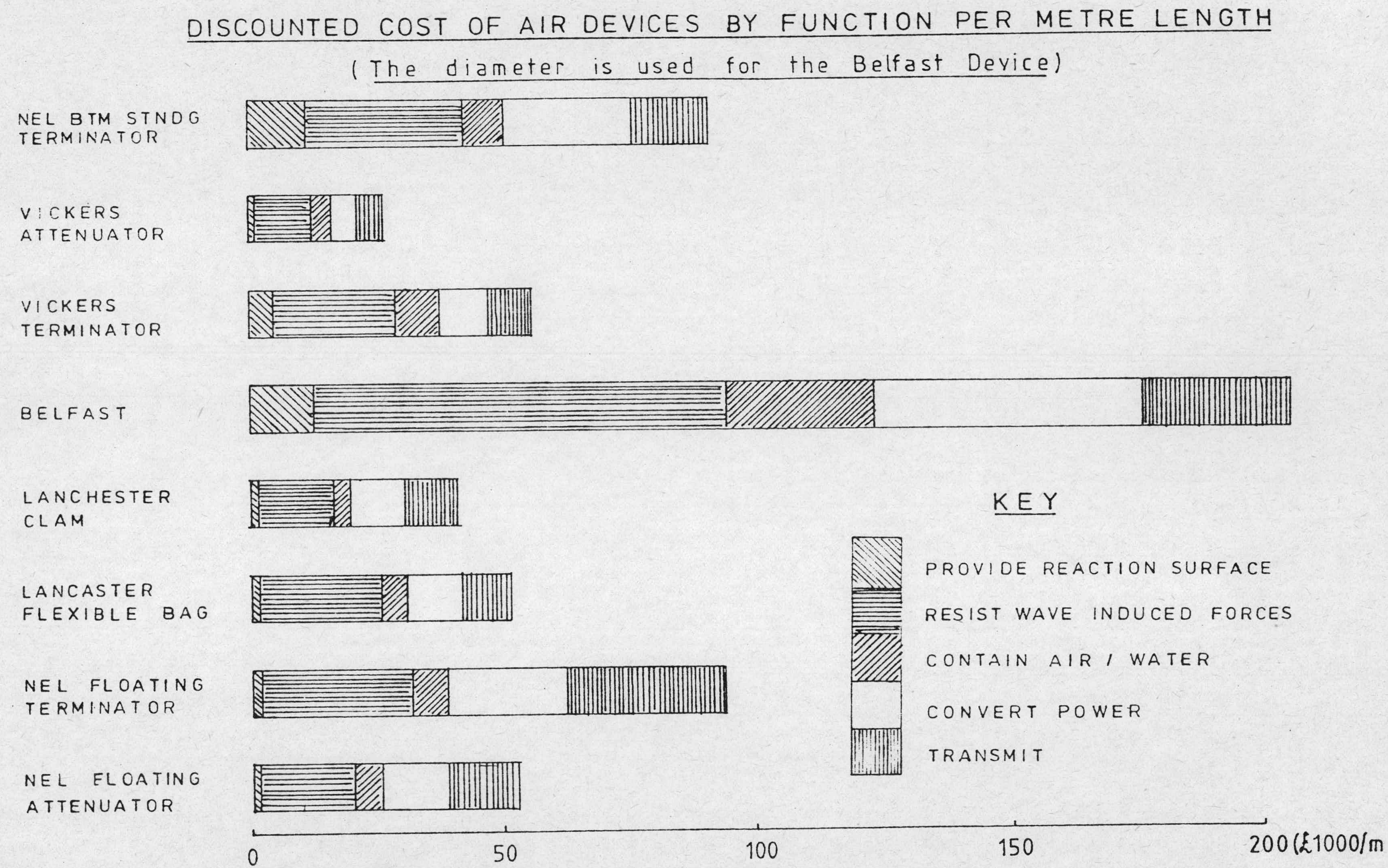

DISCOUNTED COST OF ENERGY (P / kWh)
BELFAST
BRISTOL CYLINDER
LANCHESTER CLAM
EDINBURGH DUCK
LANCASTER FLEXIBLE BAG
NEL FLOATING ATTENUATOR
NEL BTM. STDG. TERMINATOR
NEL FLOATING TERMINATOR
VICKERS ATTENUATOR
VICKERS TERMINATOR
0
5
10
15
20
p / kW,hr.

FIG. 5.



DISCOUNTED COST OF AIR DEVICES BY FUNCTION PER METRE LENGTH
(The diameter is used for the Belfast Device)
NEL BTM STNDG TERMINATOR
VICKERS ATTENUATOR
VICKERS TERMINATOR
BELFAST
LANCHESTER CLAM
LANCASTER FLEXIBLE BAG
NEL FLOATING TERMINATOR
NEL FLOATING ATTENUATOR
KEY
PROVIDE REACTION SURFACE
RESIST WAVE INDUCED FORCES
CONTAIN AIR / WATER
CONVERT POWER
TRANSMIT
0
50
100
150
200 (£1000/m)

FIG. 6.

DISCOUNTED COST OF AIR DEVICES BY FUNCTION FOR THE 2 GW SCHEME.

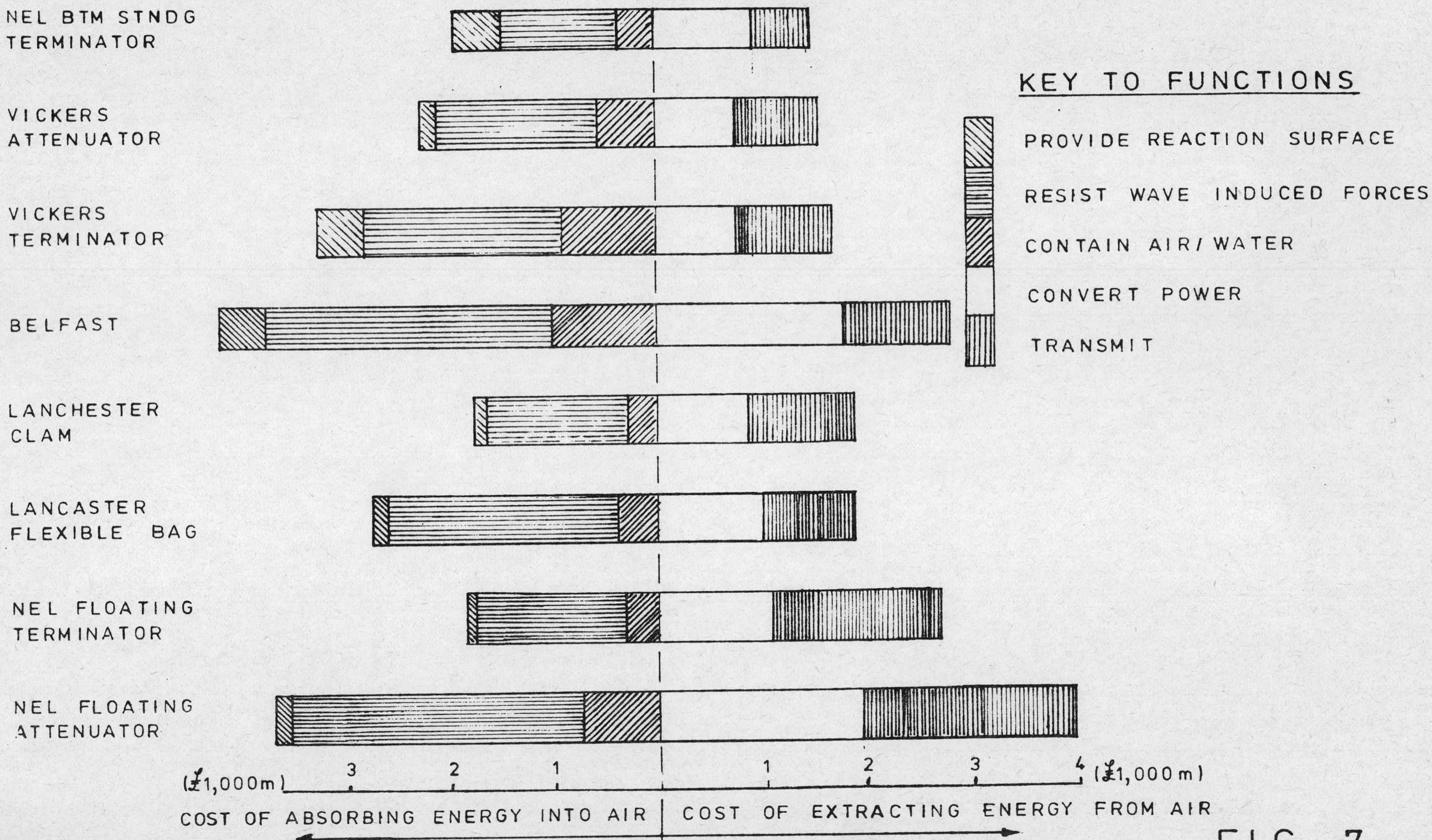


FIG. 7.

ENERGY COSTS OF AIR DEVICES BY FUNCTION

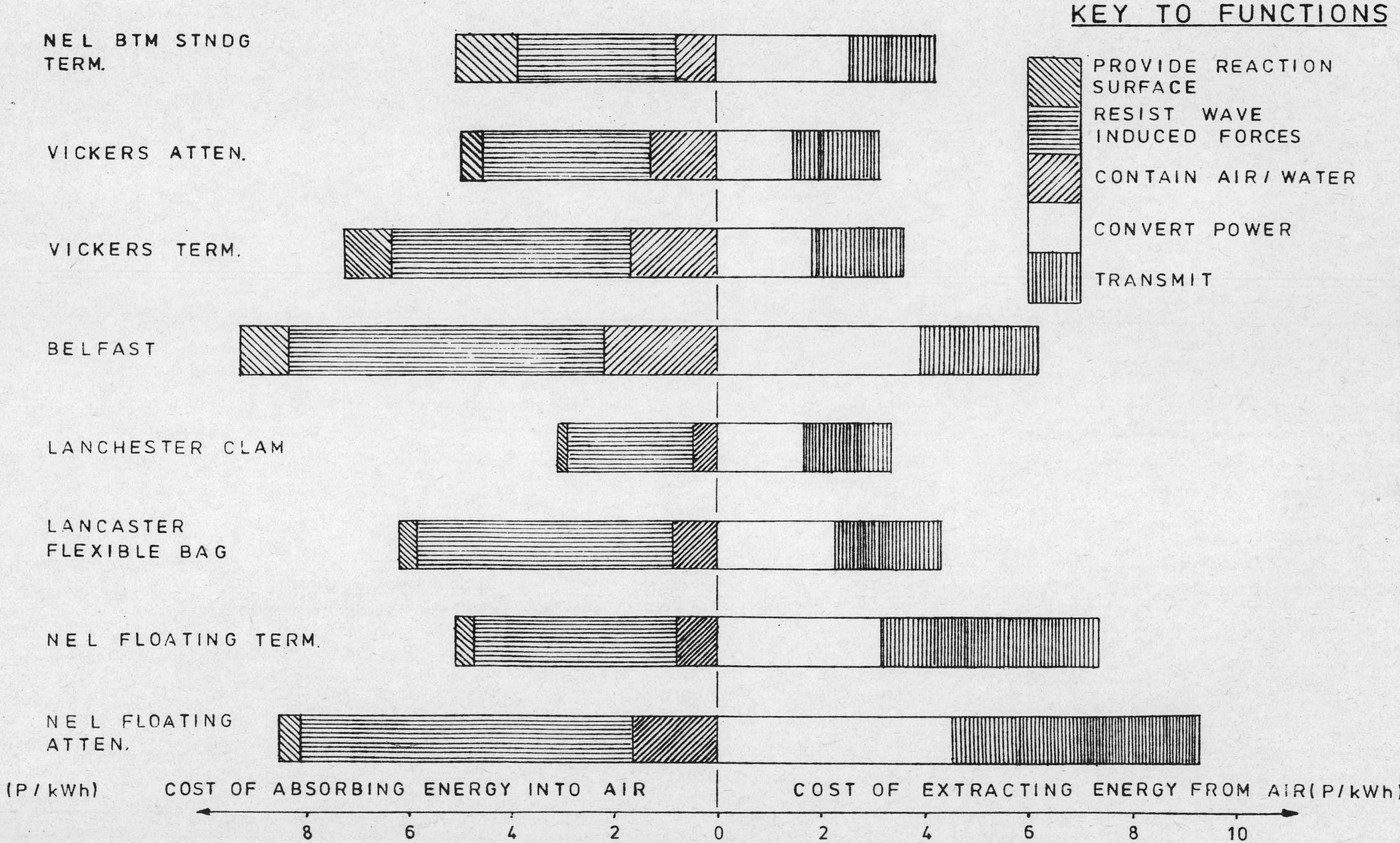


FIG. 8.

Device Capture Factors in the 46 South Uist Spectra

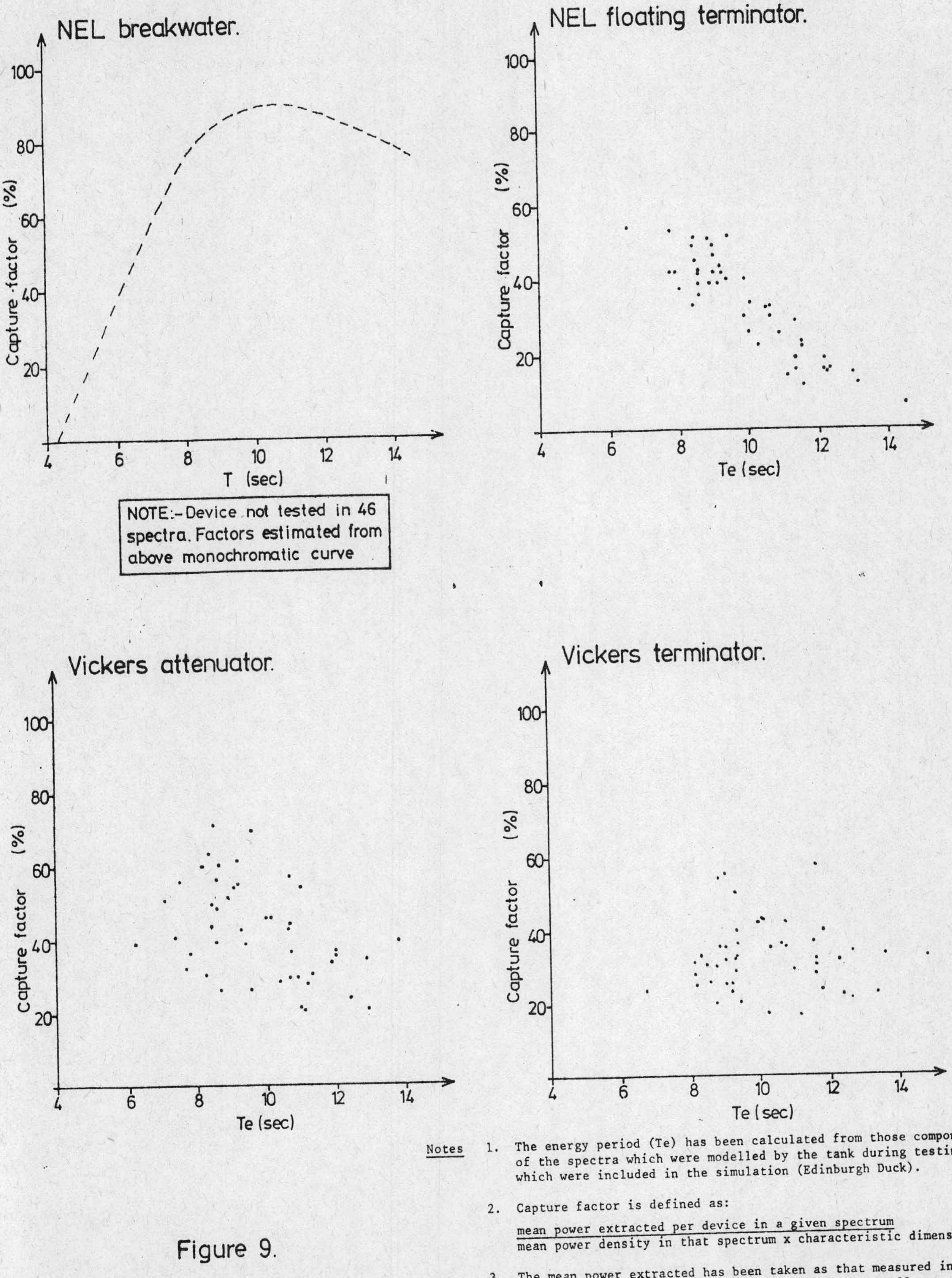


Figure 9.

Notes

1. The energy period (Te) has been calculated from those components of the spectra which were modelled by the tank during testing or which were included in the simulation (Edinburgh Duck).

2. Capture factor is defined as:

$$\frac{\text{mean power extracted per device in a given spectrum}}{\text{mean power density in that spectrum x characteristic dimension}}$$

3. The mean power extracted has been taken as that measured in the test corrected for all experimental errors (scale effects etc.).

Device Capture Factors in the 46 South Uist Spectra

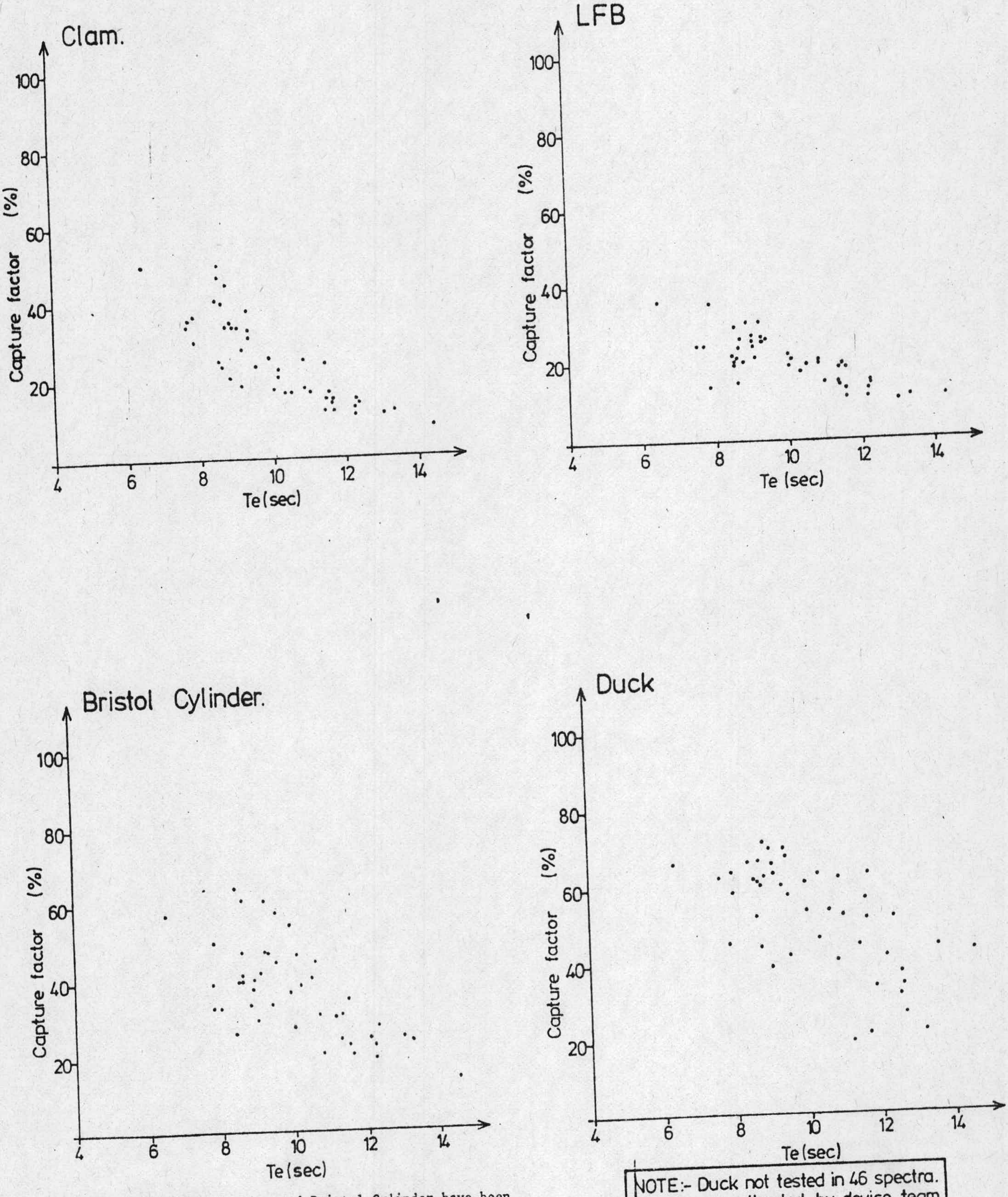


Figure 9.

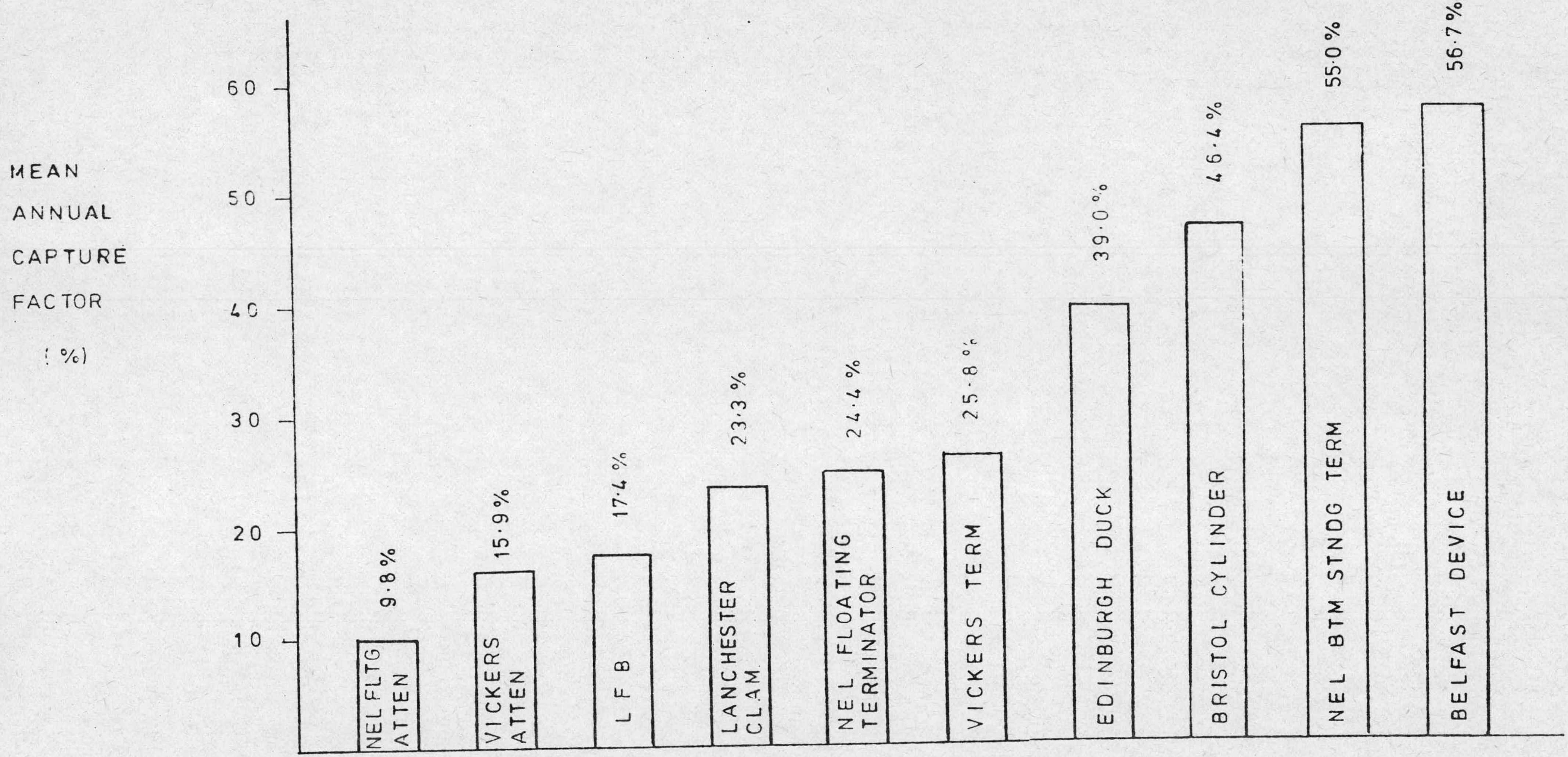
The results from the Clam and Bristol Cylinder have been further modified to take account of changes in device configuration in order to arrive at the mean annual productivity (see sections 4(vii), 4(viii), 5(i) and 5(v)).

4. The mean power density used has been that specified in the full spectrum suitably transformed to the correct depth (section 4(viii)), including those components not modelled by the wave tank.

5. The characteristic dimension has been taken as device length for all except the Vickers Attenuator where the device spacing has been taken.

COMPARISON OF DEVICE CAPTURE FACTOR*

(Allows for effect of plant cut-off on capture, but not plant efficiencies or availability)



$$* \text{ Capture factor is defined as :- } \frac{\text{Mean Annual Power captured by Device}}{\text{Power per metre in the sea at device location} \times \text{Device length}}$$

FIG. 10

COMPARISON OF MEAN ANNUAL POWER CAPTURED PER UNIT LENGTH OF STRUCTURE

(Allows for effect of plant cut-off on capture, but not plant efficiencies or availability.)

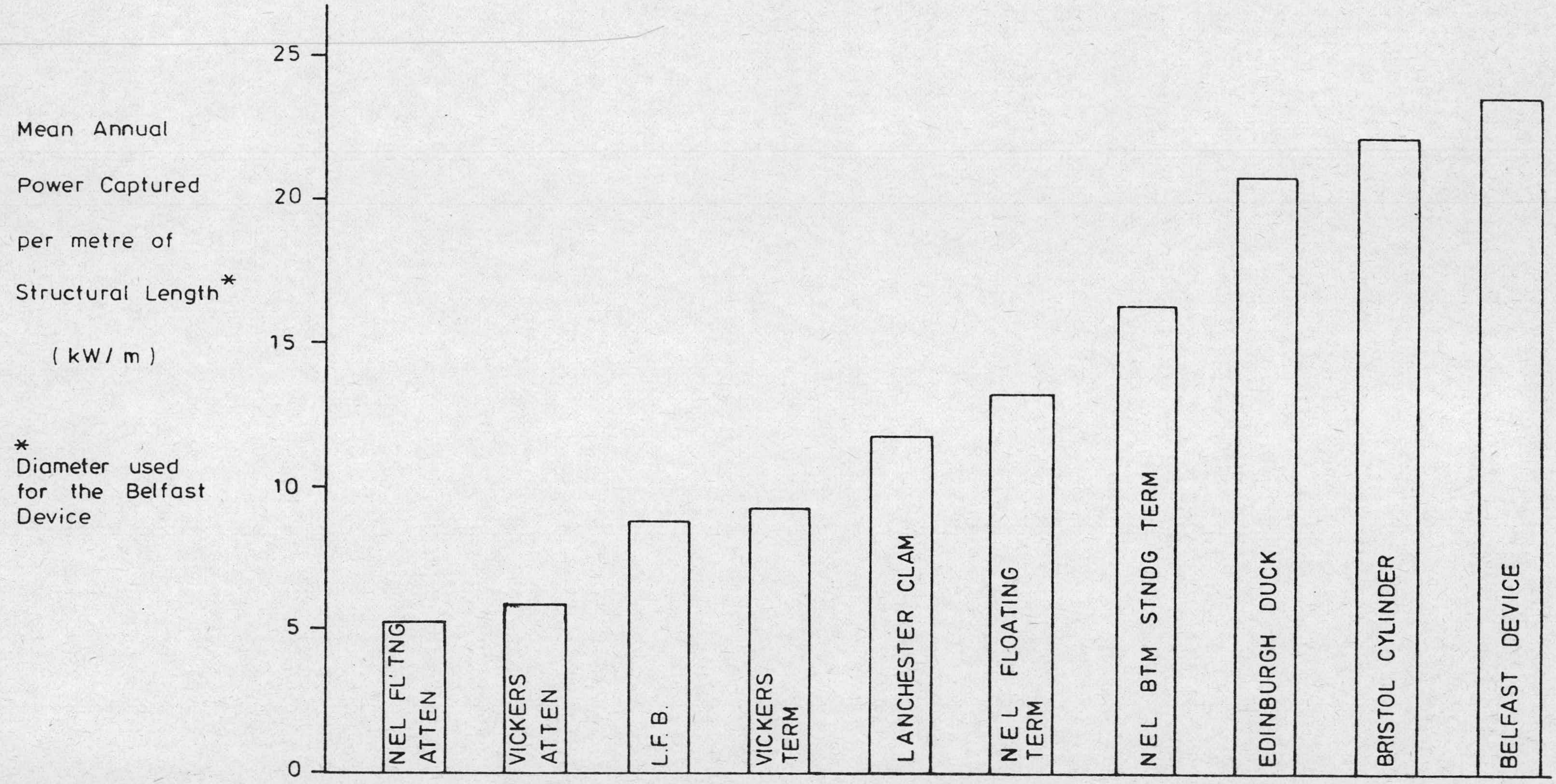
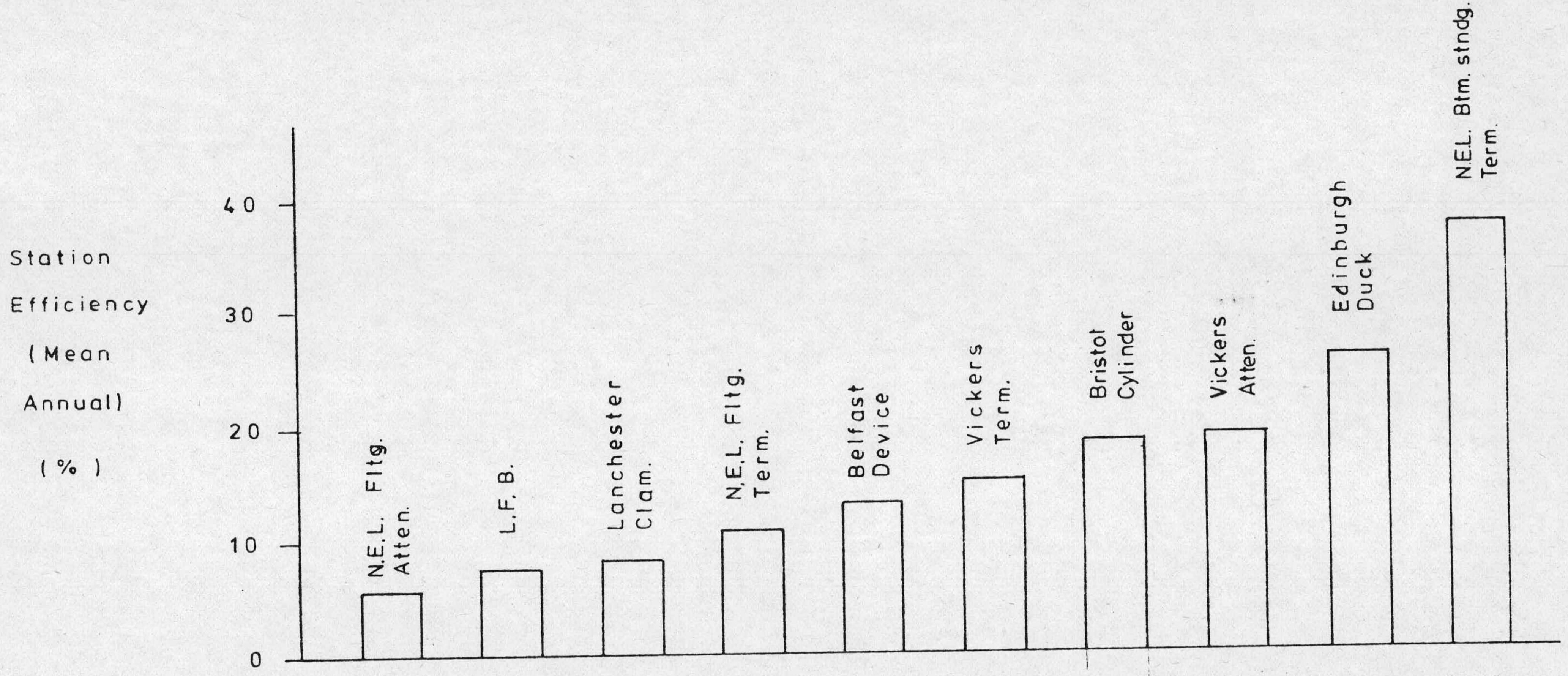


FIG. 11

COMPARISON OF OVERALL STATION EFFICIENCY

(Allowing for effects of plant cut-off, conversion and transmission efficiencies and availability)



Overall Station Efficiency is defined as

$$\frac{\text{Mean Annual Power Delivered by 2 GW Station to Skye}}{\text{Power per metre in sea at device location} \times \text{Station length}^{*}}$$

* assumes one array of regularly spaced devices
(Note: Belfast devices form a double array)

FIG. 12

COMPARISON OF MEAN ANNUAL POWER DELIVERED TO SKYE PER UNIT LENGTH OF STATION

(Allows for effect of plant cut-off, conversion and transmission efficiencies and availability.)

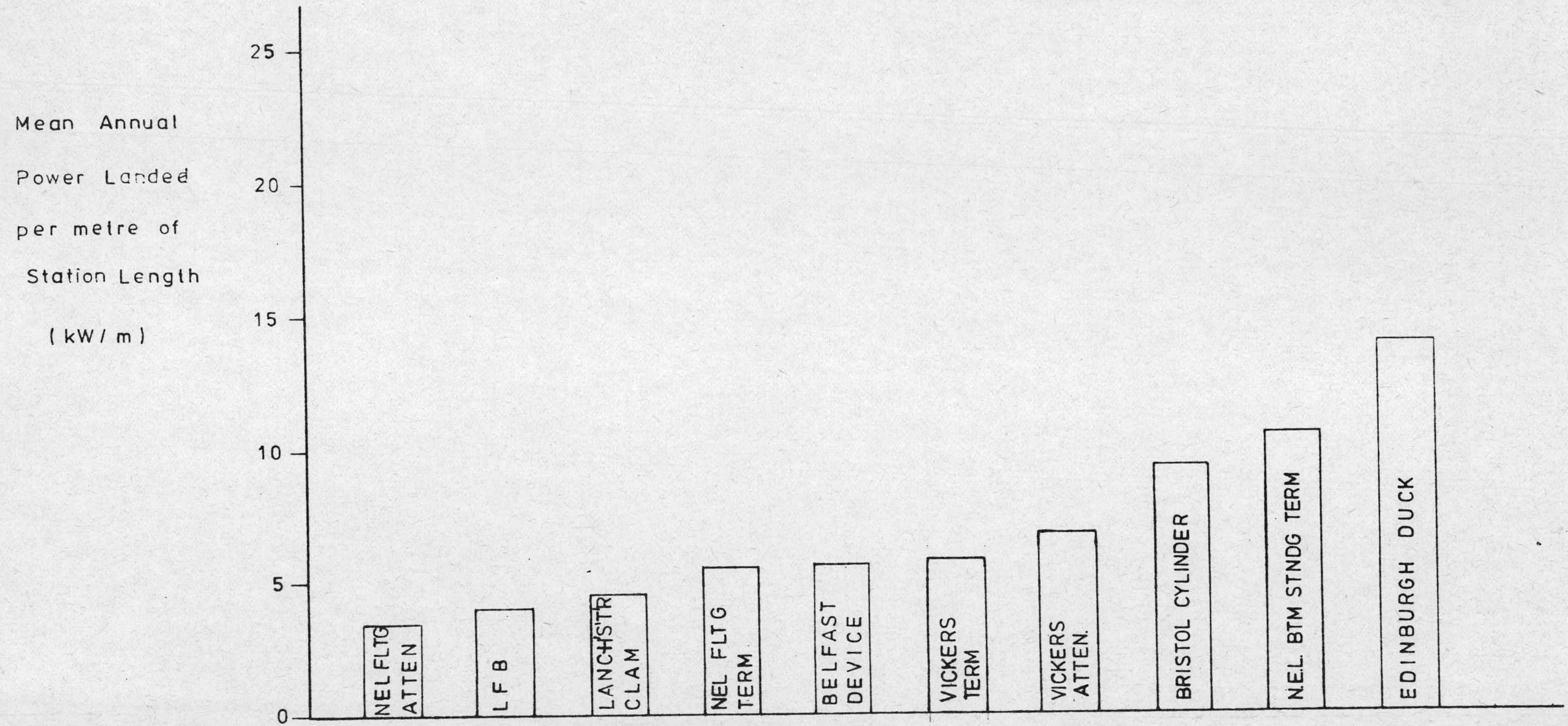


FIG.13

RELATIONSHIP BETWEEN CAPTURED POWER AND SWEPT VOLUME
(PER DEVICE AT RATED POWER)

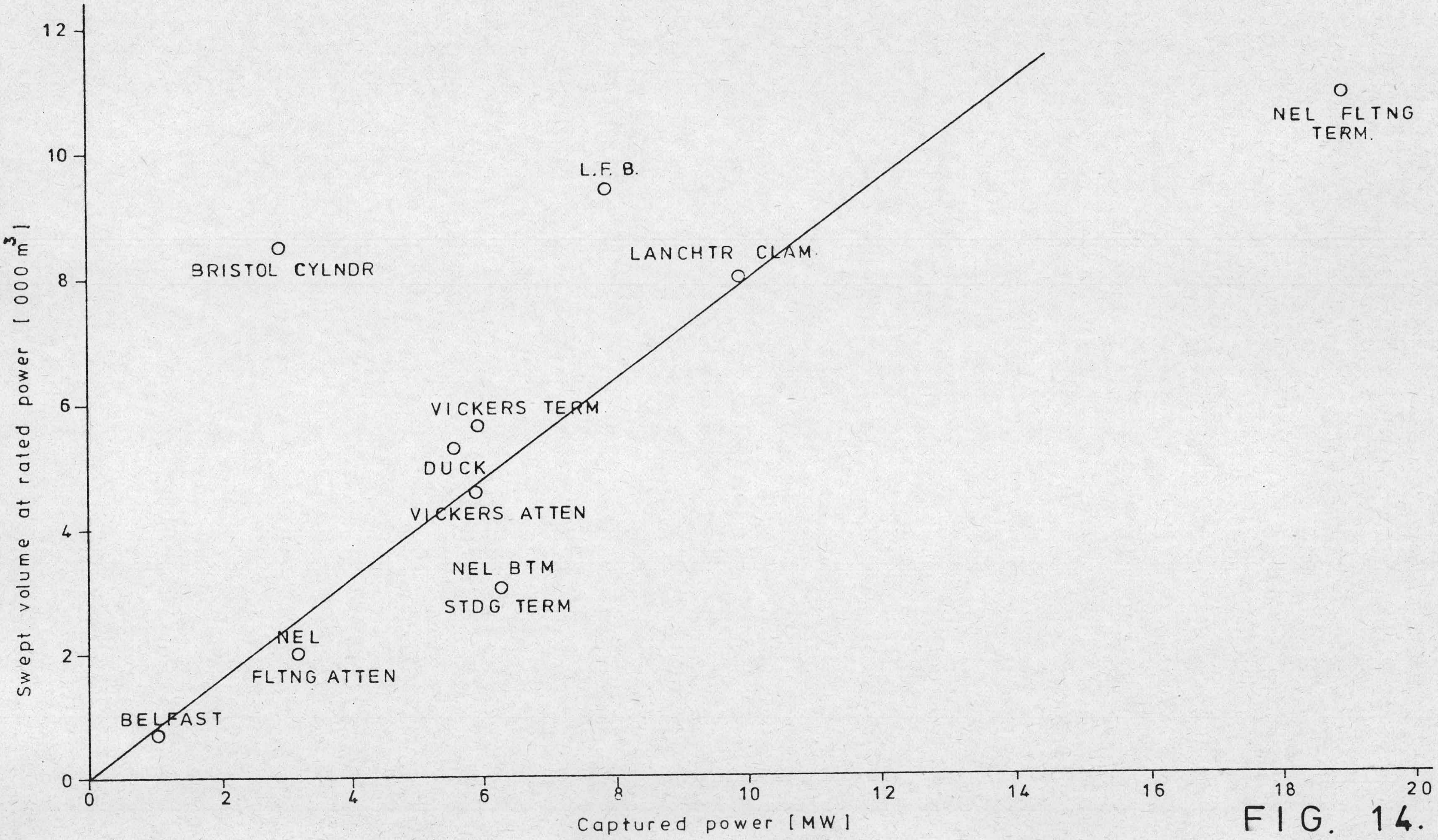


FIG. 14.

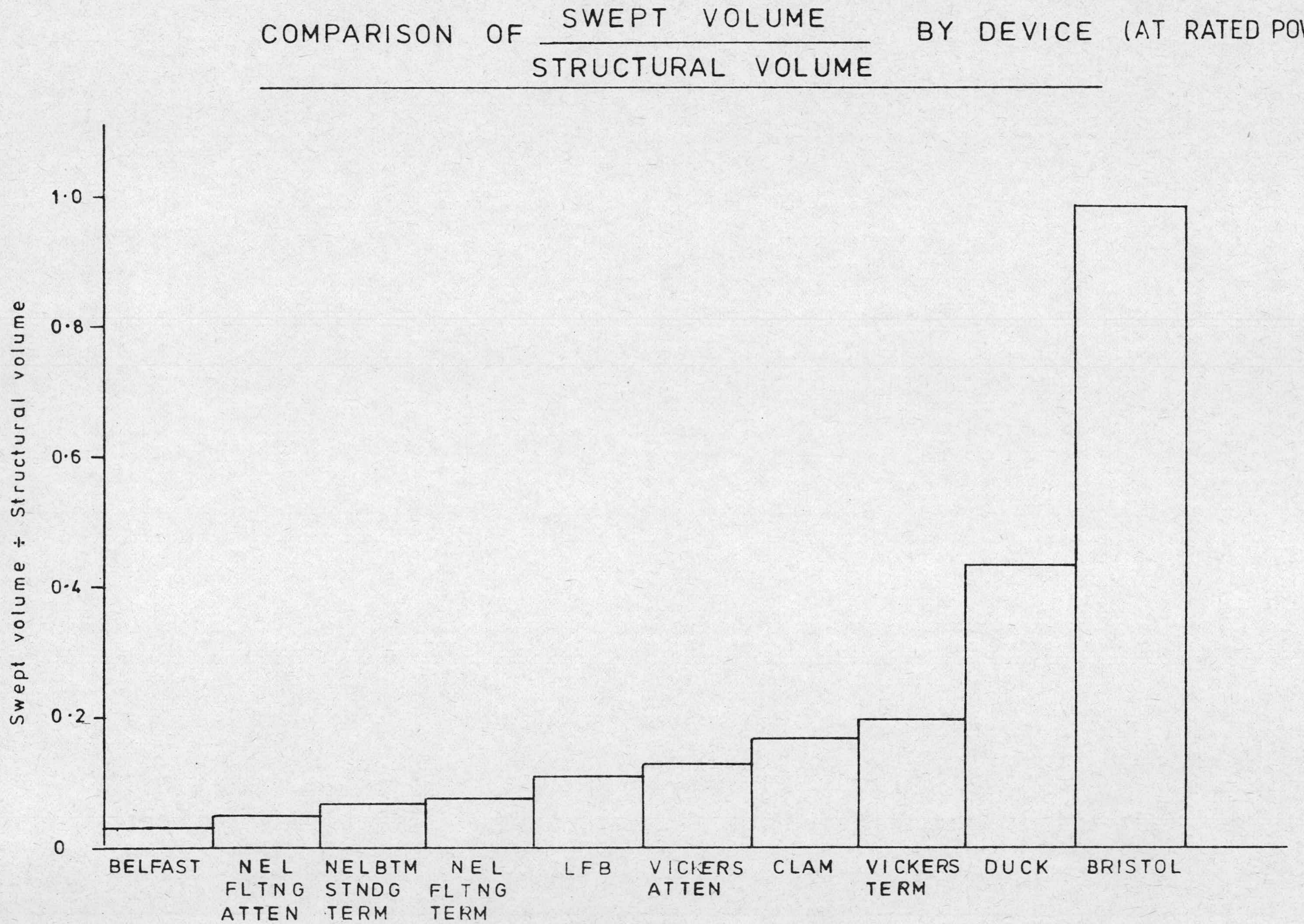

COMPARISON OF SWEPT VOLUME / STRUCTURAL VOLUME BY DEVICE (AT RATED POWER)
Swept volume ÷ Structural volume
1·0
0·8
0·6
0·4
0·2
0
BELFAST
NEL FLTNG ATTEN
NELBTM STNDG TERM
NEL FLTNG TERM
LFB
VICKERS ATTEN
CLAM
VICKERS TERM
DUCK
BRISTOL

FIG. 15.

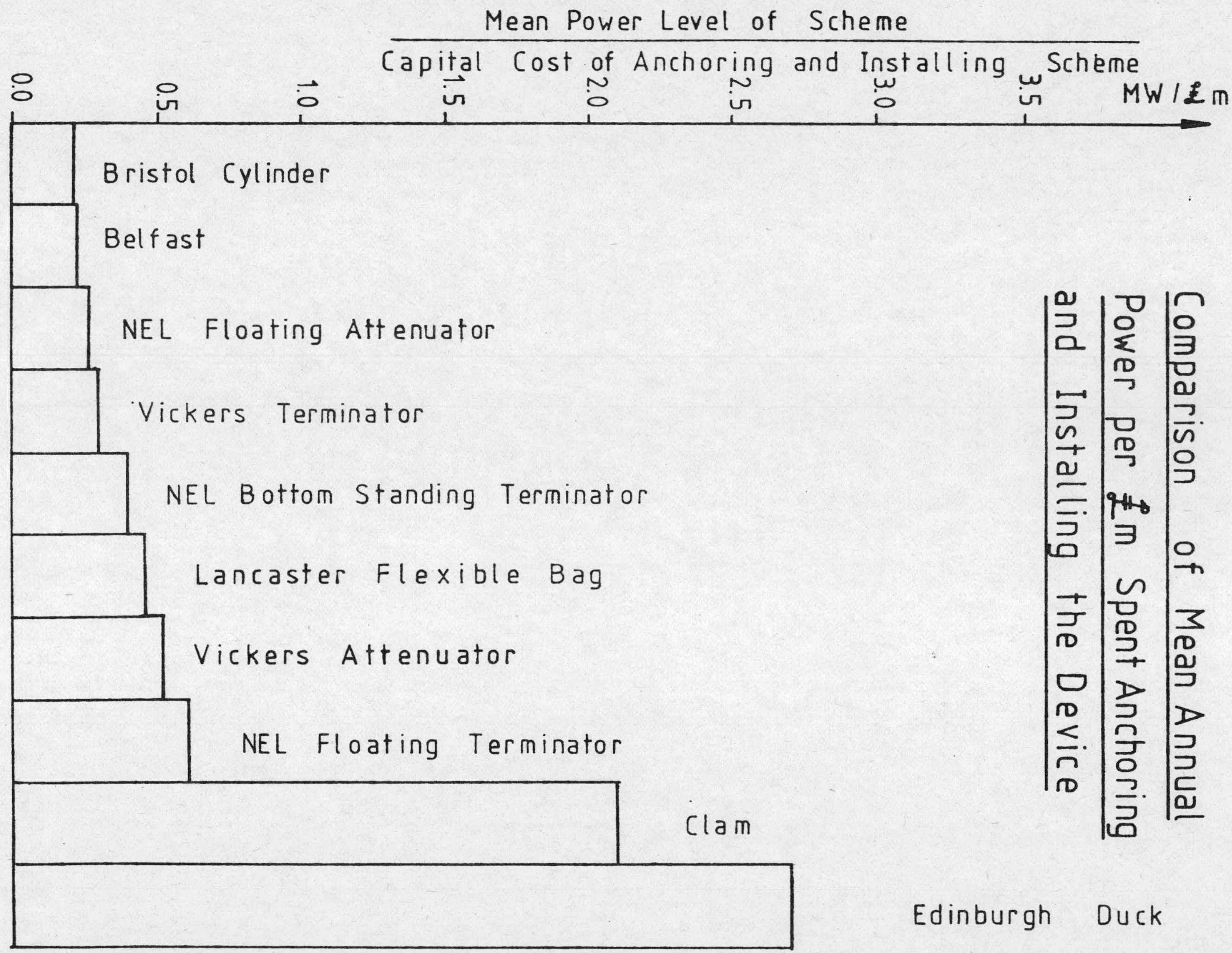
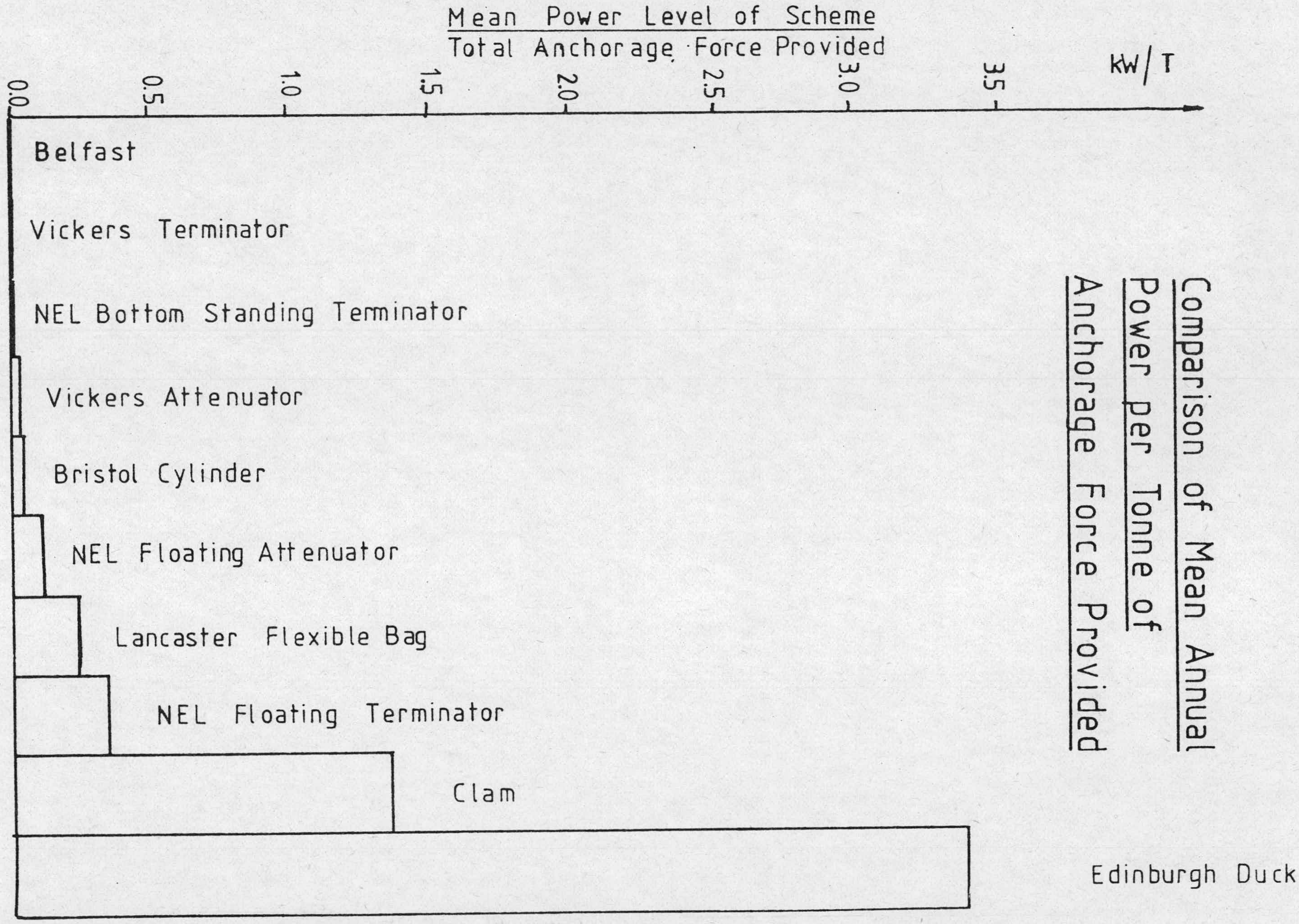


Fig. 16

Comparison of Mean Annual Power per £m Spent Anchoring and Installing the Device

Fig. 17



Comparison of Mean Annual Power per Tonne of Anchorage Force Provided

WAVE POWER

CIVIL CONSTRUCTION REQUIREMENTS FOR 2GW INSTALLATION

	BRISTOL CYLINDER	LANCASTER FLEXIBLE BAG	NEL BOTTOM STANDING TERMINAT'R	VICKERS TERMINAT'R	VICKERS ATTENUAT'R	BELFAST	NEL FLOATING TERMINAT'R	NEL FLOATING ATTENUAT'R	EDINBURGH DUCK	LANCHESTER CLAM
CONSTRN. FACILITIES										
Dry Dock Type (No)		4 ‡	—	—	—	—	4	—	—	4
Shiplift Type (No)		—	—	—	—	5	—	—	3	—
Slipway Type (No)	* 1 *	—	3	6	5	—	—	8	—	—
	* Facility incl's small dry dock.									
CONCRETE										
Total Amount (m^3)	1,192,000	7,882,000	5,296,000	10,166,000	8,008,000	8,115,000	7,030,000	13,651,000	4,074,000	5,908,000
Amount/Annum (m^3)	199,000	876,000	602,000	1,244,000	962,000	955,000	793,000	1,517,000	582,000	792,000
REINFORCEMENT										
Total Amount (t)	170,000	854,000	589,000	520,000	510,000	1,593,000	130,000	667,000	465,000	488,000
Amount/Annum (t)	28,000	95,000	67,000	64,000	61,000	187,000	15,000	74,000	66,000	65,000
PRESTRESSING STEEL										
Total Amount (t)	65,000	722,000	141,000	224,000	192,000	38,000	236,000	558,000	149,000	392,000
Amount/Annum (t)	11,000	81,000	16,000	27,000	24,000	4,000	27,000	62,000	21,000	53,000
STRUCTURAL STEEL										
Total Amount (t)	502,000 **	162,000	118,000	220,000	—	559,000	—	—	169,000	226,000
Amount/Annum (t)	84,000	18,000	13,000	27,000	—	66,000	—	—	24,000	30,000
	** Includes 78,000 t. of hydraulic pipelines.	‡ Team propose to use shiplift type								
NUMBER OF DEVICES	444	356	589	1100	756	1900	185	1444	956	341

FIG. 18.

4. NOTES ON SPECIFIC TOPICS

4. (i) BASIS OF COSTING OF CIVIL CONSTRUCTION

In view of the difficulties which had arisen in previous years, when Device Teams costed independently and the Consultants attempted to rationalise the results - with the inevitable conflicts which arose - for the present round of reporting it was decided that the Consultants would circulate a Working Paper setting out the approach for the Teams to adopt.

The Working Paper was prepared by a small committee which included representatives of many of the Device Teams. This ensured that any special points which the Teams wished to explore were adequately covered and helped the results to gain general acceptance.

The Working Paper set out standard rates for the most important items which could be anticipated in a Bill of Quantities and explained in great detail how these rates were derived.

The detail included rates for labour, plant and materials with build-ups of on-costs for such things as bonus, sick pay, site offices, overheads etc. It gave productivity rates so that a Team could check the amount of labour and plant assumed for a given operation. This Paper also set out (where appropriate) the limits of applicability of rates. Thus, having the derivation of the rates, Device Teams were in a position to develop their own rates should it be felt that the standard rates were inapplicable. The intention was that this would be the exception rather than the rule.

With this approach, problems of costing were limited to those associated with the justification for the adoption of a special rate, and the assumptions made in its derivation.

In order that everything was on a common basis, all rates etc. were based on those applicable at Hunterston. For this purpose the area at Hunterston was assumed to be infinitely large and with adequate water depth at a convenient distance offshore. With this assumption a standard construction facility, capable of an output of 200,000 cu m of concrete per annum, was costed. The variable covered in the Working Paper related to the manner in which the device was launched. Teams had the choice of ship lift, slipway or flooded basin.

Although all construction facilities were to be nominally at Hunterston, the intention was that the concept would represent a series of such facilities at various suitable sites in Scotland. In the event, Teams developed single larger facilities which indicated economies when compared with the use of multiple standard facilities. While it is accepted that such an approach could lead to some economy it could also lead to greater labour difficulties and possible environmental problems. For these reasons, and in order to retain uniformity of pricing throughout, the most likely costs quoted have in all cases been based on the use of standard sized facilities but a suitably weighted design tolerance has been postulated to allow for the possibility of economies arising from use of large facilities.

4(ii) THE COSTING OF DEVICE INSTALLATION

Device installation is one of the most difficult aspects of Wave Energy to cost. It involves the following:-

1. The development of a feasible overall method of installation.
2. The selection of appropriate marine craft.
3. The assessment of the time necessary to carry out each marine operation making up the overall installation method.
4. The assessment of the sea state in which each marine operation can be undertaken.
5. The statistical likelihood of, and waiting period for the occurrence of various sea states at the different water depths in which the Teams propose to site their devices.

   Although periods of good weather can occur at any time of the year, taken statistically over the lengthy period required for installation of the devices necessary for a 2GW station, these factors obviously vary with the season of the year.
6. The further limitations (where appropriate) due to daylight, fog or current.
7. The costing of the marine craft involved.

In order to assist, the Consultants produced a Working Paper giving the statistical parameters relevant to 5 and 6 above, and EASAMS gave information on the cost of a number of marine craft - i.e. those required for maintenance. Costings for the remainder of the craft were obtained from other sources.

The costing exercise had to deal with two essentially different types of device: floating and bottom standing.

The former involve the prelaying of moorings and the hook-up of devices thereto. Piles set in the rock sea bed were a preferred form of anchorage and necessitated the use of large specialised craft costing upwards of £40,000,000 apiece. Specialised clump anchors may prove to be a more economical solution.

The installation of bottom standing devices involves the local preparation of the sea bed, the careful lowering of the device and its final anchorage to the sea bed - in most cases using rock ties. Once again large specialised craft are involved; in this case faced with the added hazard of working in relatively shallow water depths.

The approach to costing lends itself to tabular presentation setting out operations, wave and light limitations, operational durations etc. This leads to an evaluation of the total time for the complete installation procedure, the number of devices which a prescribed fleet of vessels can instal in a year and hence the number of such fleets (and their cost) necessary to enable all the devices to be installed within the time prescribed by the Device Teams.

4(iii) COSTING OF M AND E PLANT AND TRANSMISSION

Where turbines and generators have been costed by the Teams, these costs have been checked and if necessary adjusted to allow for items which may have been omitted.

In the case of turbines and generators for devices which have not had a full design and costing exercise carried out by a manufacturer, costing formulae, based on three sources of information, have been developed by the Consultants to price. Additionally these formulae ensure that the plant costs for different devices do correlate. It must be emphasised that this costing method is very approximate and of a preliminary nature and is appliable for units up to 10MW only.

Air Turbine

Three sources of information were considered to provide a system that permitted a correlation of air turbine costs.

It must be noted that generally because of the vastly different geometries and degrees of complexity it is thought at this stage impossible to cost air turbines generally (Wells, Francis and Axial flow) according to rating or speed. The only parameter available becomes weight.

Three sources of information were considered to permit very crude costings of turbines on a common basis.

1) Quote from Airex Ltd. for SEA Clam turbine. This quote was for £45K for a single stage 3.5m Ø 8 blade Wells turbine. £5K was added by SEA to allow for splash guard, shaft balancing and module assembly. Estimated (SEA) unit weight is 6.5T.

2) Quote from Sirocco for Belfast Wells turbine. This is a 1.25m Ø 2 plane opposed flow turbine (4 rotors each of 6 blades). Weight 7.7T. The Sirocco quote was £80K for one of a batch of 5 - quoted reduction for mass production is 20% i.e. £64K per unit.

3) K & D have a tender price (1978) for a 2.3m Ø Francis turbine. This at 1981 prices is equivalent to a total of £600K. This turbine cost may be split into two components:-

   a) turbine runner - 7T @ 18K/T - £125k
   b) all other materials - 77T @ 6K/T - £475k

(The turbine runner is a 2.3m Ø single multi-blade casting, fully hand ground to profiles for hydro applications).

A price reduction of 15% for bulk production brings the total cost to £500K.

The best approximation that can be made at the present time for turbine costs is assumed to be:-

Wells and rotating parts of other turbines	£8000/T
Casings, castings, machined housings	£6000/T
Diffusers, convolutes, ducting etc.	£2000/T

Where no weights or drawings are available axial flow turbines have been priced on other device turbines and factored by the square of the diameter ratio.

Generator

The costing formula for generators has been developed from three sources of information:-

1) Clam figure from GEC for 'off the shelf' 1MW generator. This figure was £43K - 45K for 1MW diesel driven machine. 45K is the marinised version and has basically a higher insulation rating and is Lloyds approved for marine use. This price is for a constant speed machine in a 1.3 MW frame including cooling fan, casing and mounting. This machine, rated at 1MW is heat rated to 1.3 MW and is 50/60 Hz, 1100 rpm, ex works tested and assembled (wt = 8^T).

2) Merz & Mclellan figure for the Duck - 1.2 MW + 3.3 kV switch gear - 46K per unit.

3) K & D pricing figure for large 'one off' hydro generators. This figure - £3.3 $(MW/rpm)^{\frac{1}{2}}$m. is for essentially a constant speed (but with up to 90% overspeed capability) machine and includes excitation and both generator and turbine control, casing, mounting, basic cooling and is F.O.B.

The formula is based on rating and speed. It includes a basic cost of £1.56 $(MW/rpm)^{\frac{1}{2}}$ million, which figure includes casing immediate to the machine, testing and works assembly. An addition is made of 15% for variable speed machines and rather over 5% for constant speed machines. This is to cover excitation control, additional assembly on site, transport and loading out. Finally an allowance of £6,000 per MW is made for cooling separation.

The formula is, therefore:-

$$£1.56\ (MW/rpm)^{\frac{1}{2}} \times 10^{6} \times 1.15 + (6{,}000 \times MW)$$

Transmission

The transmission scheme includes two subsea crossings, (from the devices to the Outer Hebrides and from the Hebrides across the Minch to Skye) plus transmission lines and onshore installations on the Islands themselves.

For transmission lines, civil works and plant installation on the Islands (or platforms offshore) allowance has been made for cost of construction increase due to remoteness, difficult ground conditions, poor access, higher wages and more expensive transport arrangements. This has lead to an increase of between 50 and 100%.

For major submarine cable laying off Outer Hebrides and across the Minch to Skye, the Consultants have been guided by two recent and major cable contracts placed jointly with STK, Oslo, and Pirelli, Milan, by BC Hydro for supplies to Vancouver Island. Appropriate supply and lay rates have been derived from these actual and current contracts.

A counterpart check was made using cost of forthcoming channel DC link (CEGB). Derived cost supports rates used in estimates. Of interest is the fact that Consultants' rate for the cables to Skye is agreed by the Vickers Team and appears generally acceptable to LFB Team's Consultants.

The rates used for the submarine cables are as follows:-

400 kV Cables (Hebrides to Skye)	£1.75 m/km 3 phase
275 kV Cables from the devices to the Islands -	£1.6m/km 3ph ($1600mm^2$) £1.4m/km ($800mm^2$)
D.C. Series Power Connections $\pm$ 35kV £0.15m/loop km	

4(iv) THE FRAMEWORK OF COST APPRAISAL

Outline of Approach

The cost appraisal of the unit cost of energy (in pence/kWh) and of the 2GW power station (in £ M) were undertaken in an equivalent manner to previous years; but for this report a computer program has been used to allow more detailed analyses to be undertaken rapidly and easily.

Any aspect of the scheme costs can be specified separately, by giving a cost rate, a quantity, and refering to a profile of expenditure through time. These separate items could be, for example, the cost per device for installing machinery, the cost per vessel for purchasing a tug, or a lump sum for providing temporary moorings.

The program accummulates the products of cost rate, quantity and expenditure pattern by year into a framework by year, given codes for each item allocating it to a cost centre, and allocating it to either scheme capital costs or power station maintenance.

The detailed cost centres, some 16, are in fact used at the less detailed level shown in Figures 2 and 3.

The energy output of each scheme is calculated by applying the average annual energy captured per device, factored by the average power chain conversion and transmission efficiency and the average availability, to a profile giving the number of devices on station in each year.

Unit Cost of Energy

To derive an overall average unit cost, the various streams of costs and energy landed have to be brought to a common basis. For the simple scheme assumed in previous years, this was done by annualising the total capital cost and adding it to the (assumed constant) yearly maintenance cost and annual energy landed. For this assessment round, because of the variable streams of all three components arising from the more detailed assumptions adopted, a different (but mathematically equivalent) approach was used.

All streams of costs and energy were converted to net present totals, using the specified opportunity cost of capital (discount rate) of 5 percent. The total accumulated costs were then divided by the total accumulated energy to give the pence per kilowatt hour figures given.

Array Capital Costs

These figures are simply the undiscounted total expenditure incurred at the time the full energy is deployed.

Sensititivity Tests

Since all devices have broadly similar profiles of expenditure and energy production, changing the discount rate does not alter the device merit order.

Work is currently underway on testing the effect of altered component life assumptions, principally the examination of prolonging the life of the concrete structure from 25 to 50 years. This produces improvements of between about 15 to 20 percent in the unit costs, with devices with high concrete content obviously producing the higher savings. This may narrow the range of the overall costs of power, but is unlikely to alter the merit order.

Cost, quantity and energy tolerances have all been estimated for the original data, and their aggregate effect on the spread of possible results has been tested by repeated sampling from the probable range of each of the values included in the data. The results of this sensitivity test are being used to guide the emphasis of further work, in an effort to improve the precision of the less well specified devices.

4(v) THE ASSESSMENT OF AVAILABILITY

The availability of the various devices has long been a sensitive subject and until recently it has not been possible to consider it in a coherent fashion. The way has recently opened for a more logical approach with the receipt of information on failure rates now available from Yard. These data cover most of the items of plant used aboard the devices.

Based on the assumption that plant is given adequate routine maintenance, Yard have supplied information on the frequency of failure per year. In this context it will be appreciated that as the number of similar plant elements (say turbines) is increased, so proportionately are the numbers of failures per year.

Yard have also prepared logic diagrams setting out the sequence and number of plant elements. This, in conjunction with the failure frequencies enables an assessment to be made of the percentages of each of the items of plant which (statistically) have failed after one year's operation. Hence the percentage loss of power at the end of the year can be derived.

As the loss of power is presumed to vary linearly, the average (percentage) loss of power over the year is half that occurring at the end of the year. This would be on the assumption that repair teams visit each device at least once a year. The percentage availability is 100% less this average loss.

Should the incidence of failure at the end of the year be excessive, consideration has to be given to repair at more frequent intervals.

To the loss of power due to failure of plant must be added loss due to the failure of the transmission system, leading to the overall availability factor.

The Consultants have found that for most of the devices a satisfactory availability can be achieved on the basis of Yard's failure rates associated with a reasonable frequency of repair visits.

In the case of the Lancaster Flexible Bag and the S.E.A. Clam, the reliability of the flexible membranes is crucial. Yard have given a range of figures for failure for these elements and by taking a figure rather nearer the lower end of the range, a satisfactory relationship between availability and maintenance can be achieved.

In the case of the Edinburgh Duck, a different approach had to be adopted as the use of Yard's failure rates indicated that the Duck would not be operable.

The assessment of failure rates is a very difficult subject - data being scarce or non-existent and often widely varying or contradictory. Hence Yard's figures may be open to adjustment. This in fact was the 'different' approach adopted by the Consultants. A reasonable level of availability and maintenance was assumed and the corresponding failure rates derived. This approach led to a requirement that the average failure rates to be achieved to make the Duck adequately reliable must be 1/50 of those set out by Yard.

Yard's initial assessment of failure rates for the Bristol Cylinder led to an unacceptably low availability. But Yard's initial interpretation of the Team's presentation was very pessimistic. Study of the results by the Team showed failure rates could be substantially reduced at negligible additional cost, such as by providing redundancy in seals. Also failure of a rode does not cause the extreme loss in productivity assumed by Yard. Revised failure rates incorporating these factors have not been received by the Consultants from Yard in time for this report. Hence an estimated availability factor of 80% has been used in the productivity assessment.

The availabilities derived include allowances for repair as well as loss of power prior to repair. A longer repair downtime has been assumed for floating devices due to the greater difficulties of access. The availabilities taken into productivity calculations are 80% for the Duck and the Cylinder, between 83 and 86% for the floating devices and 87 - 91% for the bottom standing devices.

4(vi) NOTE ON DATA USED IN PRODUCTIVITY ASSESSMENT

1. The Bristol Cylinder has been tested in the 46 spectra selected by IOS. The water depth at the intended device location is 42m, the depth at which the spectra were measured, and therefore no further transformation for depth was necessary.

The Team has supplied detailed results showing the capture measured in the tank and the corrections necessary to allow for imperfections in their test rig and spectral components not reproduced at Cadnam. Further factors have been presented to allow for the improved productivity which the Team believe will be achieved with a cylinder of diameter larger than that tested and incorporating variable springing and damping. The Team has data to support this, but from regular wave tests only. Further tests by the Team in the near future will confirm or contradict these corrections. For the present the Consultants have allowed for all except those in respect of wave components not reproducible in the tank - the Consultants not currently not being in agreement with the Team over the validity of these factors.

Power chain efficiency curves have been supplied by the Consultants except for the rode pumps, for which a single value figure of 0.85, supplied by the Team, has been used. K & D are in general agreement with the Teams's M & E Consultants over efficiency values, for turbines, generators and transmission.

2. The Clam has been tested in the 46 spectra selected by IOS transformed to a depth of 80m. However, due to the large scale for testing chosen by the Team (1:55), the Cadnam tank was not able to generate 11 of the highest energy spectra at the specified Hs. The Team reduced the wave amplitude for these spectra and estimated capture assuming linearity, i.e. that capture efficiency is independent of wave height. This procedure, which increases the capture from that measured by 20%, is claimed by the Team to be valid but the Consultants are sceptical. In the short term the increase has been included in the Consultants' productivity assessment, but more data is awaited from the Team.

The Team have proposed further correction to power capture figures allowing for losses, differences in geometry between the model and the prototype, and capture in sea states of power less than 10 kW/m. These have been incorporated in this report, but are subject to confirmation by model tests. These corrections give an additional increase in productivity of 37%, of which 16% is due to the bag length being incorrectly modelled. Thus the total increase is productivity applied to measured data amounts to 65%.

Constant power chain efficiency values only have been supplied by the Team and therefore the Consultants have based the number of devices in a 2GW scheme also on the Team's figure.

3. <u>The Duck</u> productivity assessment has been made from tests in P-M seas in the narrow tank. Capture from the 46 selected spectra has been estimated by the Team by assuming linearity of performance (with respect to the incident direction of waves and their combination) and interpolating between narrow tank results. Steps have been taken towards substantiating these results by testing a string of six ducks in the wide tank, but on a fixed spine and in regular, unidirectional waves.

Power chain efficiency data and the number of devices have been supplied by the Team.

4. <u>The LFB</u> has been tested in the 46 spectra selected by IOS, but transformed to a depth of 75m. Capture results have been adjusted by the Team to allow for losses in the model. In addition RPT have increased the productivity results by 8% to allow for capture in seas of power less than 10 kw/m and to remove the effect of an unnecessary turbine cut-in value included by the Team. The turbines will capture power in low energy sea states, albeit at a much lower efficiency than at its design rating.

Power chain efficiency curves have been supplied by the Team and the number of devices required for a 2GW scheme agreed.

5. <u>The NEL Breakwater</u> has not been tested in the 46 selected spectra. Results received from the Team have comprised a single theoretical

monochromatic efficiency curve, which is insufficient to enable the Consultants to make a thorough assessment of the hydrodynamic performance of the device. Based on the information available, the Consultants had to make two assumptions in order to assess the device performance in the 46 selected spectra, i.e. that

(i) the device performance is independent of wave height.

(ii) the device productivity in a mixed sea can be obtained by applying a cosine rule to the 12 unidirectional componets of each multidirectional spectrum and subsequent superposition.

The device hydrodynamic efficiency thus obtained has been increased by 5% to reflect the increased directionality of the seas, due to refraction, as the waves propagate inshore. This increase has been necessary because the 46 selected spectra were linearly transformed to the design depth of 21m with the directional distribution of energy kept constant.

From the power chain efficiency curves provided by the Team, the Consultants' estimate of the number of devices for the 2GW scheme agrees with the number proposed by the Team.

6. The NEL Floating Terminator has been tested in the 46 spectra selected by IOS at a water depth of 42m, for which no transformation is required. Subsequently the Team have decided to resite the device in 100m depth, and it has been assumed the capture efficiency remains unchanged (i.e. the performance of the device is linear) even though the seas are more energetic at this depth. The Team has applied no correction to its results and therefore regards them as conservative.

Constant power chain efficiency values have been supplied by the Team, as has the number of devices required for a 2GW scheme.

7. NEL Floating Attenuator

No experimental data were supplied by the Development Team. Hence the productivity of the device had to be taken as that quoted by the Team. These results were based on narrow tank tests in monochromatic seas using pre-1981 procedure. Not being supported by any experimental results the Consultants have reservations as regards their validity.

The Consultants have applied a different availability factor to that quoted by the Team, i.e. 0.83 not 0.87.

The number of devices required for a 2GW scheme has been taken to be that given by the Team - insufficient power plant data prevented the Consultants from making an independent estimate of the number.

8. The Vickers Attenuator has been tested in the 46 selected spectra adjusted for refraction by HRS for a depth of 25m. Values of power capture in the spectra were supplied by the Team. The Team's data includes a correction for duct friction losses, the correction producing an increase in productivity of around 10% of the original value.

A combined power chain efficiency curve has been supplied by the Team, who have also determined the number of devices required for a 2GW scheme.

9. The Vickers Terminator has been tested in the 46 spectra selected by IOS transformed to a depth of 25m. Linear transformation of spectra to this water depth over the uneven seabed off the Hebrides is not valid; the spectra should be adjusted for refraction using the HRS program. The productivity of the device is likely to have been underestimated by not taking account of refraction. The Team have supplied values for power capture in the spectra which they have corrected for duct friction losses, the correction producing an increase in productivity of around 30% of the original value.

Constant value power chain efficiencies have been supplied by the Team, who have also determined the number of devices required for a 2GW scheme.

Constant value power chain efficiencies have been supplied by the Team, who have also determined the number of devices required for a 2GW scheme.

10. Belfast Device

Productivity assessment of the device in its currently proposed form is based on narrow tank testing in PM spectra. Results have been adjusted by the Team to simulate capture in the 46 South Uist spectra. There is evidence to verify this approach since agreement was found between tests on an earlier device configuration is both PM spectra in the narrow tank and the 46 spectra in the wide tank at Edinburgh.

The device is a point abøsorber and as such it is important to study its behaviour in an array. However, only a solitary device was tested in the tank. Productivity of the present double row array will therefore be less than model tests predict owing to as yet unquantifiable shielding of the second row.

A constant power chain efficiency value was supplied by the Team.

4(vii) ASSESSMENT OF PRODUCTIVITY

The productivity assessment of the various types of device is based on a steady state model using experimental random, multidirectional sea efficiency data in 46 sea states. These spectra have been selected by I.O.S., to allow the mean annual productivity of all devices to be estimated in a fair, consistent and economical manner. Their selection was made from a larger set of 399 spectra, synthesised from data collected at the offshore buoy in 42m of water off South Uist. The 399 spectra are considered to represent the mean annual sea climate.

Prior to any tests, the 46 selected spectra have to be transformed to the water depth at which the various types of device are to be placed. Two methods of transformation are used:

(i) A linear interpolation of the power level ignoring any refraction effects. This method is presumed to be satisfactory for water depths greater than or equal to 35m. The recent recommendations by TAG 2 to reduce the power in the sea at depths greater than 42m has been implemented by assuming linear device performance.

(ii) A refraction transformation for water depths between 35m and 25m.

Refraction effects have been the subject of an extensive study by the Hydraulics Research Station, who undertook the task of transforming the 46 selected spectra to 25m of water. At even shallower water depths other factors, such as wave breaking, need to be invoked to explain the observed power loss. The nature and interpretation of these effects is not yet fully understood and they should be the subject of an extensive research programme.

For the present, with no further information, the Consultants used their linear transformation method to produce an available wave climate for devices at water depths less than 25m. This places the shallower water devices at a disadvantage and allowances have to be made to take this aspect into account.

The device mean annual producticity is computed from the experimental random, mixed seas efficiency data obtained from tank tests in the 46 selected spectra (transformed to the appropriate depth). The mean productivity of the device in these spectra is obtained and subsequently modified to give the mean annual productivity. The modification is necessary in order to take into account the fact that the 46 spectra (when factored by their appropriate weightings and summed) represent a duration of 267/399 of a year. This amounts to 76.5% of the mean annual energy, the remaining 23.5% associated with the 132 spectra excluded by the selection process account for as follows:-

The energy associated with spectra whose Te value is outside the range 7-12.9 sec. are ignored (total energy loss 2.5%). Also ignored are spectra with power less than 10 kw/m. As well as being only a small percentage loss (2.4%), the power level is so low that fixed losses within the power chain will make the generated electrical output negligible.

Four spectra associated with high mean levels of power (>300 kw/m) were also excluded by the selection process. In the sea states represented by these spectra, there will occur peaks of power far greater than can be captured by devices, a cutoff being imposed on power captured by the rating of the plant. Hence the high mean power levels will probably not result in increased capture of energy. It is therefore assumed that the energy captured in these spectra is the same as the energy captured in a similar spectrum, but of reduced power level, contained in the set of 46. Spectrum 388 has been chosen for this purpose.

Finally, 27 spectra were excluded because of unusual combination of parameters, but otherwise lying within the bounds of Power and Te of the 46 spectra. The energy associated with these spectra amounts to 10.1% of the annual energy, and the device capture efficiency in these spectra is taken as the mean capture efficiency for the weighted set of 46.

The power chain productivity is obtained by assuming that for a given sea state the input power to the turbine is constant. The procedure for obtaining the mean annual productivity of the power chain, and its individual components, is similar to that applied to the device.

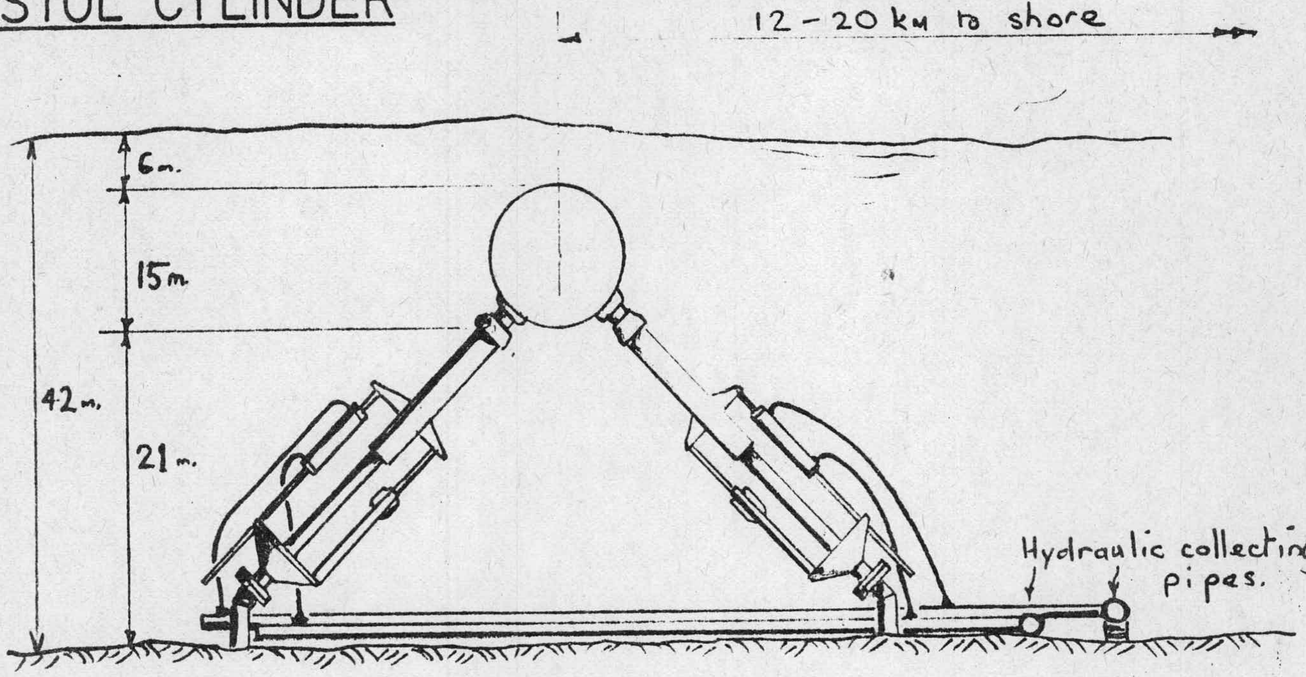
In addition to the steady state model, a time domain simulation is used, in certain cases, to quantify a factor describing the effect of the most questionable assumptions made in the steady state model. This factor is, when appropriate, used to give an improved estimate of device productivity.

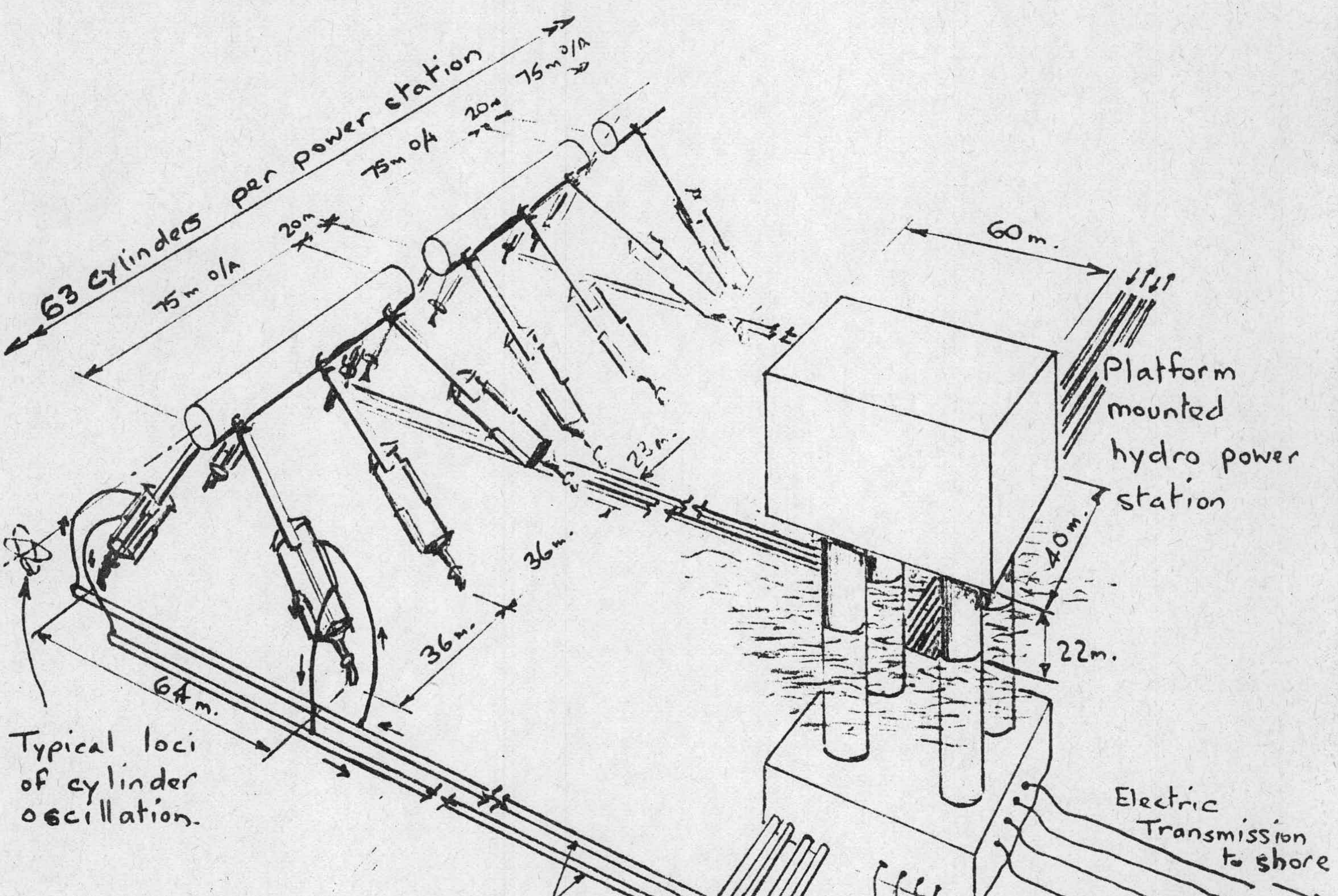
For reasons of simplicity, the simulation has been initially limited to a single degree of freedom, i.e. the power chain receives a single random input. Whilst this is adequate for a device like the NEL breakwater, it cannot accurately represent many other devices, for which simplifying assumptions must be made. However, by judicious choice of these assumptions, the time domain simulation can throw useful light on those elements of each device whose performance is least well described in the steady state model.

5. DEVICE DATA SHEETS & NOTES

BRISTOL CYLINDER

BRISTOL CYLINDER





LEADING DEVICE PARAMETERS

(Location - South Uist)

BRISTOL CYLINDER

A. Related to location

1.	Distance offshore (km)	12 to 20
2.	Water depth (m)	42
3.	Power in sea (Kw/m)	47.8

B. Related to device

1.	Overall size - length (m)	75
	- breadth (m) } - vertical dimension (m) }	15 (diameter)
	- gross cross sectional area (m^2)	176.7
2.	Weight of device (tonnes)	9000 approx.
3.	Weight of device ÷ length (tonnes/m)	120 approx.

C. Related to 2GW station

1.	Number of devices	444
2.	Spacing of devices (m)	95
3.	Length of 2GW station (km) (excl. navig. gaps)	42.2

D. Related to productivity

1.	Rating of generators (Mw)	120 Mw/25 devices
2.	Power in sea (Kw/m)	47.8
3.	Mean annual power delivered to Skye (Mw/device)*	0.87
4.	Mean annual output of 2GW scheme (GW)*	0.39

E. Related to structure economy and utilization of resource

1.	Mean annual power delivered per device ÷ length of device (Kw/m)*	11.62
2.	Mean annual power delivered per device ÷ device spacing (Kw/m)*	9.2
3.	Overall conversion efficiency of scheme* $\frac{\text{mean annual output of 2GW scheme}}{\text{mean annual power in sea x length of 2GW station}}$ (%)	19.2
4.	Capture Factor** $\frac{\text{mean annual power captured by device}}{\text{mean annual power in sea x device length}}$ (%)	46.4

F. Related to cost

1.	Cost of 2GW station (undiscounted) (£M)	4156
2.	Cost of each device (undiscounted) (£M)	9.4
3.	Cost of energy (discounted) (p/Kwh)	10.2

G. Miscellaneous

1.	Mean annual power chain efficiency (%)***	66
2.	Availability of the 2GW scheme (%)	80
3.		
4.		

* including availability factor

** not including availability factor

*** $\frac{\text{mean annual power landed at Skye}}{\text{mean annual power captured per device x No. of devices in scheme}}$ (not including availability factor)

COST BREAKDOWN

BRISTOL CYLINDER

	£ x 10^6 undiscounted		£ x 10^6 discounted	
	2GW Scheme	Per Device	2GW Scheme	Per Device
Structure				
Construction facility (for cylinders,piles,pipes & platforms)	144.6	0.33	135	0.31
Launch devices	21.3	0.05	18	0.04
Device structure (concrete cylinders)	304.6	0.68	246	0.55
	470.5	1.06	399	0.90
M & E				
Rode pumps and tube springs	951.0	2.14	767	1.73
Plant platforms and installation	83.9	0.19	68	0.15
Turbines & generators on platforms	96.0	0.22	78	0.17
Mechanical components and ancillary equipment on platforms	48.0	0.11	39	0.09
	1178.9	2.66	952	2.14
Installation/Moorings				
Anchor piles	80.1	0.18	65	0.15
Rodes (structure excluding springs and pto pumps)	732.6	1.65	591	1.33
Cylinder and rode installation vessels and operations	965.3	2.17	874	1.97
	1778.0	4.00	1530	3.45
Transmission				
Hydraulic pipelines (including installation and rock protection)	257.6	0.58	207	0.47
Generator output to islands	227.0	0.51	183	0.41
Substations on islands	48.0	0.11	38	0.09
Transmission to Skye	196.0	0.44	153	0.34
	728.6	1.64	581	1.31
TOTAL CAPITAL	4156.2	9.36	3462	7.80
Maintenance				
Maintenance base overheads & operations	67.0	0.15	27	0.06
Vessels, divers & technicians for inspection & repair	741.6	1.67	361	0.81
M & E spares	56.4	0.13	30	0.07
TOTAL MAINTENANCE	865.0	1.95	418	0.94

5/(i) BRISTOL CYLINDER

General

In 1981 this device was developed in a particular form in considerable detail sufficient for most of the elements of the scheme to have been determined, and well enough defined for detailed design to be able to proceed. However at the end of 1981 the Team advanced the prospective improvements in productivity which they predicted would be possible if a series of modifications were made to the design. The engineering associated with effecting these changes was not developed due to shortage of time so the corresponding costing changes are somewhat speculative. However although the ratings and numbers of cylinders may be accordingly adjusted to satisfy the 2 GW performance requirement, the rating of the aggregated hydraulic power conversion to an electrical output and its transmission to shore is well established. The three hydro-electric turbine generators on each of the six offshore platform structures have fairly precise specifications. Apart from being mounted on a offshore platform, the generating plant and its asssociated electrical equipment are otherwise entirely conventional in concept.

Performance

The comprehensive hydrodynamic testing programme so far carried out has led to a thorough understanding of the basic properties of the cylinder in regular waves. It has also yielded values for certain cylinder configurations of efficiency, and both peak and r.m.s values of rode forces and cylinder displacement in random seas. However the Team is not yet satisfied that it has fully optimised some device parameters or that it has provided the device with the best control system for optimum real sea performance. The reason for this is purely the time limitation on tank testing.

The productivity of the device on which the final cost of mean annual power and the size and capital cost of a 2GW scheme directly depend, derives from the results of tank tests in the sub-set of 46 spectra. The method of interpretation of the results was laid down in the Consultants' working paper 42. In principle, the productivity calculation precedure is straight-forward but the Team has identified a series of corrections to the measured data which have a substantial effect on the final productivity value. Several of these corrections involve changing the parameters of the cylinder from those actually tested, since the team is convinced that it did not test a model of the best possible device. Also, imperfections in the testing rig existed which had an adverse effect on model performance. Further shortcomings in these tests were that the Cadnam tank can produce wave components only from an arc of about 150^{o} (instead of 360^{o} as in a real sea) and that only a single cylinder was tested at a time in S. Uist spectra (due to limitations in the available instrumentation). The Team knows from earlier tests using an array of three shorter cylinders, each with only four rodes, that capture efficiency per device rises for a line of devices

The realisation that capture efficiency improvements are likely with a different cylinder came from the Team's study of previous test results in regular waves. These indicate that in regular waves, improvements in capture can be made by;

1) increasing the cylinder diameter from 12m to 15m.

2) varying the spring and damping forces according to the wave period.

3) varying the ratio of spring stiffnessess and damping forces in the fore and aft rodes.

In addition it is known that there is a significant deterioration in performance if the three rode stiffnesses on one side of the cylinder differ.

This was known to be the case with the model testing rig employed, due to imperfections. A further source of efficiency loss in the model was identified as the friction on the pulleys and drag on the chains which cause a phase shift between the wave and cylinder motions, leading to decrease in efficiency. There is no means of quantifying this loss at present but it was considered to explain the substantial differences in model efficiencies obtained in the same experiments at Edinburgh and Cadnam. As a temporary estimate the Team has allowed 9%.

For the present productivity assessment of the form of device which the Team is advocating it is therefore not possible in the present state of knowledge for the Consultants to work from a mean annual device performance which is fully substantiated by tank testing in random S. Uist spectra. Instead, the Team has taken data from the results of tests on a 75m long, 12m diameter cylinder with fixed and equal rode stiffnesses (albeit with erroneous unequal residual values giving reduced performance) and fixed damping. These data are then modified, spectrum by spectrum, on the basis of results in regular 2-D waves, the dependant variable T (the wave period in monochromatic waves) being interchanged for Te (the energy period in mixed real seas). This modification process involving multiplying output by a chain of three factors assumes that the effect of each factor is independant of the others, which the Team claims to be so. The Consultants have no means of confirming or denying the predicted productivity. The logic of the derivation is understandable, but the crucial question is how far the tendencies in regular waves are mirrored in real seas, and only further tank testing with the required device configuration alterations will demonstrate the answer. Thus it can be stated that the Team has arrived at a point in its testing programme in which it is now able to specify much more exactly the form of device desired for the next step and the further more refined tests necessary to reach a desirable productivity level.

The cylinder length, specific gravity, submergence and water depth have been determined for a 12m diameter cylinder but they are subject to modification for the 15 m diameter cylinder. Regarding length it is now realised that economic considerations could lead to a longer cylinder, since virtually the same very expensive rodes (including piling and installation) would then be more economically utilised in collecting more power. The cost of the extra length of cylinder would be relatively small. Although there is a drop in cylinder capture efficiency with increase in cylinder length, in changing from 75m to 100 m length there is nevertheless a net increase in captured power per cylinder. There will therefore be an optimum length, which the proposed estimate of 100 m is gauged to represent. However for the present assessment, a length of 75m is used since all efficiency calculations and costings referred to this.

Capture Efficiencies

The Device Team has presented a range of scheme mean annual device capture efficiencies depending on which of their predicted improvement factors are included in the efficiency calculation, and whether the cylinder remains at its as-tested length of 75m or currently-proposed length of 100m. These are as follows:

	1981 Design (Fixed tuning)	Variable Tuning (12m diameter)	Variable Tuning (15m diameter)
75m long cylinder	39%	49.4%	65%
100m long cylinder	32.8%	41.6%	56.5%

The corresponding number of devices in a 2GW scheme are as follows

75m long cylinder	615	447	331
100m long cylinder	518	377	279

The Consultants have calculated corresponding figures using the Team's tank results, but interpreting the effect of the missing wave components differently from the Team as they believe the Team has overestimated this effect. There is also a difference between the Team and the Consultants in the calculation of the available power. The Consultants have allowed the same predicted percentage improvements as the Team for friction and drag losses in the rig, unequal rode stiffnesses, variable tuning and longer cylinder, and they have also used the same loss of efficiency ratio in changing from a 75m to 100m long cylinder. The Consultants thus obtain the following mean annual capture efficiencies:

	1981 Design Fixed Tuning	Variable Tuning (12m diameter)	Variable Tuning (15m diameter)
75m long cylinder	28.6%	35.7%	46.4%
100m long cylinder	24.1%	30.1%	39%

and the following numbers of devices in a 2GW scheme

75m long cylinder	720	576	444
100m long cylinder	606	486	373

Status of Assessment Data

Simple idealised calculations, acceptable for the state of development reached, have been completed for the cylinder itself, the anchor piles, and the power take-off system.

The basic design and constructional details of the major structural elements of this device are well advanced and the Device Team has provided information on quantities and cost estimates for certain special items which have been checked whenever practicable and used as a basis for the Consultants' cost estimate. The Device Team has also provided a preliminary structural cost estimate which in total appears to be within 1% of the Consultants' own estimate, but it should be noted that the cost of the cylinder itself is less than 10% of the cost of the scheme.

The Team's advisers have provided comprehensive estimates for the platform generating equipment, transformers and switchgear. The only modification made by the Consultants is the additional cost of the inlet manifold. The electrical collection and transmission circuits have also been costed by the Team to which has been added the cost of the Skye terminal plant. These estimates have been accepted in part for budgetary purposes but the Consultants are of the opinion that the costs of submarine cabling and line construction are considerably underestimated. Furthermore some cost centres are omitted.

The installation costs have been developed in parallel by the Consultants and the Team and their advisers and there is now very good agreement between them on installation costs for both piles and cylinder.

Maintenance costs have been provisionally assessed by the Consultants in advance of final information from the Device Team, YARD and EASAMS.

It should be noted that all costing to date has been carried out assuming 12m diameter cylinders. The change to 15m diameter will alter rode and pile designs and therefore costs, as well as alter costs of the cylinder itself, and its installation and maintenance. The alteration came too late for re-costing to be carried out for this report in detail, but a nominal 15% is added to the affected items.

Development

The Team has pursued a rigorous, questioning approach to all aspects of the device, with the aid of a large team of sub-contractors, experienced in their respective fields. The process of development inevitably involves identification of new problems, leading to adoption of alternative solutions. This has been the case in this project, particuarly for the power take-off system, the rodes and the installation system, which are all inter-related.

In spite of exploring other options for power take-off, the device has retained its present form since its inception. The cylinder length had previously increased in August 1981 from 50m to 75m in order to accomodate six mooring rodes instead of four to provide rode redundancy in the event of a rode failure. Otherwise, recent alterations can all be classed as development of design details rather than alterations.

Recently, the Team focussed its attention on the possibility of using "tube-pumps" in place of the mechanical springs comprising pistons and accumulators, which they have so far developed for the rodes in the belief that they ought to use only existing, proven technology. (The term "tube-pump" is being used as this is its adopted name from other situations, but the Bristol Team sees its use in their device simply as a spring, since its single acting pumping behaviour would not be suitable for their power off take system. However since each rode contains six springs and two pumps, financial saving in using elastomeric tubes for springs could be substantial, since the rodes are the major cost centre in this device). The adoption of tube springs, besides effecting a reduction in capital cost, would lead to easier (and cheaper) installation, simpler (and cheaper) end connections and simpler and cheaper replacement. Providing future development can prove its long term performance and reliability, and Avon Rubber Company's cost estimates are correct, this component offers a very attractive improvement in this device.

For the purposes of this assessment therefore, tube springs costing £1M per device have been assumed with a corresponding reduction in the telescopic tube flexi-joints costs as proposed by the Team. It should be appreciated that this is an estimate made without redeveloping the engineering details of installation, end-connections, fatigue life, and redesigned rode and anchor forces, besides not allowing for the engineering of varying spring and damping rates.

Feasibility

The subsea nature of the device is at the same time both an advantage and disadvantage. The advantage is that it is not subject to the violent effects of extreme seas and freak waves. Rode forces in fact reduce in these as the cylinder is de-tuned. Limiting forces and displacements are therefore known and can be designed for with some confidence. The disadvantage of inaccessibility is reflected in high cost of installation and maintenance (which usually means replacement), and reliability. However the vulnerable components below the sea are relatively few (the pump, its outlet valve, the rode springs, and sea bed pipework). The major part of the power conversion plant is on the platform, well above water level and enclosed in a controlled environment and fully maintained in the same way as a conventional hydro-power station.

The interaction with YARD is continuing, but the Team has identified that the assumptions made BY YARD concerning relatively minor components (such as the number of piston seals, the type of accumulator bladder) make a dominant effect on the resulting reliability of the overall scheme. They are therefore confident that future interaction with YARD will enable them to show an acceptable reliability. In the meantime, the Consultants are using an assumed reliability factor of 0.8.

The major maritime installation operations will be critically subject to the weather, and in order to install enough devices in good weather, a large amount of expensive plant and manpower will have to be available, which for much of the time will be only waiting for good weather. There is a major technical reservation on the durability of the pelton turbine and nozzles in seawater; there are no data, practical or research, to indicate the likely performance at the very high jet velocity proposed. Identification of a suitable bucket and nozzle material must be the subject of future research. In principle however the power take-off and transmission to Skye are entirely feasible.

The relatively lengthy submarine cables required to operate at 275 kV and 400 kV would need to be constructed with a polymeric insulation in order to reduce reactive current requirements. Such cables are now being developed and should be available when required. The seabed routes have not been identified. There are known to be difficulties west of the Outer Hebrides, but this design fortunately minimises the number of individual cable routes required and does not require flexible cables.

Apart from doubts over the turbine buckets and nozzles, the Consultant's technical reservations are:

i) The fatigue life of heavily loaded rode components.

This should not be an insuperable problem with careful design.

ii) Marine fouling in the hydraulic transmission system.

Correct dosing and filtration treatment should overcome this.

iii) Integrity of the hydraulic transmission pipes.

The tendency of the pipes to move under the high internal forces and to corrode at pipe weld flaws in the salt water environment impose a very severe duty on the pipeline. Suitable pipe bedding and anchorage, and corrosion protection are vital.

iv) Provision for pipeline pressure relief in the event of a sudden drop in electrical load.

Details of the mechanism for this have not been worked out but the Team envisages automatic blow-off valves in the main, discharging direct into the sea. The stability of the hydraulic system is in some doubt due to the absence of any hydraulic storage on the high pressure side of the system.

v) Provision for the isolation of branch mains, i.e. of individual devices in the event of a branch pipe failure.

The need for this is recognised but the details of remotely operating the necessary valves have not been worked out.

vi) The flexible pipe connecting the rode pumps to the sea bed main.

An existing product designed to carry high pressure fluid (at up to 28,000 psi) exists for use in the oil industry but behaviour under the duty required here is unknown and will have to be proved.

vii) Mechanical wear of the pump chamber, pistons, and valves.

The duty required in sea water is onerous. Although Inconel 625 cladding has been allowed on the piston rods the durability of the whole system should be subject to detailed design and development.

(viii) The installation of the sea bed power collection mains by towing out long lengths (approx. 5km) and sinking in one piece on a prepared bed on the rocky floor is bound to be a delicate operation requiring calm conditions. Wharton-Williams report that a 2km length of 36 inch diameter pipe has been towed 393 km for installation in the North Sea and they consider lengths of 10 km to be feasible. The main difference off the Hebrides is the nature of the sea bed and the amount of bed preparation necessary to avoid final deformation the pipe, and to prevent it moving during service.

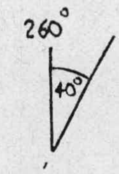
Conclusions

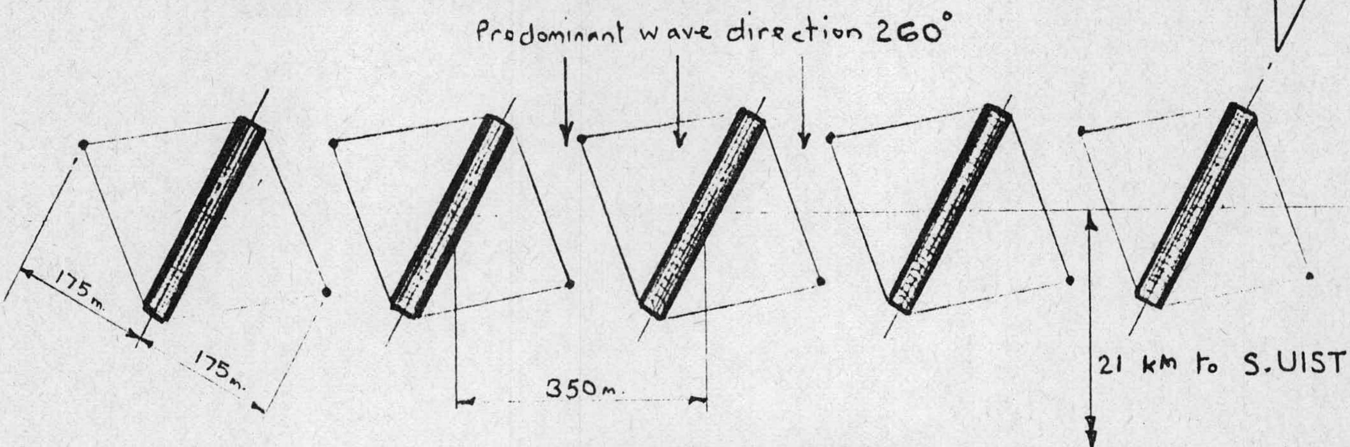
As indicated above the device remains at an interim stage of development. The further model testing planned in 1982 aims to substantiate the improvements in performance predicated in real seas. The major cost centre is the rodes (with the flexible joints making a very large contribution according to SBMs figures, but the Team's own investigations with Dunlop lead to a substantial reduction). The Team is therefore viewing the future development of tube springs with great interest.

The present assessment leading to a cost of 10.2p/kWh is therefore based on a design for which relevant model tests and costings studies have not been done in anything like the detail of the previous 1981 reference design (which had the parameters 12m diameter, 75, long, fixed tuning and mechanical springs). This cost of power is therefore dependent on the Team's many assumptions being confirmed by more detailed studies in the future, these should include material and engineering development of the tube springs and end connections, redesign of the device and anchors for different rode forces, new power take-off pump, telescopic tube and flexijoint arrangments, tank-testing with the new parameters, new installation procedures and costs, and material studies for the Pelton Wheel buckets.

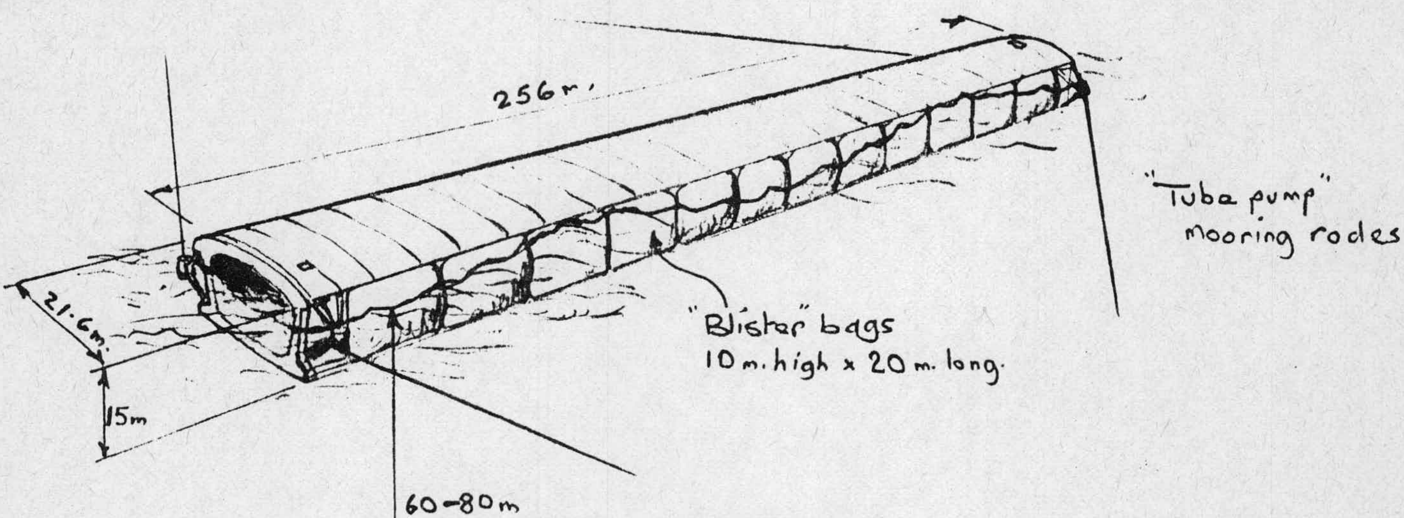
LANCASTER FLEXIBLE BAG

LANCASTER FLEXIBLE BAG

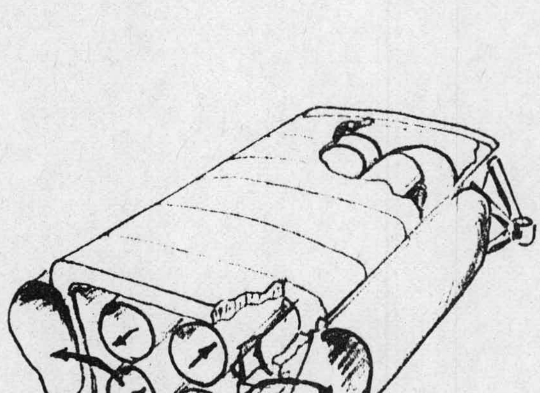




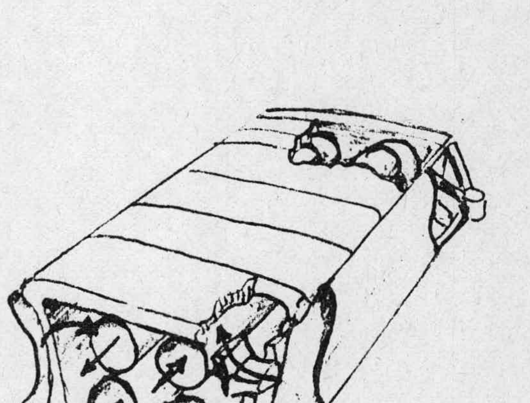
ARRAY AND LOCATION



DIMENSIONS



WAVE FALLING – BAG OPENING



WAVE RISING – BAG CLOSING

WORKING CYCLE

LEADING DEVICE PARAMETERS

(Location - South Uist)

LANCASTER FLEXIBLE BAG

A. Related to location			
1.	Distance offshore (km)		22
2.	Water depth (m)		75
3.	Power in sea (Kw/m)		50.8
B. Related to device			
1.	Overall size - length (m)	256	
	- breadth (m)	21.6	
	- vertical dimension (m)	15	
	- gross cross sectional area (m^2)	89	
2.	Weight of device (tonnes)	64000	
3.	Weight of device ÷ length (tonnes/m)	219	
C. Related to 2GW station			
1.	Number of devices		356
2.	Spacing of devices (m)		350
3.	Length of 2GW station (km) (excl. navig. gaps)		124.6
D. Related to productivity			
1.	Rating of generators (Mw)	5.5 and 2.5 Mw/device	
2.	Power in sea (Kw/m)	50.8	
3.	Mean annual power delivered to Skye (Mw/device)*	1.35	
4.	Mean annual output of 2GW scheme (GW)*	0.48	
E. Related to structure economy and utilization of resource			
1.	Mean annual power delivered per device ÷ length of device (Kw/m)*		5.3
2.	Mean annual power delivered per device ÷ device spacing (Kw/m)*		3.9
3.	Overall conversion efficiency of scheme* $\frac{\text{mean annual output of 2GW scheme}}{\text{mean annual power in sea x length of 2GW station}}$ (%)		7.6
4.	Capture Factor** $\frac{\text{mean annual power captured by device}}{\text{mean annual power in sea x device length}}$ (%)		17.4
F. Related to cost			
1.	Cost of 2GW station (undiscounted) (£M)	5254	
2.	Cost of each device (undiscounted) (£M)	14.8	
3.	Cost of energy (discounted) (p/Kwh)	10.4	
G. Miscellaneous			
1.	Mean annual power chain efficiency (%)***		71
2.	Availability of the 2GW scheme (%)		84
3.			
4.			

* including availability factor

** not including availability factor

*** $\frac{\text{mean annual power landed at Skye}}{\text{mean annual power captured per device x No. of devices in scheme}}$ (not including availability factor)

COST BREAKDOWN

LANCASTER FLEXIBLE BAG

	£ x 10^6 undiscounted		£ x 10^6 discounted	
	2GW Scheme	Per Device	2GW Scheme	Per Device
Structure				
Construction facility	329.4	0.93	308	0.87
Launch devices	39.5	0.11	30	0.08
Device structure	1807.1	5.08	1364	3.83
Towing and mooring attachments and castings	275.0	0.77	207	0.58
	2451.0	6.89	1909	5.36
M & E				
Flexible bags	142.3	0.40	117	0.33
Air ducts supports and louvre valves	386.2	1.09	292	0.82
Turbo-generators	324.1	0.91	245	0.69
Ancillary equipment	117.6	0.33	89	0.25
	970.2	2.73	743	2.09
Installation/Moorings				
Anchor piles	60.5	0.17	46	0.13
Rodes, and fittings and bearings	439.8	1.24	417	1.17
Installation vessels and operations	278.7	0.78	252	0.71
	779.0	2.19	715	2.01
Transmission				
Generator output to islands	468.0	1.31	353	0.99
Inverters and substations on islands	390.0	1.10	233	0.65
Transmission to Skye	196.0	0.55	161	0.45
	1054.0	2.96	747	2.09
CAPITAL COST	5254.2	14.77	4114	11.55
Maintenance				
Maintenance base overheads and operations	47.1	0.13	17	0.05
Vessels, divers and technicians for inspection & repair	1022.9	2.87	473	1.33
M & E spares	102.5	0.29	51	0.14
TOTAL MAINTENANCE	1172.5	3.29	541	1.52

5(ii) LANCASTER FLEXIBLE BAG

General

The LFB as presented by the current reference design is a final stage in the evolution of the flexible bag device which began with Prof. French's conceptual design of 1977. Prof. French attempted to develop the concept on the basis of 4 cardinal considerations which were:

i) To provide very cheap simple working interface with the waves (a rubber bag).

ii) To maximise the ratio of swept volume to structural volume of the device. This being identified as an essential parameter for an economic design.

iii) To function as an attenuator rather than a terminator: firstly because it was seen to be easier to stabilise a spine spanning across the crests and secondly because it is essential for the device to experience both wave crests and troughs simultaneously, within the finite length of the device.

iv) To adopt low pressure air as the ideal medium for power off-take.

Status of Assessment Data

The basic spine design and constructional detailing are at an advanced stage and the Device Team has provided information on quantities and cost estimates for certain special items which have been checked and used as a basis for the Consultants' cost estimate. The Consultants initial cost estimate, using the respective working paper was not in agreement with the Team's figures. The two substantial differences were in rates for concrete and post-tensioning. In both these areas the Device Team designed for ease of construction, not necessarily to minimise quantity. In order to permit closer correlation with other devices, the Team's lower costing rates have been used to compensate for this 'overdesign'. The reduction in cost stemming from this is of the order of 1.25p/kWh.

Very limited machinery costs have been received from the Device Team but rather more but still incomplete cost information on the transmission is available. The consultants have used mainly their own costings for mechanical plant and cabling. The costings for plant are speculative but are thought to allow correlation with other air devices.

The installation costs have been developed by the Consultants and assessed against the Device Team's report. The maintenance costs have been developed by the Consultants and compare closely with those received from the Device Team although there is some variation in approach.

Development

In 1978 the device was tentatively assessed as a good prospect, but on the basis of very limited information both in respect of structural size and productivity. Loss through local bag failure and the difficulties of designing a suitable bag were identified as problem areas.

The present design has, for the first time, had the benefit of wide-tank free floating testing and a thorough structural engineering development. The changes that have taken place since conception have been specifically:-

i) Development of discrete air cells in place of the continuous bag.

This change has little effect on the swept volume but permits a credible bag design and reduces the damage control problem.

ii) Development of hull geometry around the bags to provide a stable reference frame of adequate strength.

The result of this work has been to increase significantly the structural volume with a consequential economic penalty.

The productivity of all subsequent variations of the device during development has been below that measured for the original conceptual "bag along the top" design. Not all the reasons for this are thoroughly understood but they certainly include loss of power through spine motion and the "nowhere to go" feature of any manifolded device with limited reservoir volume. It is also clear that the Device Team is only at an early stage of understanding the hydrodynamics of the device and the current design may be far from optimal.

A comparison with the Clam is inevitable and is useful in highlighting stages in the development which now appear counterproductive. The original concept was a double-sided bag over a concrete spine. To permit an engineering solution the bag was first split into two strip bags-one along each side of the device - and was subsequently split further into discrete bag panels. The result of the independent Clam development, for quite different reasons, has ended with what can be termed the original French concept of a double sided bag, but subdivided into manageable lengths and then mounted on one side of the spine. The significant result of this is that the bag pierces the water plane and the spine can be designed independently without the requirement of a passive rear face to the bag cell. The consequence is much-improved natural stability over the LFB and as a result the structural spine of the Clam can be economically designed as a reference frame to carry wave induced forces.

Although double-sided, the LFB is not orientated as a pure attenuator. More power was absorbed by inclining the device at 30^o - 40^o to the predominent wave direction. The reasons for this are not yet fully apparent but it seems that in mixed spread seas, design of a pure attenuator is impossible and the optimum device orientation is between terminator and attenuator.

Feasibility

The flexible membrane system is extremely cost effective as an interface with the waves. The bags have been fully developed and with continuing research, particularly into interply fatigue, long life should be proved.

The reference frame has been designed comprehensively and the loadings assumed are realistic and possibly conservative. The design of the spine however could be further pursued to reduce the weight by up to 15%.

The orientation of the LFB attenuator has led to asymmetric power offtake ratings. Valve and duct design has been fully investigated and the turbine is relatively conventional and within physical design limitations. Plant design has been studied industrially and is at an advanced stage, though G.E.C. have not yet presented their report.

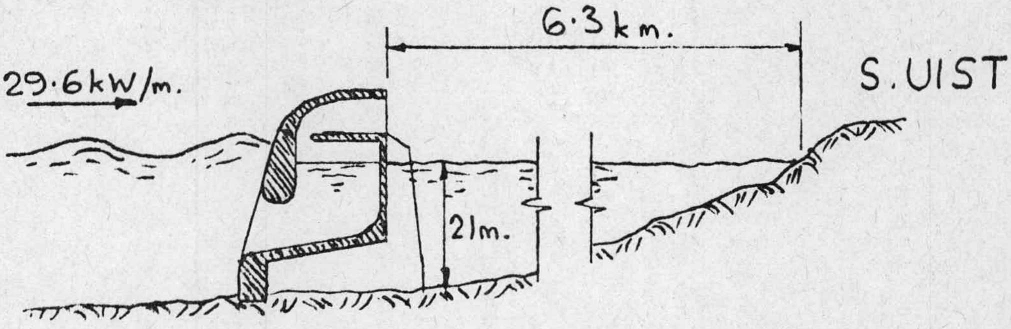
The power plant is relatively conventional and not approaching physical design limitations. The alternator, however, is a variable speed machine feeding a series d.c. load. A special excitation system is required involving rotating thyristors and this will need development.

Conclusions

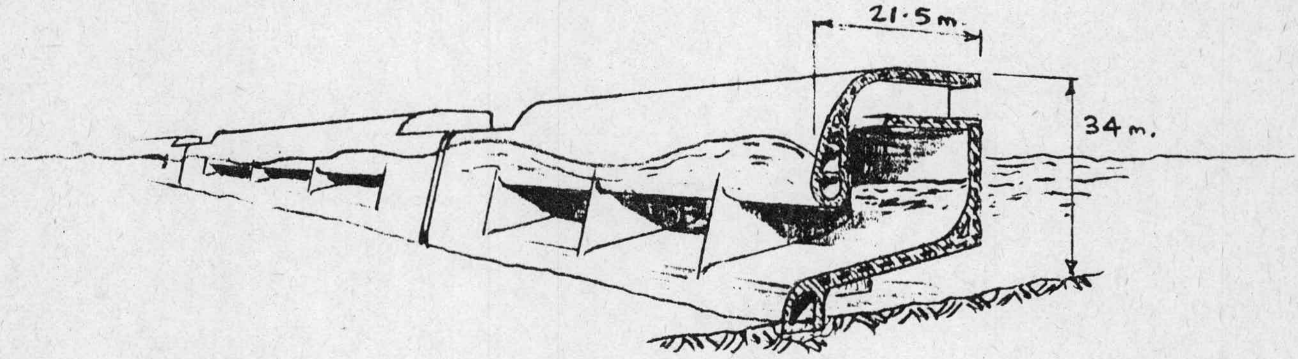
The overall result of the development at present is very disappointing to all concerned and the cost per Kwh is too high. Although some cost reductions may be possible on the spine and moorings, it is certain that the device has major built-in cost impediments in its present form which prevent it being a successful contender. The development of practical attenuators is really still in its infancy and the theory is not yet fully understood. Lancaster are continuing with development of attenuators and have made significant progress since their device was engineered into its present form by WPL. WPL themselves are turning their attention to a bottom-mounted alternative.

NEL BOTTOM STANDING TERMINATOR

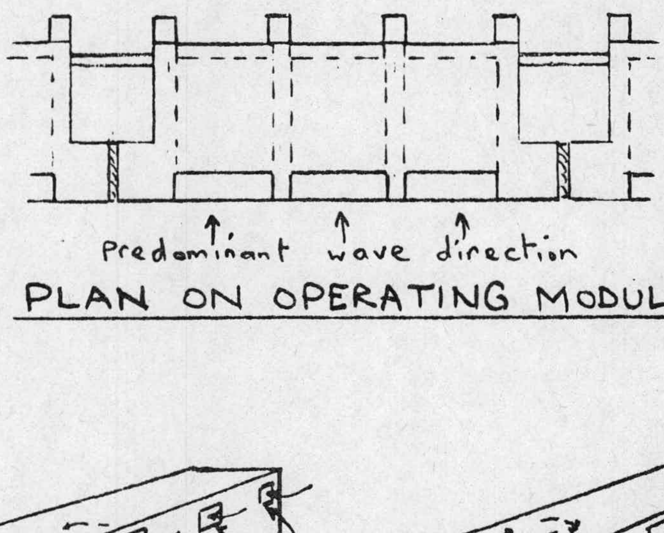
OWC - BOTTOM STANDING - NEL TERMINATOR



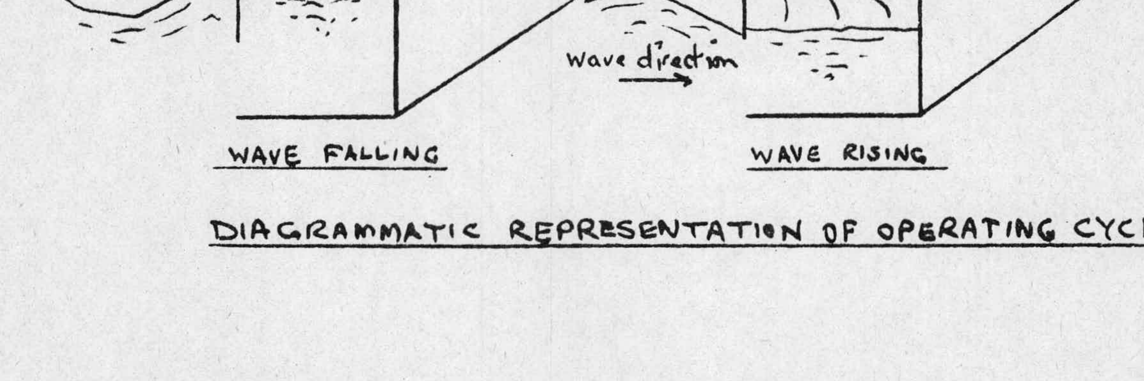
LOCATION OF SCHEME



DIMENSIONS



PLAN ON OPERATING MODULE



WAVE FALLING

WAVE RISING

DIAGRAMMATIC REPRESENTATION OF OPERATING CYCLE

LEADING DEVICE PARAMETERS

(Location - South Uist)

NEL BOTTOM STANDING TERMINATOR

A. Related to location			
1.	Distance offshore (km)		6
2.	Water depth (m)		21
3.	Power in sea (Kw/m)		29.6
B. Related to device			
1.	Overall size - length (m)	64	
	- breadth (m)	21.5	
	- vertical dimension (m)	34	
	- gross cross sectional area (m^2)	650	
2.	Weight of device (tonnes)	22500	
3.	Weight of device ÷ length (tonnes/m)	341	
C. Related to 2GW station			
1.	Number of devices		589
2.	Spacing of devices (m)		66
3.	Length of 2GW station (km) (excl. navig. gaps)		39
D. Related to productivity			
1.	Rating of generators (Mw)	3 x 1.55 Mw/device	
2.	Power in sea (Kw/m)	29.6	
3.	Mean annual power delivered to Skye (Mw/device)*	0.688	
4.	Mean annual output of 2GW scheme (GW)*	0.406	
E. Related to structure economy and utilization of resource			
1.	Mean annual power delivered per device ÷ length of device (Kw/m)*		10.8
2.	Mean annual power delivered per device ÷ device spacing (Kw/m)*		10.4
3.	Overall conversion efficiency of scheme* $\frac{\text{mean annual output of 2GW scheme}}{\text{mean annual power in sea x length of 2GW station}}$ (%)		35.2
4.	Capture Factor** $\frac{\text{mean annual power captured by device}}{\text{mean annual power in sea x device length}}$ (%)		55.0
F. Related to cost			
1.	Cost of 2GW station (undiscounted) (£M)	3772	
2.	Cost of each device (undiscounted) (£M)	6.4	
3.	Cost of energy (discounted) (p/Kwh)	9.3	
G. Miscellaneous			
1.	Mean annual power chain efficiency (%)***		72
2.	Availability of the 2GW scheme (%)		89
3.			
4.			

* including availability factor

** not including availability factor

*** $\frac{\text{mean annual power landed at Skye}}{\text{mean annual power captured per device x No. of devices in scheme}}$ (not including availability factor)

COST BREAKDOWN

NEL BOTTOM STANDING TERMINATOR

	£ x 10^6 undiscounted		£ x 10^6 discounted	
	2GW Scheme	Per Device	2GW Scheme	Per Device
Structure				
Construction facility and operation	241.4	0.41	223	0.38
Launch devices	71.4	0.12	55	0.09
Device structure	1044.9	1.77	785	1.33
	1357.7	2.30	1063	1.80
M & E				
Turbo-generators	428.0	0.73	322	0.55
Valves and ducts	260.0	0.44	195	0.33
Ancillary equipment	105.0	0.18	79	0.13
	793.0	1.35	596	1.01
Installation/Moorings				
Bed preparation	298.2	0.51	267	0.45
Installation of foundations	219.8	0.37	186	0.32
Installation of structure	207.1	0.35	173	0.29
Stabbing guides and temporary works	185.5	0.31	139	0.24
Rock Anchors	107.2	0.18	81	0.14
	1017.8	1.73	846	1.44
Transmission				
Generator output to islands	334.0	0.57	252	0.43
Inverters and substations on islands	73.0	0.12	61	0.10
Transmission to Skye	196.0	0.33	147	0.25
	603.0	1.02	460	0.78
CAPITAL COST	3771.5	6.40	2965	5.03
Maintenance				
Maintenance base overheads and operations	44.5	0.07	16	0.03
Vessels,divers and technicians for inspection & repair	687.2	1.17	323	0.55
M & E spares	299.8	0.51	148	0.25
MAINTENANCE COST	1031.5	1.75	487	0.83

5(iii)a) NEL BOTTOM STANDING TERMINATOR

1. GENERAL

1.1 DESIGN

The structural calculations for the device are based on the methods developed for the Attenuator in accordance with the OWC Note 30 and to appropriate and acceptable design criteria. The Device Team's design philosophy is fully acceptable to the Consultants.

The Device Team is undertaking a comprehensive analysis of structural effects due to wave loading. While it is accepted that further work is required on this loading case, the Consultants believe that any resulting modifications to the structure found to be necessary will have an insignificant affect on construction costs.

The installation procedure, in which the 3-cell unit is offered up to 9 stabbing guides pre-set on the sea-bed is considered by the Consultants to be a reasonable extension of accepted engineering practice.

Modifications to the design discussed in this Note are examined in Section 4.

1.2 TANK TESTING

The 21m mark II device has not itself been tank-tested. The productivity results provided at this stage by NEL are based on a simulated mathematical model using a theoretical monochromatic efficiency curve. It is emphasised that the output of this computer programme using the monochromatic curve was compared with the results from the September Cadnam tank tests for the 25 m mark I device and agreement was obtained. The Device Team intends to undertake the appropriate testing in the Cadnam Tank for the 46 spectra at an early date and this is necessary before results can be expressed with confidence.

The theoretical analysis, shows that the device has a hydrodynamic efficiency of 61.9%, comparing favourably with values obtained for the floating terminator of 25%.

1.3 SPECIFICATION

This is broadly based on the NEL Reference Design 1980 (PR22:Wave 00) and on NEL summary of M and E Plant Rating and Productivity 8th January 1982. Close liaison has been maintained between the Device Team and Consultants on the development of the above.

Due to on-going modifications to the design, as discussed later, the Device Team has not yet produced a formal specification.

1.4 COSTING

Full co-operation has been maintained between the Device Team and the Consultants on construction costs, and so far as possible, in view of design changes, on installation costs. Good agreement has been reached at all times on information so far obtained.

A formal presentation of costing for the device has not yet been provided by the Device Team for the reasons stated under 1.3 and summarised in Section 4.

2. DEVELOPMENT

2.1 GENERAL

The concept of a bottom mounted device follows naturally from an assessment of difficulties associated with mooring installation in the case of floating devices. The long term maintenance of such moorings and other factors all suggest that the reduced power capture potential due to location in shallower waters is more than compensated by ease of maintenance and of general access as well as enabling the structural design to be based on a more conventional breakwater philosophy. The Reference Design 1980, referred to above, examines the case of a breakwater device continuously mounted on the sea bed at depths of 15 - 20m with a concomitant reduced capture potential.

Subsequently the Device Team investigated a module based on the 25 m depth and founded on piled plinths. Although good capture was achieved the installation procedure was expensive mainly due to the high cost of the piling, and the Team has therefore moved the device to 21 m depth, eliminating the need for piling and producing a more effective design.

2.2 MANIFOLDING

In June and July of 1981 the concept of joining three 4-cell units and manifolding the air flow to one or two AC power units was examined by the Device Team. The Team anticipated a smoothed power input, simpler plant requirements and reduced device to shore transmission producing useful economies with small capture loss. The results of tank testing in September did not support this. The system discussed in this note therefore comprises a 1:1 cell to turbine/generator ratio. The possibility of manifolding is still being examined.

2.3 PLINTHS AND ROCK ANCHORS

In order to reduce the amount of sea bed preparation inherent in the original 1980 scheme as well as to enable the device to be located in deeper water, the Device Team decided in February 1981 to support the modules on concrete plinths, two per four-cell unit and in 25 m depth of water. The installation of the plinths prior to the module emplacement created some engineering difficulties which, although less onerous than those applying to the original breakwater design were seen by the Design Team and Consultants as representing an unacceptably high cost centre.

In the light of the above, the Team examined the possibility of integrating the plinths with the modules and also of avoiding the use of piling by adopting rock anchoring techniques. The proposed rock anchor system consisting of 57 No. 19/18 Dyform tendons is to a proven design and has the necessary safety margins against shear and overturning.

2.4 CHANGES TO DEVICE PROFILE

The 1980 Reference Design shape was essentially square in cross section, giving a high reaction area to wave forces. The current design as detailed in drawing RB/10, August 1981 is streamed on the seaward face with a thickened nose section and a smoothed run-over section for diminishing the effects of wave loadings. In the latest design all spare structure which is not specifically used in wave capture has been minimised.

3. FEASIBILITY

The Consultants consider the Bottom Standing Terminator OWC concept to be feasible. Moreover the scheme envisaged possesses the necessary degree of ruggedness combined with relatively easy maintenance due to self shelter and proximity to shore.

As compared to the 1980 OWC design, the concept of supporting the modules on stabbing guides calls for greater accuracy as regards location but over a smaller sea-bed area. The proposed construction and installation procedures present no novel engineering features. In summary, the stabbing guides are installed and rock anchored in advance of embedment. The modules are transferred from construction yard to site using additional buoyancy for skid launching and for locking down on to the stabbing guides (9 per module). Once so located, locking mechanisms in the guides hold the module firmly while buoyancy is retained. Under these conditions, i.e. before the remaining rock anchors in the structure are installed, the stabbing guides provide an ample margin of strength against shear and overturning. It is the intention of the device team to grout beneath the device before the remaining rock anchors are drilled and installed.

The proposed system of rock anchoring outlined above is based on established and acceptable practice.

The maximum forces carried per device are 282 T/M horizontal and 74 T/M vertical. The rock anchoring system provides acceptable material and load safety factors to sustain the above.

The Consultants broadly accept the construction timing sequence of 8 years suggested by the Device Team.

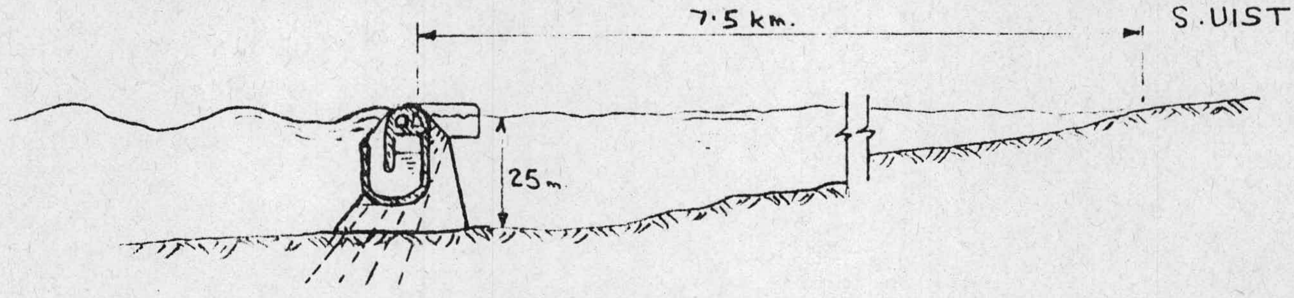
4. CONCLUSIONS

In agreeing with the Device Team's costing and programme estimates and in recognising the proposed structural design of the module as being a reasonable one, involving no significant extrapolation of current engineering practices, the Consultants confirm that the Bottom Standing Terminator is an acceptable device. Both the Consultants and the Device Team acknowledge that further work is required as regards optimising the installation procedure and in 'tuning' out the wave loadings.

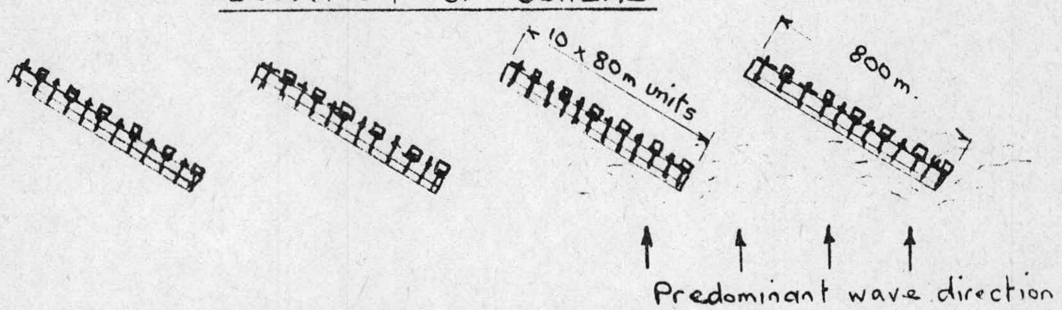
The new 21 m design has eliminated the need for separate plinths and avoided the use of piling - a high cost centre. The adoption of axial-flow turbines and general modifications to the geometry of the device has produced a compact system offering good cost-saving potential allied with a simplified embedment procedure.

VICKERS TERMINATOR

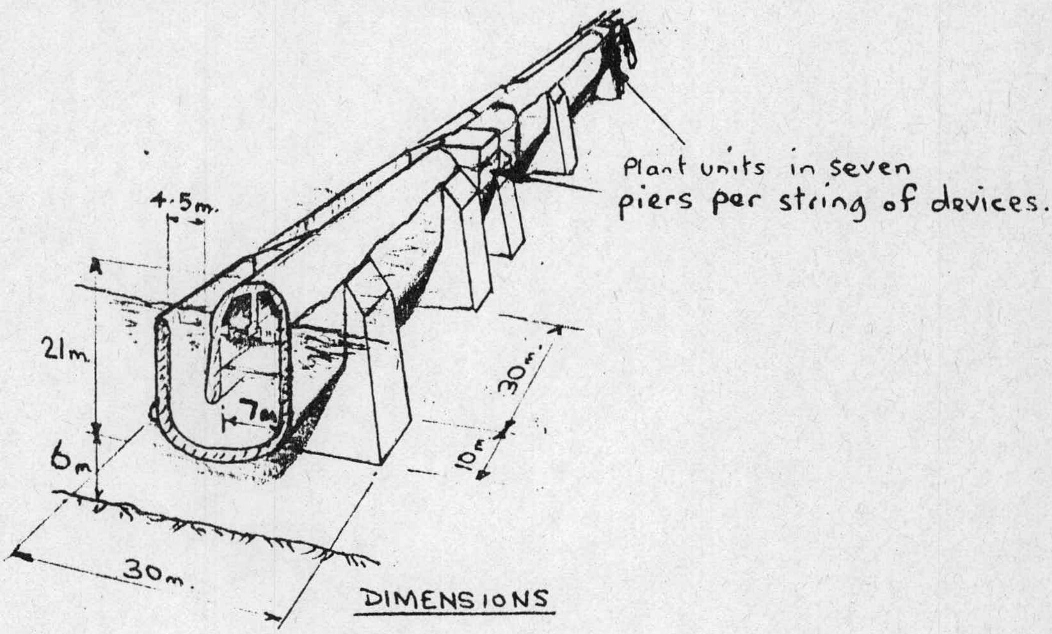
OWC-BOTTOM STANDING-VICKER'S TERMINATOR



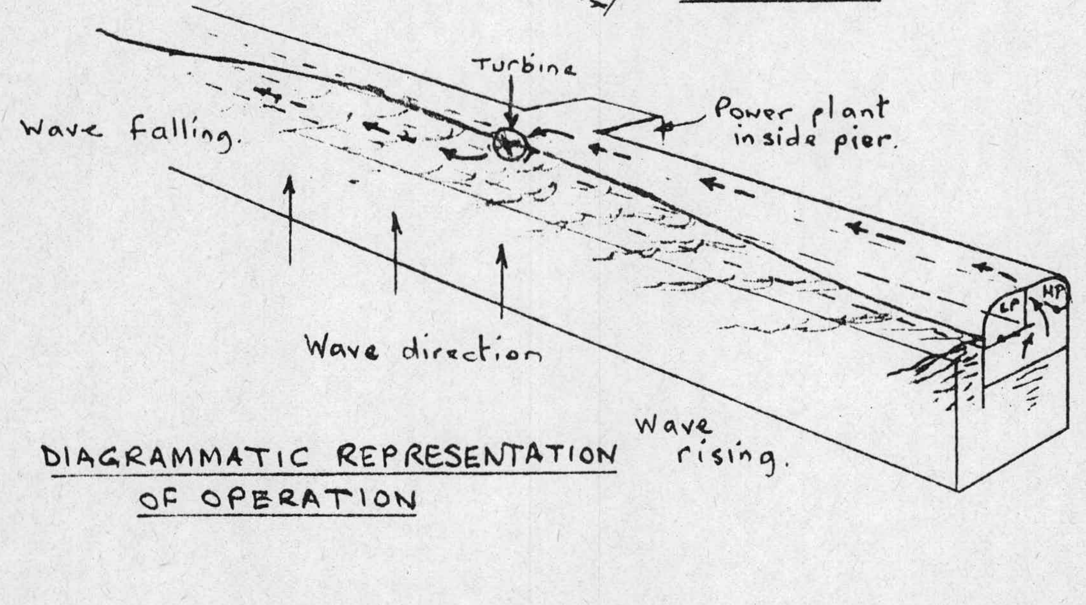
LOCATION OF SCHEME



ORIENTATION OF DEVICE STRINGS



DIMENSIONS



DIAGRAMMATIC REPRESENTATION OF OPERATION

LEADING DEVICE PARAMETERS

(Location - South Uist)

VICKERS TERMINATOR

A.	**Related to location**		
1.	Distance offshore (km)		7.5
2.	Water depth (m)		25.0
3.	Power in sea (Kw/m)		36.2
B.	**Related to device**		
1.	Overall size - length (m)	80	
	- breadth (m)	17	
	- vertical dimension (m)	21	
	- gross cross sectional area (m^2)	321	
2.	Weight of device (tonnes)	27000	
3.	Weight of device ÷ length (tonnes/m)	340	
C.	**Related to 2GW station**		
1.	Number of devices		1100
2.	Spacing of devices (m)		80
3.	Length of 2GW station (km) (excl. navig. gaps)		88
D.	**Related to productivity**		
1.	Rating of generators (Mw)	7 x 4.2 Mw per 10 devices	
2.	Power in sea (Kw/m)	36.2	
3.	Mean annual power delivered to Skye (Mw/device)*	0.46	
4.	Mean annual output of 2GW scheme (GW)*	0.50	
E.	**Related to structure economy and utilization of resource**		
1.	Mean annual power delivered per device ÷ length of device (Kw/m)*		5.7
2.	Mean annual power delivered per device ÷ device spacing (Kw/m)*		5.7
3.	Overall conversion efficiency of scheme* $\frac{\text{mean annual output of 2GW scheme}}{\text{mean annual power in sea x length of 2GW station}}$ (%)		15.8
4.	Capture Factor** $\frac{\text{mean annual power captured by device}}{\text{mean annual power in sea x device length}}$ (%)		25.8
F.	**Related to cost**		
1.	Cost of 2GW station (undiscounted) (£M)	5437	
2.	Cost of each device (undiscounted) (£M)	4.9	
3.	Cost of energy (discounted) (p/Kwh)	10.7	
G.	**Miscellaneous**		
1.	Mean annual power chain efficiency (%)***		68
2.	Availability of the 2GW scheme (%)		91
3.			
4.			

* including availability factor

** not including availability factor

*** $\frac{\text{mean annual power landed at Skye}}{\text{mean annual power captured per device x No. of devices in scheme}}$ (not including availability factor)

COST BREAKDOWN

VICKERS TERMINATOR

	£ x 10^6 undiscounted		£ x 10^6 discounted	
	2GW Scheme	Per Device	2GW Scheme	Per Device
Structure				
Construction facility	466.7	0.42	442	0.40
Launch devices	192.6	0.18	145	0.13
Device structure	1686.6	1.53	1246	1.13
	2345.6	2.13	1833	1.66
M & E				
Turbo-generators	294.0	0.27	217	0.20
Ducts + valves	164.0	0.15	121	0.11
Ancillary equipment	132.0	0.12	98	0.09
	590.0	0.54	436	0.40
Installation/Moorings				
Bed preparation	549.6	0.50	490	0.45
Installation of foundations	320.4	0.29	272	0.25
Installation of structure	235.2	0.22	212	0.19
Stabbing guides and temporary works	389.4	0.35	288	0.26
Rock anchors	200.2	0.18	148	0.13
	1694.8	1.54	1410	1.28
Transmission				
Collection platforms	155.0	0.14	116	0.10
Generator output to islands	317.0	0.29	238	0.22
Inverters and substations on islands	30.0	0.03	25	0.02
Transmission to Skye	305.0	0.27	251	0.23
	807.0	0.73	630	0.57
CAPITAL COST	5437.4	4.94	4309	3.91
Maintenance				
Maintenance base overheads and operations	44.5	0.04	15	0.01
Vessels,divers and technicians for inspection & repair	1035.9	0.94	495	0.45
M & E spares	211.2	0.19	103	0.09
MAINTENANCE COST	1291.6	1.17	613.1	0.55

5/(iii)/b VICKERS TERMINATOR

General

The productivity data for the current reference design have been obtained using a 1/200th scale model in the wide tank at Wave Power Ltd., Cadnam. These data are somewhat suspect because of the small scale of the test model and the fact that this was the first device to be tested in the modified 46 spectra representing the 25m water depth; some of which were later found to be incorrectly transformed. The Team has attempted to modify the experimental values which are now approximately consistent with comparable attenuator results but must still be treated with caution.

The Consultants have received three structural drawings, a scheme layout, a precasting drawing and the General Arrangement. Although some thought appears to have been given to dimensioning the members, no written details of the structural design have been received by the Consultants. The construction, transportation and installation of the device have been covered in a separate report.

The Consultants have been asked to assess a revised installation procedure based on cost savings achieved by the Team's Consultants in their work on the NEL Breakwater device. No details have been received but the installation costs have been calculated in proportion to the NEL device.

The mechanical and electrical plant information received from the Team is for the attenuator device rather than the terminator but the power offtake is understood to be similar. The equipment for the attenuator device has been specified in considerable detail with drawings and diagrams. The electrical design has been fairly well developed; more so than the mechanical. The d.c. series method of power aggregation from the devices has been followed, the switchgear, isolation transformers and rectifiers being accommodated in the central plant room where conditions will be good and access readily available. The turbine is located in a rather more hostile environment at approximately 2 atmospheres pressure and sealed off from the plant room. Access for maintenance can be obtained either by closing the isolation valves or by sealing and pressurising the plant chamber.

Status of Assessment Data

The basic design of the major elements of the civil works associated with this device is at an advanced stage and the Team has provided preliminary information on quantities and costs which have been independently checked and found to be accurate to within about 1% of the total device cost. The only major difference between Device Team and Consultants in the structural cost centres is over the type of facility to be used. The Team has assumed a single large facility which the Consultants agree would lead to a cost saving of 0.2p/kwh if considered practicable.

The plant and transmission design is now reasonably well defined. The Consultants originally incorporated their own assessment of the plant costs and a reliability analysis into their cost figures. The reliability analysis was based on failure rates given by Y-ARD, and although the Team's comments on the power chain model have been incorporated, the Consultants have not altered the basic data. The Team subsequently provided their own costing which substantially agrees with the Consultants in all but two items: the turbo generator set and the transmission scheme. The cost of the turbo generator has now been resolved and the current cost estimates revised. However, the Consultants have recently revised upwards the cost of all the Teams' transmission schemes. This gives an increase of 62% over the previously agreed figure, although the Consultants consider that the Team could recoup approximately 18% (0.2 p/kwh) by redesigning the transmission scheme.

The original installation procedure specified by the Device Team was checked by the Consultants who estimate a cost approximately 0.2p/kwh higher than the Teams. However the cost of materials used in the installation was not agreed for this procedure. The Consultants have revised their costing of the device installation programme in line with the similar NEL breakwater device and have estimated a saving of 0.55p/kwh over the original method. However the Consultant's figure is approximately double that of the Teams. The true disparity in costs is masked by the Teams method of costing since they only allocate half the cost of each plant item to the scheme. The Consultants cannot accept this method but feel that there may still be differences in the costing of installation which can be resolved if the Team provide a more complete breakdown.

Maintenance costs and availability have been assessed by the Consultants by combining information from Y-ARD, EASAMS and the Device Team.

Development

Although the basic concept of a submerged OWC as a terminator with a low reflector has been fixed since early 1981, the device has undergone a number of changes in an attempt to eliminate the dependence on the crest-spanning mode of operation. These changes have involved major variations of the OWC configuration and little work on optimising the final reference design has been possible. A large increase in efficiency has proved possible with the similar attenuator device and could presumably also be obtained with the terminator device.

The electrical design has been fairly well developed - more so than the mechanical. The d.c. series method of power aggregation from the devices has been followed, the switchgear, isolation transformers and rectifiers being accommodated in the plant rooms where conditions will be good and access readily available.

The operating mode has recently been changed from alternating flow using Wells turbines, to rectified flow using valves and a conventional axial flow turbine. This was found to be necessary because of the size of the Wells Turbine which could not be accomodated within the submerged duct, and the difficulty of maintaining the plant distributed along the length of a submerged device. Although the turbine is located in a pressurised manifold it is possible, by closing the isolation doors, either to work on the turbine in-situ or to remove the unit without requiring divers.

Feasibility

The reference design now resembles a low vertical face breakwater. Although the structural concept is not unusual, the depth of water in which it is placed and the small freeboard are both unconventional and lead to difficulties in assessing the breaking wave forces on the device. As with all bottom mounted devices, the installation phase represents an extrapolation of current practice.

The mechanical and electrical plant are generally fairly conventional and there do not appear to be any insurmountable practical difficulties with this device.

The Consultants have reservations about the following detailed aspects of the design:

i) Analysis of the breaking wave loads on the reflector.

ii) Emplacement loads between the modules and the stabbing guides specified in the revised installation programme.

iii) The homogeneity of the bed rock which has to provide a very large anchorage resistance to overturning moments.

iv) The inaccuracy of the productivity data obtained from the tank tests.

v) The generator itself is conventional but the Team has not adopted brushless thyristor excitation which the Consultants consider is essential. Furthermore the method of excitation proposed by the Team is of doubtful suitability. The Consultants also consider that the speed increasing belt drive for the pilot exciter is undesirable for the duty required.

vi) The cell air valves are large and apparently self actuating. Any leakage will partly nullify column performance.

vii) An inherent disadvantage with the submerged device is that the enclosed air is above atmospheric pressure and needs a compressor supply - leakage will eventually flood the turbine.

Conclusion

The major cost centres in this device are structure (40%), plant (16%) and installation (30%). Because of the extreme environmental conditions off the coast of South Uist it is difficult to conceive how the cost of the breakwater element of the structure could be substantially reduced.

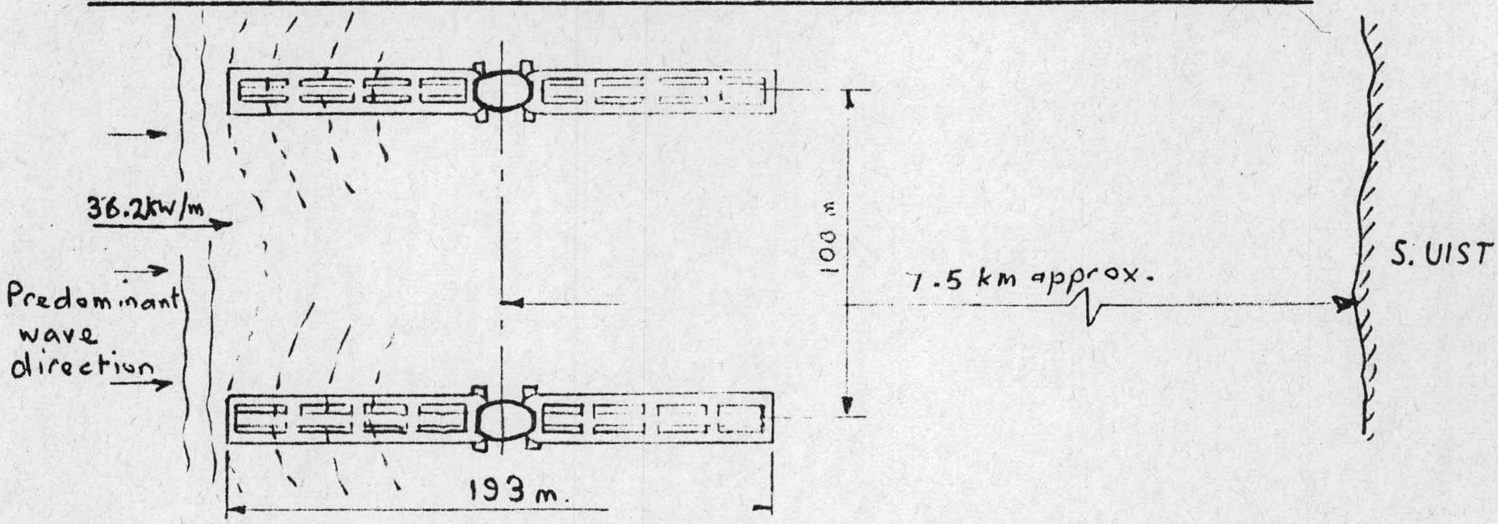
It is possible that a saving in structural costs could be made in those elements not loaded by reflecting waves or breaking wave forces. The plant design and installation sequence have been well thought out and would seem unlikely to yield significant savings. The most likely source of increased cost efficiency would be a gain in productivity, especially considering the small amount of work that has been spent optimising the current design. It is also possible that duct losses and scale effects which have been shown to cause significant errors in the attenuator tests could be similarly reduced in the terminator by better design of the duct bend.

The theoretical efficiency of this device in seas which do not overtop the reflector is 100%. Because the reflector is only 2m above mean sea level this restricts the maximum efficiency to seas with wave heights of less than 4m. Since the bore and stroke of the device is limited, this overtopping is a desirable feature and also considerably reduces the forces on the device. One of the main disadvantages of the device is its reliance on the crest-spanning mode of operation which is imposed by the closed air cycle. Despite linking devices into 800m long blocks, the Consultants suspect that this is one reason for the relatively low efficiency of the device.

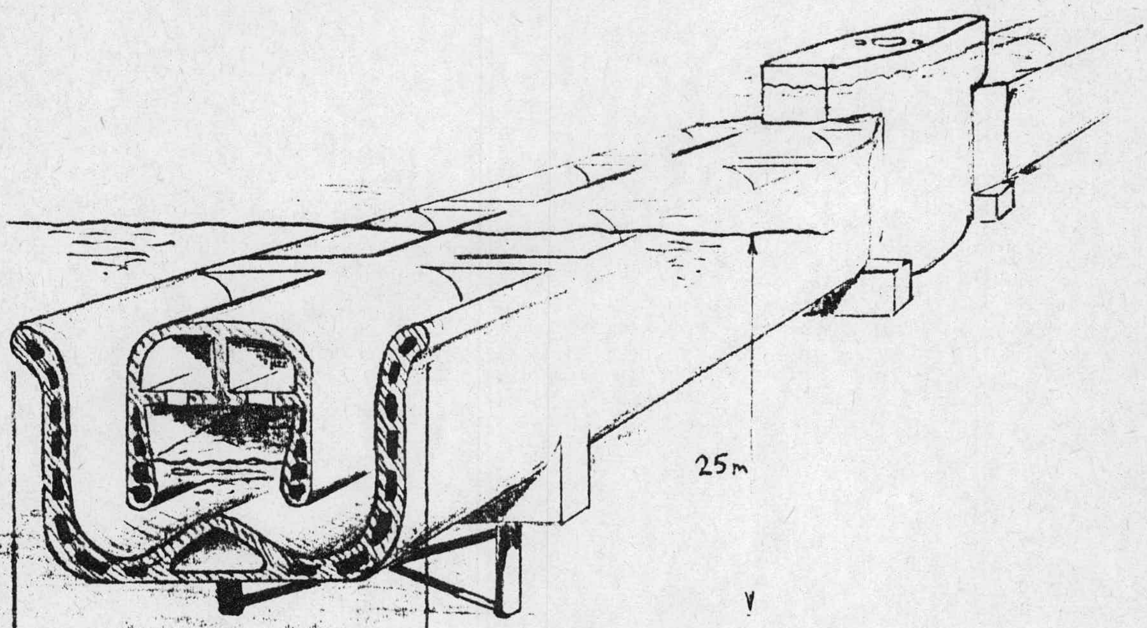
One feature of the device is its high power availability because of the common manifolds which connect seven generating sets in parallel. This permits 30% of the rated capacity to be lost with only a 10% reduction in mean annual power output.

<u>VICKERS ATTENUATOR</u>

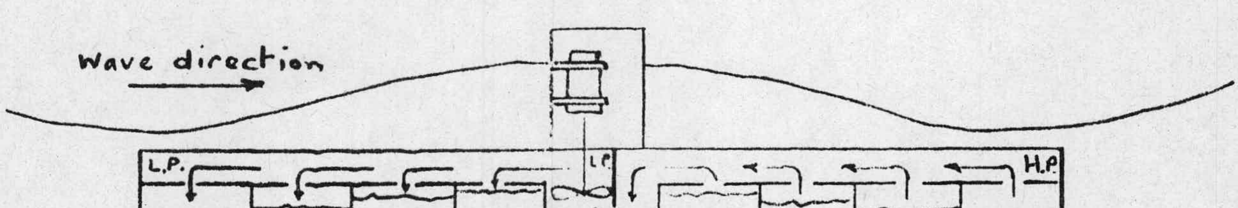
OWC-BOTTOM STANDING-VICKER'S ATTENUATOR



PLAN ON PART OF DEVICE ARRAY



DIMENSIONS



DIAGRAMMATIC REPRESENTATION OF OPERATING CYCLE

LEADING DEVICE PARAMETERS

(Location - South Uist)

VICKERS ATTENUATOR

A. Related to location

1.	Distance offshore (km)		7.5
2.	Water depth (m)		25
3.	Power in sea (Kw/m)		36.2

B. Related to device

1.	Overall size - length (m)	193	
	- breadth (m)	15.6	
	- vertical dimension (m)	11.4	
	- gross cross sectional area (m^2)	178	
2.	Weight of device (tonnes)	28000	
3.	Weight of device ÷ length (tonnes/m)	157	

C. Related to 2GW station

1.	Number of devices		756
2.	Spacing of devices (m)		100
3.	Length of 2GW station (km) (excl. navig. gaps)		76

D. Related to productivity

1.	Rating of generators (Mw)	4.2 Mw/device	
2.	Power in sea (Kw/m)	36.2	
3.	Mean annual power delivered to Skye (Mw/device)*	0.69	
4.	Mean annual output of 2GW scheme (GW)*	0.52	

E. Related to structure economy and utilization of resource

1.	Mean annual power delivered per device ÷ length of device (Kw/m)*		3.6
2.	Mean annual power delivered per device ÷ device spacing (Kw/m)*		6.9
3.	Overall conversion efficiency of scheme* $\dfrac{\text{mean annual output of 2GW scheme}}{\text{mean annual power in sea x length of 2GW station}}$ (%)		19.0
4.	Capture Factor** $\dfrac{\text{mean annual power captured by device}}{\text{mean annual power in sea x device length}}$ (%)		15.9

F. Related to cost

1.	Cost of 2GW station (undiscounted) (£M)	4172	
2.	Cost of each device (undiscounted) (£M)	5.5	
3.	Cost of energy (discounted) (p/Kwh)	8.1	

G. Miscellaneous

1.	Mean annual power chain efficiency (%)***		71
2.	Availability of the 2GW scheme (%)		87
3.			
4.			

* including availability factor

** not including availability factor

*** $\dfrac{\text{mean annual power landed at Skye}}{\text{mean annual power captured per device x No. of devices in scheme}}$ (not including availability factor)

COST BREAKDOWN

VICKERS ATTENUATOR

	£ x 10^6 undiscounted		£ x 10^6 discounted	
	2GW Scheme	Per Device	2GW Scheme	Per Device
Structure				
Construction facility	390.4	0.51	359	0.47
Launch devices	60.3	0.08	47	0.06
Device structure	1380.3	1.83	1032	1.37
	1831.0	2.42	1438	1.90
M & E				
Turbo-generators	288.0	0.38	215	0.28
Ducts + valves	113.0	0.15	85	0.11
Ancillary equipment	130.0	0.17	97	0.13
	531.0	0.70	397	0.52
Installation/Moorings				
Rock anchors	158.0	0.21	118	0.16
Device support plinths	113.4	0.15	85	0.11
Installation vessels and operations	732.0	0.97	625	0.83
	1003.4	1.33	828	1.10
Transmission				
Collection platforms	155.0	0.21	116	0.15
Generator output to islands	317.0	0.42	238	0.32
Substations on islands	30.0	0.04	25	0.03
Transmission to Skye	305.0	0.40	251	0.33
	807.0	1.07	630	0.83
CAPITAL COST	4172.4	5.52	3293	4.36
Maintenance				
Maintenance base overheads and operations	44.5	0.06	16	0.02
Vessels, divers and technicians for inspection & repair	1072.5	1.42	512	0.68
M & E spares	75.6	0.10	38	0.05
MAINTENANCE COST	1192.6	1.58	566.5	0.75

5(iii)c VICKERS ATTENUATOR

General

A 1/100th scale model of the current reference design has been thoroughly tested in the wide tank of Wave Power Ltd., Cadnam. The productivity data were then obtained from tests on this and a 1/67th scale model of the optimum device configuration in the 46 selected IOS spectra. The 1/67th scale tests indicate a much better performance than the smaller scale tests. This is partly due to a refinement in the internal geometry of the duct and partly due to the fact that the Team has calibrated the later model so that the output power reading includes those losses which they expect to disappear at full scale. The Consultants have agreed the general principle of this method but are in the process of checking the detailed application. Unfortunately it has been discovered that the Team was given incorrect information about the spectra in the wave tank and a factor has been applied to their results to account for this. Although the Device Team is continuing to refine the hydrodynamic performance of the device, the basic concept is well developed and has not changed in the last year.

The only structural drawing received by the Consultants, as yet, is the General Arrangement. Although some thought appears to have been given to dimensioning the members, the only written details of the structural design received by the Consultants refer to the wave loads. However, installation and construction are well documented.

The mechanical and electrical plant, ancillary equipment and transmission system have been specified in considerable detail with drawings and diagrams. The electrical design has been fairly well developed - more so than the mechanical. The d.c. series method of power aggregation from 4 MW devices has been followed, the switchgear, isolation transformers and rectifiers being accommodated in the central plant room where conditions will be good and access readily available.

Status of Assessment Data

Although the basic design of the major elements of this device is fairly advanced the Team have asked for several amendments to the design to be considered at a very late stage. For various reasons these amendments have not been properly detailed but despite the unsatisfactory nature of the presentation the Consultants have attempted to incorporate these revisions into the latest cost estimates. The costs of the civil associated with the design which was thought to be final at the beginning of January 1982 were agreed with the Device Team. Modifications made to the shell stucture of the device have also been costed and more or less agreed with the Device Team. However, the modification to the cost of the end support has been made unilaterally by the Consultants since it is difficult to extract the required figure from the Device Team's overall installation cost.

The plant and transmission design is now reasonably well defined. The Consultants originally incorporated their own assessment of the cost of the plant and a reliability analysis into their cost figures. The reliability analysis was based on failure rates specified by Y-ARD in association with the power chain specified by the Team. This figure hs not been modified. The Team subsequently provided their own costing which substantially agrees with the Consultants in all but two items: the turbo generator set and the transmission scheme. The cost of the turbo generator has now been resolved and the current cost estimates revised. However, the Consultants have recently revised upwards the cost of all the Teams' transmission schemes. This gives an increase of 62% over the previously agreed figure, although the Consultants consider that the Team could recoup approximately 18% (0.2p/kwh) by redesigning the transmission scheme.

The installation costs have been developed by the Consultants with verbal inputs from the Device Team. Subsequently the Team has issued an installation manual and several amendments which have been checked by the Consultants and found to agree in most particulars. Maintenance costs have been provisionally assessed by the Consultants using information from the Device Team, YARD and EASAMS.

Development

Although the device design has remained more or less fixed since late 1980, two recent modifications have been made to increase its credibility and performance. The first was to change from an alternating flow to a rectified flow scheme with a central plant chamber and a more conventional uni-directional air turbine. This has allowed the generator and ancillary plant to be located in a closed machinery hall at atmospheric pressure giving better reliability and easier access to the electrical plant for maintenance. The turbine is pressurised and needs a means of isolation. The second change was to increase the bend radius in the water column duct. This alteration has been incorporated into the new $1/67^{th}$ scale model made for the productivity tests.

Feasibility

The current reference design structure is made up of three different components, the caisson, the outer supports and the OWC cell modules, each of which can be compared to a similar conventional structure. The only extrapolation from current practice is the installation of these structures in an exposed location. However the Team's proposed installation method has been considered in detail by the Consultants and the costs have been based on the Consultants' timing of each step in the procedure.

The mechanical and electrical power chain is relatively conventional. Although access to the generator and ancillary plant is straightforward, the turbine and valve boxes are rather more difficult to maintain being situated in pressurised air. Generally, however, there appear to be no major practical difficulties involved in the construction, installation operation or maintenance of this device.

The Consultants have some reservations about detailed aspects of the design. These are:

i) Acknowledged uncertainties in the analysis of the breaking wave loads on the caisson which will probably require a model study.

ii) Loads between the cell modules and the foundations during emplacement.

iii) The small tolerances required on the sea bed preparation under the caisson.

iv) The resistance to sliding of the caisson structure. The Consultants would prefer to see a definite shear key.

v) The internal OWC losses measured by the Team are very high and the Consultants would like a more thorough investigation of the mechanism of these losses to ensure that they will not be significant at full scale.

vi) The generator itself is conventional but the Team has not adopted brushless thyristor excitation which the Consultants consider is essential. Furthmore the method of excitation proposed by the Team is of doubtful suitability. The Consultants also consider that the speed increasing belt drive for the pilot exciter is undesirable for the duty required.

vii) The cell air valves are large and apparently self actuating. Any leakage will nullify column performance.

Conclusion

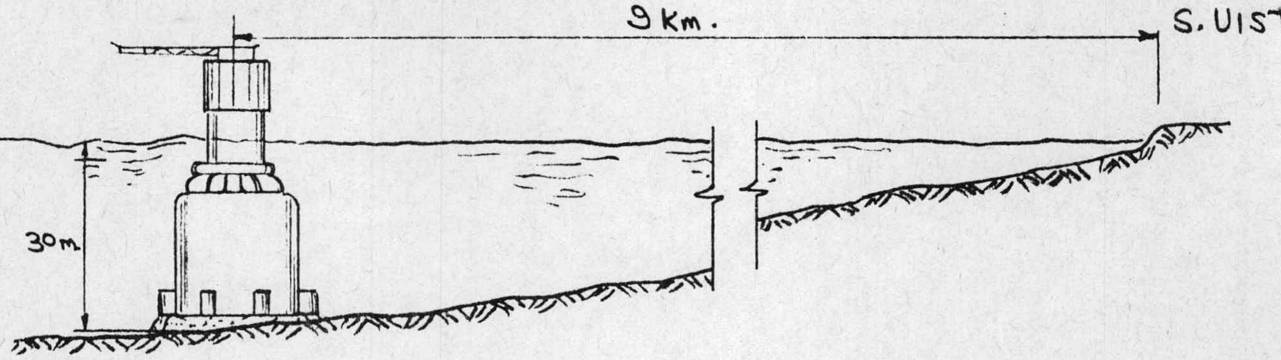
The major cost centres in this device are structure (42%), plant (20%) and installation (22%). The latest modification to the device has been to reduce the thickness and simplify the construction of the main OWC hulls. The Team has indicated that it would like to go further and change the configuration of the device by reversing the flow and placing oscillating water columns at the outside with the inlet duct between them. By this means the Team hope to increase the hull strength and device efficiency with a reduction in the quality of materials required. Furthmore, by increasing the swept volume of the device the Team feel that they would reduce the unit cost allocated to the plant caisson, plant module, installation and the collection network. The Team consider that the optimisation of the model scale by which this device was defined did not fully account for the high fixed costs associated with each device.

The installation method has already been considered in some detail and can only be significantly reduced by eliminating certain key operations which require concerted action between divers and surface personnel. This type of operation has been restricted to lm sea states in daylight and therefore involves a large amount of waiting time for the expensive installation plant.

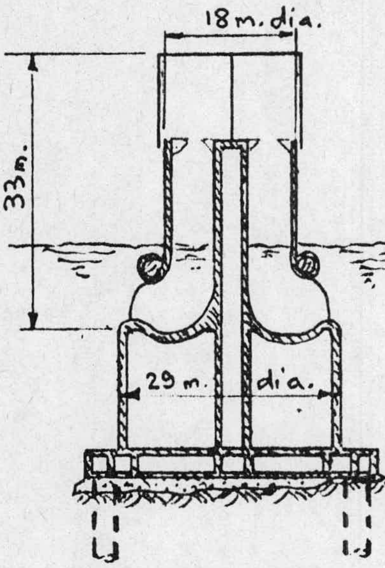
This type of device, being submerged, can never hope to be as efficient as a surface piercing device in practice, although the theoretical efficiency of an attenuator array is 100%. The Consultants consider that there is some room for improvement in the device efficiency and that the structural costs could still be reduced. The main attraction of a submerged device is the lower force to which it is subjected. This allows optimisation of the device configuration without major structural constraints and the Consultants consider that some improvements in the design, including an increase in of the swept volume, can still be achieved.

BELFAST

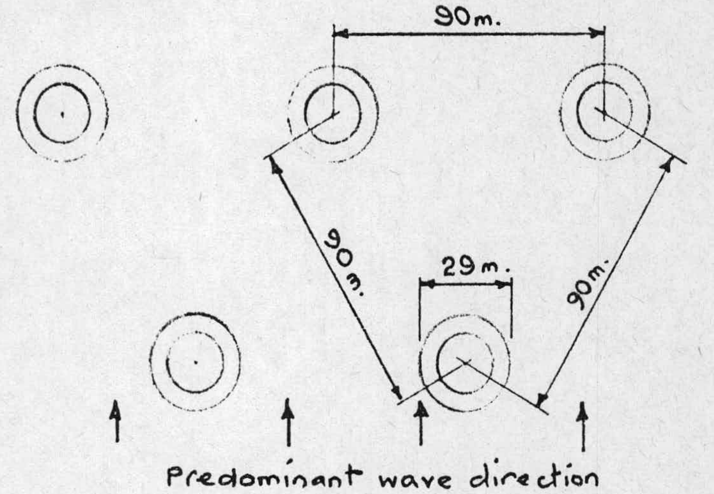
OWC - BOTTOM STANDING - BELFAST POINT ABSORBER



LOCATION OF SCHEME

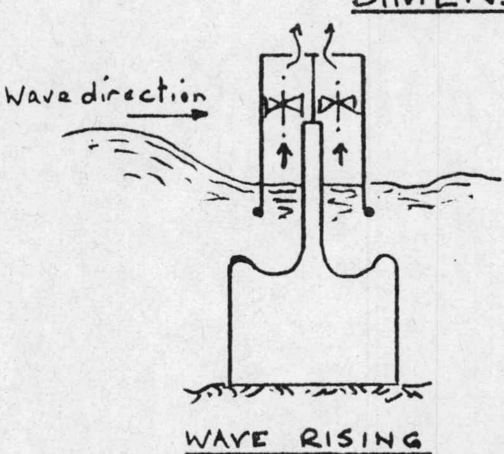


ELEVATION

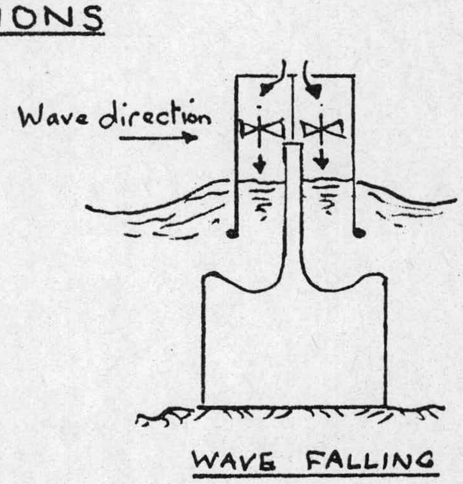


ARRAY

DIMENSIONS



WAVE RISING



WAVE FALLING

WORKING CYCLE

LEADING DEVICE PARAMETERS

(Location - South Uist)

BELFAST

A. Related to location

1.	Distance offshore (km)	9
2.	Water depth (m)	30
3.	Power in sea (Kw/m)	41.7

B. Related to device

1.	Overall size - length (m) } - breadth (m) }	18m diameter
	- vertical dimension (m)	51
	- gross cross sectional area (m^2)	254
2.	Weight of device (tonnes)	10400
3.	Weight of device ÷ length (tonnes/m)	577

C. Related to 2GW station

1.	Number of devices	1900
2.	Spacing of devices (m)	90m in array
3.	Length of 2GW station (km) (excl. navig. gaps)	85.5

D. Related to productivity

1.	Rating of generators (Mw)	6 x 0.25 Mw/device
2.	Power in sea (Kw/m)	41.7
3.	Mean annual power delivered to Skye (Mw/device)*	0.25
4.	Mean annual output of 2GW scheme (GW)*	0.48

E. Related to structure economy and utilization of resource

1.	Mean annual power delivered per device ÷ length of device (Kw/m)*	14.0
2.	Mean annual power delivered per device ÷ device spacing (Kw/m)*	2.8
3.	Overall conversion efficiency of scheme* $\frac{\text{mean annual output of 2GW scheme}}{\text{mean annual power in sea x length of 2GW station}}$ (%)	13.3
4.	Capture Factor** $\frac{\text{mean annual power captured by device}}{\text{mean annual power in sea x device length}}$ (%)	56.7

F. Related to cost

1.	Cost of 2GW station (undiscounted) (£M)	7266
2.	Cost of each device (undiscounted) (£M)	3.8
3.	Cost of energy (discounted) (p/Kwh)	15.5

G. Miscellaneous

1.	Mean annual power chain efficiency (%)***	67
2.	Availability of the 2GW scheme (%)	88
3.		
4.		

* including availability factor

** not including availability factor

*** $\frac{\text{mean annual power landed at Skye}}{\text{mean annual power captured per device x No. of devices in scheme}}$ (not including availability factor)

rough ner = 0.687
e.c. = 1.456

COST BREAKDOWN

QUEENS UNIVERSITY BELFAST

	£ x 10^6 undiscounted		£ x 10^6 discounted	
	2GW Scheme	Per Device	2GW Scheme	Per Device
Structure				
Construction facility and operation	448.7	0.24	415.3	0.22
Launch devices	173.5	0.09	133.5	0.07
Device structure	2169.0	1.14	1647.2	0.87
	2791.2 38%	1.47	2196.0	1.16
M & E				
Turbo-generators	1227.1	0.64	932.3	0.49
Valves and ducts	126.7	0.07	96.3	0.05
Ancillary	205.8	0.11	156.3	0.08
	1559.6	0.82	1184.9	0.62
Installation				
Bed preparation	870.8	0.46	728.0	0.38
Plant and operations	1184.5	0.62	990.4	0.52
	2055.3	1.08	1718.4	0.90
Transmission				
Generator output to islands	285.0	0.15	216.5	0.12
Inverters and substations on islands	379.0	0.20	307.1	0.16
Transmission to Skye	196.0	0.10	158.8	0.08
	860.0	0.45	682.4	0.36
CAPITAL COST	7266.1	3.82	5781.7	3.04
Maintenance				
Maintenance base overheads and operations	70.5	0.04	25.3	0.01
Vessels, divers and technicians for inspection & repair	1921.0	1.01	950.3	0.50
M & E Spares	604.2	0.32	264.7	0.14
MAINTENANCE COSTS	2595.7	1.37	1240.3	0.65

5(iii)d QUEEN'S UNIVERSITY, BELFAST DEVICE

General

The Team has carried out testing in its own narrow tank and has also worked in the wide tank at Edinburgh, producing productivity results for the 46 IOS selected spectra. The Team has not carried out any measurements relating to wave loading on the device.

The Consultants have not received any calculations or specification from the Team. QUB say they have designed for 1 in 50 year waves and that outline calculations for the structure, consistent with the rate of development, have been made. The structure is an inherently strong shape and should work satisfactorily in the form proposed.

The Team has submitted a report on construction and installation; the Consultants generally agree with the methods proposed and consider that they are technically feasible.

QUB intend using six Wells turbines for each device, coupled to a directly driven 250 kW generator. The detailed design of the turbine generator unit and its associated ducting has recently been submitted. The Team is proposing a twin turbine having two stages, mounted on a horizontal axis. As an alternative to the usual, 440V synchronous type alternators, QUB are also unwisely considering operating the machine at full d.c. loop voltage, retaining the diode rectifier but eliminating the transformer. The method of power collection is that generally adopted for variable speed generating systems. Costs have not yet been given by the Team.

Status of Assessment Data

The basic design and constructional detailing of this device are in outline form only and the Consultants' cost estimate is based on their own appraisal of the likely form of the constructional details. However, the Device Team has provided their own cost estimate for a substantial part of the works which appears to be in resonably close agreement with the Consultants estimate.

The assessment of this device has been carried out using the Consultants' preliminary estimate of the electrical plant costs in conjunction with a cost for the mechanical plant provided by the Team. Cabling for power collection has been estimated assuming series interconnection of devices and the remainder of the transmission has been costed as for other similar schemes.

The costs of installation have been developed by the Consultants with verbal inputs from the Device Team. Maintenance costs have been provisionally assessed by the Consultants in advance of final information from the Device Team, YARD and EASAMS.

Development

The reference design under consideration has maintained, since its inception in 1977, the principles of a point absorbing oscillating water column device. It uses air driven Wells turbines. Throughout, the Team's philosophy has been to keep the device simple, both in terms of structure and power take off. Development has been aimed at improving and optimizing performance, primarily by means of parametric hydrodynamic studies and fundamental research into improved Wells turbine characteristics.

The major change to six cells was made in January 1981. The decision to bottom mount the device was made in August 1981 following initial wide tank testing in Edinburgh and the form of the reference structure was frozen in November 1981.

Feasibility

Using a multistage turbine necessitated by column damping requirements will add to the cost and complexity of the power take off. Other teams have found that inlet guide vanes (bi-directional) improve performance: this may be also the case for the Belfast Device. The design of a single stage turbine provided by the Team's industrial advisers appears to be entirely practicable, although performance under simulated wave conditions needs to be investigated. The proposal to operate the generator at d.c. system voltage saves little cost and involves a larger machine and probably a higher electrical failure rate.

The key areas of the structural design which require further development are:

i) design of the pile to caisson joint; no details of this have been proposed. The area is highly stressed and important to the integrity of the structure. The connection has to be made under water. RPT consider that a suitable design for this joint can be made.

ii) design and development of a semi-submersible jack-up drilling vessel carrying three or six drill heads. A vessel of this type is reqired by most of the bottom standing devices and RPT do not question the feasibility of the concept.

Costs

The Team has submitted costs for civil construction and installation; these figures are in general agreement with the costs estimated by the Consultants. The Consultants' costs are based on 1900 devices to be constructed over a 10 year period. Based upon their latest productivity figures, the Team calculated that 1336 devices are required to fulfil the 2 GW scheme requirement, but RPT have insufficient information to verify this.

Conclusion

There is no doubt that the Belfast Device is technically feasible in all respects, and a prototype could be constructed and installed using techniques already proven. The basic concept is robust and should prove reliable. The Device is non-directional and necessarily over-planted.

The Consultants share with the Team the view that there is considerable scope for development of the device, which in its present form has only been studied for a few months. QUB is aiming at halving the cost of power in the short term by a combination of improved productivity and by having an optimized structural size.

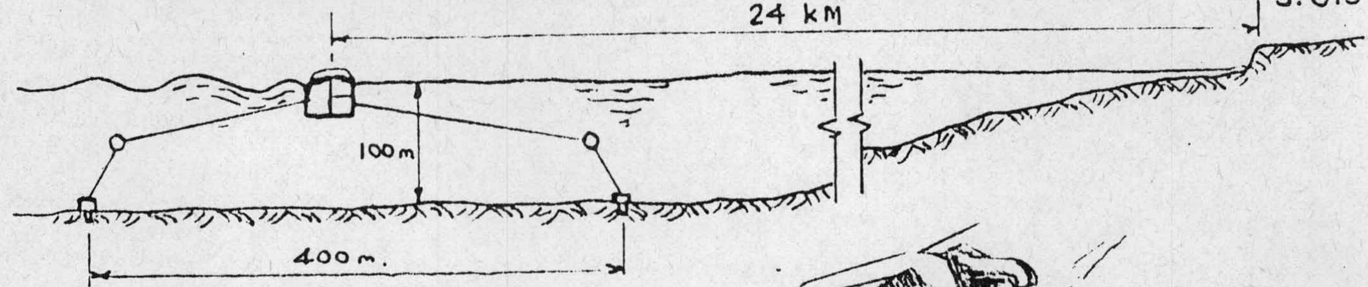
The most important area for development is on productivity which the Team admits is disappointingly low, due largely to the device having too low a resonant period. Further narrow tank testing is currently being performed, studying primarily the results of a variation of the J-tube entrance angle.

The Team has studied optimization of the structural and installation costs, taking into account that a bigger device will capture more power, particularly in the longer period waves. This study showed that cost was almost independent of size and therefore the Device size has not been changed. Further optimization studies could also be made on the depth below water level of the pile/caisson joint.

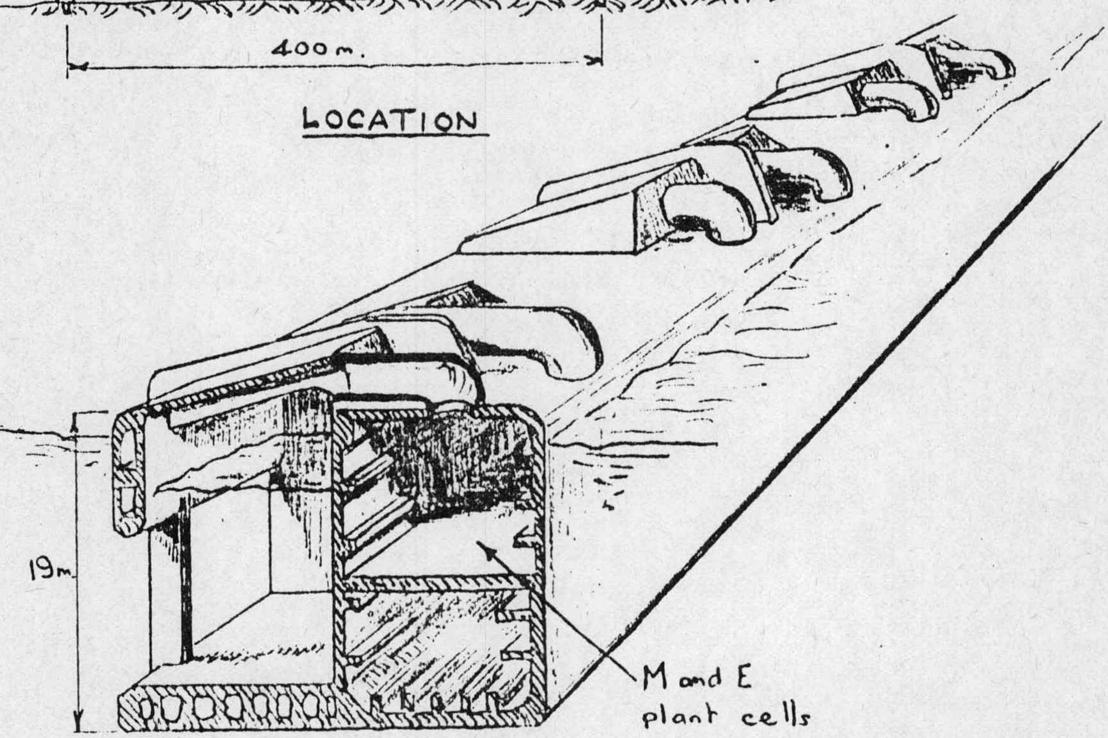
In the longer term, it will be necessary for the Team to carry out wide tank testing on arrays of point absorbers in order to optimize spacing and to improve the resource utilization, which at the moment is low. The Team considers that more information on the variation of available energy with depth must be obtained before meaningful studies on depth optimization can be carried out.

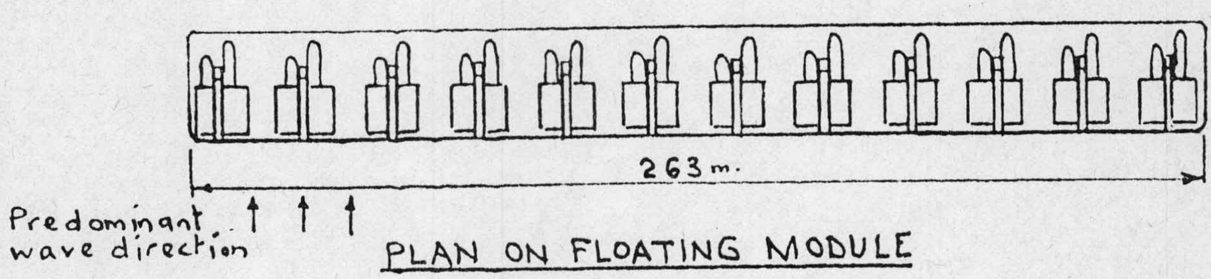
NEL FLOATING TERMINATOR

OWC-SPINE FLOATING-NEL TERMINATOR

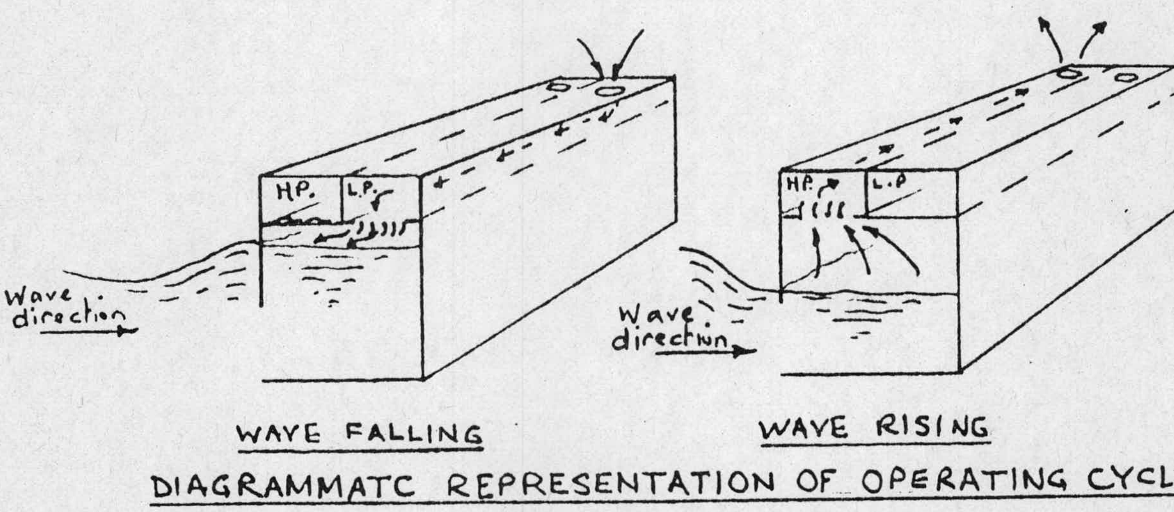


LOCATION





PLAN ON FLOATING MODULE



DIAGRAMMATC REPRESENTATION OF OPERATING CYCLE

LEADING DEVICE PARAMETERS

(Location - South Uist)

N.E.L. FLOATING TERMINATOR

A. Related to location

1.	Distance offshore (km)	24
2.	Water depth (m)	100
3.	Power in sea (Kw/m)	53.5

B. Related to device

1.	Overall size - length (m)	263 ✓
	- breadth (m)	28 ✓
	- vertical dimension (m)	19 ✓
	- gross cross sectional area (m^2)	532
2.	Weight of device (tonnes)	66000 ?
3.	Weight of device ÷ length (tonnes/m)	251

C. Related to 2GW station

1.	Number of devices	185
2.	Spacing of devices (m)	383
3.	Length of 2GW station (km) (excl. navig. gaps)	71

D. Related to productivity

1.	Rating of generators (Mw)	12 x 1.2 Mw/device
2.	Power in sea (Kw/m)	53.5
3.	Mean annual power delivered to Skye (Mw/device)*	2.11
4.	Mean annual output of 2GW scheme (GW)*	0.389

E. Related to structure economy and utilization of resource

1.	Mean annual power delivered per device ÷ length of device (Kw/m)*	8.0
2.	Mean annual power delivered per device ÷ device spacing (Kw/m)*	5.5
3.	Overall conversion efficiency of scheme* $\frac{\text{mean annual output of 2GW scheme}}{\text{mean annual power in sea x length of 2GW station}}$ (%)	10.3
4.	Capture Factor** $\frac{\text{mean annual power captured by device}}{\text{mean annual power in sea x device length}}$ (%)	24.4

F. Related to cost

1.	Cost of 2GW station (undiscounted) (£M)	5021
2.	Cost of each device (undiscounted) (£M)	27.2
3.	Cost of energy (discounted) (p/Kwh)	12.5

G. Miscellaneous

1.	Mean annual power chain efficiency (%)***	71
2.	Availability of the 2GW scheme (%)	86
3.		
4.		

* including availability factor

** not including availability factor

*** $\frac{\text{mean annual power landed at Skye}}{\text{mean annual power captured per device x No. of devices in scheme}}$ (not including availability factor)

COST BREAKDOWN

NEL FLOATING TERMINATOR

	£ x 10^6 undiscounted		£ x 10^6 discounted	
	2GW Scheme	Per Device	2GW Scheme	Per Device
Structure				
Construction facility	341.1	1.85	313	1.70
Launch devices	35.0	0.19	27	0.14
Device structure	1020.5	5.52	759	4.11
Mooring universal joints	58.0	0.31	43	0.23
	1454.6	7.87	1142	6.18
M & E				
Turbo-generators	682.7	3.70	508	2.75
Ducts + valves	324.2	1.75	241	1.31
Ancilary equipment	35.4	0.19	27	0.14
	1042.4	5.64	776	4.20
Installation/Moorings				
Anchor piles & attached universal joints	111.7	0.60	83	0.45
Rods and buoys	407.4	2.20	248	1.34
Installation vessesl	221.7	1.20	198	1.07
	740.8	4.00	529	2.86
Transmission				
Collection pontoons	525.0	2.84	390	2.13
Generator output to islands	946.0	5.12	702	3.89
Inverters and substations on islands	116.0	0.63	94	0.50
Transmission to Skye	196.0	1.06	157	0.85
	1783.0	9.65	1343	7.27
CAPITAL COST	5020.8	27.16	3790	20.51
Maintenance				
Maintenance base overheads and operations	74.1	0.40	30	0.16
Vessels,divers and technicians for inspection & repair	1156.8	6.26	530	2.87
M & E spares	453.7	2.46	222	1.20
MAINTENANCE COST	1684.6	9.12	782	4.23

5(iii)e NEL FLOATING TERMINATOR

1. GENERAL

1.1 DESIGN

The structural calculations for the device are based on the methods developed for the design of the Attenuator and are in accordance with the NEL OWC Note 30 and to appropriate design criteria. The device team's design philosophy is fully acceptable to the Consultants.

The Team has recognised that the device length of 263m will call for a thorough check on torsional loading during installation and operation. This work is being undertaken with full liaison with the Consultants and it is not anticipated that any modifications that may be found necessary to increase the torsional rigidity will have a significant effect on construction costs.

It is apparent that the mooring system is very much a part of the overall design both as regards static and dynamic loading on the device/mooring interface. The Consultants are in contact with the further design work being undertaken by SBM and are aware of its possible implications on the structural design of the device. Again it is not expected that any necessary modifications will have a significant cost penalty.

1.2 TANK TESTING

The device has been tested for the 46 spectra and these tests together with parallel analyses undertaken by NEL indicate that the device has a hydrodynamic efficiency of 25%. This is low in comparison with other devices but, as discussed later, is compensated by the overall capture potential at 100m depth and the higher number of cells that can be incorporated in one module (12 no. cells) resulting in an overall need for only 185 devices as compared to 589 devices in the case of the Raised Breakwater, both for a nominal 2 GW station. Technical Advisory Group 2 have recently recommended a reduction in the

the power available at 100m depth which has been incorporated into the device assessment but not the device optimisation.

1.3 SPECIFICATION

Information to date is broadly based on the NEL summary of Mechanical and Electrical Plant Rating and Productivity 20th November, 1981, on the structural design philosophy as used in the Attenuator design and on the earlier NEL reference designs. Close liaison has been maintained between the Device Team and the Consultants on any developments and major modifications.

Due to on-going work on the design and the capture philosophy as discussed later, the Device Team has not yet produced a formal specification.

1.4 COSTING

Full co-operation has been maintained between the Device Team and the Consultants on construction costs and the information that is becoming available on installation costs as the mooring design approaches completion. Good agreement has been reached on the structural costing and the mooring philosophy.

Owing to the above continuing modifications a formal presentation of costing for the device has not yet been provided by the Device Team.

2. DEVELOPMENT

2.1 GENERAL

The Floating Terminator represents the most up-to-date of the Oscillating Water Column devices as originally conceived, namely a moored terminator square to the sea. It is immediately evident that any cost and engineering penalties related to the installation and up-keep of the moorings is compensated by the long-term average sea power obtaining at 100m depth (53.5Kw/m).

2.2 MANIFOLDING

In June and July of this year the concept of manifolding six of the 12 cells into one AC power unit, i.e. two such power units per 12 cell device, was examined by the Device Team. It was anticipated that the smoothed power input, the simpler plant requirement and the reduced device-to-shore transmission could produce useful economies with a small capture loss. The results of tank testing did not support this view and the system discussed in this note therefore comprises a 1:1 cell to turbine/generator ratio. The possibility of manifolding is still being examined and the current Cadnam tests on a raised breakwater device uses a manifolded model.

2.3 CHANGES TO DEVICE PROFILE

It is expected that the profile of the device will be essentially in accordance with drawing No. FT/1 revision 1 of September 1981. The modifications to this will be due to the incorporation of one plant unit per cell but it is anticipated that this will be located in the area presently occupied by the HP and LP ducts with adequate facilities being provided for access, maintenance and part replacement.

3. <u>FEASIBILITY</u>

Although accepting that some modifications may be necessary due to the mooring systems and to mooring loading on the device, the Consultants consider that the Floating Terminator OWC concept is feasible.

Essentially the construction sequence is based on well established methods, a comparatively small number of 12 cell modules will be required thus easing any problems associated with optimising the construction sequence and in tow-out and installation.

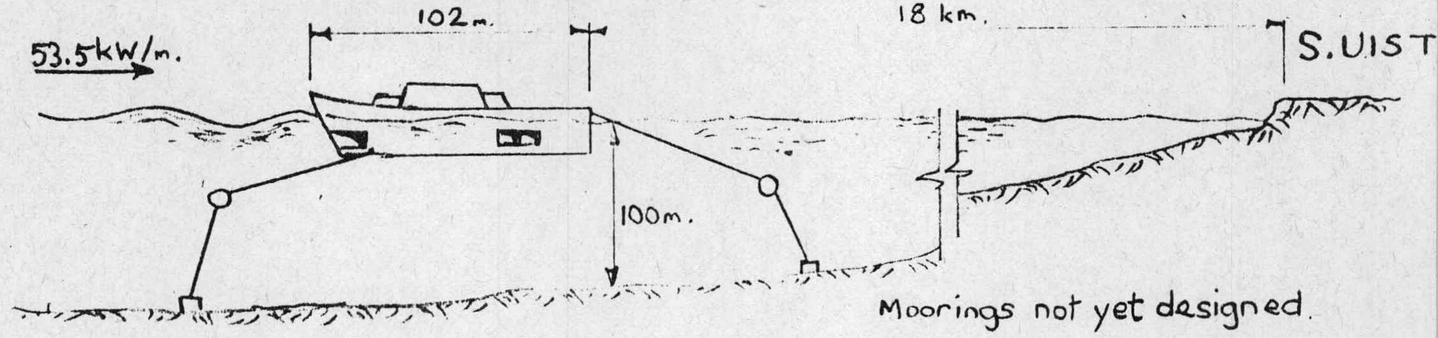
The device obviously suffers from the problems of any moored device in this water depth, namely maintenance for the moorings themselves and access for maintenance of the plant.

4. CONCLUSIONS

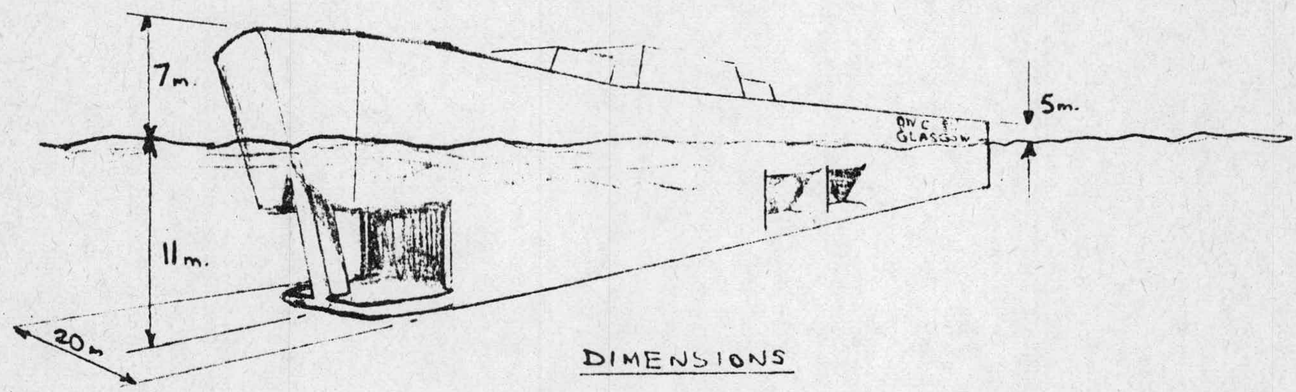
In agreeing with the Device Team's costing and programme estimates and in recognising the proposed construction of the module as being a reasonable one, involving no significant extrapolation of current engineering practices, the Consultants confirm that the floating terminator is an acceptable device. Both the Consultants and the Device Team acknowledge that further work is required on the torsional rigidity of the structure and also possible interaction with the proposed mooring system when finally agreed. Both these aspects are actively under examination by the Device Team with full interaction with the Consultants. It is not anticipated that any final and necessary modifications will have significant cost or installation time penalties.

NEL FLOATING ATTENUATOR

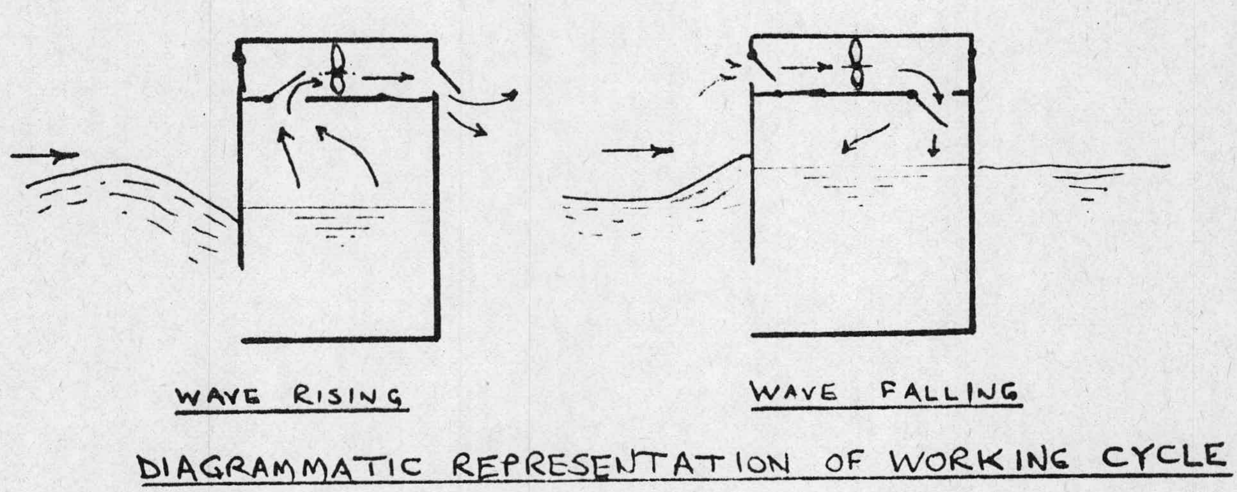
OWC - SPINE FLOATING - NEL ATTENUATOR



LOCATION OF SCHEME

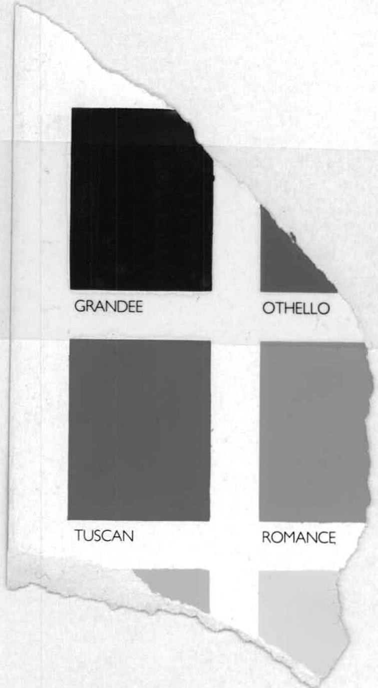


DIMENSIONS



WAVE RISING   WAVE FALLING

DIAGRAMMATIC REPRESENTATION OF WORKING CYCLE


GRANDEE
OTHELLO
TUSCAN
ROMANCE

LEADING DEVICE PARAMETERS

(Location - South Uist)

NEL FLOATING ATTENUATOR

A. Related to location

1.	Distance offshore (km)		24
2.	Water depth (m)		100
3.	Power in sea (Kw/m)		53.5

B. Related to device

1.	Overall size - length (m)	102	
	- breadth (m)	20	
	- vertical dimension (m)	16	
	- gross cross sectional area (m^2)	320	
2.	Weight of device (tonnes)	17610	
3.	Weight of device ÷ length (tonnes/m)	180	

C. Related to 2GW station

1.	Number of devices		1444
2.	Spacing of devices (m)		100
3.	Length of 2GW station (km) (excl. navig. gaps)		144.4

D. Related to productivity

1.	Rating of generators (Mw)	1.8 + 2 x 0.18 Mw/device	
2.	Power in sea (Kw/m)	53.5	
3.	Mean annual power delivered to Skye (Mw/device)*	0.322	
4.	Mean annual output of 2GW scheme (GW)*	0.465	

E. Related to structure economy and utilization of resource

1.	Mean annual power delivered per device ÷ length of device (Kw/m)*		3.2
2.	Mean annual power delivered per device ÷ device spacing (Kw/m)*		3.2
3.	Overall conversion efficiency of scheme* mean annual output of 2GW scheme / mean annual power in sea x length of 2GW station (%)		6.0
4.	Capture Factor** mean annual power captured by device / mean annual power in sea x device length (%)		9.8

F. Related to cost

1.	Cost of 2GW station (undiscounted) (£M)	8272	
2.	Cost of each device (undiscounted) (£M)	5.7	
3.	Cost of energy (discounted) (p/Kwh)	18.0	

G. Miscellaneous

1.	Mean annual power chain efficiency (%)***		70
2.	Availability of the 2GW scheme (%)		86
3.			
4.			

* including availability factor

** not including availability factor

*** mean annual power landed at Skye / mean annual power captured per device x No. of devices in scheme (not including availability factor)

COST BREAKDOWN

NEL FLOATING ATTENUATOR

	$£ \times 10^6$ undiscounted		$£ \times 10^6$ discounted	
	2GW Scheme	Per Device	2GW Scheme	Per Device
Structure				
Construction facility	590.2	0.41	555.5	0.38
Launch devices	65.2	0.05	52.3	0.04
Device structure	1934.2	1.34	1489.6	1.03
	2589.6	1.80	2096.4	1.45
M & E				
Turbo-generators	1068.9	0.74	823.0	0.57
Ducts and Valves	592.0	0.41	455.8	0.32
Ancillary equipment	143.9	0.10	110.8	0.08
	1804.8	1.25	1389.6	0.97
Installation/Moorings				
Anchor piles, universal joints, rodes and buoys	1402.1	0.97	1080.5	0.75
Installation vessels	289.5	0.20	266.7	0.18
	1691.6	1.17	1347.2	0.93
Transmission				
Collection pontoons	716.6	0.50	593.1	0.41
Generator output to islands	1150.0	0.79	885.5	0.61
Inverters and substations on islands	123.0	0.08	101.8	0.07
Transmission to Skye	196.0	0.14	162.2	0.11
	2185.6	1.51	1742.6	1.20
CAPITAL COST	8271.6	5.73	6575.8	4.55
Maintenance				
Maintenance base overheads and operations	85.9	0.06	36.0	0.02
Vessels,divers and technicians for inspection & repair	1191.2	0.83	574.5	0.40
M & E spares	1067.1	0.74	543.3	0.38
MAINTENANCE COST	2352.2	1.63	1153.8	0.80

5(iii)f NEL FLOATING ATTENUATOR

1 GENERAL

1.1 DESIGN

The structural feasibility of the three devices proposed by NEL was originally examined in the context of a detailed design of the Attenuator, this design being in accordance with the NEL OWC Note 30 and to appropriate and acceptable design criteria. The design philosophy and the calculations are fully acceptable to the Consultants.

Of the three devices, the Attenuator sustains the least onerous loading both in installation and during its operational life. Further design modifications may be necessary when the mooring system has been finally decided though this is not expected to give rise to any modifications to the structure that would significantly effect construction costs.

1.2 TANK TESTING

Due to earlier tests indicating inherent limitations in capture potential, only preliminary tank tests have been carried out on the Attenuator. Bearing in mind that the device comprises one front column with a hydrodynamic efficiency of 41% and two side columns of only 4.6% it is apparent that the performance of the Attenuator must compare unfavourably with the other devices where each cell is fully utilised. For the above reasons the Attenuator has been tested in the NEL tank for PM conditions but not for the 46 designated spectra.

1.3 SPECIFICATION

This is broadly based on the NEL summary of Mechanical and Electrical Plant Rating and Productivity 20 November 1981. Close liaison has been maintained between the Device Team and Consultants on such developments and modifications that have been carried out, though essentially the design was frozen in July 1981.

The Device Team are not in a position to produce a formal specification before mooring details have been finalised.

1.4 COSTING

Full co-operation has been maintained between the Device Team and the Consultants on construction costs and close agreement has been reached on this. An assessment of installation costs has to await completion of mooring design.

2 DEVELOPMENT

2.1 GENERAL

The Attenuator forms a variation on the original NEL theme of a floating device originally conceived as being normal to the wave front. It was apparent that, as in other devices, some advantage could be gained by capturing the waves on a longitudinal basis and, by suitable spacing of the devices, being able to extract the same amount of energy from a passing wave as that abstracted by the Terminator device from a reflected wave. The Device Team considered device lengths of 100m - 200m and finally decided upon the 100m as being the most economic as regards construction, preliminary tank testing having indicated that the three cell unit proposed was marginally less efficient than a four cell unit - one full size cell in the bow, one full size cell in the stern and two half cells on the Attenuator sides. A further modification was the shaping of the forward cell into the conventional bow shape thus making tow-out and emplacement comparatively easy and general sea-keeping behaviour tolerable.

2.2 AC GENERATION

Between July and September 1981 some attention was directed to the possibility of AC generation using axial flow turbines and synchronous alternator units with the associated advantage of fewer cables to shore at the expense of a marginally reduced overall efficiency. This idea was abandoned at the same time as the idea of manifolding for the other two devices was discontinued, mainly because of the apparent failure of manifolding.

3 FEASIBILITY

At 105m water line length the design is credible and the sea-keeping characteristics would be expected to be satisfactory. However, due to the low capture potential and hence to the fact that some 1300 modules are required it is seen that on economic grounds the Attenuator device cannot be considered a feasible one and it cannot compete with the NEL Floating Terminator or Raised Breakwater. The efficiency gap cannot be compensated by hydrodynamic or overall hydromechanical chain improvements and the device is essentially a point absorber only.

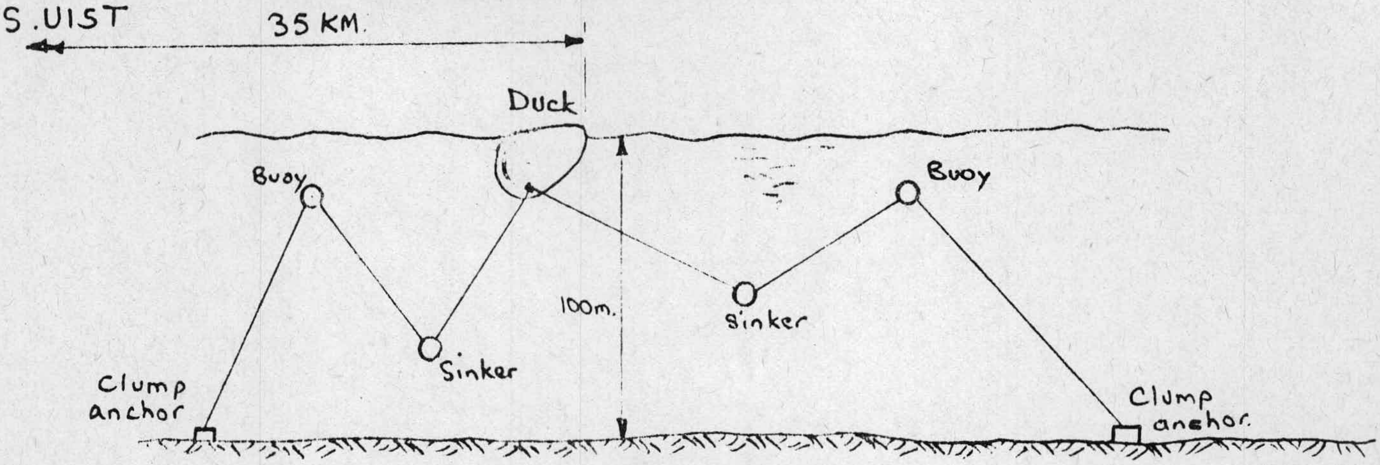
Mooring details are not finalised but it is expected that some form of fixed point mooring at the bow and two trailing moorings at least at the stern will be required. If the devices are to be positioned sufficiently close together for capture to be optimised, not more than 100m, then some difficulties with the mooring system can be anticipated though to no greater extent than that obtaining in the Floating Terminator.

4 CONCLUSIONS

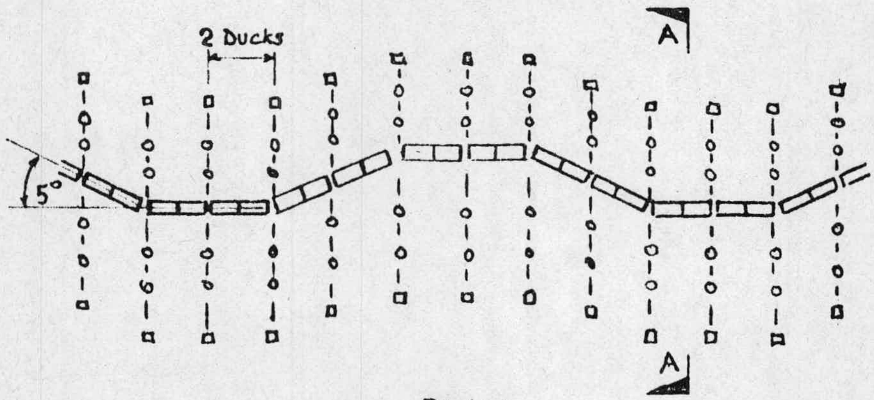
While agreeing with the Device Team's construction costing and design philosophy the Consultants believe that sufficient work has been undertaken on the Attenuator device to indicate that it has no future, its overall performance cannot be made to match that of the Floating Terminator and the Raised Breakwater.

EDINBURGH DUCK

EDINBURGH DUCKS

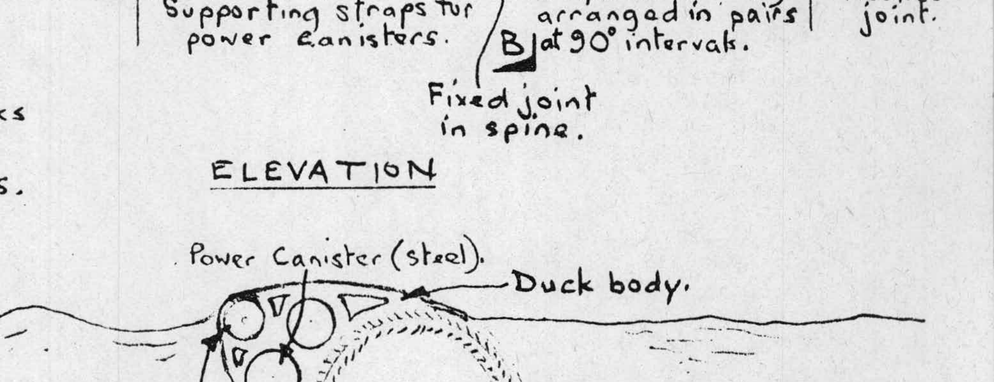


SECTION A-A



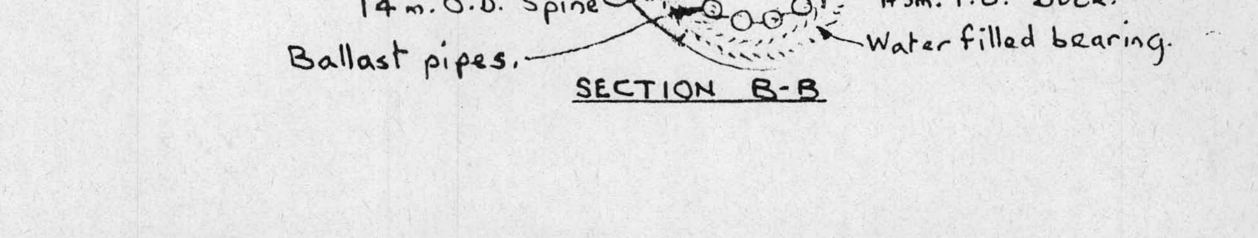
PLAN

GENERAL LAYOUT



NOTE:-
Each power canister contains 2 gyros and 1 generator, and converts power from precession of gyros by high pressure oil hydraulics from ring cam pumps to swash plate pump/motors.

ELEVATION



SECTION B-B

LEADING DEVICE PARAMETERS

(Location - South Uist)

EDINBURGH DUCK

A. Related to location

1.	Distance offshore (km)		35
2.	Water depth (m)		100
3.	Power in sea (Kw/m)		53.5

B. Related to device

1.	Overall size - length (m)	37	
	- breadth (m)	24	
	- vertical dimension (m)	16	
	- gross cross sectional area (m^2)	265	
2.	Weight of device (tonnes)	8000	
3.	Weight of device ÷ length (tonnes/m)	216	

C. Related to 2GW station

1.	Number of devices		956
2.	Spacing of devices (m)		45
3.	Length of 2GW station (km) (excl. navig. gaps)		43

D. Related to productivity

1.	Rating of generators (Mw)	2 x 1.2 Mw/device	
2.	Power in sea (Kw/m)	53.5	
3.	Mean annual power delivered to Skye (Mw/device)*	0.623	
4.	Mean annual output of 2GW scheme (GW)*	0.595	

E. Related to structure economy and utilization of resource

1.	Mean annual power delivered per device ÷ length of device (Kw/m)*		13.9
2.	Mean annual power delivered per device ÷ device spacing (Kw/m)*		13.9
3.	Overall conversion efficiency of scheme* $\frac{\text{mean annual output of 2GW scheme}}{\text{mean annual power in sea x length of 2GW station}}$ (%)		25.9
4.	Capture Factor** $\frac{\text{mean annual power captured by device}}{\text{mean annual power in sea x device length}}$ (%)		39.0

F. Related to cost

1.	Cost of 2GW station (undiscounted) (£M)	3068	
2.	Cost of each device (undiscounted) (£M)	3.2	
3.	Cost of energy (discounted) (p/Kwh)	5.6	

G. Miscellaneous

1.	Mean annual power chain efficiency (%)***		83
2.	Availability of the 2GW scheme (%)		80 (TARGET)
3.			
4.			

* including availability factor

** not including availability factor

*** $\frac{\text{mean annual power landed at Skye}}{\text{mean annual power captured per device x No. of devices in scheme}}$ (not including availability factor)

COST BREAKDOWN

EDINBURGH DUCK

	£ x 10^6 undiscounted		£ x 10^6 discounted	
	2GW Scheme	Per Device	2GW Scheme	Per Device
Structure	254.9	0.27	237	0.25
Construction facility	78.5	0.08	61	0.06
Launch devices	965.2	1.01	719	0.75
Device structure	255.3	0.27	190	0.20
Universal joint couplings and shrouds	1553.9	1.63	1207	1.26
M & E	741.4	0.78	552	0.58
Mechanical power take-off units	88.5	0.09	66	0.07
Electrical power take-off units	13.4	0.01	10	0.01
Ancillary equipment	843.3	0.88	628	0.66
Installation/Moorings	134.3	0.14	100	0.11
Clump anchors, sinkers, floats and rodes	76.6	0.08	70	0.07
Installation vessels and operations	210.9	0.22	170	0.18
Transmission	217.0	0.22	162	0.17
Generator output to islands	47.0	0.05	38	0.04
Inverters and substations on islands	196.0	0.21	159	0.16
Transmission to Skye	460.0	0.48	359	0.37
TOTAL CAPITAL	3068.1	3.21	2364	2.47
Maintenance	85.9	0.09	33	0.03
Maintenance base overheads and operations	1343.9	1.41	612	0.64
Vessels, divers and technicians for inspection & repair	91.7	0.09	45	0.05
M & E spares / TOTAL MAINTENANCE	1521.5	1.59	690	0.72

5(iv) EDINBURGH DUCK

General

It is assumed that the members of WESC are familiar with the Duck, following presentations by the Team earlier in 1981.

The Duck, as proposed, is at the extreme end of the range for most of the parameters used to measure the effectiveness of wave energy devices.

It has,

- the highest output/m of sea
- the lowest mooring forces
- the second lowest mass/kW
- the second highest swept volume ratio
- conceptually the most cost effective power chain
- the greatest number of interlocking and interdependent systems
- and in consequence the lowest availability
- a unique dependence on successful mechanical engineering development to achieve viability.

This is results from a conscious decision by the Team to match the complex randomness of the input energy of the sea by a damping system capable of instantaneous intelligent response, and to meet the damaging high wave amplitudes with a controllably compliant spine. Resulting from this philosophy, power output is maximised and structural and anchoring forces are minimised. The result is a design which must be near optimal in weight and efficiency, and which must be assessed in terms of the probability of success or failure at the end of a significant development phase.

Assessment of the Concept

Primary Interacting Surface

This is probably the most efficient in the wave energy programme. The wedge action allows a high swept volume and the natural movement of the sea is well matched. The facility to flip over in a high sea is a valuable means of limiting forces in high seas.

Reference Frame

This is likewise very efficient, in that for most working seas the spine can be kept rigid (if required) to maximise output. In seas where there is an excess of energy the spine is able to "break" at hinge points to limit forces, both on the spine structure and on the moorings. Use of gyroscopes to resist rotation makes the whole device concept possible.

Power Offtake

High pressure hydraulics using a multiplicity of pumps on cam rings confers a high volumetric efficiency which leads to low installed swept volume and relatively low machinery cost. It also makes possible the system of energy interchange with the two fly wheels, which in turn allows the power smoothing over many wave cycles, and synchronous generation. The gyros also provide a large reserve of stored energy, the benefit of which has not been costed.

Given the engineering means of realising it, the concept is hard to fault.

Assessment of the Engineering

The device is engineered round the concept of "sealed for life" power canisters in each of which 256 ring cam pumps, 5 swash plate motors, and two gyroscopes work continuously without maintenance for up to 25 years. Pumps and motors are over provided to give some redundancy to allow for breakdown, but essentially the engineering stands or falls on the feasibility of achieving a very consistent maintenance free life as indicated. Experts consulted (Mr. Baggett of Commercial Hydraulics Ltd. the National Centre of Tribology at Risely and others) are not prepared to discount the possibility that this may be achieved if the necessary effort is made available.

An attempt to draw comparisons between the required life of components of the Duck power train and similar components in present day service are presented in Figs. A and B.

The Duck flywheel bearings rotate in excess of 10^{10} revolutions over a 25 year period which is greater by 1 or 2 orders of magnitude than most rotating machinery; but it is equalled by the bearings in large turbo-alternater sets (660 MW), and by individual rollers in critical roller bearings in equipment as diverse as the Rolls Royce RB 211 engine and in the main traction axle hubs on the London Underground. The bearing linear surface travel on large T/A and hydrosets exceeds that on the Duck and provides some reassurance that the life expectancy required on bearings can be attained.

The total piston travel on the swash plate motor pump is considerably in excess of that for other equipment such as internal combustion engines of all sizes - but these have to cope with high temperatures causing oxidation of the oil, contamination of the oil from products of combustion, and expose to unclean air and fuel, and metal particles from wear of bearings. The long life necessary for this critical component and for the whole high pressure hydraulic system is to be achieved by ensuring complete integrity of clean oil supply in a dry low pressure environment. This has to be proved but the uncertainty rests heavily on achieving an acceptable level of reliability of the whole system and hence all its component parts. The reliability analysis by YARD gives an unfavourable result. Notwithstanding that it has had to be based on some data obtained from non comparable applications the fact remains that it clearly shows that an order of magnitude improvement in reliability is required for the device to approach viability.

The environmental factor (to be applied to the failure rates) chosen by YARD does not reflect the Team's claim to create a near perfect working environment by enclosing equipment within low pressure sealed power cannisters, and there may be some immediate gain to be identified here. . The Consultants assess that an increase in reliability of about 50 times over the YARD assumptions is needed to meet the system reliability requirements concommitant with the availability of 80% used in the device costing. Marginally lower component reliability might be accommodated by more redundancy and system redesign.

However the design of the power train already incorporates redundancy in some components which are in parallel "fail to safety", and this has been allowed for already.

Productivity

The Duck has only been tested in P-M seas in a narrow tank and productivity has been assessed by assuming linearity of performance with respect to combination of incident waves from various directions.

One set of tests in the wide tank has given encouraging results, but more results are required before one can be sure that the Duck will not suffer the loss of efficiency experienced by other devices in the wide tanks.

Meanwhile the Consultants have based their productivity assessment on the assumption that there will be no such drop in efficiency.

Conclusion

The Consultants are currently concentrating all their efforts to obtain the best assessment of the chance of achieving success by say 1995.

The case for continuing work rests on the inherently high efficiency of the device, and its inherently low use of raw materials. It offers the most scope to benefit from advances in technology in the future.

EDINBURGH DUCK - FLYWHEEL BEARINGS COMPARED TO EXISTING COMPARABLE COMPONENTS

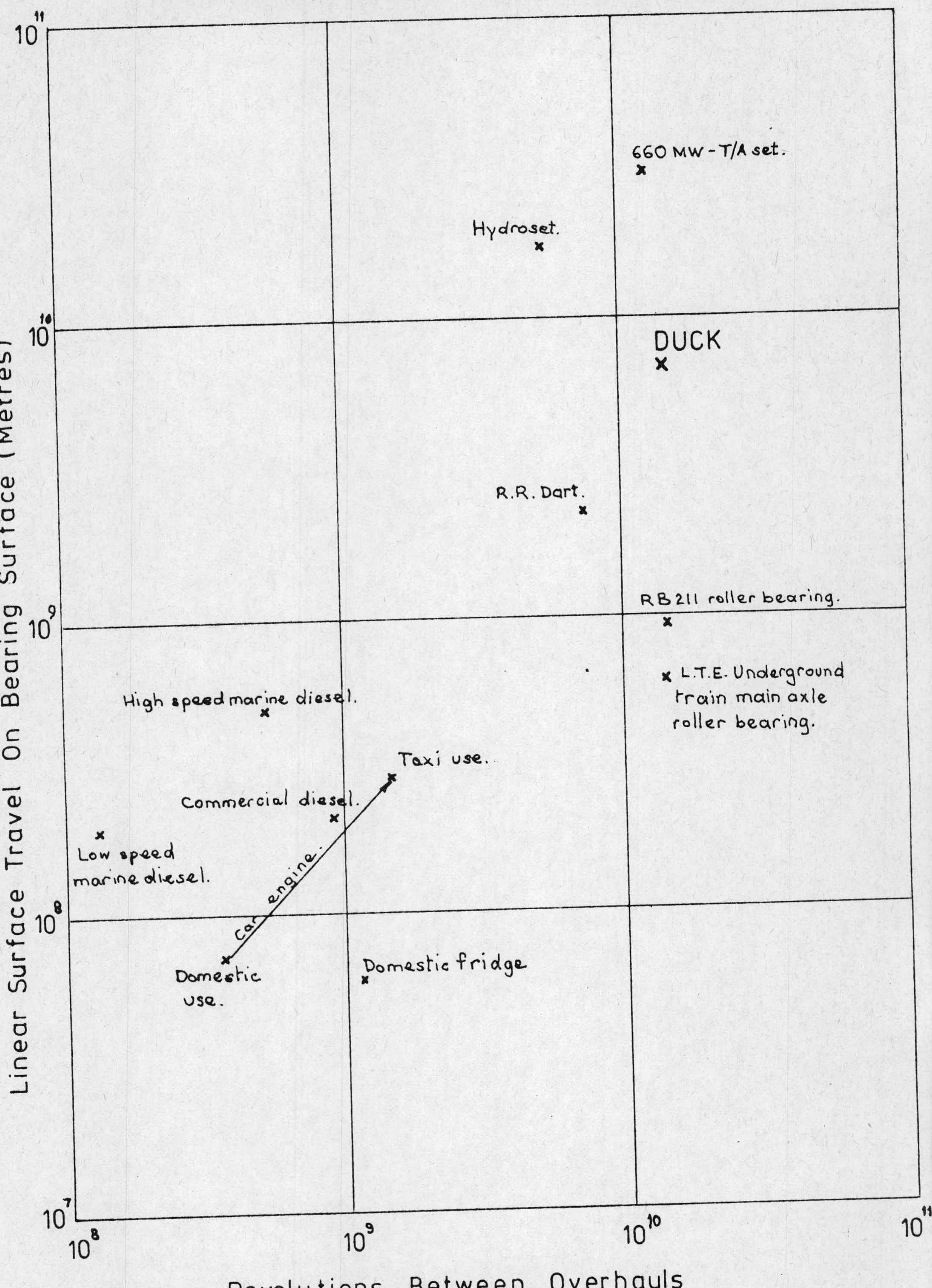


FIG. A

EDINBURGH DUCK - PISTON TRAVEL COMPARED WITH EXISTING COMPARABLE COMPONENTS

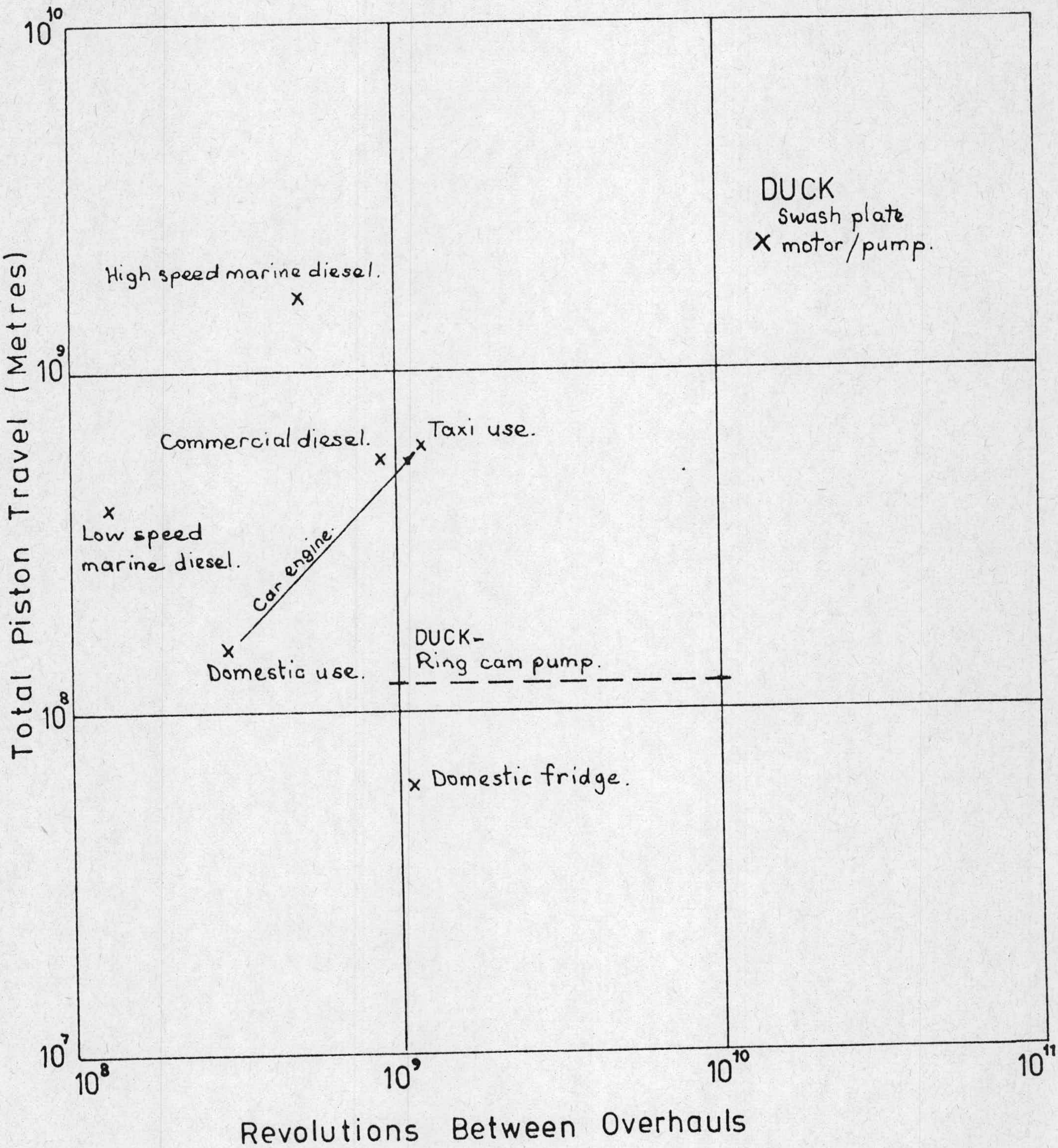
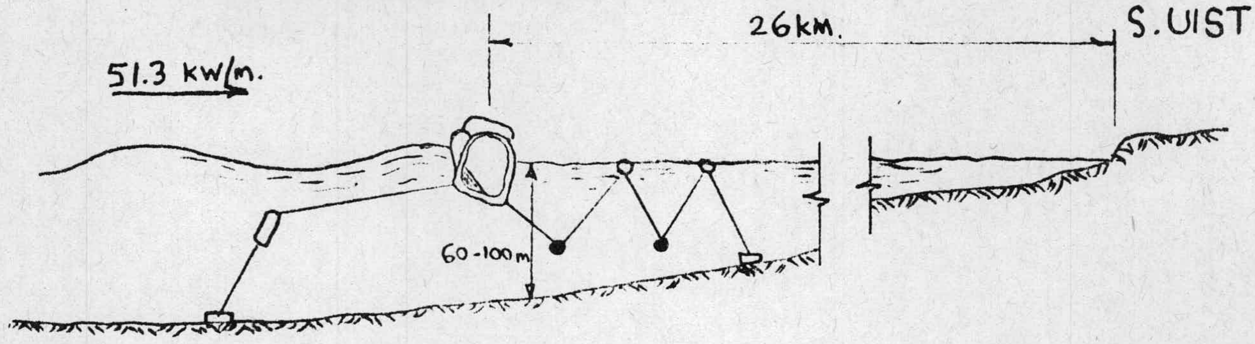


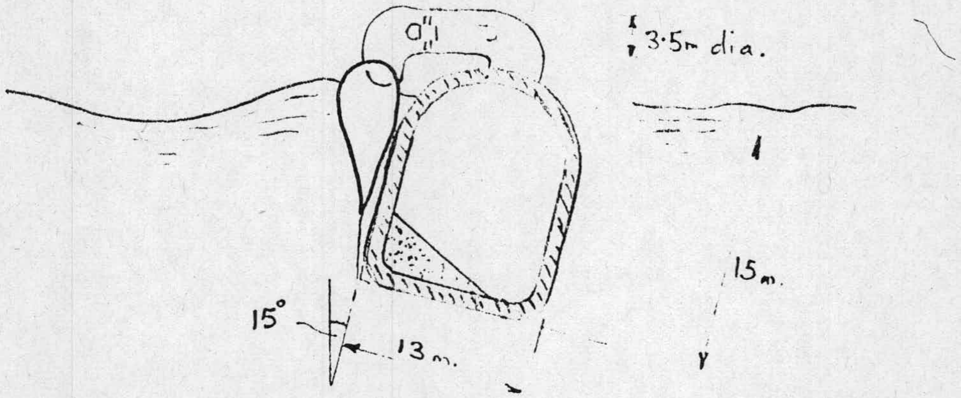
FIG. B

LANCHESTER CLAM

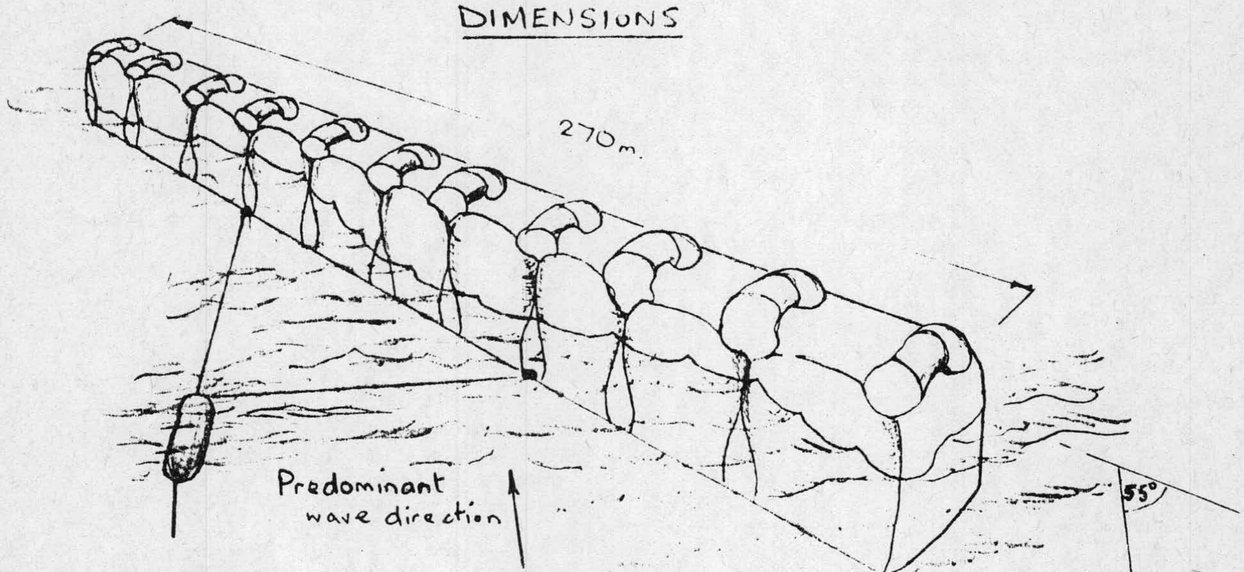
LANCHESTER CLAM

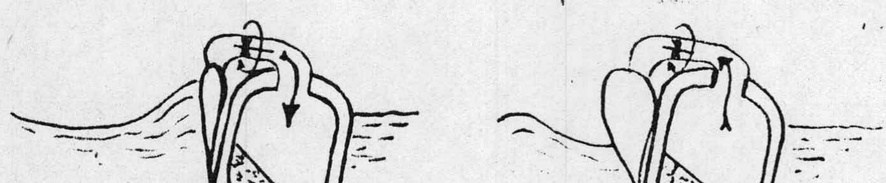


LOCATION OF SCHEME



DIMENSIONS





WAVE RISING

WAVE FALLING

OPERATING CYCLE

LEADING DEVICE PARAMETERS

(Location - South Uist)

LANCHESTER CLAM

A.	**Related to location**		
1.	Distance offshore (km)		26
2.	Water depth (m)		80
3.	Power in sea (Kw/m)		51.3
B.	**Related to device**		
1.	Overall size - length (m)	274	
	- breadth (m)	13	
	- vertical dimension (m)	15	
	- gross cross sectional area (m^2)	169	
2.	Weight of device (tonnes)	45000	
3.	Weight of device ÷ length (tonnes/m)	164	
C.	**Related to 2GW station**		
1.	Number of devices		341
2.	Spacing of devices (m)		400
3.	Length of 2GW station (km) (excl. navig. gaps)		136.4
D.	**Related to productivity**		
1.	Rating of generators (Mw)	10 x 1.0 Mw/device	
2.	Power in sea (Kw/m)	51.3	
3.	Mean annual power delivered to Skye (Mw/device)*	1.77	
4.	Mean annual output of 2GW scheme (GW)*	0.60	
E.	**Related to structure economy and utilization of resource**		
1.	Mean annual power delivered per device ÷ length of device (Kw/m)*		6.5
2.	Mean annual power delivered per device ÷ device spacing (Kw/m)*		4.4
3.	Overall conversion efficiency of scheme* $\frac{\text{mean annual output of 2GW scheme}}{\text{mean annual power in sea x length of 2GW station}}$ (%) ← in gaps		8.6
4.	Capture Factor** $\frac{\text{mean annual power captured by device}}{\text{mean annual power in sea x device length}}$ (%)		23
F.	**Related to cost**		
1.	Cost of 2GW station (undiscounted) (£M)	3986	
2.	Cost of each device (undiscounted) (£M)	11.7	
3.	Cost of energy (discounted) (p/Kwh)	6.7	
G.	**Miscellaneous**		
1.	Mean annual power chain efficiency (%)***		65
2.	Availability of the 2GW scheme (%)		83
3.			
4.			

* including availability factor

** not including availability factor

*** $\frac{\text{mean annual power landed at Skye}}{\text{mean annual power captured per device x No. of devices in scheme}}$ (not including availability factor)

COST BREAKDOWN
LANCHESTER CLAM

	£ x 10^6 undiscounted		£ x 10^6 discounted	
	2GW Scheme	Per Device	2GW Scheme	Per Device
Structure				
Construction facility	300.0	0.88	274	0.80
Launch devices	33.2	0.10	25	0.08
Device structure	1502.8	4.40	1158	3.36
	1836.0	5.38	1447	4.24
M & E				
Flexible bags	150.1	0.44	87	0.26
Turbo-generators	498.0	1.46	380	1.11
Ducts	70.4	0.21	53	0.16
Ancillary equipment	130.1	0.38	99	0.29
	848.6	2.49	619	1.82
Installation/Moorings				
Anchors	53.9	0.16	41	0.12
Rodes, terminators, joints, floats & sinkers	171.7	0.50	131	0.38
Installation vessels and operations	60.9	0.18	54	0.16
	286.5	0.84	226	0.66
Transmission				
Generator output to islands	485.0	1.42	370	1.09
Inverters and substations on islands	334.0	0.98	276	0.80
Transmission to Skye	196.0	0.57	161	0.47
	1015.0	2.97	807	2.36
CAPITAL COST	3986.1	11.68	3099	9.08
Maintenance				
Maintenance base overheads and operations	71.4	0.21	25	0.07
Vessels, divers and technicians for inspection & repair	1285.2	3.77	601	1.76
M & E spares	164.4	0.48	83	0.24
MAINTENANCE COST	1521.0	4.46	709	2.07

5(v) LANCHESTER CLAM

General

The Lanchester Clam developed from the early Duck programme and was originally conceived as an attempt to yield an entirely credible, simple device in contrast to the complexity of the Duck. A conclusion of the early Duck work in Loch Ness was that short finite spines work and the Clam arose as a 'short' spined simple wave maker acting in reverse.

The first engineered reference design yielded a credible system with rigid flaps on hinges and a rubber membrane bellows between the flap and spine. Costing of this device produced very encouraging figures but the flap and associated hinges attracted both cost and credibility penalties. The present design utilises a double faced soft rubber bag which removes the cost problem and considerably improves the credibility.

This device has been tested in the wide tank at Cadnam and has, similarly to the LFB, yielded lower productivity than expected. The efficiency of the Clam is significantly higher than the LFB. This is partly explained by manifolding losses in the LFB. The device has, however, had only one testing period in the wide tank with a model that is not truly representative of the reference design. A 1/10th scale working model is at present in Loch Ness and results will soon be available. This should provide some useful confirmation of what must be regarded as crude power measurements at Cadnam where air power from a single cell of less than 'A3' size is measured and scaled by a factor of 10^6.

Status of Assessment Data

The basic design and constructional detailing of the spine are at a fairly advanced stage and the Device Team has provided information on quantities which has been checked and used as a basis for the Consultants' cost estimate. The Device Team has also provided full details of their own estimate which in total is within approximately 5% of the Consultants' estimate. At present a four construction facility system is used for costing purposes. The Device Team is working on optimising the construction costs by using only two facilities.

Main and auxiliary plant costs have been provided by the Device Team and have been accepted provisionally by the Consultants until further information from the Working Party is available. Transmission costs have been provided based on the Consultants current working Paper. This working Paper is about to be revised significantly and the transmission costs have been modified to take account of these major revisions.

Installation costs have been developed by the Consultants for the deadweight anchor system proposed by the Team. Costing of the mooring components is the Device Teams costing and has not been verified. The overall mooring costs including installation for the Clam are about 25% of that taken for the LFB. This reduction is totally a result of lower absolute mooring loads. The validity of lower peak mooring loads for the Clam has not yet been established.

Maintenance costs have been assessed by the Consultants and correlate reasonably with the Easams Study. Availability has been derived from the failure rate study carried out by YARD.

Development

The design philosophy adopted by Lanchester has been to minimise the reference frame cost. This they have succeeded in doing. Although the method of arriving at design moments is totally different from that adopted by WPL they are in agreement over the magnitude of these forces. By utilising the allowable stresses in the spine to the limit and by avoiding the need to widen the structure for roll stability, the spine, although 7% longer is in fact over 30% lighter than the LFB.

It is interesting to note that although conceived as a pure terminator, power was optimised in the wide tank by orientating the device 55^{o} from the predominant wave direction. The desired orientation is as a result within about 15° of that for the double sided 'attenuator' LFB.

Feasibility

As mentioned for the LFB, a rubber membrane is a very cost effective system. It has not, so far, been possible to develop the shape of the Clam bags to the extent to which the LFB bags have been developed, but work on the latter as regards manufacture, design and handling all contribute to confidence in the Clam bag. This does have a more complex shape and will therefore require extra development particularly in the region of the duct connections. The bag cords are always in tension while the internal air pressure is above atmospheric (Mean inflation pressure 1.5 atmospheres). This tension permits the bag to take a significant shear load before the cords are put into compression. This shear capacity appears greater than the lateral wave loading. It is however conditional on internal pressurisation.

The reference frame has been developed in sufficient detail to permit realistic cost and design capacity estimates to be made. As mentioned previously, the spine is fully stressed under extreme environmental loadings. No weight reductions are therefore conceivable.

The mooring system adopted must be considered as near the lower bound with regard to cost, and includes a number of features which are at present unproven:-

i) Sufficient compliance is provided by the leading 100^T buoy to prevent maximum design loads being exceeded.

ii) A Doris type 'Deadweight Anchor' would be available of sufficient size and shape to hold when dropped onto the seabed.

iii) Polyester parafil rodes, terminations and joints assumed to have 25 year life.

Although the Clam requires ten individual power units utilising single stage Wells turbines, each unit contains only the single rotating shaft. The power units are therefore simple and should be reliable. Cyclic efficiencies are reasonably high.

Conclusions

Productivity testing of this device in mixed spread seas is very limited and there may be considerable scope for improvement. The productivity assumed for this device however is a considerable modification of the raw test data measured at Cadnam and although the adopted figure is agreed, part must be considered as speculative. The Loch Ness testing at $1/10^{th}$ scale and the retesting at Cadnam in March should permit greater confidence in the assumed values and may even demonstrate greater productivity.

6. WHERE THE MONEY HAS GONE

WHERE THE MONEY HAS GONE [£1,000 per metre of device]

	BRISTOL CYLINDER	LANCASTER FLEXIBLE BAG	N.E.L. BOTTOM STANDING TERMINATOR	VICKERS TERMINATOR	OWC VICKERS ATTENUATOR	BELFAST DEVICE	N.E.L. FLOATING TERMINATOR	N.E.L. FLOATING ATTENUATOR	EDINBURGH DUCK	LANCASTER CLAM
PROVIDE INTERFACE WITH WAVES (A)	CYLINDER	BAG CELLS	O.W.C.	O.W.C. INNER SHELL	OWC INNER SHELL		O.W.C.	FRONT & REAR OWC CELLS	DUCK & BEARINGS	BAG CELL
	41.4	6.0	19.7	13.7	4.6	41.7	8.8	6.4	14.9	4.5
RESIST WAVE INDUCED FORCE (B)	RODES; PILING	SPINE; MOORINGS	STRUCTURE; FOUNDATION; ROCK ANCHORS	O.W.C. OUTER SHELL; PLINTH; ROCK ANCHORS	OWC OUTER SHELL; CENTRAL CAISSON; LEGS & BRACING; ROCK ANCHORS	STRUCTURE; PILES & BALLAST	SPINE; MOORINGS	STRUCTURE; MOORINGS	SPINE; HOOKES JOINT & RAMS	SPINE; MOORINGS
	17.4	24.3	31.0	23.9	11.5	81.7	29.6	18.9	21.4	15.3
CONVERT POWER (C)	RODE PUMPS, SPRINGS, VALVES, PIPEWORK, HOSES; SEA BED PIPELINES; POWERSTATION PLATFORMS; TURBINE ALTERNATOR SET & SWITCHGEAR STEP-UP TRANSFORMER CONTROL EQUIPMENT	VALVES & DUCTS; TURBINE & GENERATOR	TURBINES, GENERATORS & VALVES	DUCTS; VALVES; TURBINE GENERATOR INLET EXHAUST CHAMBER	DUCTS; VALVE BOXES; GENERATOR AND TURBINE	TURBINE	GENERATOR & TURBINE	GENERATOR & TURBINE	FLOATS, WEIGHTS, ANCHORS, MOORINGS; POWER CANNISTERS 2 Nº PER DUCK; GYROSCOPES; HYDRAULIC DRIVE; A.C. GENERATOR & AUXILIARIES	DUCTS, TURBINES & GENERATORS
	36.7	11.1	25.4	9.4	5.0	52.8	24.0	13.4	27.0	10.4
TRANSMIT (D)	CABLES TO ISLAND; ISLAND INSTALLATION; BENBECULA, SKYE, CABLES TO SKYE	CABLES TO ISLAND; ISLAND INSTALLATIONS; CABLES TO SKYE (S. UIST, SKYE)	CABLES TO ISLANDS; ISLAND INSTALLATIONS; CABLES TO SKYE (UIST, SKYE)	COLLECTOR PLATFORM 5 No. AND CABLES TO S. UIST; ISLAND INSTALLATION; S. UIST, SKYE, CABLES TO SKYE	COLLECTOR PLATFORM 5 No. AND CABLES TO S. UIST; ISLAND INSTALLATION; S. UIST, SKYE, CABLES TO SKYE	CABLES TO ISLANDS; ISLAND INSTALLATIONS; CABLES TO SKYE (S. UIST, SKYE)	CABLES TO ISLANDS; ISLAND INSTALLATIONS; CABLES TO SKYE (SOUTH UIST, SKYE)	CABLES TO ISLANDS; ISLAND INSTALLATIONS; CABLES TO SKYE (UIST, SKYE)	CABLES TO ISLANDS; ISLAND INSTALLATION; CABLES TO SKYE (S. UIST, SKYE)	CABLES TO ISLAND; ISLAND INSTALLATIONS; CABLES TO SKYE (S. UIST, SKYE)
	20.6	9.7	15.4	8.9	5.3	29.0	31.6	13.8	15.9	10.5
TOTAL SUM	116.1	51.1	91.5	55.9	26.4	205.2	94.0	52.5	79.2	40.7
INSTALL AND PROVIDE ANCHORS/MOORINGS [COST INCLUDED IN CENTRES (B)-(D)]	3 Nº SEMI-SUB/JACK UP; 12 Nº CRANE SHIPS & BARGES; 13 Nº TUGS & OTHER VESSELS	4 No. TUGS & BARGES; 4 No. OTHER VESSELS; 4 No. DRILLING VESSELS	6 No. SEMI-SUB/JACK UP; 4 No. CRANE SHIPS & BARGES; 43 No. TUGS & OTHER VESSELS	10 Nº SEMI-SUB/JACK UP; 6 Nº CRANE SHIPS & BARGES; 62 Nº TUGS & OTHER VESSELS	3 No SEMI-SUB/JACK UP; 13 No CRANE SHIPS AND BARGES; 16 No TUGS AND OTHER VESSELS	12 Nº SEMI-SUB/JACK UP; 33 Nº CRANE SHIPS; 36 Nº TUGS & OTHER VESSELS	3 No. TUGS & BARGES; 6 No. OTHER VESSELS; 3 No. DRILLING VESSELS	4 Nº TUGS & BARGES; 8 Nº OTHER VESSELS; 4 Nº CRANE SHIPS	4 Nº OTHER VESSELS; TUG & FLAT BARGE 2 Nº EACH; CRANE VESSEL 2 Nº	4 No. TUGS & BARGES; 3 No. DIVING SUPPORT VESSELS
	45.9	7.8	22.4	16.0	5.7	50.2	10.9	9.1	4.0	2.4
MAINTENANCE [COST INCLUDED IN CENTRES (A)-(D)]	3 TUGS + BARGES; 6 DIVING SUPPORT VESSELS	4 No. TUGS; 2 No. OTHER VESSELS; 4 No. DIVING SUPPORT VESSELS	4 No. OTHER VESSELS; 3 No. DIVING SUPPORT VESSELS; 4 No. TUGS AND BARGES	6 Nº TUG + BARGES; 3 Nº OTHER VESSELS; 9 Nº DIVING SUPPORT VESSELS	4 No TUGS AND BARGES; 6 No OTHER VESSELS; 2 No DIVING SUPPORT VESSELS	10 Nº TUGS & BARGES; 17 Nº OTHER VESSELS; 8 Nº DIVING SUPPORT VESSELS	3 No. DIVING SUPPORT VESSELS; 2 No. TUGS; 4 No. OTHER VESSELS	9 Nº TUGS; 5 Nº OTHER VESSELS; 6 Nº DIVING SUPPORT VESSELS	10 No. TUGS; 8 No. DIVING SUPPORT VESSELS	4 No. TUGS; 4 No. OTHER VESSELS; 4 No. DIVING SUPPORT VESSELS
	12.5	5.9	12.9	7.0	3.9	36.3	16.1	7.8	16.0	7.6

7. WHAT IS THE AVAILABLE RESOURCE AT SOUTH UIST ?

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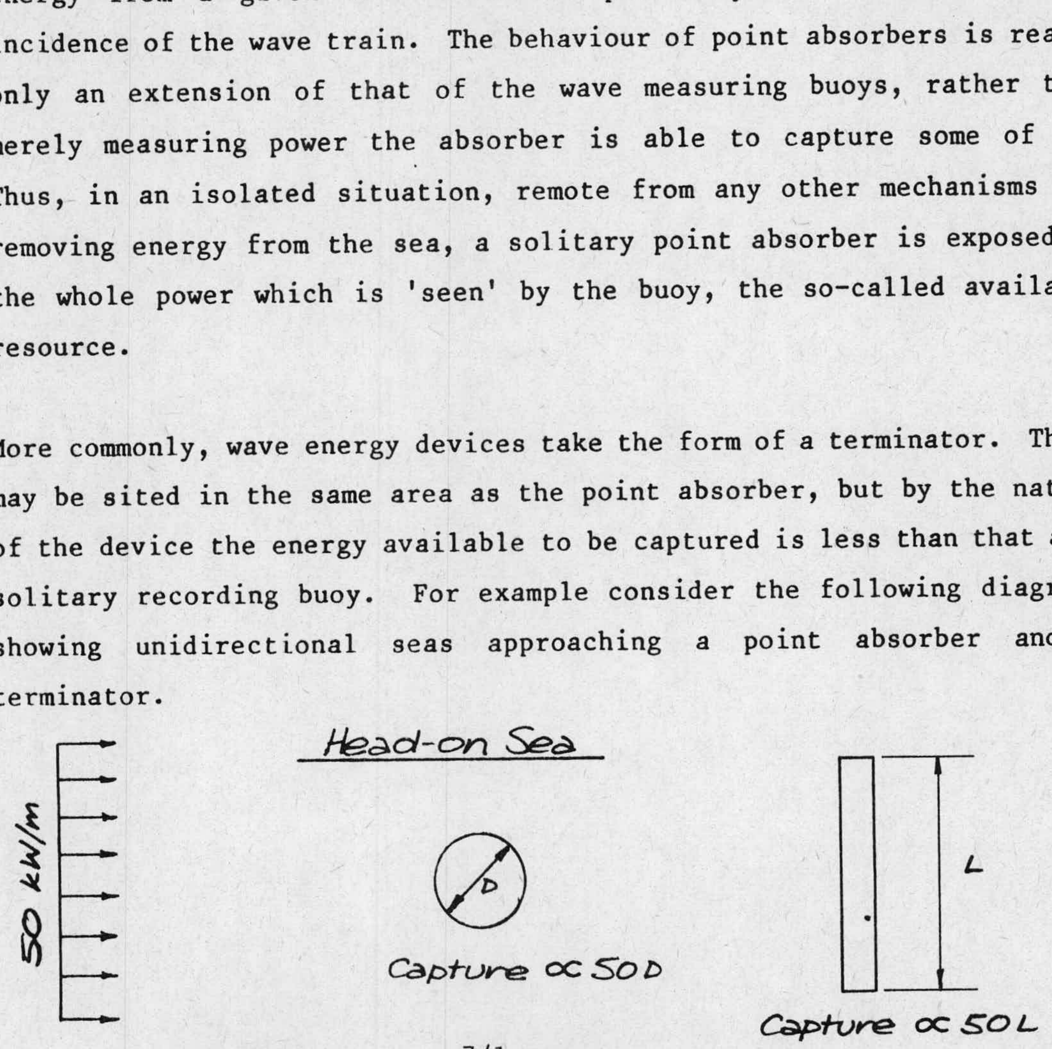
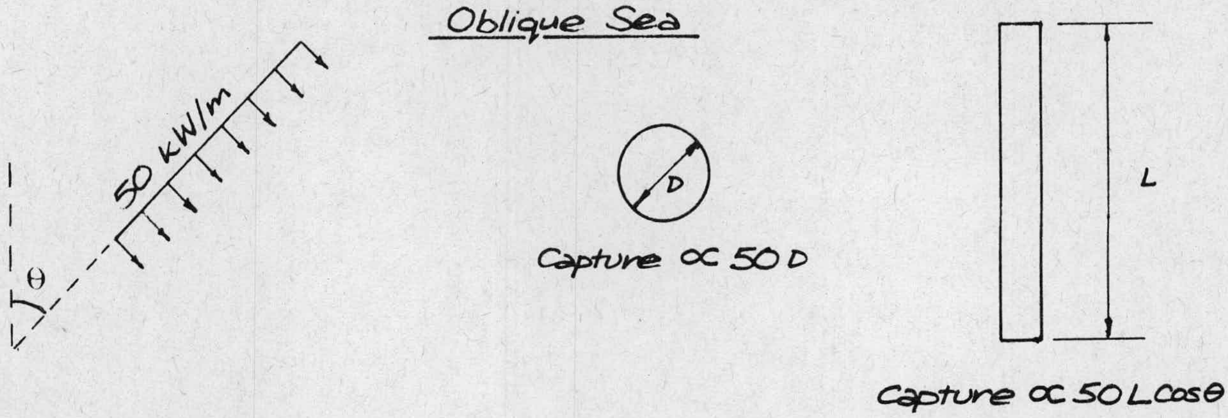
Real seas comprise a multitude of component waves of various heights and periods propagating in all directions of the compass. The power in the sea is calculated using wave records from buoys, three of which have been deployed by IOS off South Uist to collect data for the Wave Energy Programme. However, these buoys can only give information about the overall vertical displacement of the water surface and not the direction in which particular wave trains are travelling. Thus after Fourier analysis of the raw data it is possible to calculate only the total power in a given sea state. Conventionally this is expressed as a power density in kilowatts per metre, which is most usefully visualised as the rate at which energy crosses a cylinder of one metre diameter, stretching vertically from the seabed to the water surface. It is this figure which is at present taken to be the available resource.

In fact this is a fallacy. The power expressed in this way is available only to a single, isolated point absorber. Such a device is perfectly symmetrical and responds to all waves in a similar manner regardless of their direction of approach. Thus it can capture an equal amount of energy from a given wave train independently of the direction of incidence of the wave train. The behaviour of point absorbers is really only an extension of that of the wave measuring buoys, rather than merely measuring power the absorber is able to capture some of it. Thus, in an isolated situation, remote from any other mechanisms for removing energy from the sea, a solitary point absorber is exposed to the whole power which is 'seen' by the buoy, the so-called available resource.

More commonly, wave energy devices take the form of a terminator. These may be sited in the same area as the point absorber, but by the nature of the device the energy available to be captured is less than that at a solitary recording buoy. For example consider the following diagrams showing unidirectional seas approaching a point absorber and a terminator.

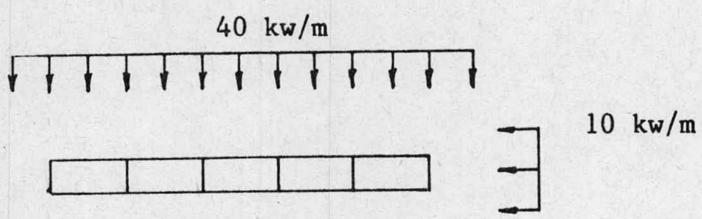


Oblique Sea



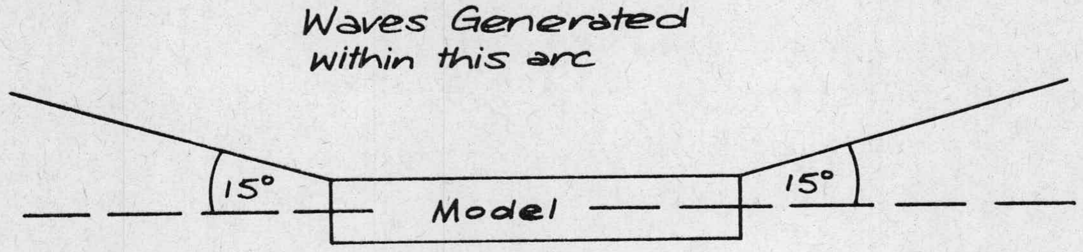
In the latter diagram, it is seen that the effective resource available to the terminator is reduced from that available to a buoy by a factor of cos θ. This is purely a consequence of the reduction in device length presented to the wave crests because of its oblique attitude. It is not to be confused with any variation in the energy captured by the device due to alterations in its capture efficiency due to variations in the angles of wave incidence.

An alternative way of looking at the reduced resource available to a terminator is to imagine a multi-directional spectrum resolved into two orthogonal components, one normal to the device, the other parallel.



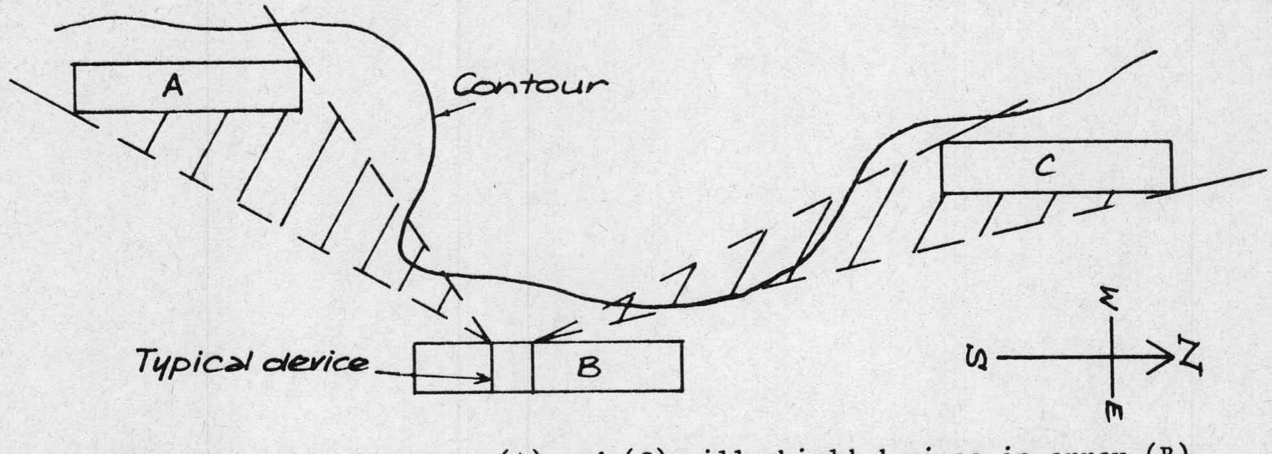
An isolated point absorber would be able to capture from both components but for the terminator, once the parallel component has been captured by the end cells it no longer exists and is not available to the remaining cells along the line. This effect is particularly pronounced for an array of terminators many kilometres long. The energy which may be captured from waves travelling along the line of the array is negligible. This argument applies to any linear array of devices, not just to terminators. The array acts as a very long attenuator in which only the end few devices capture any appreciable energy from wave trains travelling parallel to the array. It has been suggested that diffraction will take place to transfer energy along wave crests and replenish that which is extracted. However, from evidence of diffraction around breakwaters it seems unlikely to be of significant consequence.

It should be realised that due to space limitations it is not possible to study the behaviour of long arrays of devices by wide tank testing. Therefore care is needed in the assessment of results from single or small groups of models. One of the limitations of the wide tanks presently used for testing at Cadnam and Edinburgh is that they can produce waves only from an arc of approximately $\pm 75^{o}$ about a central direction for a device central in the tank.



In the RPT estimation of the productivity of arrays of devices off the Hebrides this limitation has been regarded as removing from the sea those components which contribute to the available resource as measured by buoys, but are not effectively available to the devices. This is an approximation which the Consultants believe to be reasonable within the current state of knowledge. However, some Teams disagree with this approach.

The above has implicitly assumed that devices will be sited in one straight line array. However, in practice a wave energy station would require a number of arrays which would be deployed to suit sea bed conditions. They would change course to follow contours and avoid unsuitable underwater topography. It is clear that arrays and devices will interfere with each other's resource, some devices shielding certain directional components from others.



In the above sketch arrays (A) and (C) will shield devices in array (B) and reduce the resource available to (B). Thus model tests based on the full resource will overestimate the productivity of devices in array (B). No work has yet been done in assessing the likely reduction this effect will have on annual capture since teams have not yet put forward detailed proposals for array layouts. However, it is an important factor which must not be overlooked in the ultimate productivity assessment.

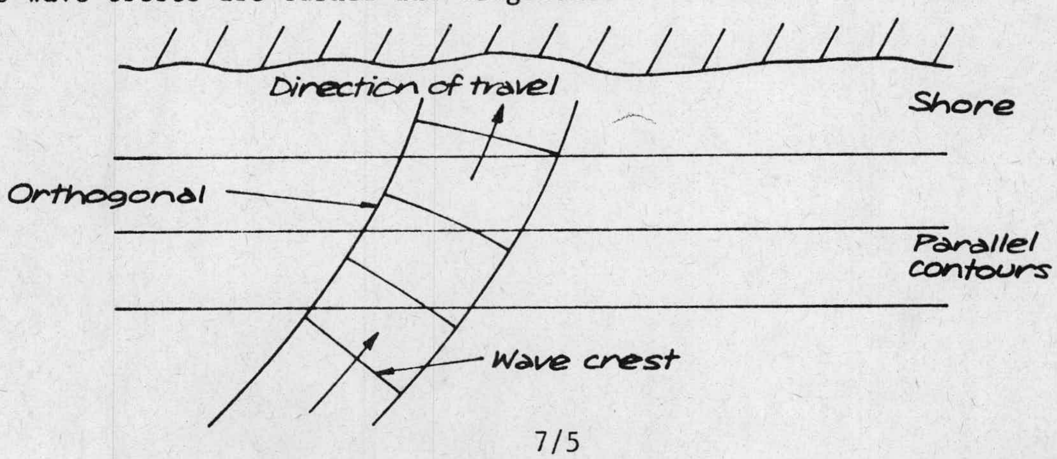
The previous paragraphs have shown that the resource actually available to wave energy devices is less than that apparently available from buoy measurements. But it is also important to draw attention to the reliability of the data which forms the apparently available resource. The mean annual wave energy fluctuates from year to year and therefore, in order to form a meaningful estimate of device annual productivity, Crabb of IOS synthesised a wave climate comprising 399 directional wave spectra. This work was based on only one year's recorded wave data, from which spectra representative of long term conditions were selected using 24 years' wind data. The long term mean annual power density in the sea was determined from these spectra as 47.8 kw/m in the reference depth of 42m. This value has been accepted by the wave energy community, but it must be emphasised that it is only an estimate, the accuracy of which is not known due to the limited data available. Subsequently, using a different procedure and more data, Mollison has predicted a slightly increased figure of 50.3 kw/m. Comparison should also be made with the average power density actually measured by the offshore buoy. Recording began in March 1976, but due to breakdowns the data available to date amounts to three complete years. The average power density of these years has been 42 kw/m, less than the long term prediction, but close enough to show it is of the correct order.

Even more uncertainty lies with the directional distribution of energy within each spectrum. Since the existing buoys off the Hebrides are incapable of making directional measurements the distribution had to be inferred from wind data. A directional buoy is being deployed in 1982, but it will be some months before it will have acquired sufficient data to allow predictions to be made and the assumptions checked. Also it is important to realise that the directional distribution has been inferred only for the reference depth of 42 m. Most devices are intended to be sited in different water depths for which there is not even an estimated directional distribution. Hence it must be appreciated that spectral data used for model testing and assessment of productivity, whilst being a significant advance from monochromatic and Pierson-Moskowitz seas, is far from perfect and can only be used to give comparisons and approximate estimates.

As has already been stated, devices have been proposed which would be sited in depths different from 42m. Estimates for the resource at these sites have been made by interpolation between data available for water depths of 15m, 25m and 100m. Long term mean power levels have been predicted by IOS for these depths by comparing spectra recorded simultaneously by buoys at these locations and the buoy at 42m.

Buoy	Depth (m)	Long term mean power density (kw/m)
Deep water	100	59.2
Offshore	42	47.8
Inshore 3	25	36.2
Inshore 1	15	15.3

Values are related to the reference power density of 47.8 kw/m at 42m, but measured data is such that the proportions can be expressed with confidence. Thus it may be thought at first sight that the available resource is reducing in shallower water depths. Several mechanisms have been suggested to explain the reducing values, but there is no complete, satisfactory explanation. Power can be lost in a number of ways, eg. turbulence from waves breaking or friction applied by bed roughness and submarine growth. Such means are necessary to explain the rapid decay of power in depths shallower than 25m, but work by HRS using a refraction model suggests that no power is lost in water deeper than this. The apparent reduction in power density is merely due to dilution as wave crests are turned and lengthened.



No energy crosses the orthogonals and hence the density reduces as the crest lengths increase. The energy density is what is measured by a buoy. The energy flux normal to the contours is unchanged. It should be noted that the dimension between two orthogonals measured parallel to the contours is constant. Thus the length of coastline occupied by a wave does not progressively increase as it moves inshore, a common misinterpretation of the above diagram and one which would clearly be impossible.

The HRS refraction model incorporates the charted sea bed contours off the Hebrides. The irregularity of these contours is such that the pattern of refraction of waves is very complex and not easy to visualise as in the above idealised sketch. Refraction causes power density to be locally concentrated and spread. Therefore the distribution of power density off South Uist varies along contours as well as with depth. Estimates at five different locations on the 25m contour using the model range from 27.7 kW/m to 37.3 kW/m with a mean of 30.6 kW/m. Thus according to HRS it appears that the value of 36.2 kW/m predicted from Inshore buoy 3 could be an overestimate of the mean power density available on that contour. Further work is necessary. Modification of spectra by refraction over parallel contours running north-south along the Hebridean coast will yield a more typical mean power density distribution for a long length of coastline, which would be required for an array of wave energy devices. This is yet another illustration of the uncertainty associated with the available resource off South Uist.

Refraction is believed to play a major role in modifying the waves from the Offshore to the Inshore-3 buoy. However, HRS do not regard it as being a significant effect in deeper water. Thus further mechanisms have to be sought for the apparently enhanced resource at 100m. The site lies approximately 30 km offshore and hence has a greater fetch available to the east than the other buoy sites for seas to be generated by winds blowing offshore. Also it is in a more exposed location and therefore could be in a position to be affected by waves from around the north coast of Scotland which would be shielded from the other buoy sites by the Monach Islands and North Uist. Salter has put forward a theory that relatively small, regular undulations in the sandy bed at this depth are responsible for selectively attenuating certain wave frequencies. However, the answer is as yet unknown.

For the present, with no further data for tank testing and productivity assessment, RPT have set out a linear transformation for the IOS spectra determined for 42m depth to produce an available wave climate for devices at other depths. This is based on the long term power density predicted for all the buoy sites. The transformation applies to water depths deeper than 30m for which depths it has had to be assumed that the directionality remains constant. For 25m depth, where the directional band of wave energy has been narrowed due to refraction, spectra resulting from the HRS refraction model have been used. Doubts concerning their representativeness have already been expressed.

In conclusion, the answer to the question posed at the beginning of this discussion is that after nearly 6 years of recording there are still many unknowns and it is not possible to state with confidence the mean power a device will be exposed to during its lifetime. At the site with the best data (42m depth) the accepted value for long term mean power density of 47.8 kW/m used as a reference for all sites, is an estimate and its directional distribution has had to be inferred from wind data. Even less confidence can be put on data for other sites owing to refraction, shielding, energy dissipation and perhaps other, as yet unidentified effects. Tank tests at this stage should be used to compare devices, not to assess their absolute productivity, but even so it must be realised that fair comparisons may not be possible without further understanding of wave behaviour off South Uist. Finally it is important to realise what is implied in defining the available resource using a power density only. Due to device shape, interaction and shielding this is not the power per metre run the devices are exposed to.