WAVE ENERGY STEERING COMMITTEE
UNITED KINGDOM WAVE ENERGY PROGRAMME
CONSULTANTS SECOND REPORT
VOLUME 2
TECHNICAL APPRAISAL OF THE DEVICES
AUGUST 1978

PART II

CH 8 ON

CHAPTER 8.0 FRENCH FLEXIBLE BAG (DEVICE TEAM - LANCASTER UNIVERSITY)

8.1 GENERAL DESCRIPTION

8.1.1 DESCRIPTION OF THE DEVICE

The Device comprises a number of air-filled bags attached along the top of a submerged hull lying head-on to the sea. The bags are formed by dividing a long tube made from flexible material about 8.0 mm thick, by partition membranes of the same flexible material.

The hull is a narrow prestressed concrete structure, 193 m overall length, 6.3 m beam, and 8.4 m deep, containing high and low pressure air ducts connected to the bags by non-return valves.

The ducts are connected together through a pair of air turbines located in a machine housing midships. Together the bags, ducts and turbine comprise a closed circuit air system. The main part of the hull lies submerged with its base some 13 m below mean wave level. Raised tank structures at each end of the hull provide trim and reserve buoyancy.

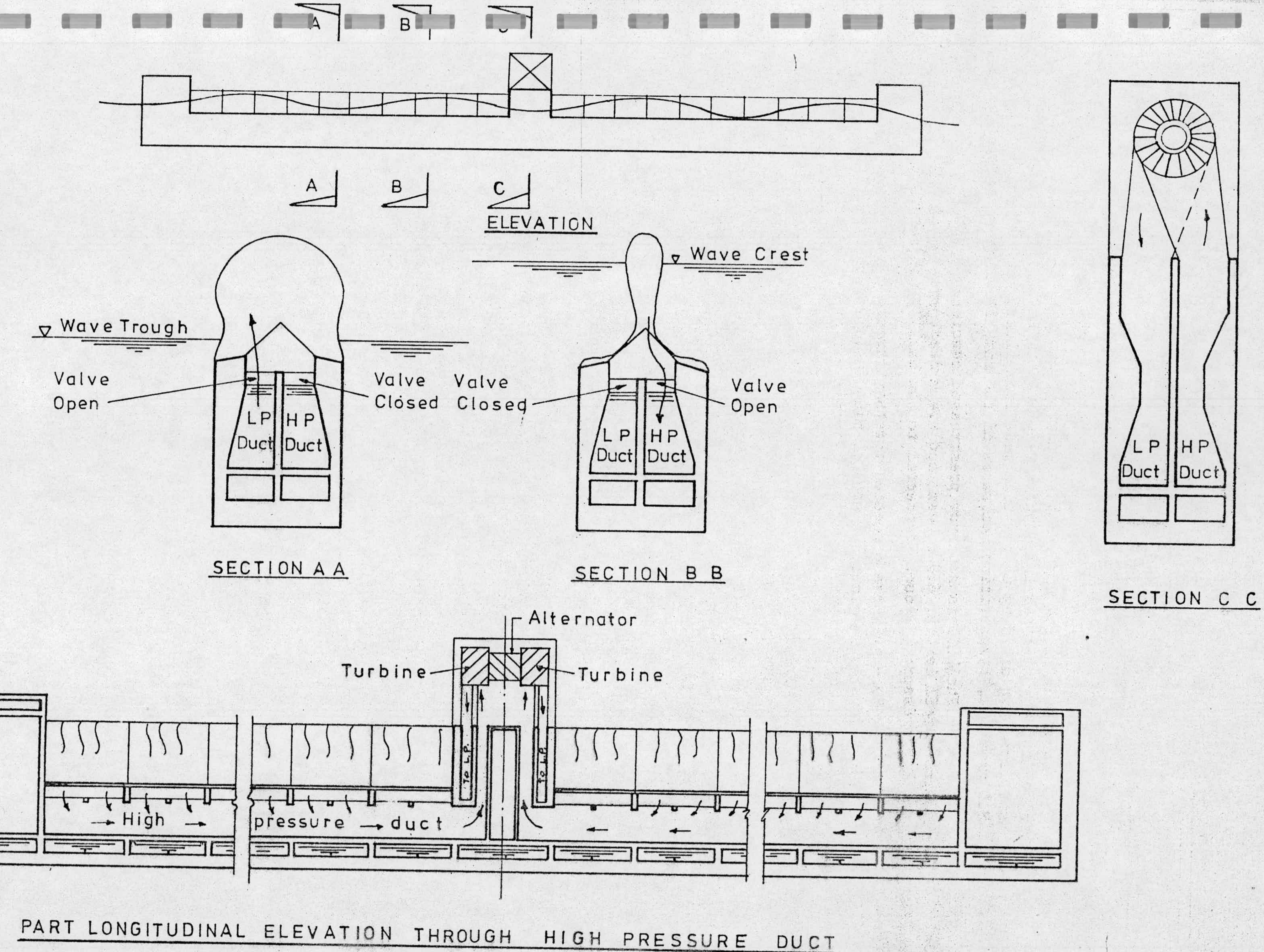
In operation the devices are moored in line with the direction of the incident waves and side by side, spaced sufficiently apart to swing clear of one another under the most adverse weather conditions.

8.1.2 PRINCIPLES OF OPERATION

8.1.2.1 General

The Device is unique in the programme, in that the vertical planes converting the wave energy lie normal to the wave motion, the waves being attenuated as they travel through channels formed by adjacent devices. As the wave trains run along a Device the rise and fall of the water on each side of the bags causes the latter to act as bellows pumping air from the low to the high pressure ducts. The differential pressure between the high and low pressure sides is governed by the power offtake turbines. The system is illustrated in Fig. 8.2.

The device is also unusual in that it was not conceived as a resonant device. The surface from which the wave energy is extracted is a light flexible membrane. The motion of this membrane is such that the hydrodynamic added mass is also very small. This means that the bag does not have a resonant period within the wave spectrum. However, the added damping (the ability to radiate waves, or conversely absorb waves) is high and the device could in theory have a high effiency over a very wide bandwidth, that is covering the whole of the wave spectrum. The device will not therefore exhibit the same characteristics as the other floating devices, but it is interesting that the Salter Duck Device is evolving in the same direction, now being a low inertia/high added damping/wide bandwidth device.



F.F.B. DEVICE
WORKING CYCLE

FIGURE 8.2

8.1.2.2 Geometrical Parameters Related to Device Performance

- Length and depth of hull

The long concrete spine is required to hold the air bags at a relatively constant level, so that the bags are subjected to alternatively high and low water pressure as the waves pass. To achieve this the spine needs to have a length at least equal to the wave length of the design wave so that there is good pitch and heave stability in the design sea.

The design depth will have a minimum value determined by the structural requirement to resist bending moments and shears in large waves. To minimise these the length of the spine will need to be as short as possible so that the spine "rides" the waves in severe seas. These conflicting requirements of performance and survival will tend to produce a spine length close to the design wave length.

The requirement on the spine to provide very large ducts may also place a lower limit on spine depth and breadth.

- Breadth of hull

The size and geometry of the ducts has an important influence on performance. Broadly speaking, large ducts are necessary. If the spine is designed as a box, the depth needed for strength is also adequate for the ducts. The breadth of spine is also the width of the air bags. The Team have shown that a wide root width to the bag is a factor in obtaining optimum performance.

- Shape of bag

The Team have shown that the bag profile can be broadly tuned to give optimum air displacement for a given wave height, the key parameter being a function of the ratio of the circumference of the bag to the root width.

It is important that the Device has a smooth hydrodynamic profile from the hull to the bag.

- Cut water area

This Device has variable geometry in the sense that the air bags are constantly changing their volume, and this volume change is produced by the incident sea. The Device thus has a constantly changing area at the water surface, which affects its trim and tends to produce instability in pitch. Any tendency for, say, the bow to sink will be exacerbated by further air being forced out of the affected bag units. This inherent instability of the device imposes a requirement to incorporate features in the device specifically to counter this tendency.

8.1.2.3 Operational Parameters Related to Device Performance

- Operational pressures

Present indications are that the pressure difference across the turbine needs to be about half the wave height. At the design point this corresponds to a pressure difference of 14 KN/m^2.

- Valve response

Rapid valve response and as near as possible unrestricted flow through valves is essential.

- Bag integrity

The whole operational viability of the Device depends on very high reliability in the air bags. For reasonable economics, this reliability must be obtained over a long period between maintenance or replacement. Over their working lives the bags are required to flex continually, and exist in the hostile environment at the sea air interface (although in fact much of the bags remain permanently submerged).

- Power offtake system

The action of waves passing down the length of the device is to cause sequential compression of the flexible air cells leading to pressure increase and air discharge through non-return valves into air delivery ducts from the fore and aft ends of the device towards central up-takes.

It has been explained that the air bags are pre-inflated to about half an atmosphere (0.5 bar). Wave energy is therefore abstracted in the form of a pressurised air flow, pulsating in character but some 15 kNm^{-2} above the datum pressure.

The summated air flows from the ten forward and ten aft air bags rise and fall cyclically in keeping with the wave period byt with intervening periods of several seconds when the bags are being re-inflated by the return air in the low pressure duct.

The design, however, is such that fore and aft air flows are generally about 180^{o} out of phase. On a time basis this results in a more steady delivery of compressed air energy to the power turbines used to drive a single alternator.

The characteristics of the secondary power offtake are shown in Fig. 8.3. The two air turbines are connected to a common rotor shaft with an alternator in the centre. The diagram shows the two power output loops and the power absorbed in driving the turbine rotor during the null period whilst the air bags in the particular section are re-filling.

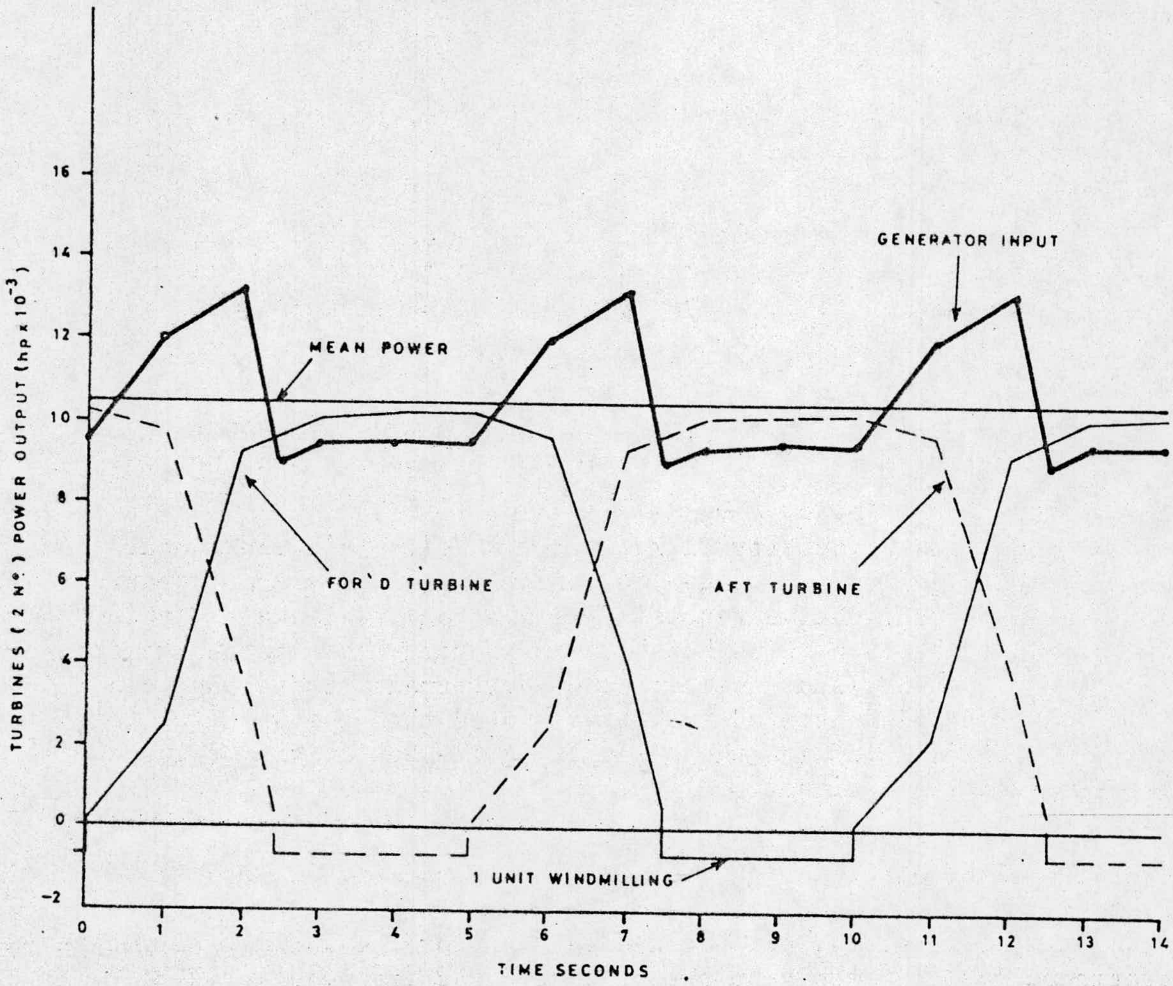
The diagram also shows the resulting power delivered to the alternator couplings and the mean power input on the basis that the alternator rotor would be given sufficient flywheel effect to absorb power above the mean level, returning it a few seconds later by virtue of relatively small speed changes.

Owing to the variable speed nature of power generation each device would be arranged to deliver a.c. power via a flexible submarine cable to an adjacent platform mounted converter station. Here the outputs of numbers of French devices would be summated by adopting a series connected transformer/diode rectifier unit - precisely as for all other devices.

8.2 STATE OF DEVELOPMENT OF DEVICE

8.2.1 GENERAL

The device is the invention of Professor French of Lancaster University, and development has been centred at that Institution. The device was given WESC funding in 1977.



CHARACTERISTICS OF THE AIR TURBINE POWER OUTPUTS

AND THE ALTERNATOR SHAFT POWER INPUT

IN A REGULAR WAVE

FRENCH – LANCASTER UNIVERSITY DEVICE

FIGURE 8·3

8.2.2 MODEL STUDIES

The present form of the Device was evolved following a range of static single and seven cell model tests at 1/12 and 1/36 scales. These proved the viability of the concept and assisted in optimising the geometric parameters for the building of a 1/40 scale model.

Tank testing has progressed over the past year using the 1/40 scale model successively in tanks at Lancaster, Salford, and Glasgow.

a) Lancaster University Tank (0.75 m wide). The results from this series of tests served mainly to optimise certain variable factors including the depth of immersion and the ballast weighting.

b) Salford University Tank (1.25 m wide). This has provided the most useful set of results, and the performance characteristics of the Device have been derived from this test series.

c) Glasgow University Tank (4.58 m wide). This tank should have enabled the model to perform at its maximum potential, but quantitative results were poor due to leakage problems and the main value has been in mooring force measurements and in a visual assessment of performance in various sea states and attitudes. It was noted that the width of this tank enabled the whole length of the Device to work with equal efficiency.

With the exception of some mooring tests at the Glasgow University tank, all testing has been on pitch-controlled models. This restriction must impose a significant limitation on the validity of the results obtained, but not necessarily for the worse. Prototype performance could possibly be better as regards improved valve performance and optimised trim control, which could not be produced in the model.

Performance data is still rather thin. The best work was carried out at Salford, but the tank was narrower than ideal for the model and some of the cells were not working. Power outputs have been factored up to compensate for this, on the basis of the observed behaviour at Glasgow. Refinement of valves, ducts, etc., should bring the actual power closer to the theoretical.

Model results suggest that performance is to some extent frequency dependent, though not apparently within the range of wave periods from about six seconds to twelve seconds, (full scale), which covers the majority of waves anticipated. More tests are proposed to examine this in greater detail.

8.2.3 ENGINEERING DEVELOPMENT

Work has thus far been primarily devoted to determining the parameters which will govern the engineering requirements, and engineering is thus still at an early stage. However, the problems to be overcome, though fairly severe in one or two cases, are not too many. The spine which will be the largest cost centre has been designed, and a start has been made in bringing industrial knowhow to bear on the bag design.

8.3 THE REFERENCE DESIGN ADOPTED FOR THE STUDY

8.3.1 INTRODUCTION

The Reference Design is based on the 1/40 scale model that has been tested in the wave tanks at Lancaster, Salford, and Glasgow Universities. Constructional and maintenance considerations have modified some parameters but the model is considered to be representative of the Reference Design.

8.3.2 SPECIFICATION

The following specification was laid down by the Consultants as a basis for the Reference Design. It is based on the proposals of the Device Team, supplemented by certain engineering requirements imposed by the Consultants.

Location: The Design Team propose that the French Flexible Bag (FFB) Device is to be moored in 40 m depth off the west coast of the Western Isles.

Moorings: Devices moored head-on to sea by three-point moorings.

Size of FFB device:-

Length, 20 bags @ 8000	160 m
Length of machine housing	10 m
Length of fore and aft buoyancy chambers 2 @ 11.5 m	23 m
Total Length	193 m

Cross section of hull, generally 8.4 m deep, 6.3 m beam.

Materials and design parameters:-
Concrete and steel structure, as the specification set down in Chapter 3. Bag material: 8 mm thick, 4 x 1 ply P1610 type cord.

Sea states for structural design - based on OWS India. Two load cases considered:-
Case 1 12 times a year, either 17.3 m high wave, length of hull
or 21 m high wave, 231 m long.
Case 2 Once a life-time (50 year wave), either 27 m high wave, length of hull
or 34 m high wave, 238 m long.

Design loading for concrete hull
Load case 1 above, bag volume 16 m^3/m ballast tanks full
Load case 2 above, bag volume 26m^3/m (corresponding to partial failure of control system), ballast tanks full.

Construction Restrictions:- Full construction to be completed in dry. Several units can be manufactured at the same time. FFB Devices cannot be floated out and installed without buoyancy provided by the bags units.

Provision for Maintenance:- Access to HP and LP ducts in hull from machine housing; separate access to valve chambers from machine housing by bulkhead doors in septa sealing walls.

8.3.3 DEVELOPMENT OF THE REFERENCE DESIGN (REF.DRG. WP78/FREN/3 & 4)

8.3.3.1 Hull

The structural duties of the hull are to provide a reference frame for the bag units, to accommodate the HP and LP ducts and to locate the bow and stern unit and the midship machine housing.

Design to meet the survival loading automatically provides the volume for the ducting. The depth of the hull was optimised on a very simple basis for least structure cost. Since device performance is not dependent on particular shape details of the hull, design of this component is relatively straightforward. The solution adopted is a prestressed concrete structure with a minimum wall thickness of 0.5 m.

8.3.3.2 Bags and Septa

The performance of the bag units is the sine qua non of the device, since the bags perform the dual function of primary power take-off and of hull support.

The Device Team regards this as a key feature in the evaluation of a full-size unit and are taking appropriate specialist advice. Severe environmental loading imposed by splash zone operation, fatigue loading due to large deflections, the integrity of fixing details of the bags to the septa and both to the hull are all design problems which have to be overcome. Some experience exists in associated fields, such as inflatable dams, hovercraft skirts, dracones, boats and motor tyres, and manufacturers are confident that there are good prospects that a suitable design can be developed for a life of 25 years.

Design will be closely determined by the requirements of survival. The bags must survive with one or more sectors damaged and flooded, and adjacent sectors still pumping. This will impose severe strains at the diaphragms. Development will have to include careful examination of bag unit performance under nominal damage conditions, such as a short tear or porosity due to local wear.

8.3.3.3 Duct Valves

The inlet and outlet valves connecting the bag units to the HP and LP ducts will be of such a size as to make replacement difficult except with the bags removed. Thus they will have a required design life of say, 30 years, corresponding to about 100 x 10^6 cycles. The Device Team is proposing to undertake tests at 1/4 scale with the purpose of obtaining a best configuration based on the following criteria:

a) reasonably rapid rate of opening and closing,

b) flow rate of 20 m^3/s with minimum head loss,

c) good sealing properties,

d) capable of withstanding pressure differences corresponding to the Device sinking,

e) systems to fit into 1.5 m by 7.0 duct.

The design currently proposed by the Device Team is shown in Drg. WP78/FREN/3 though it is emphasised that this is preliminary. A one-way valve unit comprises some 8 overlapping aerofoil vanes. Rubber sealing strips are provided where adjacent valves contact and where valves seat on the side walls of the valve chamber. It is hoped that any differential wear resulting in leakage will be restricted to the sealing strips which will be readily replaceable under normal maintenance conditions. The inlet valves will be of similar design to the outlet valve. It is proposed that the air valves be made in aluminium or steel.

8.3.3.4 Emergency Valves

In the event of bag rupture, the device is immediately endangered by a flow of water directly into the ducts. This flow must be cut off very quickly and to accomplish this fully automatic emergency valves are provided in series with the duct valves. These are housed in the valve chambers.

The Device Team has several notional designs for these items, one basic concept being described in Drg. No. WP78/FREN/4 In this design the mechanism would trip under gravity, possibly assisted by explosive or spring loaded bolts.

The trip would be actuated by a signal from sensors located in the LP ducts and consisting of an array of pilot indicators or similar, data being passed to a micro-processor which would assess the validity of the input (3 out of 4 alarm system), locate the fault and initiate the shut down in the bag units affected.

It is apparent that the survival of the FFB device must depend heavily upon the prompt operation of the emergency valves with the minimum of false trips. Effective maintenance and testing of the emergency units will form an important part of station maintenance.

Some arrangements may be required to automatically reset the emergency valves since manual resetting might not be possible, and will certainly not be convenient. In any case the need for periodic testing would seem to preclude such ideas as explosive bolts, and development should be directed to designing a system with rapid acting powered closure and powered opening. This seems to suggest something like air actuated pistons.

8.3.3.5 Power Plant

Characteristic features of the closed circuit air cycle were referred to in Section 8.1.2.3. In the following paragraphs more detail is given of the main features of the mechanical and electrical stages necessary to convert the primary compressed air energy to electrical power in readiness for transmission to the mainland.

The proposals are of a preliminary nature, conform essentially with those of the Device Team, but include a number of changes dictated by electro-mechanical plant design.

Air System

The fore and aft air bags extend over approximately one wave length and are subject to alternate compression and re-inflation periods. It has been estimated that the normal maximum air delivery could be about 450 m^3s^{-1}. The alternating flows along the high pressure ducts leading from the fore and aft ends of the device conform generally with the power curves of Fig. 8.3, this being on the basis of ten separate bags at each end. The delivery pressure is about 15 kNm^{-2}. After passing through the associated turbine, the same air is discharged into the low pressure duct in which the air used to re-fill the bags must be at a hydrostatic balancing pressure of between 0.5 and 0.65 bar.

In the horizontal portion of the device the ducts have a section of 8.5 m^2. This should be gradually reduced in the vertical section at the centre so as to increase the velocity of the air as it approaches the turbine to somewhere near 90 ms^{-1}. At the base of the vertical h.p. duct there should be a smooth curve and in addition, suitably designed flow directing guide vanes.

In considering the low pressure return duct, continuous through the main structure, it would be rational to slighly increase the duct section in recognition of the greater volume to be handled at the datum re-charging pressure. Design features to improve pneumatic efficiency should be included.

Air Turbines

Two reaction type air turbines are required, one for each pressure duct. The Device Teams' proposal that the two turbines be arranged on a common shaft with a central generator is accepted. The fore and aft turbines then provide power to the generator alternately A preliminary review of the operating cycle, as illustrated in Fig.8.3 shows that in a nominal 10 second wave period each turbine would provide power for about 7 - 7½ seconds, but would require power from the other machine to overcome windage losses during the unproductive 2½ - 3 seconds in each cycle.

An assessment of turbine design on the basis of 90% bag compression at each end in turn shows that each turbine should have a normal maximum rating of 10,000 h.p. Other parameters derived from consideration of maximum air transit velocity and blade tip speed suggest a single stage high speed turbine with a 3.5 m rotor and a hub diameter of probably 1.75 m. Turbine speed would be in the range 1500 - 2000 rpm. This would keep the blade tip velocity around Mach 0.9

It so happens that with the arrangement proposed the two turbine wheels would be identical for the same direction of rotation. Fixed and adjustable guide vanes would be provided, the former to improve performance efficiency and the latter to prevent over-speeding on loss of electrical load, and as discussed later in this section, to provide a measure of pneumatic throttling in order to assist control of the pitching moment in rough seas.

Generator

This would be a conventional three phase alternator, having insulation and air cooling suitable for marine application. The machine could be a normal 50 Hz design with four pole rotor. The suggested continuous rating would be 7.5 MW. The generation voltage 6.6 kV. The operating power factor would be high owing to cable capacitance and the ensuing d.c. conversion. The alternator would rely on closed circuit air cooling with heat exchanger and an external air circuit.

Whilst basically a normal industrial design, the alternator would in this application be rated to withstand additional eddy current heating due to harmonic components arising from the six pulse diode output connection. The excitation would be of the brushless type, probably involving a new application of thyristors, since rapid control of generator output voltage will be necessary. This in turn dictates a magnetic circuit having a very short response time. A normal overspeed ratio of 30 per cent would apply.

Electrical Equipment (Device Mounted)

The central power compartment would provide accommodation, in addition to the twin air turbine generator unit, for a step-up transformer of 8 MVA, 6.6/22 kV, a main 6.6 kV switchboard, together with automatic control and protection equipment and provision for terminating the flexible 22 kV submarine cable used to transmit the output of the device to the nearby platform mounted converter station.

Auxiliaries

A reliable power supply will be required to operate essential device auxiliaries. As the generator will operate at varying frequency and voltage, it will be necessary to include means of stabilising the L.V.A.C. supply. A small converter-battery-inverter is proposed.

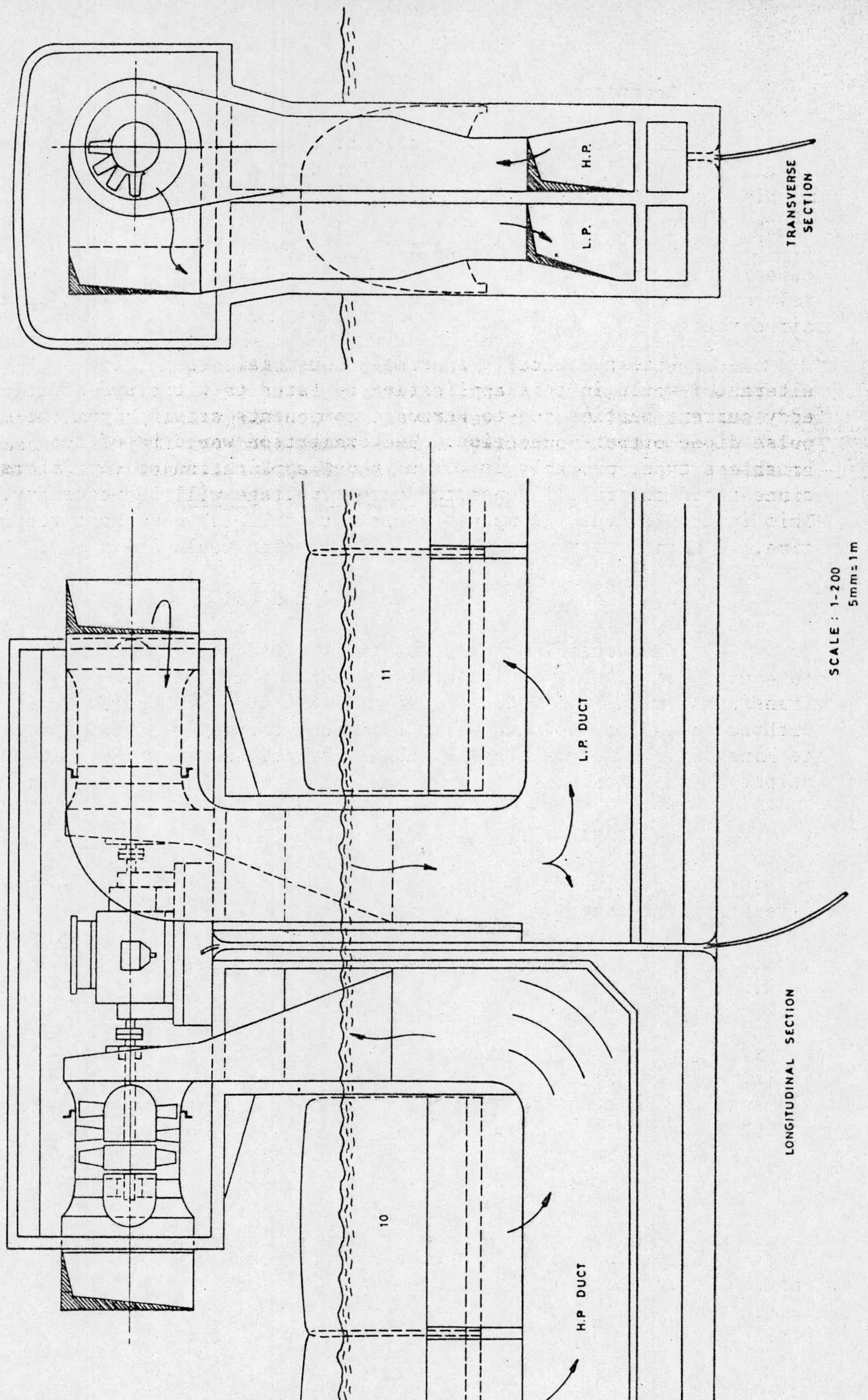
The on-board auziliaries will include the following: bilge pumps, air compressor (for ballast ejection), air blower (for bag inflation), control systems and communications, heating, lighting and services, battery charging, and possibly also servo assistance in the operation of the inlet and outlet valves.

Power Plant Module

The power-house visualisation in the Device Teams' drawing, P5881 No.4, is an interesting approach but could hardly be large enough to accommodate the amount of plant described above. An alternative arrangement with approximate dimensions is shown in Fig. 8.4.

8.3.3.6 Control Principles

The general philosophy of system readiness to absorb all wave energy output applies equally to the French Device. Power input to the twin air turbines will alternate and be random in magnitude as a direct reflection of wave amplitude and period. Excessive speed and power outputs will be controlled by automatic guide vane closure.



PROPOSED AIR TURBINE/GENERATOR INSTALLATION

FRENCH – LANCASTER UNIVERSITY DEVICE

FIGURE 8·4

There is, however, the over-riding problem of device stability in pitching motion, since compression of the forward air bags reduces the forward buoyancy which would tend to allow the bows to drop deeper into the water. Correspondingly, the stern would rise due to additional buoyancy of the re-inflated air bags. It is intended that the bow and stern buoyancy tanks would restore stability. It may be necessary to adjust the displacement so as to improve the restoring couple.

However, it would be possible to include a measure of automatic compensation by rapid throttling of the appropriate turbine. This would lead to a higher discharge pressure and some resistance to collapse of the air bags resulting in some additional retained buoyancy. Such a stabilising characteristic could be achieved by a motion sensing device acting on the appropriate turbine guide vane servomotor.

8.3.3.7 Emergency Deballasting System

In the event of a bag rupture the Device loses buoyancy immediately, and this must be counterbalanced by rapid deballasting under the appropriate part of the hull. This is accomplished by injecting compressed air from tanks located in the front and rear buoyancy chambers.

8.3.3.8 Mooring

The mooring system proposed by the Device Team is described in Drawing No. WP78/FREN/2. The converters are in three ranks with triple moorings from the bow units, one of which carries the power cable to two sea-bed power lines cross-connected at appropriate intervals. 1,000 Tonne Parafil mooring lines are proposed. The bow mooring is effected by a swivel buoy floated up from the sea bed to mate with a housing in the bow unit of the hull, providing a sealed swivel attachment. Very little work has been done on establishing the required compliance of the system, and this aspect should be considered as "notional only" in the Reference Design. Furthermore in the proposed array of Devices the leeward rank will have a very reduced performance. Consideration of the energy available suggests that only two ranks, at most, are likely to be economic.

8.3.3.9 Summary Data for Reference Design

Volume of concrete in device.
Area of rubber bag.
Air turbines.
Rated output.

8.4 CONSTRUCTION, INSTALLATION AND SITING

8.4.1 REFERENCE DESIGN CONSTRUCTION SEQUENCE

8.4.1.1 Introduction

The narrow beam of the FFB device favours the concept of multi-unit construction on a single site. The relatively shallow draught means that units can be finished in one construction location with no need for final construction and fitting out in deep water.

The Device Team has suggested that twelve units could be fabricated in a basin 230 m x 230 m x 10 m draught. While the Consultants agree with the idea they consider that a maximum of four or five units to a basin would be a more effective approach. This would reduce the number of finished Devices occupying basin space whilst the last devices were being completed ready for float out, and would require a smaller number of temporary moorings for parking the finished Devices. By the same argument, a series of docks on one site which would permit the separate launching of individual Devices might prove even more cost effective.

An alternative construction procedure would consist of full completion on land, the Device then being skidded on to a submersible barge, taken out to the required depth, the bags inflated and the barge submerged and withdrawn. This approach would imply a sophisticated system of control to accomplish the transfer to the barge without breaking the back of the slender concrete unit, but there is no reason why this should not be attainable. A third approach might be slipway construction.

The main point is that the Device lends itself equally to construction in existing or new facilities of no great complexity, in any part of the UK. An integrated facility would be developed capable of handling all civil, mechanical and electrical work.

8.4.1.2 Hull Construction

The hull geometry of the FFB device presents no unusual features as regards concreting and prestressing. A possible sequence is outlined in Drawing No. WP78/FREN/5. The number of Devices fabricated at a time would depend on plant and manpower availability and on the site layout. Four Devices side by side could be serviced by overhead gantry cranes or by mobile cranes facilitating the effectively continuous placing of concrete to be undertaken over much of the hull height. Concrete could also be pumped or a combination of skipping and pumping adopted.

The guide vanes, valve seatings, valves, emergency valves and valve chamber grid would be installed after concrete completion and after full prestressing.

8.4.1.3 Bag Manufacture and Assembly

There might be advantages in providing a manufacturing plant for the bags and septa on site to reduce transport costs and bottlenecks. The bags and septa would be cut and formed into their 80 metre lengths on site in covered workshops and craned into position by means of demountable external or internal frameworks. After location, the bags and septa would be bolted into position.

8.4.1.4 Site Safety

The bag installation sequence (section 8.4.1.3) would be partially carried out from inside the Device and the appropriate safety regulations as regards fire precaution and emergency exits would be required. Bulkhead doors will be operational at this stage, and provision will have to be made for emergency escape routes.

8.4.1.5 Constructional Period

The time taken for construction of any device is governed by (a) The resources brought to bear (b) the number of operations that have to be carried out sequentially. Related to this is the extent to which the device lends itself to assembly from prefabricated elements and modules. This device is clearly ideal from the point of view of (b). Being long and low, concrete can be completed to its full height very rapidly. Both functionally and constructionally the device has five relatively separate parts which can be worked on in parallel (two ends, one machine house, and two working sections of ducted hull).

Given the need, and maximum use of prefabrication and the use of a self-contained power module, turn around time of four months on a bay might be achieved. Yards working on offshore platforms have achieved pours of 1000 cu.yds/day. In estimating the throughput of an efficiently organised facility for FFB production, output might be based on a continuously rated concrete output of 500 cu.yds/day.

8.4.1.6 General Construction Aspects

a) Personnel. An economic construction facility might absorb a total workforce of between 500 and 1000 at any single location.

b) Cranes. Travelling goliath cranes of up to 60 m span with a load capability of 25 tons would be required to span a facility for the concurrent side by side construction of four devices. Mechanical plant heavier than 25 tons would be positioned by mobile crane. Alternatively 40 ton mobile cranes would be used in place of the goliath system.

8.4.2 REFERENCE DESIGN INSTALLATION AND SITING

The Device Team has made a preliminary suggestion that the mooring depth should be 40 m. This is because their design philosophy envisages the possibility of salvaging sunken devices and this they do not consider to be feasible at depths greater than 40m.

The Consultants have a number of reservations on this approach. The freedom to place a device in the best position for the incident sea energy, independent of depth (up to some limit) is a valuable advantage of a floating device which should not be lightly given up. Also compliance in the mooring system is more difficult to achieve in shallow water.

Salvage has not been a governing criterion for any other device, and appears here because of the accepted risk of bag rupture.

The Consultants do not believe that this particular design could be salvaged because it would break up on the bottom. However there may be possibilities of producing a design that would survive sinking and salvage, particularly for the early prototypes.

Installation should be relatively straightforward. The Device is firmly ship shape and is an ideal size for handling. The mooring arrangements should permit rapid installation, and equally rapid removal for major maintenance or refit. For the purpose of the Reference Design a location west of the Hebrides has been envisaged.

8.5 MAINTENANCE

The Device Team has suggested the use of mother ships permanently on duty for undertaking routine maintenance and for emergencies.

The FEB device, being essentially a submerged hull, has better sea-keeping characteristics than fully floating devices and hence routine maintenance of generating machinery, compressors, ducting, and services can be undertaken in reasonable comfort. The fact that the Device operates on a closed air circuit will greatly improve the working environment for the moving parts. For maintenance it is envisaged that the bags would be over inflated in a reasonably calm sea, and the air flow stopped by a suitable door.

For major maintenance, the Device will be returned to a maintenance base. This will probably be an area of sheltered water with a floating dry dock fully equipped for total maintenance and replacement of parts as required. Such a dock could also be used at sea in calm weather to effect certain repairs on station, and for the inspection of the air bags and valves.

The major problem to be faced will be the situation of a collapsed air bag. A study is required into the safety and economics of having one or more bag units out of commission and the Device continuing to operate at reduced power and reduced buoyancy margins as compared to removing the faulty Device from the moorings and towing to service base for full repair.

8.6 CRITICAL ASSESSMENT OF THE DEVICE

8.6.1 GENERAL

This Device has many very attractive features which must make it a Device well worth pursuing. These include relatively low structure weight, potentially good sea-keeping, and simple power take-off in a relatively benign closed circuit air environment. Thus far the survivability of the Device is not proven. This depends on the integrity of the air bags and the development of an emergency survival system to deal with an accidental rupture. Survivability also depends on the development of a system for pitch control. No work has yet been done in these areas.

8.6.2 DEVICE CONCEPT

This is based on sound thinking. The air turbine is accepted as an attractive power take-off for Wave Power Devices, and in this case there is the added advantage of a closed air circuit. The reference frame is provided by a spine which spans from crest to crest, which seems to be possibly the cheapest reference frame (apart from the sea bed itself). The spine doubles as the duct system, which is a further economy. It is also the only part of the structure which has to resist dynamic and hydrostatic loading. The rubber bag, if it proves to be workable at prototype scale, is a very economic air pump. Its compliance automatically protects both itself and, to some extent, the spine, from the most extreme loading from breaking waves. The device shape and size makes it suitable for a point mooring to allow acceptance of energy from the full 360° of incident sea.

Although there is no reason to believe it will not work, the effectiveness of the spine as a reference frame has not yet been proved in performance tests.

8.6.3. THE CONCRETE HULL STRUCTURE

This is relatively simple to construct by conventional methods. It is monolithic, is a naturally good structural section, and has low draught which makes for cheap construction. It has not been checked out for lateral bending strength in mixed seas, and if there proved to be a problem this could add to the cost, but probably not by very much.

DRAFT

8.6.4 THE AIR BAG UNITS

These represent a bold extrapolation from existing applications of flexible fabrics, but the fabrics proposed are within present experience and technology. The areas of doubt are -

a) Fatigue - At the bag to hull junction, and at the junction between the bag and septum, there will tend to be severe alternating curvatures of the fabric which will tend to induce wear and fatigue. Much will depend on the extent to which clever design can remove the stress hot spots in the rubber fabric.

b) Damage Resistance - The bags will have to withstand the normal beating of the sea and the impact of flotsam.

c) Survival with changed bag geometry - If one bag is pierced and flooded, adjacent bags, and in particular the septum, will be subject to a new (and unfavourable) pattern of distortion. Survival in this situation could prove to be a real problem.

d) Porosity - Some porosity will be acceptable, given the necessary control and correction mechanisms in the device.

The survival of the FFB device depends uniquely on the reliability of the bag units. If full scale development of the Device is to proceed, extensive testing and proving of material performance and long term properties will be required, including a full scale working representation. Overall, though this component is new, there are grounds for optimism that success might be achieved.

8.6.5 VALVES AND EMERGENCY VALVES

The Device valves are to efficiency what the bag units are to survival and it is in this area that there is the greatest extrapolation from model performance. The overlapping aerofoil type of valve has the advantage of simplicity but the disadvantage of possible differential wear. The large valve size proposed by the Device Team will require proving in full scale representations. The valves should not prove an insuperable obstacle to the success of the Device.

8.6.6 POWER PLANT

The power plant concept adheres largely to conventional mechanical and electrical equipment. The single stage air turbines are relatively novel features but there should be no great difficulty in developing designs on the basis of known aero-dynamic technology. The pressure is low but there is no temperature problem. Materials would be chosen to withstand sea water contamination.

The generation system feeding into a series connected d.c. circuit requires a sensitive and powerful excitation system. A rotating thyristor application would be new but capable of development.

The device mounted electrical equipment would need careful design and some development, but vacuum switchgear would be suitable and there could also be an application for the type of transformer specially developed for railway service. These are of minimum dimensions and designed to withstand acceleration forces.

Overall the simplicity of the power plant, the collection of power into convenient amounts for the first stage power take off, and its accessibility are definite advantages of this Device.

8.6.7 MOORING

If any wave power device can be moored economically, it should be this one. The shape is streamlined to the waves, and in line forces can be reduced in the most severe conditions by increasing the mean air pressure and thereby reducing the undulation in the bags. See also Chapter 14. One problem is that the Device is given freedom to rotate freely about its single mooring point, and this at present presents difficulties in taking off the power.

8.6.8 TRIM

The Device has a certain inherent instability in pitch, but there are a number of ways this can be controlled (including the method proposed by the Device Team). There is a possibility that active pitch control might involve some loss of power.

8.6.9 SURVIVAL

This is the major question mark hanging over the Device. It probably depends on the ability of the bag system to survive for a protracted period with one bag damaged and flooded and sealed out of the system by the emergency valve. It may be that this could best be accomplished by inflating the whole system to a higher pressure to minimise the movement of the bags - or by the injection of foam into the ruptured bag - or by some method yet to be thought of. Survival clearly presents a major field for investigation but there seem to be enough grounds for encouragement to anticipate that the problem may prove soluble.

8.6.10 MAINTENANCE AND LIFE

Leaving aside the unknown territory associated with the rubber bags, the device appears to be emminently maintainable. It's sea keeping qualities will make on station maintenance practicable.

8.6.11 TIME NEEDED TO COMPLETE DEVELOPMENT TO A TEST DEVICE

In the sense that the geometry and the type of power offtake are already well defined, this device could proceed forward very quickly to a realistic sea trials of a complete scaled down device.

8.6.12 POTENTIAL FOR FURTHER DEVELOPMENT

The Device Team are not pursuing any alternative arrangements of this device, and it does seem that in its present form it represents the logical development of a floating air bag device, and no dramatic improvements in effectiveness should be looked for in this form of the device. Two directions offer themselves for possible exploration. The first might be to turn the device upside down so that air is trapped under the hull rather than contained in a bag above it. This then becomes very similar to an in line NEL device which will be investigated by the NEL team next year.

The second line of development would be to use the sea bed as the reference frame. This would immediately make the device directional, and this would have a number of implications. This option ought to be checked out.

8.6.13 CONCLUSION

This is a very promising device well worth following through to further stages of development and testing.

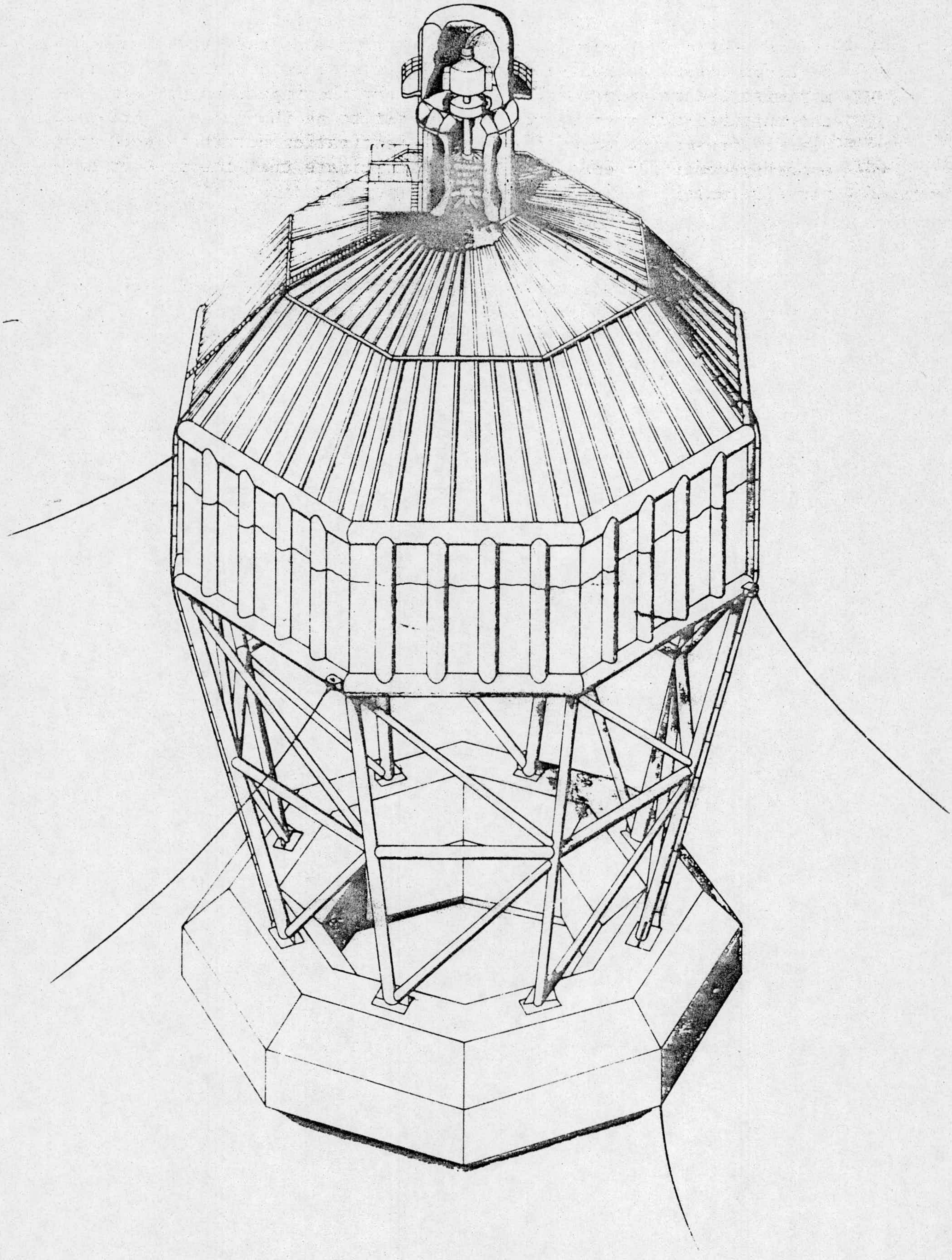


FIG 9·1

CHAPTER 9.0 - WELLS OSCILLATOR - DEVICE TEAM QUEEN'S UNIVERSITY, BELFAST

9.1 GENERAL DESCRIPTION OF THE CONCEPT

9.1.1 DESCRIPTION OF THE DEVICE

The device consists of a hollow dome with an open bottom sitting on the surface of the sea, and vented to the atmosphere through an air turbine in a duct at the top of the dome. The dome is attached to a deeply submerged toroidal vessel by a tubular framework. This torus is ballasted for neutral buoyancy. Additional buoyancy for the device is provided by air chambers around the periphery of the dome. Flexible moorings are attached at four points around the base of the dome.

A key feature of the device is the novel design for the air turbine, which appears particularly suitable for the extraction of power from the reversible flow in the air duct.

9.1.2 PRINCIPLES OF OPERATION

Oscillation of the level of the water in the lower part of the dome forces air through the turbine, venting to atmosphere in the first half cycle and sucking air back in during the second. The device was conceived as a means of applying optimum pressures over a circular area of the surface of the sea for maximum power extraction. First designs were based on simplified hydrodynamic theories which assumed that the device only interacted with the sea at the surface. The device in fact belongs to the oscillating water column/air buoy family of devices and there are very close parallels between the principles of operation of this device and the NEL device; even though the form is quite different. In particular both rely on a water column resonating with the incident waves. The geometry is selected to ensure that the mass plus added mass and buoyancy stiffness of the column form a system which resonates at wave frequency, and the damping of the column. Both also rely on a large inertia structure as a reactive frame, which is detuned from the waves by correct choice of buoyancy and mass. However, the motions of the devices are not the same. The NEL device is non-symmetric and roll, surge and heave restraint are all of concern. The Wells Device is symmetric and the inertia was intended to provide heave restraint, and other motions were intended to be free. Both Teams now recognise that some movement of the inertial frame is beneficial if this movement is in antiphase with the water column.

The important differences between the Wells and NEL devices are as follows:-

a) The Wells oscillator is a point absorber designed to collect energy from any direction over a wave front greater than its own diameter.

b) The inertial frame of reference which restrains the dome vertically is situated below the levels most affected by wave action in normal conditions. Storm waves penetrate to greater depths and the inertial frame will then move and allow the device to ride the storm.

9.1.3 PARAMETERS DIRECTLY AFFECTING THE EFFICIENCY OF THE WATER COLUMN

- Wave Height

Extraction efficiency for this device is very dependent on wave height (see Chapter 13). The maximum measured capture width is approximately halved as the waveheight increases from $\lambda/200$ to $\lambda/100$. Non-linear behaviour is to be expected of a resonant point absorber, but it is not clear to what extent such a rapid fall off in efficiency is a function of the details of the present tank models. For example, it may be necessary to round off the edges at the base of the dome.

- Device Diameter

Tests on 0.6 m diameter models with toroidal, flat plate and spherical (2 sizes) immersed inertial bodies give peak capture efficiency when the device diameter was between 0.26 and 0.29 of the incident wavelength. These figures compare with theoretical predictions for optimum device width of 0.32λ from 2-dimensional theory and 0.37λ from 3-dimensional theory.

- Depth of skirt below water level

For all of the 0.6 m diameter model tests, a skirt depth of 1/5 of the device diameter was used. The same figure has been used in the Reference Design, but the Device Team hope to improve performance by increasing the depth of the skirt.

- Size of the air chamber

For the device to act efficiently, the air above the water column should be perfectly incompressible. Since it is not, the volume of the air chamber should be kept as small as possible within the weight limitations imposed by the requirement for survival.

- Damping - the power take-off

The size and characteristics of the turbine must be chosen to give the optimum energy conversion efficiency. Too little or too much damping increases the transmitted and reflected energy respectively, at the expense of absorbed energy. The damping constant used in all of the early model tests has been derived from three-dimensional theory. The latest indications are that increasing the damping constant could lead to improved performance.

9.1.4 PARAMETERS AFFECTING THE OVERALL MOVEMENT OF THE DEVICE

- Size and shape of the immersed body

Theoretical considerations based on the requirement of little vertical movement of the device indicated that the total effective inertia should be at least $1/4\pi\rho g d T^2$ (where d is the device diameter and T is the incident wave period). Model tests have shown that for bodies of the same outer diameter, 15% better extraction efficiencies resulted from using a torus rather than a sphere or a flat plate to provide the total effective inertia. The latest thinking is that a degree of vertical movement of the device, which would move in antiphase to the water column, would be beneficial. To achieve this condition, the total effective vertical inertia would need to be reduced.

- Depth of submergence of immersed body

The immersed body must be sufficiently far below the working chamber that it does not interfere with the entry and exit of water. Also, it must be below the level of large water particle motions in regularly occurring waves.

- Buoyancy stiffness of the working chamber

This quantity determines the natural period in heave of the whole device and must be kept to a minimum for efficient device operation.

9.2 CURRENT STATE OF DEVELOPMENT

Preliminary tank testing work is now well advanced and the Team now has a fairly good understanding of the device. At least another six months testing will be needed before it will be known if current output levels can be improved upon. Apart from a very short sea trial, testing experience is still restricted to monochromatic waves in a laboratory flume. Design development of the structure is at a very early stage, and nothing has been done on moorings. The power offtake turbine is under active development, and first testing has been carried out with encouraging results.

9.2.1 EXPERIMENTAL WORK

Tests have been carried out on 0.6 m diameter models of the working chamber with various forms of immersed body to provide the vertical inertia. The width of the flume was 1.5 m and the water depth 1.0 m. Extraction efficiencies for the models were determined from incident power calculated from measured values of incident waveheight and period, and extracted power measured from a calibrated porous plug in the neck of the working chamber. Efficiency curves show a peak of about 100% over the device width for small waves, ($\lambda/200$) falling rapidly as the waveheight increases. Early theoretical work suggested that the device would be able to extract energy from a wave front of 7 times the device diameter. The Device Team now believe that a capture width of 2 will be the maximum achievable when optimisation has been carried out on the size and shape of the submerged body, the power offtake damping and the skirt depth.

9.2.2 SEA TRIALS

A large scale glass fibre resin model with a 4.5 m diameter working chamber and a 4.0 m spherical inertial body has been constructed and was installed in Strangford Lough. It operated for two months in calm seas, before being damaged by a series of severe storms. However, damage to the structure was not severe and it is hoped to recommission the model later this year.

9.3 THE REFERENCE DESIGN ADOPTED FOR THE STUDY

The Reference Design has been based as closely as possible on the 0.6 m diameter model with a toroidal inertial body. The working chamber has been flattened to reduce the wind resistance and reduce losses due to compressibility of the air volume. A 30 m diameter dome has been chosen for the Reference Design. Based on the efficiency curves presented by the Device Team, this size of Device deployed at South Uist would give a near maximum value of power captured per unit device volume (a first measure of cost effectiveness), and sufficient power output to warrant a 1 MW rated generator.

9.3.1 SPECIFICATION

- Location - 60 m water depth.
- Rating of power take-off - 1 MW based on latest efficiency curves.
- Moorings - 4 compliant moorings attached to the edge of the working chamber and designed to restrain the device from rotation in response to the torque of the turbine.
- Size of device - 30 m diameter working chamber with toroidal ballast body to the scale of 0.6 m diameter model.
- Materials - high yield steel for working chamber and connecting struts, reinforced concrete for the toroidal ballast body with circumferential prestress.
- Wave climate for power estimates - South Uist.
- Design loading - little information available. Design based on general offshore experience.
- Construction restrictions - site must allow launching of the whole structure in the vertical position. This will require a large dry dock.

9.3.2 DEVELOPMENT OF REFERENCE DESIGN

9.3.2.1 Working Chamber

For ease of construction, the cross-section of the Reference Design has been made octagonal rather than circular. The design is entirely in steel for lightness and watertightness, the buoyancy being supplied by large diameter tubes around the lower edge of the working chamber. The advantage of using tubes rather than a double skin to provide the buoyancy is in ease of construction, ease of maintenance, and stiffness. The upper part of the working chamber is fabricated from stiffened panels, the lower panels being stiffened with closed section stiffeners for high lateral stiffness, reserve buoyancy and corrosion resistance, and the upper part with flat stiffeners for lightness and ease of construction. Plate thicknesses as low as 8 mm have been chosen for some components where the loadings are thought to be low. The adequacy of these components can only be checked when loadings from test results become available. Tubular cross-bracing is provided in the plane of the bottom edge of the working chamber to resist distortional forces.

9.3.2.2 Power Take-Off Module

This is supported at the top of the working chamber on a stiffened octagonal tube approximately 5 m wide. The module contains the five stage multiblade air turbine, the double thrust bearings and guide vanes, the alternator and brushless exciter, and the transformer. This module can be removed from the working chamber in one piece. Access is provided to all parts of the power take-off insitu. The transmission cable passes from the top of the power take-off module to the submerged ballast body and partway to the sea bed in a tubular member running down the outside of the structure.

9.3.2.3 Toroidal Ballast Body

The circular cross sections of the torus have been replaced by octagons for ease of construction. The complete torus is made up of eight self-contained units with 0.5 m thick walls and 0.5 m thick end diaphragms. The wall thickness is locally increased to 1.0 m to allow connection to the steel struts from the working chamber. Pumps sited in a housing at the top of the working chamber enable water to be pumped out of the ballast body and air to be pumped in. The ducts for this purpose run from the pump house down the outside of the structure and into the ballast body. A remote controlled valve beneath each unit enables water to be let in for ballasting. In this way, accurate control of the buoyancy of the torus is possible. The eight units are stressed together by steel cables running through the walls of each unit.

9.3.2.4 Connecting struts

No information on the loading is available for these members. The sizes adopted have been taken from typical offshore platform practice. Connections are welded except at the junction with the concrete torus where Macalloy bars run through the end plates to be grouted into holes drilled into the top of the concrete body.

9.3.2.5 Stability

The structure was checked for stability in its working position assuming neutrally buoyant connecting struts and ballast body.

9.3.3 POWER TAKE-OFF - AIR TURBINE GENERATOR

A single stage version of the turbine has been tested by the Team. From the theoretical work and these test results the Team have concluded that the turbine will have the following advantages:

a) No rectification of the airflow is needed.

b) Direct drive to compact electrical generators is possible.

c) The speed fluctuations are comparatively small and could perhaps be further reduced by using flywheels.

d) The damping characteristic is very nearly linear, which corresponds to the theoretical optimum for the Device.

e) The turbine has a self-limiting response in that above the design air velocity the turbine stalls, and the efficiency drops sharply to zero, thus avoiding possible overspeeding of the generators in extreme sea conditions.

f) The turbine is self-starting.

The CEGB (at Marchwood Engineering Laboratories) have studied the theory of the turbine and are proposing to test a more developed design in their laboratories. The turbine adopted for the Reference Design is based on these studies.

In their "Preliminary Feasibility Study", Queen's University, Belfast have indicated a power plant having a maximum rating of 300 kW. This they regarded as the power cut-off level for a point absorber device of 25 m diameter. The Consultants have, however, re-estimated the optimum dimension for energy capture, and as explained earlier in this Chapter, a Reference Design diameter of 30 m has been adopted. As power is proportional to about the cube of the diameter, the plant rating on the QUB basis would become 520 kW. It is felt, however, that this would be more appropriate as a representative mean hourly rating, being only 17 kW/m captured power. In the absence of more precise design data, it seemed reasonable to adopt a plant rating of about 1000 kW so as to accept much of the valuable storm weather input.

For the purpose of this interim device assessment, a power unit design has been worked up using the basic data for a smaller turbine developed at Marchwood. The result is shown in Figure 9.2 . This shows a five stage six bladed air turbine unit having inter-stage flow directing guide vanes, and at the lower end, servo-adjusted guide vanes for turbine control and when required, pneumatic throttling. The rotor has a diameter of 2.6 m and a suggested hub to tip ratio of 1:2. Normal speed would be about 850 rpm, giving a conservative blade tip speed of only 0.35 mach.

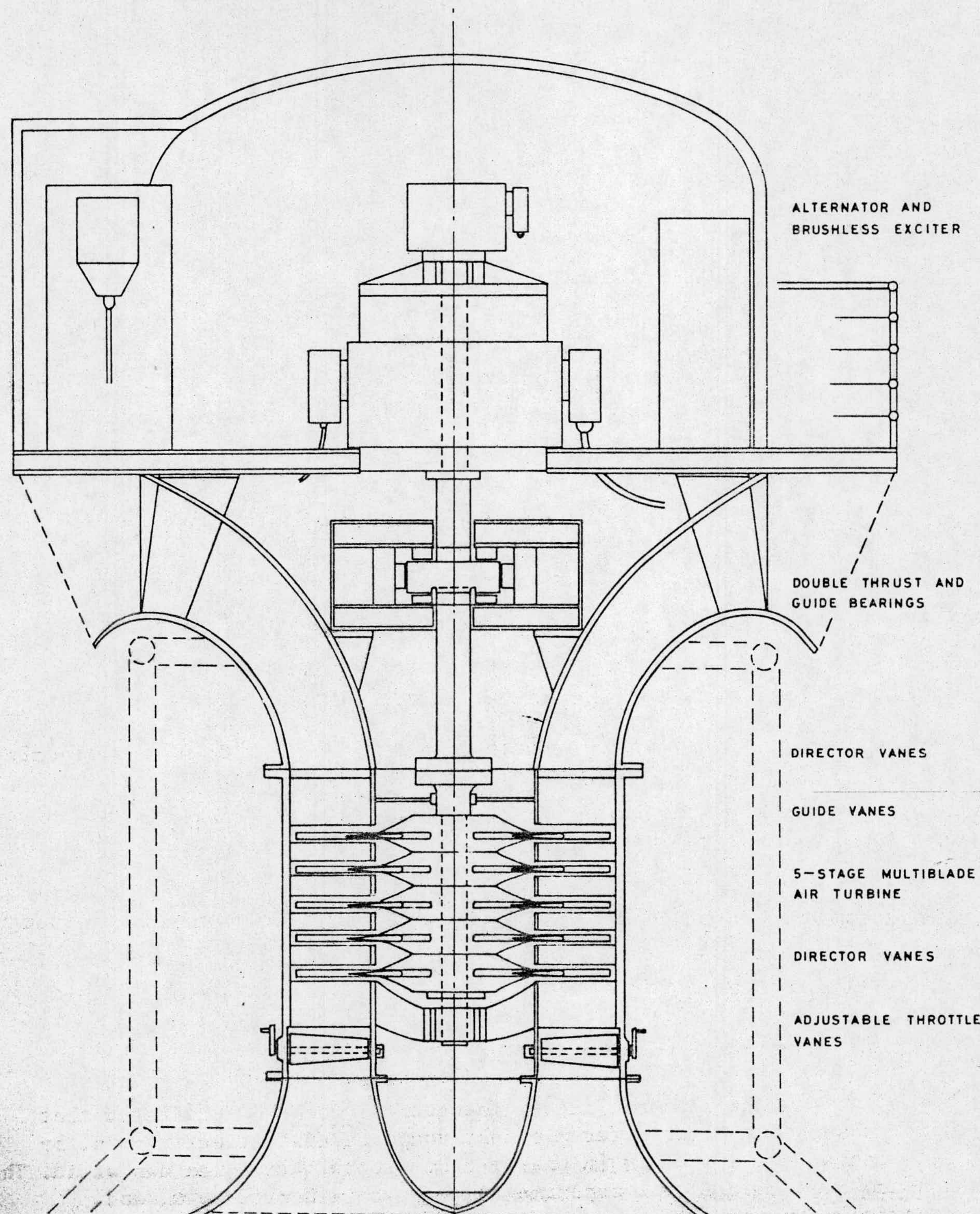
The air inlet and outlet ducts would need to be designed for high aerodynamic efficiency but would be generally of the form shown. The lower entry cone would have an air seal attachment to the top of the device. It should also be protected from water surges, both inside and outside the unit.

The velocity and force vectors of the Wells air turbine rotor give considerable resultant axial thrust loads which operate both upwards and downwards. For this reason it will be noted that the design includes a specially arranged thrust bearing with oil lubricated pads above and below the central collar. The upper part of the power module would accommodate the alternator and its exciter and also the associated step-up transformer and control switchgear. The machinery space would also include accommodation for auxiliary power supplies, heating, lighting and ventilation andcommunications equipment. The electrical output would be taken by flexible 22 kV three phase cable around the outside of the structure down to the under-water mass balancing toroid, before being taken along the sea bed to an adjacent centralised converter platform structure.

The rotor and possible also the stator guide vanes of the turbine would probably be made of cast g.r.p. with a polished finish. Other parts of the turbine should be constructed in stainless steel. The upper and lower air ducts could again be of g.r.p. with a good finish. Design matters needing further investigation would include the turbine performance characteristic up to the advent of overloading and stall; also the practical aspects of possible icing and erosion of the rotor blades. The principles of automatic guide vane control must also be investigated.

9.3.4 CONSTRUCTION, INSTALLATION AND SITING

It is proposed that the Device should be completely constructed in a dry dock. With the concrete vessel completely de-ballasted, the dry dock could be flooded and the structure floated out. The draught required is only 5 m due to the large excess buoyancy of the



WELLS POINT ABSORBER

PROPOSED DESIGN FOR WELLS MARCHWOOD AIR TURBINE GENERATOR

1000 kW 850 r·p·m

FIGURE 9·2

toroidal body in this condition. The structure has been checked for stability in this float-out condition. On reaching the required site, which would require a minimum water depth of 60 m, ballast water would be let into the toroidal vessel at a controlled rate to enable the structure to reach the working depth of immersion. During the operational phase additional water would seep into the concrete vessel only slowly and could be removed with the pump used to control the buoyancy of the ballast body during installation.

9.4 CRITICAL ASSESSMENT OF TECHNICAL FEASIBILITY

9.4.1 LIMITATIONS TO THE ASSESSMENT

The data available only allows a preliminary appraisal of this device. The Device and the turbine have both been demonstrated as working concepts, but the following work remains to be completed.

a) Component sizes and power offtake characteristics have not been optimised. This includes the size and shape of the ballast body, the depth of immersion of the working chamber skirt and the power offtake damping.

b) Performance data is only available for monochromatic waves. The efficiency shows a marked reduction as wave height increases and the power captured in a particular sea state can only be estimated approximately (see Chapter 13).

c) The turbine proposed has not been tested.

d) The models were restrained in surge and so do not completely represent the true full scale situations.

e) The tank width was such that a particular frequency a transverse standing wave was set up near the device and efficiency was reduced.

f) Loads on the device from storm waves in random seas are not available.

9.4.2 ASSESSMENT

General - point absorbing

A year ago preliminary theoretical work had indicated that point absorbency might offer a breakthrough in cost effectiveness, by allowing a device to draw in energy from several times its own width. This has now been checked out experimentally by this Device Team, and separately by the NEL Team for TAG 1 in the Edinburgh tank. The results have been disappointing, due primarily to narrow band width and reduced efficiency due to non-linearity, even in quite modest waves. Thus, it now seems that point absorbency as such is a much less attractive concept than it seemed previously. The situation is not helped by the fact that two disadvantages of point absorbency - mooring and small parcels of power to be individually collected - remain significant problems to be overcome.

Technically, the Device has no more problems than most others, and is definitely superior in some respects.

Specific comment

a) The use of steel for the dome presents a major maintenance problem, particularly at the sea/water interface (the so-called splash zone). The most rigorous standards of corrosion protection will be necessary, using epoxy paints and probably cathodic protection. Even so, it is not certain that the dome will be able to last the full design life of, say, 30 years without being towed back to base for removal of marine growth, blast cleaning and renewal of protective coating and electrodes. Fibre reinforced composite construction would have many advantages and a design exercise will shortly be carried out to check on the technical and economic feasibility of GRP construction. However, it is likely to prove expensive and also suffer from lack of ductility, and is not immune from material degradation in severe environments. Concrete construction would be too heavy.

b) The principle used for stabilising this Device are similar to those used in semi-submersible vessels. The latter are a proven means of achieving maximum stability in exposed locations, at the same time incurring the minimum wave forces. The use of these principles for wave power devices therefore merits full investigation. Experience suggests that general survivability of these vessels is excellent.

c) The most likely problem areas for the structure are the localised effect on the dome panels due to wave impact loadings, the overall distortion resistance of the dome, and the fatigue life of the connection between the bracings and the dome. (These load conditions will be particularly hard to deal with in GRP construction).

d) Construction, tow-out and installation present no major problems.

e) The primary power take-off is extremely simple and is well positioned for ease of maintenance and protection from the sea. It should not be endangered by storm wave conditions provided the water column does not reach the top of the dome, which it is not expected to do. A control system will not be required for the turbine itself.

f) Preliminary studies indicate excellent prospects for the turbine. This design deserves to be assessed independently of the device, since it is applicable to all oscillating water column devices.

g) The collection of the relatively small electrical outputs from many moving devices will be one of the major problems for any point absorber scheme.

h) Ease of maintenance of this Device should be a major advantage, due to the small number of components and their accessibility. This Device and the Vickers device are the only devices which do not require any moving parts or valves prior to the turbo-generator. The absence of rectification removes the need for large ducts, and the resulting power offtake is sufficiently compact to allow removal of all mechanical parts in one module, should this be required.

i) The moorings for the Device have not been investigated, but this device will share the problems of all short devices which need to be close moored in large arrays (see Chapter 14).

j) The productivity of the Device is discussed in Chapter 13. It seems clear that a major problem to be overcome is the rapid fall of of efficiency with wave height. This can be beneficial in reducing the peak power levels in large waves, but the present results show a poor efficiency even in moderate waves. It is too early to say to what extent this is due to inherent limitations in the design. The Team have yet to fully investigate possible remedial measures.

k) Technically this Device appears to have good overall prospects for successful development. However, it will be necessary in the near future to judge the merits of this device on the grounds of cost effectiveness relative to other equally feasible oscillating water columns.

9.5 FUTURE RESEARCH AND DEVELOPMENT

It is essential that this Device should be brought as soon as possible to a stage where it can be compared on a cost effective basis with other floating oscillating water column devices. This would enable a strategy to be drawn up concerning the development of such a generic group. In particular the following work needs to be done.

a) Optimisation of the geometry of the device determination of efficiency curves for a model in both monochromatic and random seas taking account of all the relevant points made in 9.4.1. Attempts to improve the performance of the device in steeper waves should be made.

b) Measurement of forces on the device from storm waves in random seas.

c) Aerodynamic assessment of the turbine rotor.

d) Design studies for the structure, moorings and power collection system.

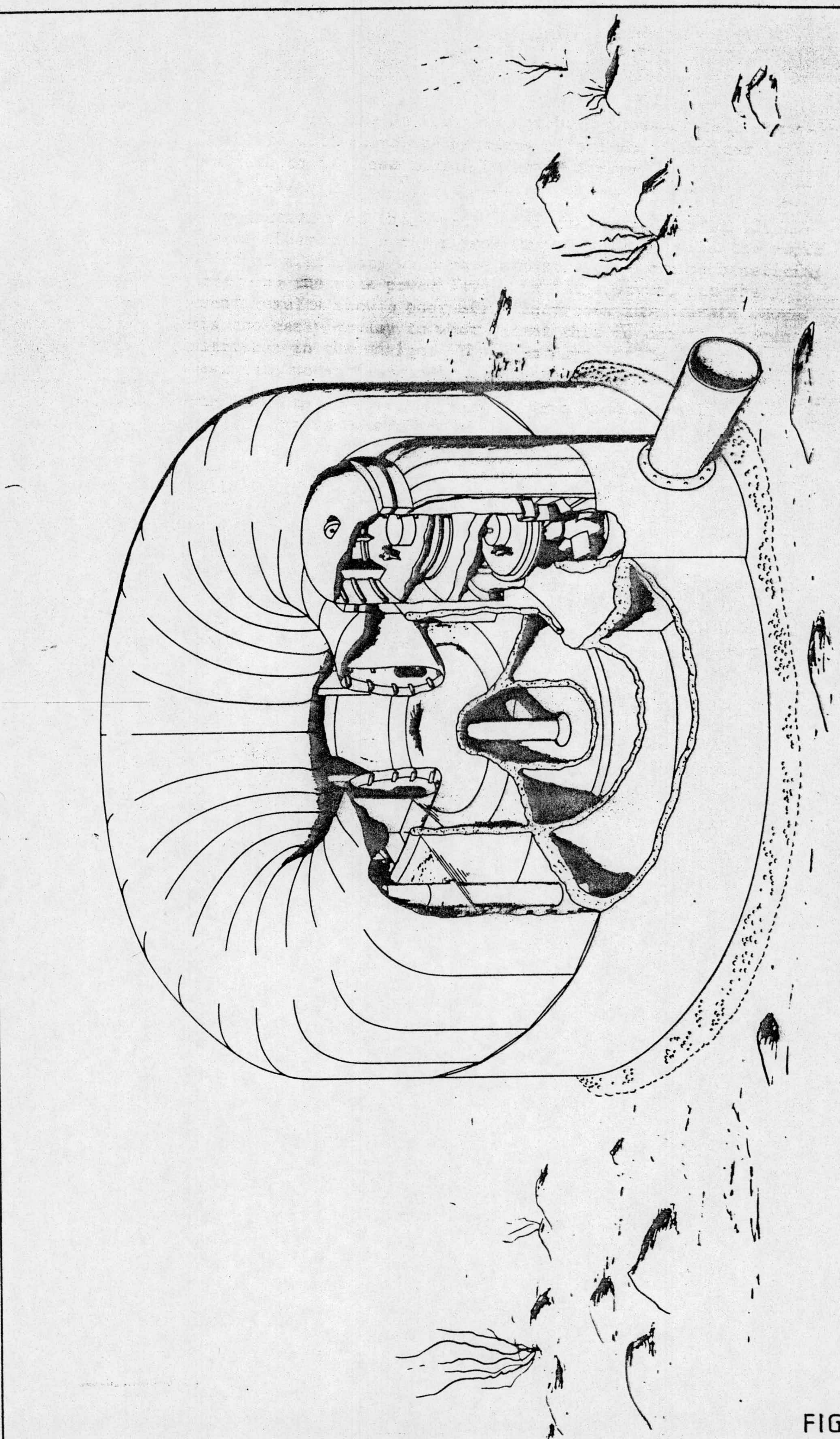


FIG 10·1

CHAPTER 10 - VICKERS DEVICE

Note - This Chapter is included for completeness, but will be superseded by a more comprehensive appraisal to be prepared in the near future. The Device Team are at present carrying out a series of tests which should provide the data needed for the preparation of preliminary Reference Design. The drawings shown in this report are a visualisation, not a Reference Design.

10.1 GENERAL DESCRIPTION OF THE CONCEPT

10.1.1 DESCRIPTION OF THE DEVICE

A large dome containing air under pressure sits on the sea bed. The top is flattened and contains a large orifice, leading to an annular U shaped duct inside the dome. Waves induce oscillating of the water around the U shape and water overflows into an annular trough. The trough is connected through a turbine to an exit draught tube.

10.1.2 DEVICE TEAM'S PHILOSOPHY

Based on their extensive experience of designing marine systems, the Team have adopted the following design criteria.

a) Submerged structure for survival.
b) Simplest possible power take-off machinery - that is a water turbine working in unidirectional flow.
c) No other moving parts.
d) Power capture by resonant oscillation for maximum efficiency.

DRAFT

10.1.3 PRINCIPLES OF OPERATION

This device, like the NEL and Wells Devices is an oscillating water column, the geometry of which determines the resonant frequency and hence the wave period in which maximum efficiency will be achieved. The principle novelty in the action of the device lies in the nature of the damping applied to the column. As the column rises firstly work is done on compressing the contained air, which acts as a zero rate spring, and this continues as the water overflows into the annual trough. As the column falls work is done on the column by the air, but as on the return water cannot flow back from the trough into the water column, the volume displaced is less, and over a cycle the net flow of energy is from the column into the air. During the whole cycle the air which has been compressed above the equilibrium hydrostatic pressure, by the net flow of water from the column into the trough, is forcing water through the turbine at a fairly constant rate. The damping applied to the column is hydrodynamically non-linear, that is the resistance is not proportional to the water velocity. Linear damping is required for optimum power extraction from a resonant system, but the sensitivity of the output to this factor is not known.

A large volume of contained air is required for two reasons. Firstly, if the air compression adds significantly to the stiffness of the water column the column becomes detuned from the waves. An infinitely compressible or zero rate spring would be ideal. Secondly, the energy storage in the air is very effective in smoothing the flow through the turbine, it is in fact equivalent to the accummulators in the hydraulic circuits of other devices. However, as the excess pressures in this device are very small, very large volumes of air are required.

10.1.4 PARAMETERS AFFECTING DEVICE EFFICIENCY

The Team's knowledge of the relationship between the various geometric parameters and device efficiency is very incomplete. Further experimental work is in progress.

a) <u>Duct length and diameter</u>

For a long narrow duct the added mass at the inlet is much less than the actual column mass and the resonant period of the column depends only on its length. Based on this simple case, the optimum duct length is $\lambda/2\pi$ where λ = wavelength.

For a wide short duct (as in the Reference Design) the added mass at the inlet will be of the same order as the actual mass of the column. In this case the resonant period of the columns is more difficult to predict.

The area of the duct at the air interface also determines the 'stiffness' of the column, which in turn affects the resonant period. The area of the duct at the inlet is one of the parameters which determine the added damping of the column, and hence its ability to absorb energy. In the above, however, it is assumed that the column area is kept constant from inlet to air interface. Constant velocity in the ducts helps to minimise turbulence losses.

In summary the duct geometry is crucial to the effectiveness of the device and will be determined by the requirements to optimise the blend of column mass, added mass, column stiffness and added damping. The Team currently think that the duct diameter will be of the order of $\lambda/6$.

b) <u>Depth of immersion of duct inlet</u>

This parameter will affect both the hydrodynamic damping, and added mass. Oscillating systems at depth are able to extract power from waves, but the range of wave periods over which they are effective is very narrow at large depths. From theory, the Team expect the best depth to be from 0.2 to 0.3λ.

c) <u>Overtopping height</u>

This is the difference in level between the column air interface at rest and the top of the internal weir. It can be varied either by changing the height of the weir, or, more plausibly, by pumping more air into the dome. The Team consider that the optimum height will be approximately half of the amplitude of an undamped column.

d) <u>Surface area of collecting trough</u>

The larger this area the better. Ideally the water level in the trough would be very close to the top of the weir to minimise energy losses, and the trough would have sufficient area to minimise cyclic fluctuations in level. Hence the area is determined by the volume of water delivered in a wave cycle, divided by the acceptable fluctuation in level.

e) Volume of entrapped air

Again the bigger this volume is the better, as explained in 10.1.3. Approximate calculations suggest that a volume of four times that of the water column may be adequate.

f) Duct geometry

The Team suggest an inlet radius equal to the duct radius to reduce turbulence losses. The rest of the duct must also be streamlined.

10.2 PRESENT STATE OF DEVELOPMENT

Development work has so far been confined entirely to laboratory testing of idealised forms of resonant water columns. Power extraction efficiencies are not yet available. The experimental programme is designed to explore systematically each of the main device parameters.

10.3 THE VISUALISATION ADOPTED IN THIS STUDY

The drawings in this report are included only to illustrate the general concepts behind this device and do not constitute a proper design proposal. Rudimentary structural calculations have been made, but the turbine ratings and average output are not known.

10.3.1 STRUCTURAL CONSIDERATIONS

The top half of the dome is under excess internal pressure, the bottom half is under excess external pressure. Hence the top of the shell must be air tight and is predominantly in tension. The structure consists of intersecting doubly curved shells and diaphragm walls. These factors add up to a strong case for the use of steel, which has to be balanced against corrosion problems and the need for extra ballast. Concrete is still a possibility, but would require sealing, probably with a flexible liner, and would need heavy reinforcment. Shuttering, the temporary supports, and placement of the concrete would all present problems adding considerably to the costs of construction.

The lower half is less complex geometrically, and is predominantly in compression. Concrete is certainly the most suitable material, and will help to reduce the quantities of ballast required. Seepage of water into the air chamber will occur, but will easily be dealt with by small pumps.

Construction has not been considered in detail but the structure would almost certainly be completed in a dry dock, floated out to site, ballasted and sunk to position. A critical phase would occur during flooding of the ducts and troughs when the water ballast, if unrestrained, would cause stability problems. During sinking the device would be connected to cables anchored on the sea bed to control the attitude and position of the device. Careful bed preparation, perhaps with tipped gravel, would be required. Foundation skirts or a rock fill toe may well be required for scour resistance.

10.3.2 POWER TAKE-OFF

It is believed that the head of water across the turbine will be of the order of the wave height. Suitable turbines will be very large.

For the present study turbines similar to those chosen for the Russell Rectifier have been used.

For maintenance purposes the turbo-generator is shown in a removable pod. Routine inspection and minor maintenance will be possible in the pressured air chamber housing the alternator.

10.4 PROVISIONAL ASSESSMENT OF TECHNICAL FEASIBILITY

This device will require the minimum of maintenance and should have excellent survival characteristics. The turbine is certainly feasible, if somewhat outside the desirable range of heads and flows for efficient operation. The smoothing of the power input will be the effectiveness of the device. The scale of the device is dictated by the requirements for enormous air storage voids, and by the size of the collecting trough. To have a ratio of scale to power output comparable to other wave power devices it can be shown that the column will need to capture power over several times its own width. The prospects for achieving this in realistic wave conditions are not thought to be good and the Team may need to depart radically from the device configuration shown in this report to achieve the required effectiveness.

As with other resonating devices, the size of the device is inextricably related to wave length, and there is the added need to provide both a water reservoir and a very large air spring. It seems unlikely therefore that the device will prove to be a way forward to a significantly more cost effective device.

CHAPTER 11

GENERATION AND TRANSMISSION

11.1 Conversion to electrical energy

11.1.1 Wave energy abstracted by the particular device has been used to drive a prime mover, in all cases of the turbine type but using either air, oil or water as the operating medium. These are unidirectional machines characterised by cyclic variation of power output, being a reflection of the cyclic nature of wave energy as modified by the smoothing provided. With such a large number of generators individually driven, synchronous operation is not practical. A modified system of generation has therefore been adopted as described in earlier chapters. It is particularly relevant to acknowledge the guidance of the specialist advisers to TAG 6, in particular Mr J D Ainsworth of GEC and Dr J R Bumby of IRD.

11.1.2 Consideration has been given by others to a form of gear driven reversing generator. Fatigue problems associated with frequent reversal of stress - estimated at between four and six million reversals per annum - would make this machine wholly unsuitable. All the reference designs in the present report relate to straightforward unidirectional three phase alternators. It is important to note that for the seven devices considered, the alternators required come within the rating bracket 1 - 9 MW. In most cases, the generation voltage could be 3.3 kV at rated output. For the two largest machines of 7.5 MW and 9 MW, the alternative generation voltage might be 6.6 kV. In both cases reliable forms of stator insulation are available. The generators would be of the totally enclosed air cooled type, probably also with external heat exchangers for separate water cooling.

11.1.3 This review of wave energy development looks at the overall plant requirements for a notional 2 GW system. It is relevant to be aware of the large numbers of alternators installed in the device, all of which require separate automatic control of voltage and load. Relevant numbers are given on the following table -

Device Type	No of Generators
NEL	512
WPL	1144
HRS	1200
SEA	224
FRENCH	300
WELLS	2200
VICKERS	2200

From a generation point of view, those device types requiring a smaller number of machines are to be preferred.

11.1.4 Having ruled out multiple synchronous generation, the most practicable method of combining the outputs of large numbers of alternators is to allow each to feed its own diode rectifier unit at an appropriately controlled voltage and to connect these in series groups. The coast-wise length of 2 GW array and limitations of transmission circuit rating, have led to the choice of a total of eight 250 MW groups. Each of these is again split into pairs of 125 MW groups, one of positive polarity and the other negative. It is proposed that the circuit voltage be ± 250 kV. The electrical energy output of each machine is reflected in the controlled generation voltage. It is a prerequisite of generation system design (2GW) that the interconnected mainland systems of the two Scottish Boards shall be fully receptive to all wave energy input of whatever magnitude and up to full transmission capacity.

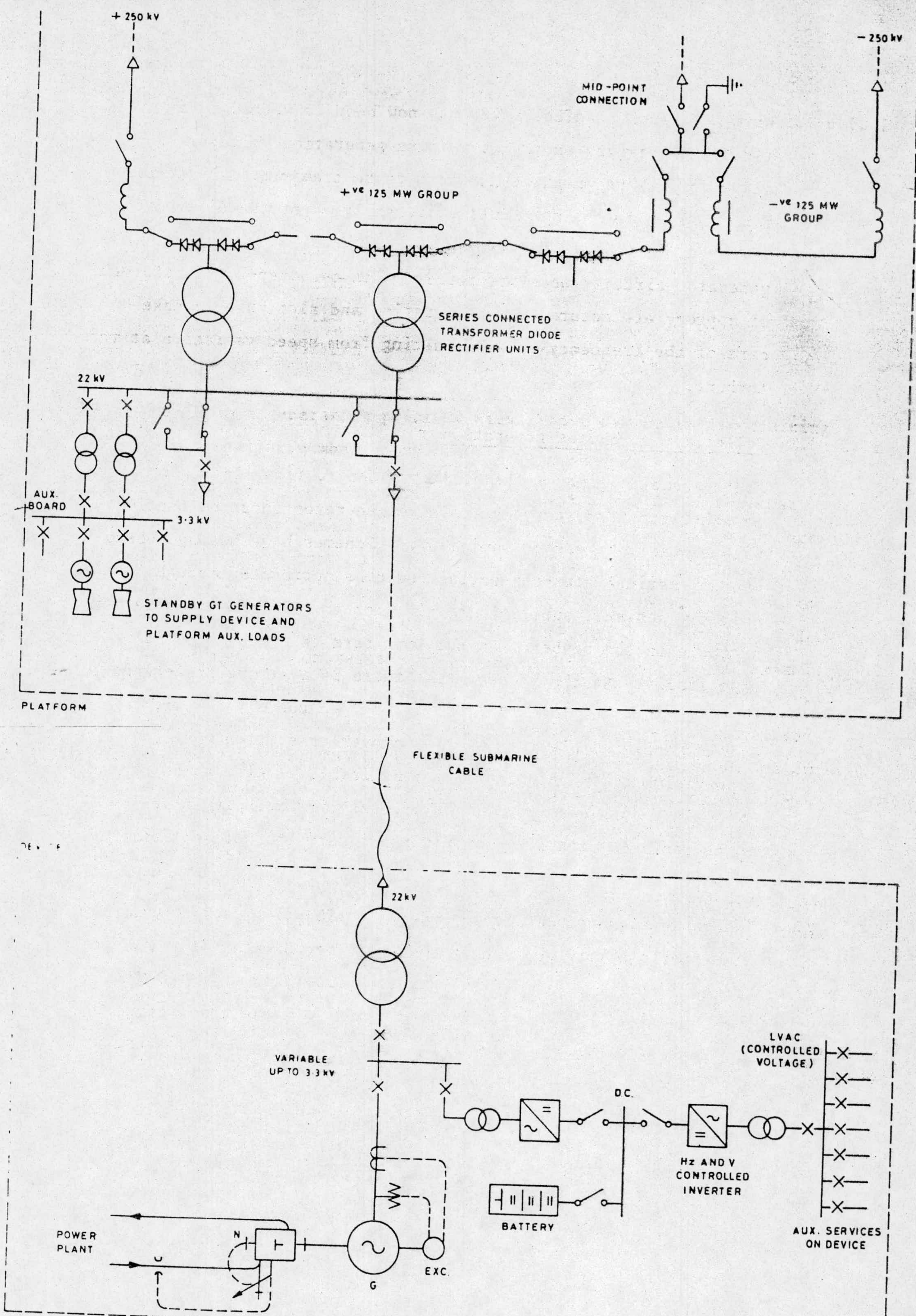
11.1.5 Special generic features of the wave power alternators include a generous thermal rating so as to accept short term peak turbine power, as also the iron circuit heating due to the harmonic circulating currents resulting from the proposed arrangement of six pulse diode rectification. A specially responsive excitation system is also required. This would be based on brushless a.c. exciters requiring development of rotating thyristor rectifiers with some form of inductor control. At least four per unit excitation voltage combined with a very short response time will be necessary.

11.1.6 Wave derived mechanical power has now been converted to a flow of electrical energy at varying generation voltage. Power at up to 9 MW per machine has next to be transmitted by seabed cable. This can be done most efficiently, over the distances involved, by raising the voltage to about 22 kV. Each generator circuit therefore requires its own step-up transformer of appropriate naturally cooled rating and also able to take care of the frequency range resulting from speed variation at the turbine.

11.2 Collection of device generation

11.2.1 At this stage it may be helpful to refer to fig. 11-1 which shows, in schematic form, a typical single generator inter-connection with a nearby converter equipment. Schemes have been proposed whereby series inter-connection would be performed through suitably designed submerged rectiformer units connected together by cable on the seabed. In the long term this might become practicable. At the present time there is a strong preference for an electrical installation entirely in the dry and within a totally enclosed platform mounted converter station where supervision and maintenance are practicable. Also where bypass switching could easily be included, enabling a faulty unit to be replaced with no more than short term loss of section energy output.

11.2.2 The cable required to inter-connect the floating device with the converter platform would need special development. It would be of the 3 core type for 22 kV operation and rated up to 10 MVA. Paper insulation would be inappropriate. A cable manufacturer would probably consider synthetic rubbers of the e.p.r. type. It is also proposed that the flexible inter-connecting cable should be designed with additional pilot cores for purposes of remote control and indication, for alarms and communication. The mean flexible cable route length could be between 5 and 8 km depending on the type of device and the distance to the rear of the 250 MW converter platform. Some devices need deep water (80 m) but it is proposed that the platform structures would not be taken any deeper than 50 m (25 f) - or 30 fathoms at the most. It is relevant to mention that in the case of the HRS device which is /



SCHEMATIC DIAGRAM OF TYPICAL WAVE ENERGY GENERATION, TRANSMISSION AND AUXILIARY CIRCUITS.

FIGURE 11·1

bottom mounted and close inshore there would be no requirement for flexible cables.

11.2.3 It is appropriate to add that the 22 kV 3 core special flexible submarine cables are essentially for six of the seven devices and whilst not available commercially at the present time, could be produced by UK manufacturers given an adequate design and development programme.

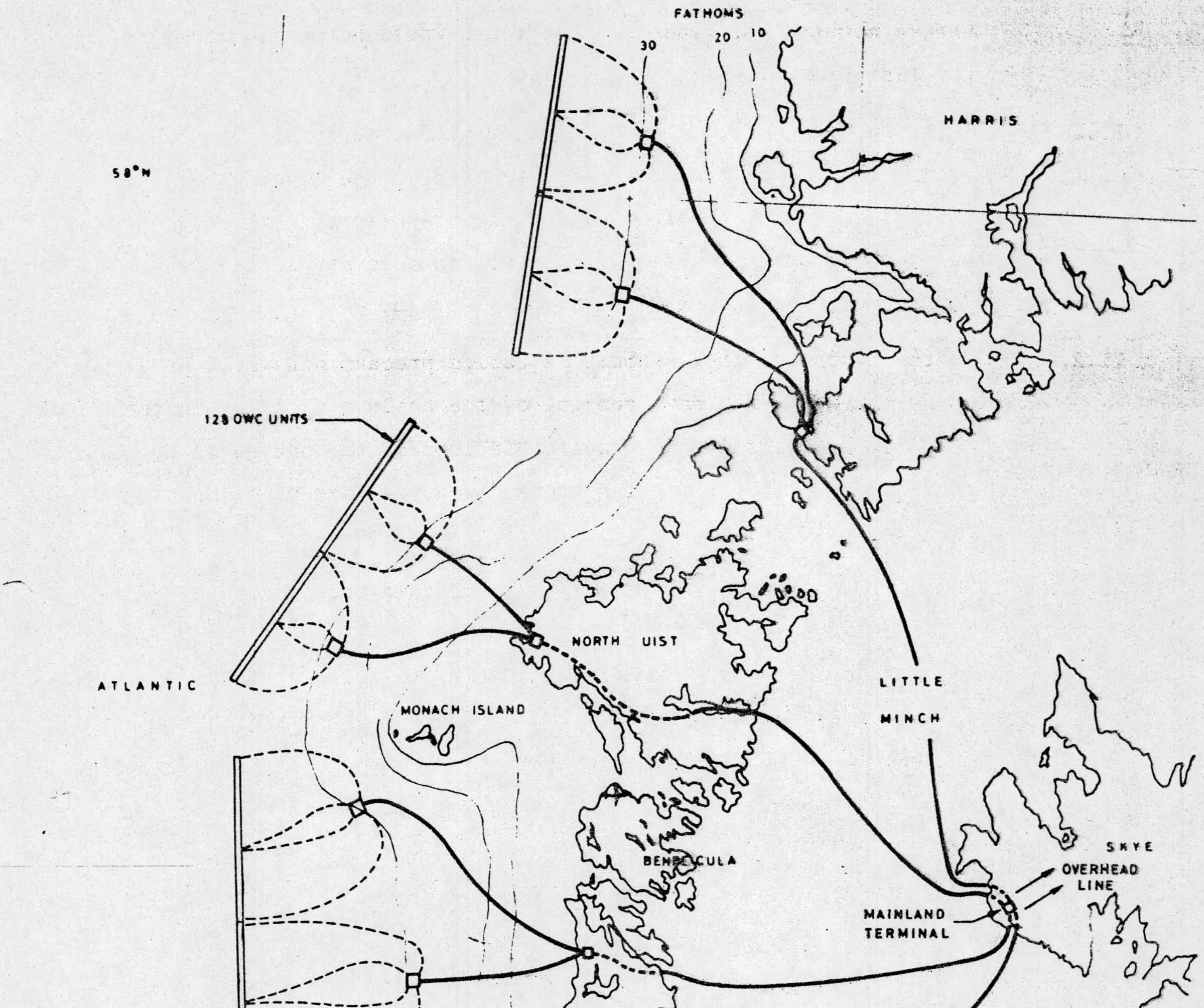
11.2.4 In the laying of these submarine cables precautions would have to be taken to eliminate rubbing of the cable over rocks on the seabed. It would not be practicable to bury the cables so that submerged buoys might be considered, as a means of keeping the cable clear of the bottom until all motion has disappeared.

11.2.5 Connection of the flexible power cables to floating devices calls for the development of some form of universally jointed termination. The point at which the cable enters the device should be in the area of minimum motion, e.g. the rear raft of the WPL device, and for the SEA system the rearward face of the power module, itself attached through suitable joints to the stable spine units. Whilst it is hoped to reduce the effect of wave motion on the cable, there is also a further requirement that it should be possible to disconnect the cable easily and transfer the end to a temporary mooring buoy. This would allow removal of the device and its replacement and reconnection.

11.2.6 Of the four principal devices under review, three require the use of considerable route lengths of 22 kV submarine cable. The areas in which they are required are indicated by dotted lines in figs 11-2-3-5 for the NEL, WPL and SEA types. Similar cables would be necessary for installations of the French, Wells and possibly Vickers designs.

11.3 Converter Platforms

11.3.1 Electrical energy incoming from an effective 250 MW of wave energy converters, i.e. a net 250 MW after allowing an appropriate diversity factor, would be received via groups of 22 kV cables arranged in two sets on what may be described as the longer north and south faces of marine platform structures. It has been explained that owing to the considerable length of a 2 GW /

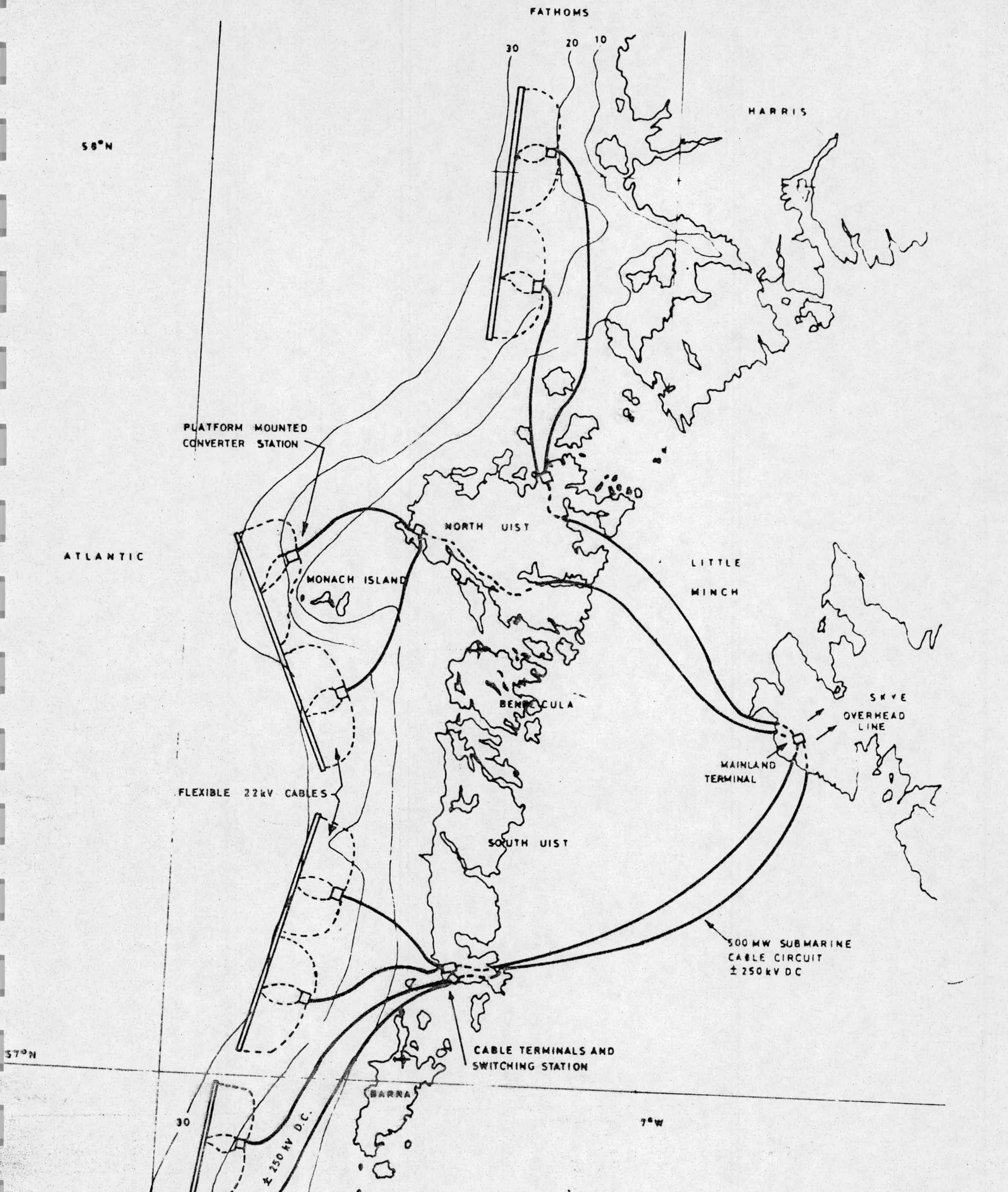


SUBMARINE CABLES

LOCATION PLAN : 2GW INSTALLATION FOUR 500MW GROUPS IN 40f

NEL DEVICE

FIGURE 11·2

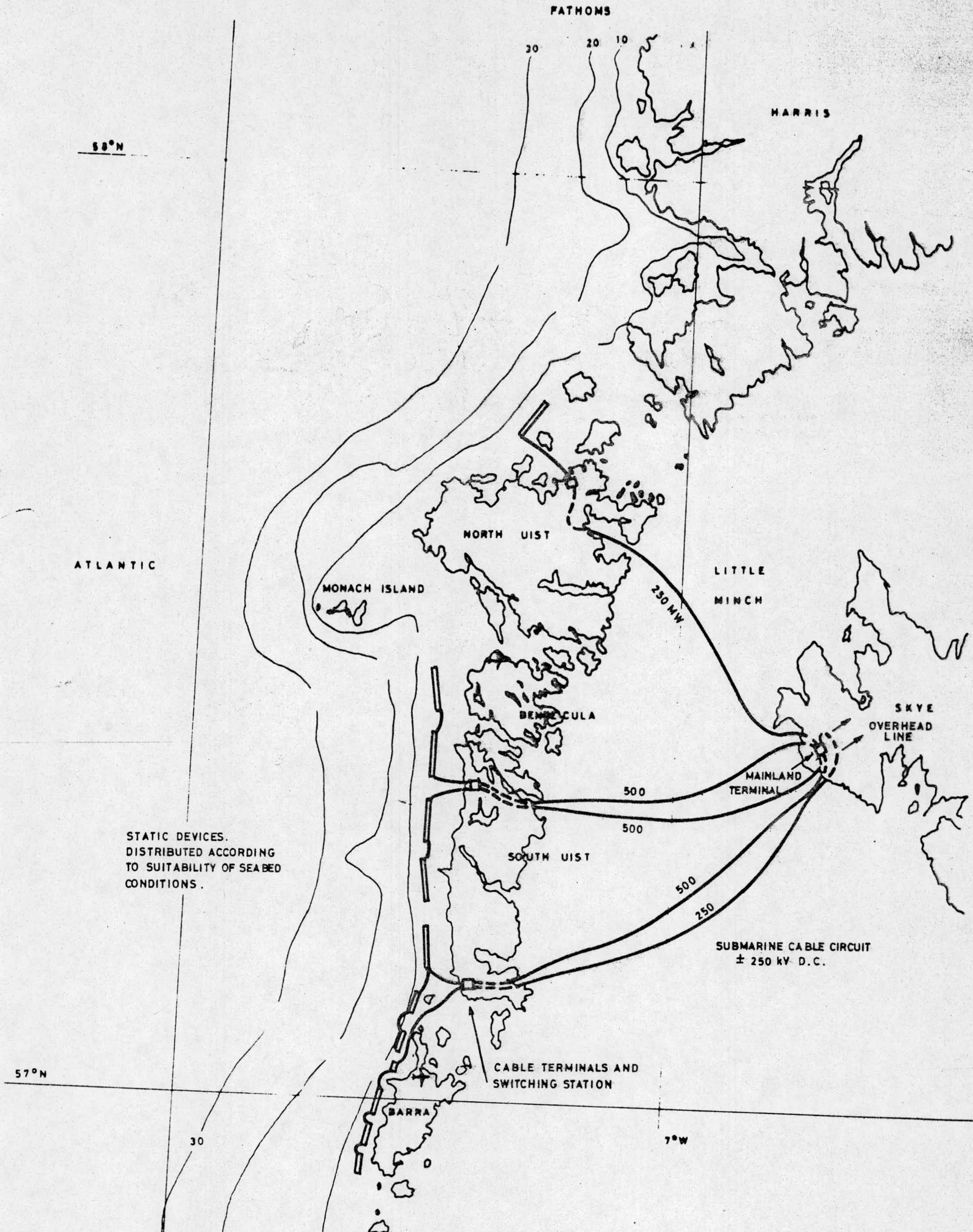


SUBMARINE CABLES

LOCATION PLAN : 2 GW INSTALLATION FOUR 500 MW GROUPS IN 25 f

WPL DEVICE

FIGURE 11.3

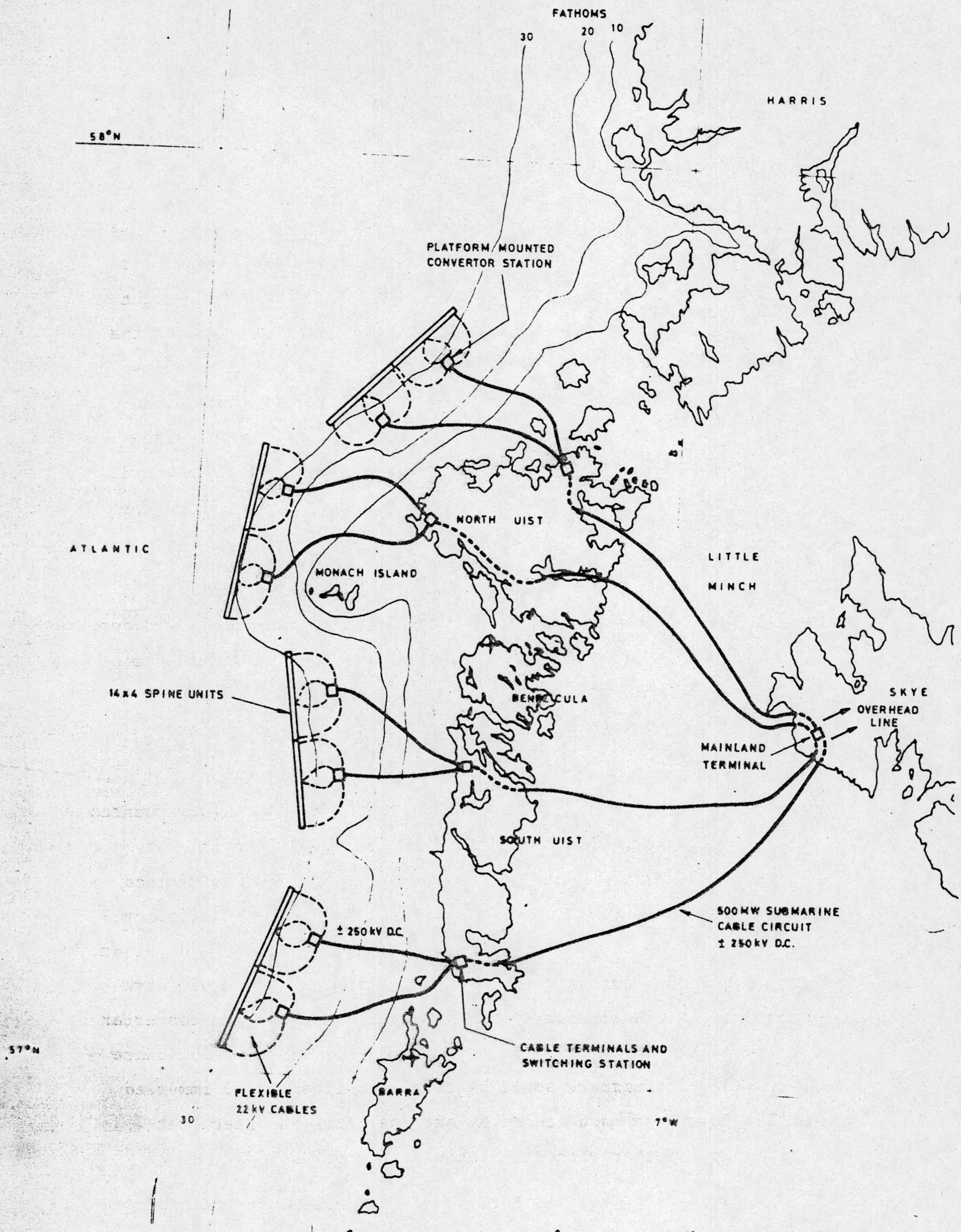


SUBMARINE CABLES

LOCATION PLAN : 2 GW INSTALLATION - DISTRIBUTED GROUPS IN 7·5f

HRS DEVICE

FIGURE 11·4



SUBMARINE CABLES

LOCATION PLAN : 2 GW INSTALLATION – FOUR 500 MW GROUPS IN 301

SEA DEVICE

FIGURE 11.5

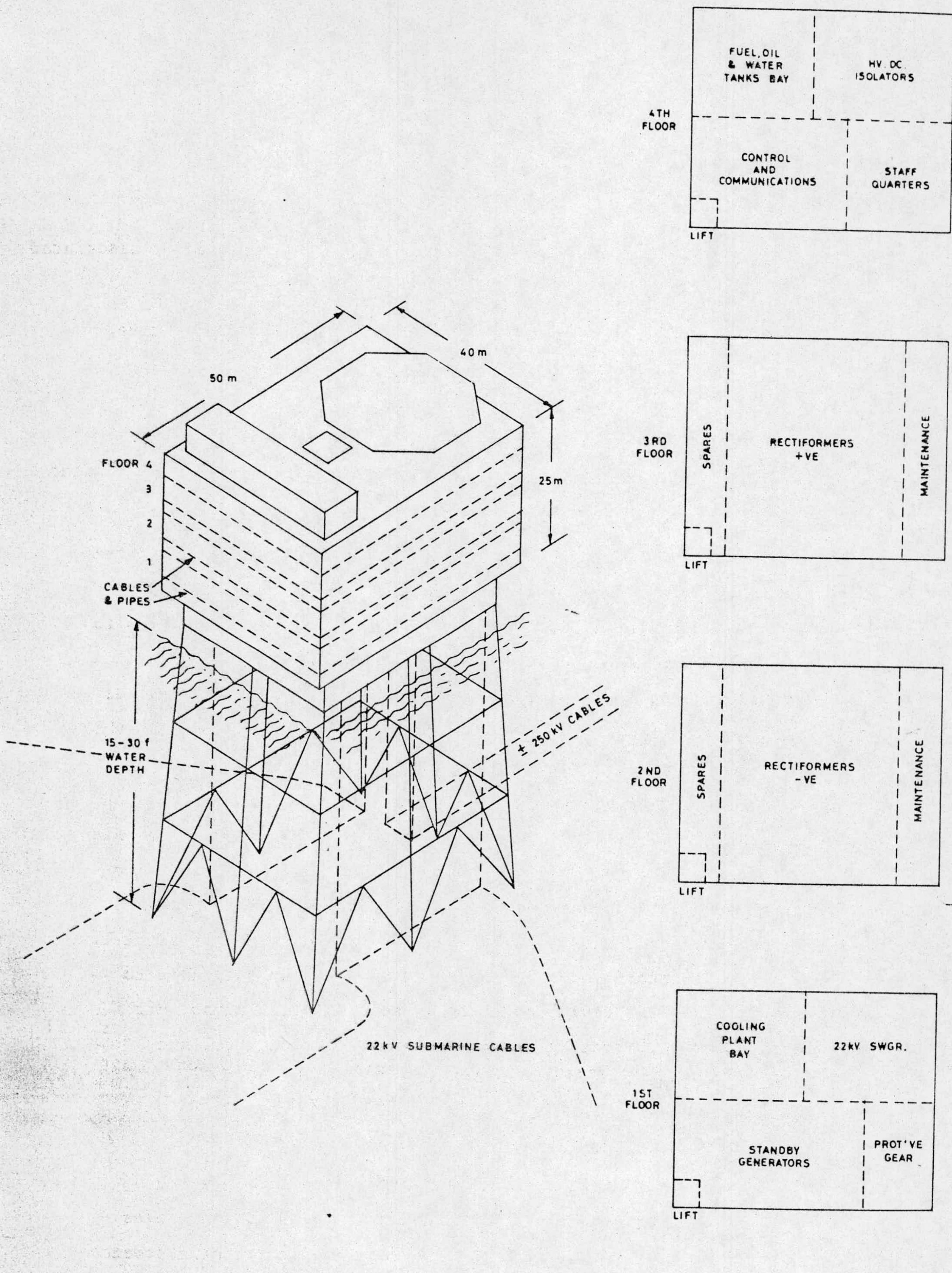
array off the Hebrides, it is proposed that there be a total of 8 separate platforms standing on the seabed in water depths probably limited to 25 fathoms. The locations of the platforms are illustrated in figs.11-2-3-5. Platforms would not be required in the case of HRS device.

11.3.2 An indication of the likely dimensions and internal layout of a converter platform is given in fig. 11-6. The total weight of the large number of oil immersed rectiformer units and of the associated switchgear and control equipment and of the standby generating plant, auxiliary services and living accommodation would probably amount to some 800 to 1,000 tons, varying with the number of converter units required. The deck housing would be a robust structure largely constructed in steel, giving inherent screening against radio interference.

11.3.3 Access to the platform would normally be by helicopter to a landing pad on the roof. Access by sea would also be allowed for, care having been taken to bring the 22 kV cables up within the structure and well clear of vessels lying alongside. Upper and lower access hatches would be provided with appropriate lifting equipment.

11.3.4 Fig. 11-6 indicates the general proportions of a platform mounted converter station. The deck structure is 40 m x 50 m in plan and is expected to be some 25 m high. This height is divided into unequally spaced floors. The series connected rectiformer units occupy the second and third floors with 2 x 125 MW of plant. Each converter floor is given a low-headroom cable and pipework mezzanine. It is also intended to include space on the converter floors to accommodate spare units and also provide a maintenance area. The rectiformers would be totally enclosed, oil immersed (or SF_6 insulated) and cooled by external oil/sea water heat exchangers together with circulating water pumps.

11.3.5 The lower floor of the platform would accommodate the main 22 kV switchgear, the heat exchangers just mentioned, much of the electrical protection equipment and also an auxiliary plant room to accommodate standby gas turbine generators. This form of prime mover is advised in view of the reduced vibration. Finally, /



250 MW CONVERTER STATION

PLATFORM MOUNTED

FIGURE 11·6

the upper floor would accommodate h.v. d.c. isolation equipment and control and communications panels. Also, fuel, oil and water stores. A necessary part of the upper floor area would be reserved for staff quarters. It is considered that staffing of the platforms would be essential for supervision and maintenace of the main converter plant and for surveillance of the wave power devices in the group associated with the particular platform.

11.3.6 D.c. isolators would be provided in both positive and negative poles of the converter centre. The +ve and -ve sections would be connected at the centre where there would be further isolators for the mid-point cable connection and also for the single marine earthing point, preferably arranged at the sending end.

11.3.7 Auxiliary supplies on the platform would normally be derived from the 22 kV switchboard. In the event of loss of input, the stand-by generators would be used. A similar consideration applies to the devices themselves. Whilst normally able to take care of their own auxiliary loads, there will be times when the devices will require an external power supply. It is proposed that this be given as a back-feed down the 22 kV flexible cables by appropriately interlocked switching at the two ends. The multicore circuits included in the submarine cables would enable this to be achieved by remote control from the platform. One might ask what happens if the connecting cable has failed? It is proposed that this eventuality would be covered by a light l.v. a.c. cable inter-connecting adjacent devices but only able to supply essential device auxiliaries such as bilge pumps, air compressors, internal heating, warning lights, control and communications.

11.4 HV. DC. Submarine Cables

11.4.1 The four location plans figs.11-2-3-4-5 also indicate the proposed routes of the ± 250 kV main d.c. transmission cables which transmit the platform power across the intervening stretch of sea to small switching stations provided along the west coast of the Outer Hebrides. Each circuit would comprise three single /

core cables having 500 A conductor section, i.e. 250 MW rating. Normally the mid-point cable would carry only the small out-of-balance currents but, in the event of the loss of either positive or negative pole, could be used as a fully rated return circuit for the healthy pole, i.e. only a 50% loss of transmission capacity for the single circuit.

11.4.2 These high voltage cables would probably be of the oil impregnated paper insulated type similar to those presently in service on the 1,000 MW Skagerrak crossing between Norway and Denmark. It is quite likely that official requirements will dictate that the three cables be laid closely in parallel and possibly within a 2 m band.

11.4.3 The long term reliability of submarine cables laid directly on the seabed would be too low. Where laid across sea areas of interest to inshore fishermen and traversed by shipping, the risks of damage by trawling operations and by anchors would be too great. Although a very expensive operation, it is recommended that the 250 kV d.c. submarine circuits should be buried to a depth of 0.8 - 1.0 m wherever practicable. In areas where rock is exposed, the cables should be protected by bags of heavy ballast. Tidal stream velocities off the Outer Hebrides are fortunately low. Nevertheless, precuations would have to be taken to prevent movement of the cable against projecting rock surfaces.

11.4.4 It should have been explained that although the foregoing precautions are necessary, the cables themselves will be protected by double steel wire armouring and by impervious outer plastic sheaths probably given a special chemical treatment to inhibit attachment of marine growths.

11.4.5 In the alternative 2 GW schemes being considered the outputs from 250 MW platforms are taken in pairs to a common switching point on the adjacent island - generally North or South Uist. There are then a total of four 500 MW wave energy supply points. The next step is to transmit this energy across the islands to their east coasts and thence under the deep water stretch of the Little Minch to the proposed main terminal point on the West Coast of Skye. The arrangements for the four primary devices are shown in figs. 11-2-3-4-5 previously referred to.

11.4.6 The 500 MW cables would again comprise positive and negative poles and an equal section mid-point return conductor. The /

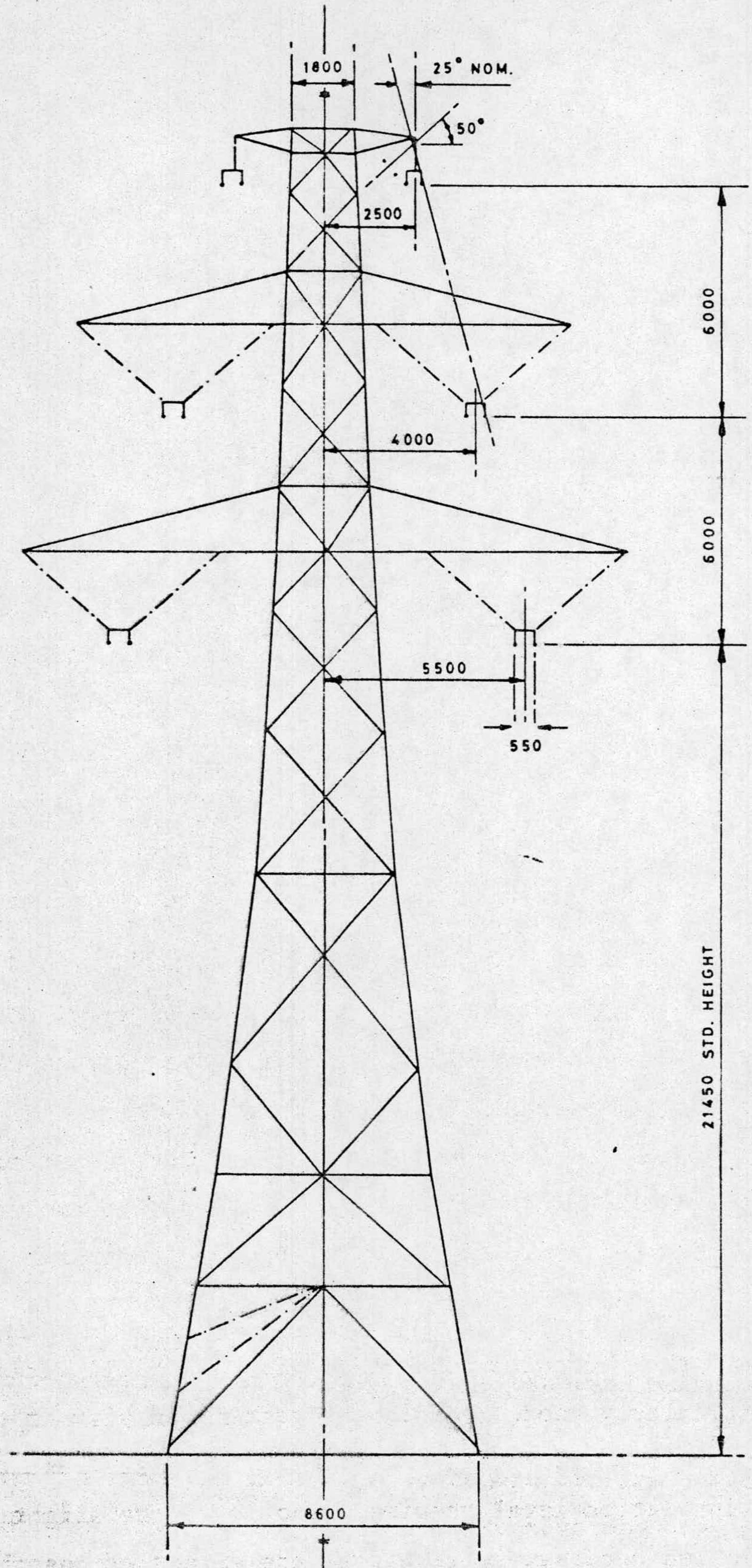
copper sections would, however, be double those of the earlier cables. Trenching of the four circuits in the shallower depths of the long sea crossing would be advisable. It remains to be seen whether it would be practicable and within acceptable costs to endeavour to bury the circuits in the deeper water sections. Arriving off the west coast of Skye at the Durinish peninsula the circuits would come ashore in pairs via Ramasaig Bay and Lorgill Bay immediately to the north and south of a coastal hill promontory known as Hoe Point. A cable termination and switching compound on level ground at the back of the hill would also accommodate the terminal tower of a double circuit overhead line used to transmit the wave power across the Highlands to an inverter station at a suitable location on the main Scottish transmission system to the North East of Perth in Strathmore.

11.5 Overhead Line Transmission

11.5.1 Switching arrangements at The Hoe substation would enable any pair of submarine cable circuits to be connected to one of the overhead line circuits each of which would have a continuous rating of 1,000 MW. The station would also include protective equipment, surge divertors together with main and reserve communications and indications facilities. Some small buildings would be required for auxiliary plant; for the storage of spare units and as mess accommodation during visits by maintenance workers.

11.5.2 The transmission line would be of the double circuit type having positive and negative pole conductors and also a mid-point circuit of the same conductor section but only lightly insulated. The general appearance of the towers used in straight line positions is shown in fig. 11-7. Although for $\pm$ 250 kV d.c. operation the tower height is only some 35 m, this is a significant reduction and of advantage as regards environmental impact.

11.5.3 Each pole would be made up of twin 'MARTIN' steel cored aluminium conductor (ACSR) capable of carrying 2000 A continuously. It will also be noted from fig. 11-7 that the conductors would be supported between insulators in 'VEE' configuration. Whilst reducing the overall tower height this also helps to limit conductor swing. The mid point conductors /



OUTLINE OF TYPICAL ± 250 kV DC DOUBLE CIRCUIT SUSPENSION TOWER
1000 MW PER CIRCUIT

FIGURE 11·7

are arranged on the top cross arm of the tower where they can also act as shield wires, there being no separate earth wires.

11.5.4 The criteria to which the proposed line has been designed would be more stringent than those applying to the conventional tower designs presently used elsewhere in the United Kingdom. It is only intended to provide one double circuit transmission line capable of transmitting the full 2 GW - but without spare circuit capacity. It is felt that line costs and possibly overriding environmental problems make it undesirable to have more than one line. Whilst there will be ample opportunity to undertake maintenance and repair work during the summer months it is essential that the line has a high availability factor during the winter months when wave power will be at its most productive. For this reason the line design criteria pay full regard to extreme weather conditions of wind, snow and ice loading and the difficulties of access to parts of the route both for emergency repairs and for normal routine maintenance.

11.5.5 The typical straight line tower shown in fig. 11-7 would be about 35 m high and would require 13 tonnes of steel work and fittings. This height and weight compares with 46 m and 13 tonnes of the present CEGB L8 design and 50 m and 22 tonnes of their L6 design. If the same stringent design criteria were to be applied to an equivalent AC tower, the amount of material required would be somewhere between that of the CEGB L8 and L6 designs.

11.5.6 The use of the mid point conductor pairs as shield wires should give particularly good lightning protection in view of the arrangement proposed. This would be at some detriment to the minimum insulation level required. However, the slight increase of insulation necessary will offset the effect of possible salt spray insulator pollution in coastal areas. Direct current polarisation might be expected to aggravate this.

11.5.7 It will be appreciated that having crossed the island of Skye on a carefully selected route with environmental considerations primarily in mind, the d.c. line is confronted with the navigable straits between Skye and the mainland at Kyle Rhea. /

The North of Scotland Hydro Electric Board are presently constructing a 132 kV steel tower line between Quoich in Glen Garry and Broadford in Skye. This includes a crossing at Kyle Rhea. It is also proposed that the new h.v. d.c. line should cross at Kylerhea but further to the south. Precise location could only follow a detailed site survey and examination of levels of proposed tower sites and of foundation conditions. For present purposes provision has been made for a long span - about 1.1 km - crossing with two high towers and their associated back anchor towers. Mid-span clearance under maximum temperature conditions and at high spring tide would comply with statutory shipping requirements.

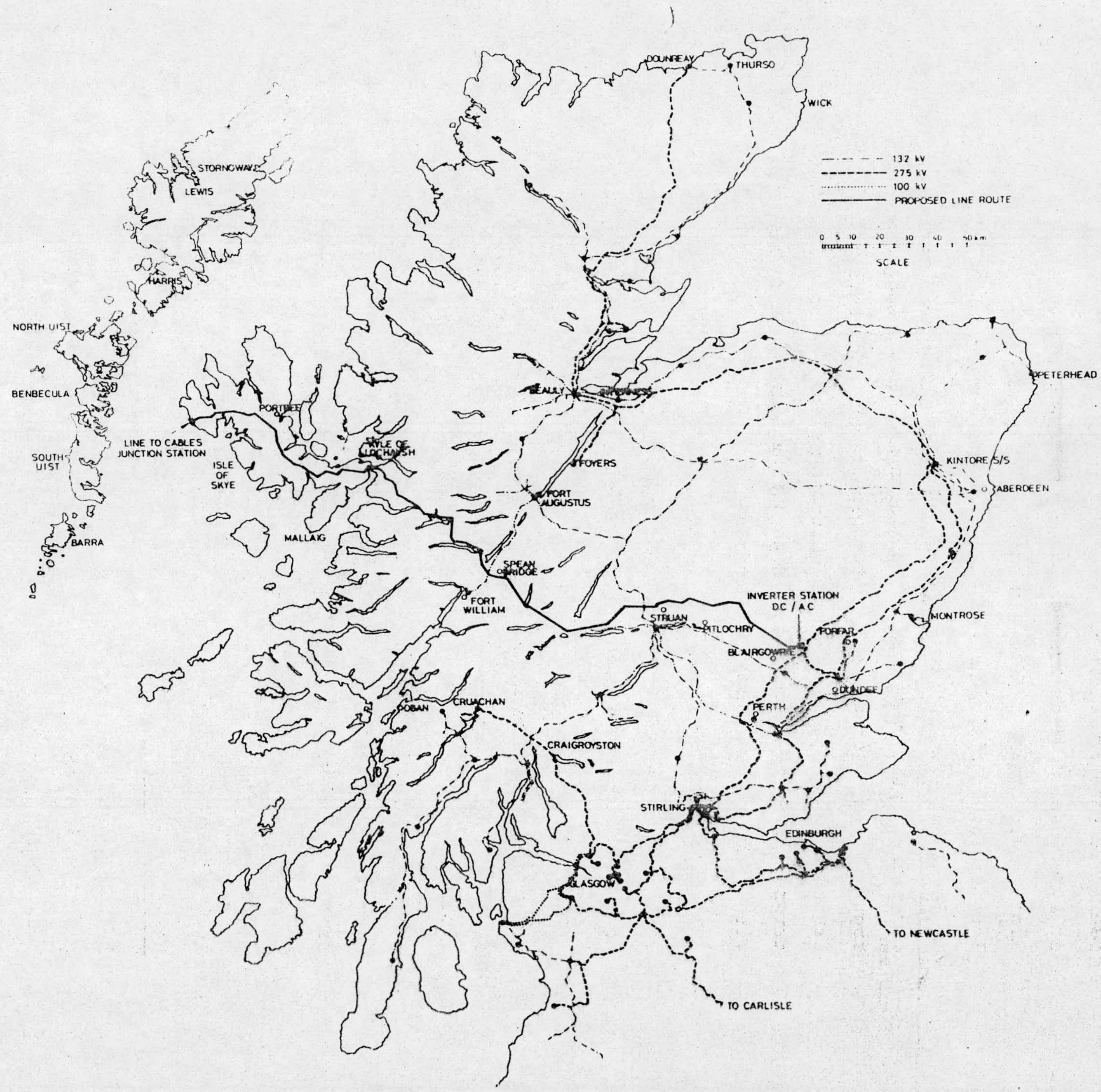
11.5.8 The basic tower design illustrated in fig. 11-7 would be augmented by normal and hillside frame extensions. Separate designs would be prepared for angle positions and for section points.

11.5.9 The overhead line would follow a carefully chosen route through from the cable terminal point at The Hoe on the west coast of Skye to the proposed wave energy inverter station near to the existing mainland 275 kV network in the vicinity of Ruthven to the north east of Perth. The total route length is about 280 km. Details of the route of interest to the NSHEB, the HIDB and local authorities are described and illustrated in a separate Overhead Line Appendix. A summarised definition of the route follows.

11.6 Description of Line Route

11.6.1 It is appropriate to preface the description by explaining that the proposed line route has been examined by site inspection. Particular regard was paid to minimising the impact of the line on the countryside. Natural regard for the beauties of the Highland scenery is considered to have produced a route which is at the same time compatible with limitation of line altitude and total route length but without making the line unduly difficult to construct. The results of this survey are illustrated and described at length in a separate overhead line appendix. In the meantime, please refer to fig. 11-8.

11.6.2 It so happens that the route was investigated in a westerly direction starting from the location of the terminal inverter station in Strathmore - possibly in the Ruthven area some /



WAVE ENERGY PRELIMINARY PROPOSAL FOR 2,000MW H.V D.C TRANSMISSION
OUTER HEBRIDES TO CENTRAL SCOTLAND A.C. SYSTEM

FIG 11·8.

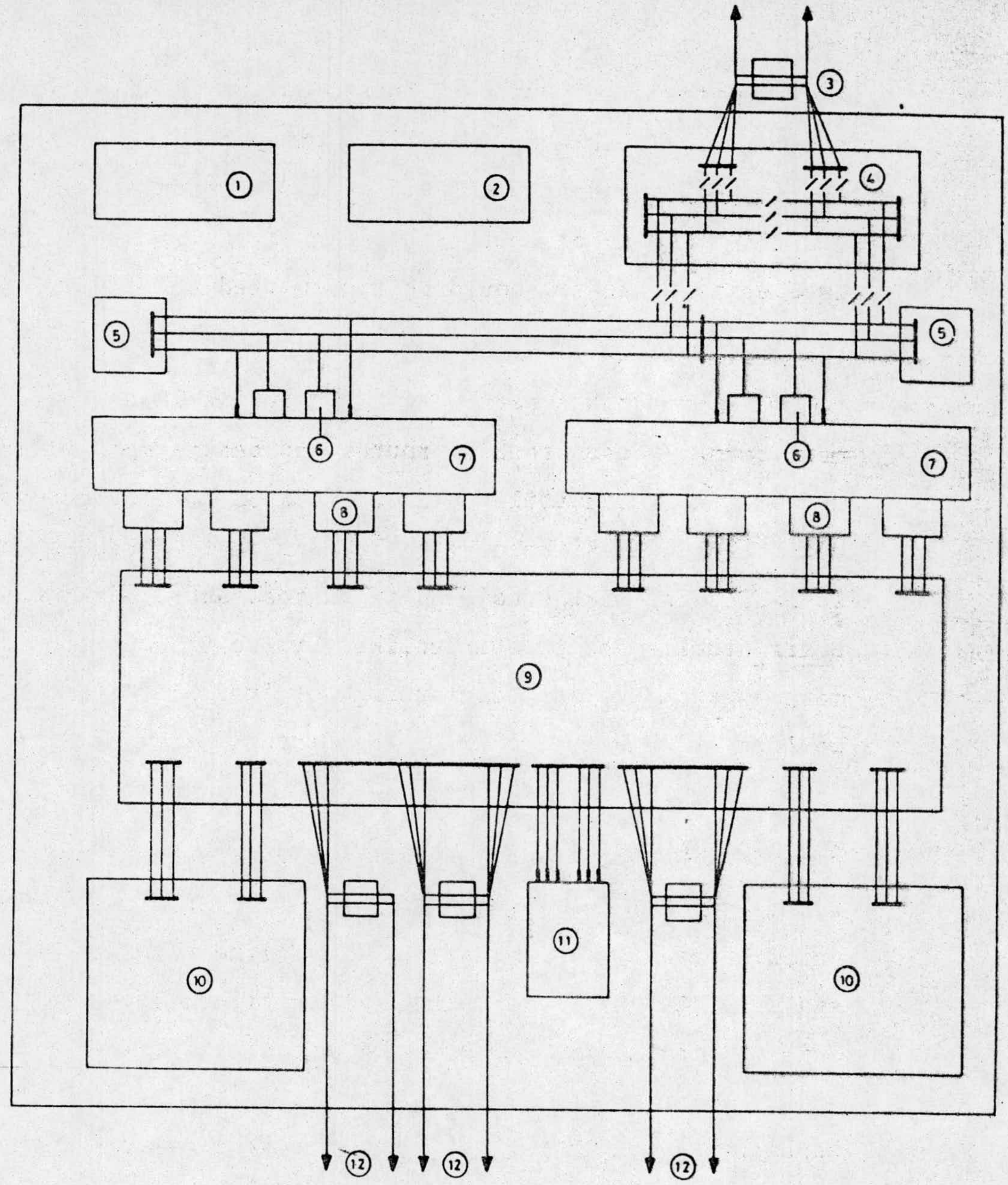
20 km northwest of Dundee. This location is adjacent to two parallel double circuit lines and a tee junction between them on the existing NSHEB 275 kV a.c. system and would be a convenient point of inter-connection from which wave energy, as electrical power, could be transmitted to the load centres of Stirling/Dunfermline, Dundee, Fife and Aberdeen.

11.6.3 Every endeavour has been made to route the line away from the more commonly used tourist routes and beauty spots. From Ruthven the route follows an existing 33 kV line across open country towards Kirkmichael. Turning west the route converges to a crossing of the main A9 trunk road about 12 km west of Blair Athol. The line is unlikely to be visible from the main road except at the crossing, or from Blair Athol which it would pass some 4 to 5 km to the north.

11.6.4 After crossing both A9 and railway, the route follows broken ground with little public vehicular access, to a point halfway along the north shore of Loch Rannoch. Here the road parallels that of an existing 132 kV line from the nearby hydro station. The h.v. d.c. line would continue towards Rannoch Railway Station on the West Highland line, following the direction of the railway to a point south of Loch Treig. The section from Rannoch Station through to Spean Bridge is remote from public access, there being only occasional footpaths near the line route.

11.6.5 Turning north by Spean Bridge, the route crosses the River Lochy and the Caledonian Canal close to Gairlochy before passing between the two lochs by Lochy and Arkaig and continuing along its northern shore for some 12 km. The shoreline and adjacent foothills are tree covered for most of the way and with the line set some distance back from the road, it would only be visible at the few points where tree cover thins out.

11.6.6 From Loch Arkaig, the line route turns north, crossing into Glen Garry and passing close to Quoich dam. From this point westwards the NSHEB are constructing a 132 kV steel tower line between Quoich and Broadford in Skye. The new h.v. d.c. line would generally parallel the recently built section of the 132 kV line via Loch Hourn to the proposed short sea crossing to the Island of Skye at Kylerhea. Through the more rugged sections, it might be necessary to arrange deviations of the 132 kV line since the width of route is restricted and it would be advisable/



KEY

1 CONTROL ROOM

2 MAINTENANCE HALL

3 INCOMING DOUBLE CIRCUIT BIPOLAR HV DC LINE

4 DC SWITCHYARD

5 DC FILTERS

6 DC REACTORS

7 THYRISTOR VALVE HALL (HEIGHT APPROX 20m)

8 CONVERTER TRANSFORMERS

9 AC SWITCHYARD

10 AC FILTERS

11 SYNCHRONOUS COMPENSATORS

12 INCOMING 275kV AC LINES

TOTAL AREA APPROXIMATELY 70,000 m^2

SCALE: 1cm = 20m

POSSIBLE LAYOUT OF INVERTER STATION

FIGURE 11·9

to avoid crossing of the two lines. The crossing of Kyle Rhea would be a little distance to the south of that recently constructed by the Board.

11.6.7 On the Island of Skye there is less tree cover and it is consequently more difficult to screen the line from all points of public access. Nevertheless, care has been taken in routing the h.v. d.c. line so as to minimise the impact on the scenery: this by passing through areas remote from public access, here paying greater regard to amenity than the practical problems of line construction. A practical suggestion is that where towers are unavoidably visible from the principal roads used by tourists, they might be painted a neutral colour so as to blend more readily with their background.

11.6.8 The h.v. d.c. line would reach its western termination at a small switching station and cable circuit terminal on a flat site in the lee of Hoe Point adjacent to Ramasaig and Lorgill Bays on the Duirinish coast. The area is very remote and it would be necessary to extend the single narrow access road to the site.

11.7 Inverter Station

11.7.1 Power received at ± 250 kV d.c. from the 2 GW wave energy system off the Outer Hebrides would be changed back to an alternating current supply, probably at 275 kV, at a large inverter station to be located, as previously described, near Methven. The general arrangement of the inverter station and its approximate dimensions are shown in fig. 11-9.

11.7.2 There would be two separate 1000 MW inverter plants, one for each incoming d.c. circuit. In addition to the inverter equipment, there would be transformers with winding connections appropriate to 12 pulse inversion. Also switchgear and protection for the outgoing 275 kV feeder circuits which would distribute the wave energy into the Scottish national power system.

11.7.3 It is proposed that the inverter should use thyristor valves, probably of the air insulated, air cooled type. Each pole of the inverter would include a 12-pulse bridge using 3 'quadrivalve' /

assemblies. Each valve might have a rating of 150 kV and 2000 A.

11.7.4 The inverter valve hall would be of considerable size, being 16 m wide x 18 m high x 200 m long. It would contain four 12-pulse poles each pole having three quadrivalves mounted vertically. The arrangement proposed would be similar to that already being used successfully on the Skagerrak h.v. d.c. inter-connection in Scandinavia.

11.8 Control System

11.8.1 The philosophy behind the design of a control system for a large 2000 MW wave power system including collection and long distance transmission of the output would be based on the following principles -

1. Each design should be self protecting and self controlling and only subject to overriding signals to start up or shut down.
2. It is axiomatic that control should be exercised so as to maximise the energy productivity of the devices.
3. The generators to have rapid response excitation in the interests of stable system operation and fault current limitation.
4. The bipolar inverter should operate so as to minimise the out-of-balance current in the mid-point conductor.
5. The Scottish mainland system shall be regarded as fully receptive to all wave energy input.
6. The plant associated with the wave energy system being so extensive should be automatically monitored by a comprehensive data acquisition system.

11.8.2 The generator/rectifier loop operates on the principle of steady current circulation but variable generator voltage. Excitation voltage thus reflects mechanical power input to the generator shaft if the speed is kept sensibly constant. The actual current taken by each machine would be determined by the requirements of the particular pole of the d.c. transmission system being commensurate with the total transmitted load.

11.8.3 Control of the inverter would be such that for any given direct current, the rectifier pole voltage would be determined by /

the net power input to the associated group of devices. The inverter pole voltage could be set to any value by means of tap-changers on the transformers and adjustment of the thyristor firing angle. The direct current would then be determined by the difference between rectifier and inverter voltages and the circuit resistance. A complete control loop would be established with inverter voltage as a controllable variable. To run the transmission system at maximum efficiency it would be essential to keep the system voltage close to the rated $\pm$ 250 kV.

11.8.4 It is a practical circumstance that the net power outputs of the groups connected to positive and negative poles of the rectifier will not be identical as a result of local variations in the mean sea state and possible outages of devices. It would be necessary to balance the current in each pole in order to eliminate mid-point return current - particularly if there were any likelihood of this being transmitted as an earth return current. This automatic current balancing feature of the inverter could be achieved by making one pole the 'master' voltage and the other a 'follower' voltage, automatically adjusted to equate the two currents.

11.8.5 In the event of a fault on one pole of a circuit, e.g. on one line conductor, the control system should first limit the overcurrent to about 1.2 p.u. and then trip the generators associated with that pole. The other pole would continue to operate at rated power using the mid-point return conductor. In the example quoted the reduction would be from 1000 MW to 500 MW. With a fault on one of the Little Minch submarine cable circuits, however, the reduction, pending fault repair, would be from 500 MW to 250 MW.

11.8.6 Assuming that a central control station is established at the inverter - or receiving end of the system - it would be necessary to establish communications with the proposed 8 platforms (or their landward equivalent in the case of the HRS device) and probably also the main switching points. These could be implemented by power line carrier over the $\pm$ 250 kV d.c. transmission line circuits, and by suitable means over the d.c. submarine cables. Radio communication in the u.h.f. band would /

also be necessary as back-up. Data transmission together with coded operational instructions and v.f. telephony would be required. The control link between platform and devices would normally use device specific telecommunication circuits included within the flexible submarine cables. These links could be of the coaxial or fibre-optic types. Again, there would be back-up radio links between platform and device. It is foreseeable that sophisticated control instructions and data acquisition might be handled by microprocessors.

11.8.7 The long term viability of a large wave energy system relying on relatively inaccessible seaward devices must depend on extensive condition monitoring, data acquisition and programmed maintenance work. It would therefore be advisable to include means for the remote monitoring of the equipment on the devices, of that on the converter platforms and of the main transmission system through to the inverter station at the wave energy delivery point.

CHAPTER 12 - RELIABILITY

12.1 INTRODUCTION

Any wave power system will consist of large numbers of components linked together and interacting with each other. These components will be subject to failures and the purpose of reliability studies is to examine the effect on the total system of such individual breakdowns. In this way it is possible to identify those areas which are most crucial to the operation of the system and to measure the effect of improving component reliability in terms of increased overall power output. In the future these studies will also provide basic data for estimating maintenance costs and for optimising the maintenance strategy.

The optimal amount of reliability built into the various components is of course an economic question. The marginal cost of added reliability should be equal to the marginal benefit. At this stage, however, the available data is insufficiently precise for making such economic judgements and the studies have been restricted to assessing the probability distributions of power delivered to the Grid under various reliability assumptions and transmission configurations.

The crudeness of the data is due in part to the novelty of some of the technology used and in part to the unusual environment in which conventional equipment will be expected to operate. Many of the components are obviously not yet clearly specified or designed.

The method of analysis has been kept as simple as possible. It involves predicting the availability associated with individual components, and combining these to model the output of the system under the various combinations of failures that can occur. The model allows for the fact that in the winter months repairs will not be carried out on submarine cables or on equipment installed in devices, due to adverse weather conditions. It also allows for different levels of power being generated. Obviously, an outage in the transmission system will be most serious when it is under full load.

The calculations have been based on a notional wave power generation scheme of the floating type (e.g. WPL, NEL, etc.) with individual generators of 2.5 MW each, connected by flexible A.C. cables to platform structures containing diode rectifier equipment. The total rating of the complete scheme is taken as 2 GW.

No attempt has yet been made to compare the relative reliabilities of the various proposed devices, as detailed information on the design of each has not been available. This very important aspect of the studies will proceed as more firm designs are obtained for the different devices.

12.2 AN OUTLINE OF THE NOTIONAL SCHEME FROM THE RELIABILITY VIEWPOINT

From the prime mover on the device to the diode rectifier on the platform there are a number of components all connected in series. These include the turbine, generator, transformers, auxiliaries, 22 kv flexible cable and various items of switchgear. If any of these are out of action the device cannot transmit power. Repairs cannot be carried out on this equipment during the winter season with the exception of one of the transformers and the diodes which are situated on the platform. In the case of a failure of an individual device a loss in capacity of 2.5 MW occurs. A failure does not affect other devices.

From the platform to Uist, the effects of installing redundant transmission circuits have been investigated. The alternatives are submarine cables connecting the platform to Uist directly and inter-connecting adjacent platforms. They are rated at 1,000A and 500A respectively. Thus, if a direct route cable fails, power can be transmitted via another platform as long as the link cable and that platform's direct cable are in operation. The terrain in this area is rocky and it seems unlikely that these cables will be able to be buried.

From Uist to Skye the sea bed is such that burying cables may be a more likely proposition. There are four sets of two-pole and neutral cables each with a rating of 500 MW and when one cable of a set fails the capacity of the transmission system is assumed to be reduced by 500 MW. These studies have examined the improved reliability that will be brought about by burying cables or by laying a third set on each route of this crossing.

The overhead line section from Skye to Perth consists of a double circuit bipolar D.C. line with neutral conductors. If the positive or negative conductor of one circuit fails, the capacity of that circuit is reduced to 500 MW, with conduction continuing through the healthy pole and neutral.

Finally, there are two independent bipolar invertor stations each rated at 1,000 MW, and the loss of a single pole reduces the potential output by one quarter.

12.3 METHOD OF ANALYSIS

The basis of the model is that each component in the system always resides in either of the two states, operative and failed. The system outcome (that is, the power delivered at Perth) depends on the input power and upon the state of each of the components.

The rate of entry into the failed and operative state is termed the failure rate (λ) and the repair rate (μ), respectively.

defining q-probability of component being in service (operative)
p-probability of component being out of service (failed).

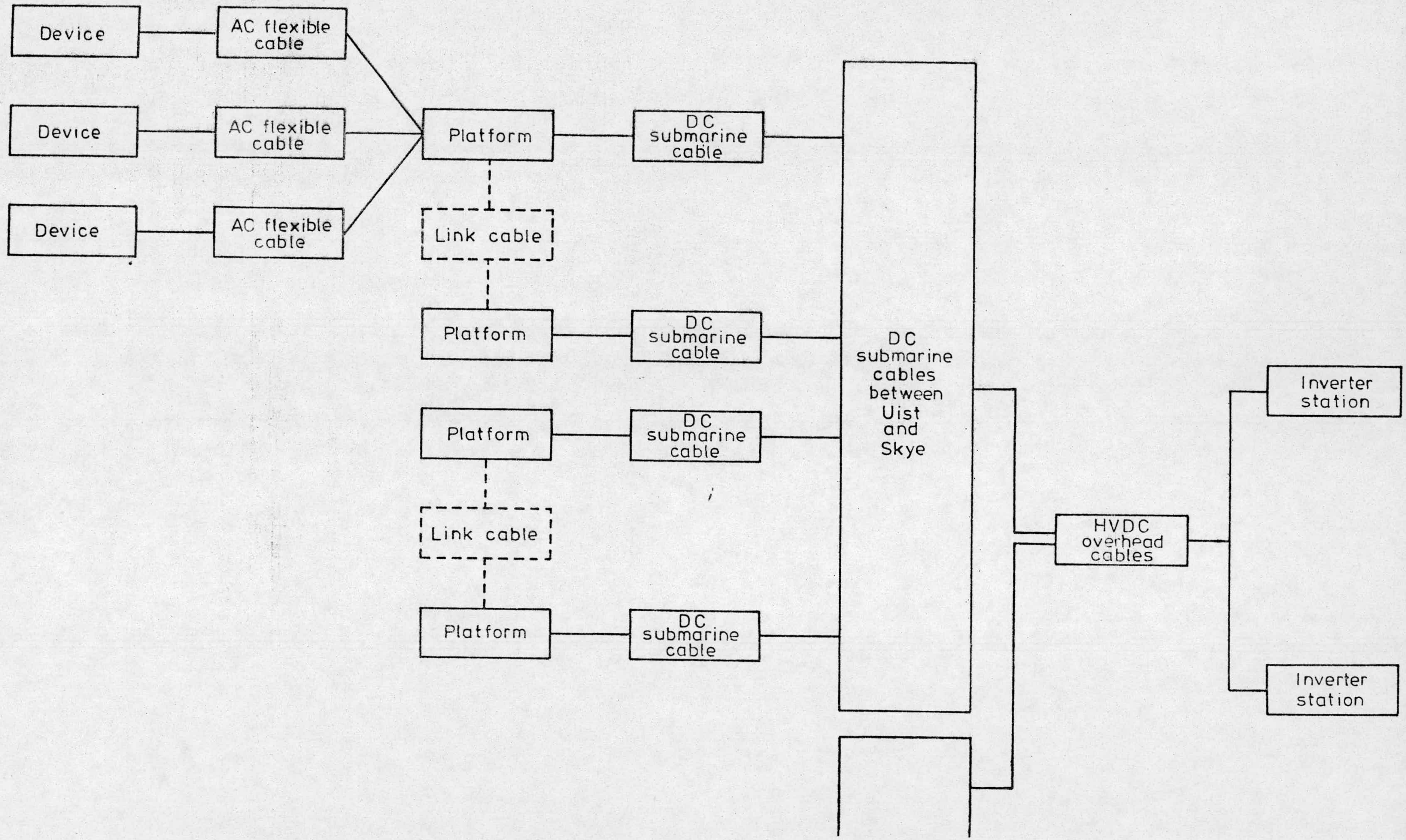
under steady state conditions:

$$q = \frac{\mu}{\lambda + \mu} \qquad p = \frac{\lambda}{\mu + \lambda}$$

Over a sufficiently long period of time, the probability of a component being in service approaches the expected proportion of time for which it will be in service. This is termed the availability of the component.

Over the whole system there are a very large number of combinations of component states. They can be reduced considerably, however, by taking into account the symmetry of the layout. For example, there are eight hundred identical devices, two identical overhead line circuits, etc. For this reason the calculation process moves through the system, computing the load probability distribution at various points, until the final load point, where the system enters the grid, is reached.

A computer program was written to calculate the probability distributions. The order in which they are calculated is as follows:-



BLOCK DIAGRAM OF NOTIONAL 2GW SYSTEM

FIGURE 12.1

a) the output of a single device.
b) the output of one hundred devices connected to a platform.
c) the output of four hundred devices at one S.Uist switching station.
d) the output of eight hundred devices at Skye switching station.
e) the output of eight hundred devices at Perth invertor station.

The input of the program consists of the probabilities (q) for each type of component in the system. For some components this probability varies throughout the year due to the inability to carry out repairs during adverse weather conditions. In particular this is true for components on board devices and for submarine cables.

For these components it is assumed that each year can be divided into two basic segments, a four month adverse weather period and an eight month 'summer' period. In the former no repairs can be carried out on devices and cables while in the latter the repair operation may commence as soon as a failure occurs. The time dependent probability equations can be derived for each month of the year.

In all calculations we have ignored planned outages due to routine maintenance. The reason for this is that they will be carried out during periods of low power output when the transmission system will have considerable spare capacity. Our assumption, therefore, is that such operations will not affect the capacity of the system to any significant extent. The routine maintenance of on-board equipment may have more effect but will presumably be programmed so that a fairly constant low proportion of devices are out of service at any one time.

12.4 DATA COLLECTION

Suitable data has had to be collected for components operating in different environments. These include components working on the devices themselves and off-shore platform installations, LVAC and HVDC submarine cables, and conventional HVDC overhead transmission lines ashore.

Data for each component is usually given in the form of an average failure rate and an average repair time. These have then been used to obtain an expression for availability (Q) or unavailability (P) as described in the previous section.

Valuable information and advice have been obtained from the following authorities:-

a) Wave Energy Technical Advisory Groups.
b) North of Scotland Hydro-Electric Board.
c) Reliability Engineering Group, C.E.G.B. Barnwood.
d) Department of Fleet Maintenance, Ministry of Defence, Foxhill, Bath.

Using this information as a basis and exercising reasonable engineering judgement, a list of data was prepared. This data is summarised in Table 12.1.

For all equipment on devices it is assumed that there is a 4 month period of adverse weather conditions during which repair is impossible on component outages. The basic data used is for those conditions when repairs can be carried out immediately, with the restricted repair effects being modelled by the program.

Group	Location	Component	Average Failure Rate λ (fails/yr)	Average Repair Time (hrs) 1/μ
1	Wave Energy Device	All mechanical components up to generator shaft Generator Switchboard Transformer	0.25 0.20 0.01 0.02	144 144 144 144
2	Sea-bed	A.C. flexible cables (unburied)	2/100km/ year	1000
3	Off-shore Platform	Rectiformer unit Vital auxiliary equipments affecting complete platform output	0.02 0.05	48 240
4	Sea-bed	D.C. cables/set Buried Unburied	 0.3/100km/ year 2/100km/ year	 2000 1000
5	Mainland	HVDC Transmission Line	1/100km/ year	48
6	Inverter Station	Inverter pole	6	30

<u>Note:</u> Repair time for items on device consists mainly of waiting time, assuming that limited resources are available.

<u>Table 12.1</u>

Faults in submarine cables include armour, sheath and joint failures due to corrosion and ship's anchor damages, insulation failures due to lightning and switching surges, overloading, etc. According to the North of Scotland Hydro-Electric Board's experience, the majority of the failures are caused by corrosion and anchor damages rather than by electrical causes. A.C. flexible cables will, in addition, be susceptible to wearing and abrasion due to the frequent movements of cables and joints. There is also a distinction between buried and unburied types of submarine cables. The mean failure rates of cables in the former case are much lower than the latter case. The mean repair time of the latter is, however, shorter because of the ease of recovering unburied cables for repair purposes. As with the devices, cables have a restricted repair period.

The data referring to platforms assumes that rectiformer units can be rapidly replaced with spare units by a mobile repair team.

Operation experience of HVDC installations indicate that HVDC and HVAC transmission lines are subject to the same order of failures. Most failures are caused by insulator pollution and adverse weather effects. The data given is based on information from the North of Scotland Hydro-Electric Board (mainly on HVAC systems) and from CIGRE Publications. This data is for sustained line outages as active failures involving switching actions are not considered.

Finally, at the invertor station modern thyristor valves are expected to be much more reliable than mercury arc valves. As there is yet little performance data available on thyristor valve convertors, data for the mean failure rate and repair time have been extrapolated from available performance data on existing convertor stations of both types.

Refinement of data is still necessary, especially as design stages are developed further. There are a number of possible sources still to be consulted, including the U.K. System Reliability Service. In addition, some of the sources already mentioned are still in the process of collecting suitable data for our purposes.

12.5 RESULTS

A number of computer runs have been carried out to investigate the reliability of the system under different loads and with various configurations of components. As already explained the performance of the system varies throughout the year. Our results refer to the best and worst cases, that is, the times just before, and at the end of, the four month no-repair period. It must be emphasised that this worst case only applies to a very short period of the year, and is therefore not the average winter condition.

The base configuration is that in which the least provision has been made on the submarine cable runs. It assumes that they are not buried in trenches and also that no standby cables have been laid. This leads to a large reduction in output and alternative ways of reducing this have then been examined.

To illustrate the seasonal variation in the availability of components, Figure 12.2 shows the probability of a single device being out of service at various times throughout the year. When a large number of devices are considered together, this is equivalent to the average proportion of those devices that will be out of service at any given time, and hence the average proportion of power that will be lost in this part of the total system. It can be seen that the probability ranges from 1% to 15%.

Figure 12.3 shows the complete probability distribution of power output in the two cases before and at the end of the no-repair period. They assume that 2,000 MW would be output if there were no components out of service. These distributions refer to the base case and their shape is dominated by failures in the submarine cables.

Figure 12.4 shows the average proportion of power lost due to breakdowns in the various sections of the system. These are again for the base case and are for different levels of potential output. At the end of the no-repair period the losses occur mainly in the devices themselves (15% of the potential output), and in the two submarine cable runs (12% and 16% respectively). When repairs can be effected immediately the devices become much more reliable and most of the losses are due to submarine cable faults. In both cases it can be seen that the HVDC overhead lines caused very small losses. Altogether, an average of 49% of the potential power is lost at the end of the no-repair period and 17% at the start of this period.

In an attempt to improve the situation in the submarine cable runs, a number of ways were investigated of increasing the reliability of the two sections. Table 12.2 indicates the results obtained.

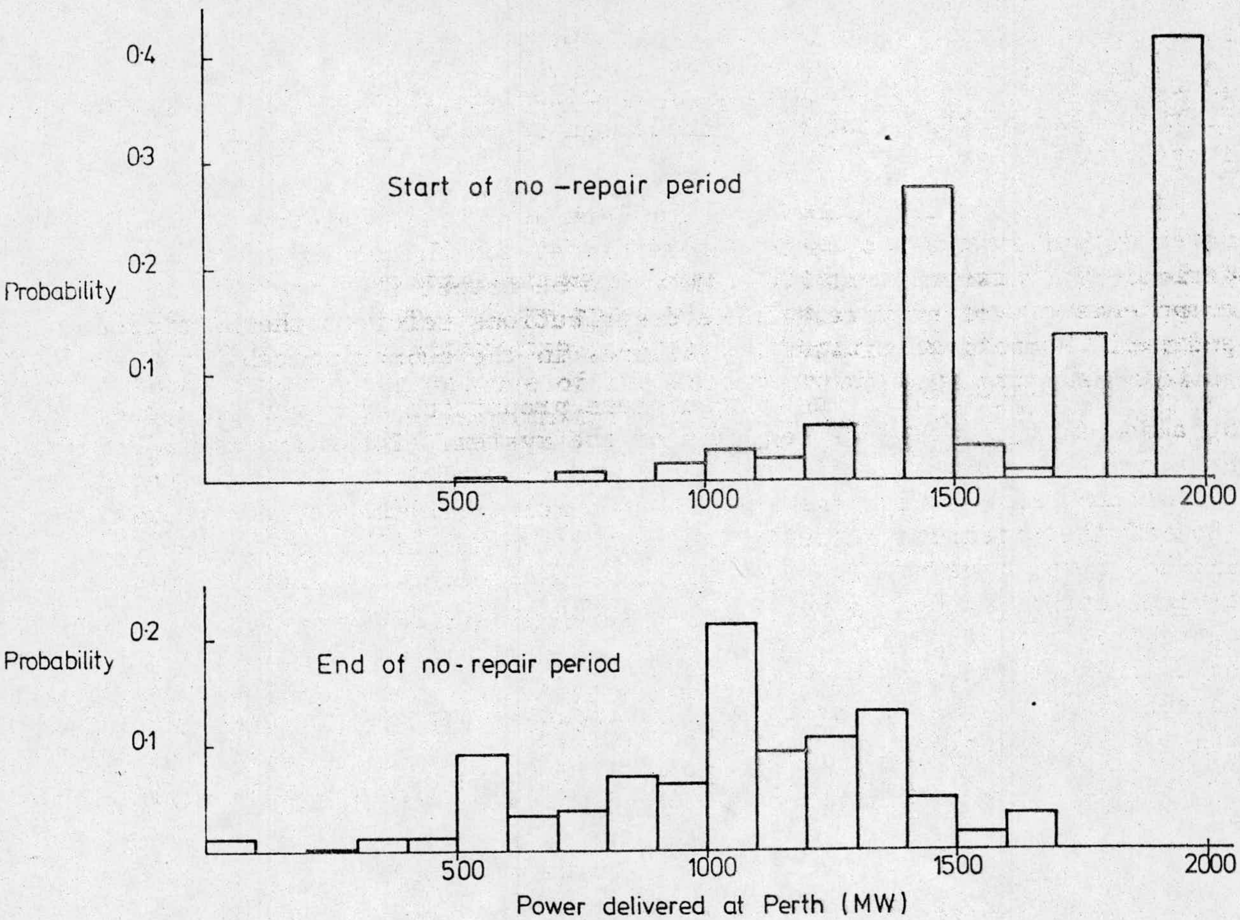
Installing additional cables between pairs of platforms to provide alternative routes between them and S. Uist makes a small reduction in the size of the losses. When in conjunction with this measure, additional standby cables are installed between S.Uist and Skye or the original cables are buried, the reduction in losses is more marked. Of these two ways of increasing reliability on the S.Uist to Skye run, burying the cables appears to be marginally the best though it will probably be the more expensive of the two options.

12.6 CONCLUSIONS

The data that we have used in this study is naturally approximate. However, a number of important points emerge from the analyses that we have carried out.

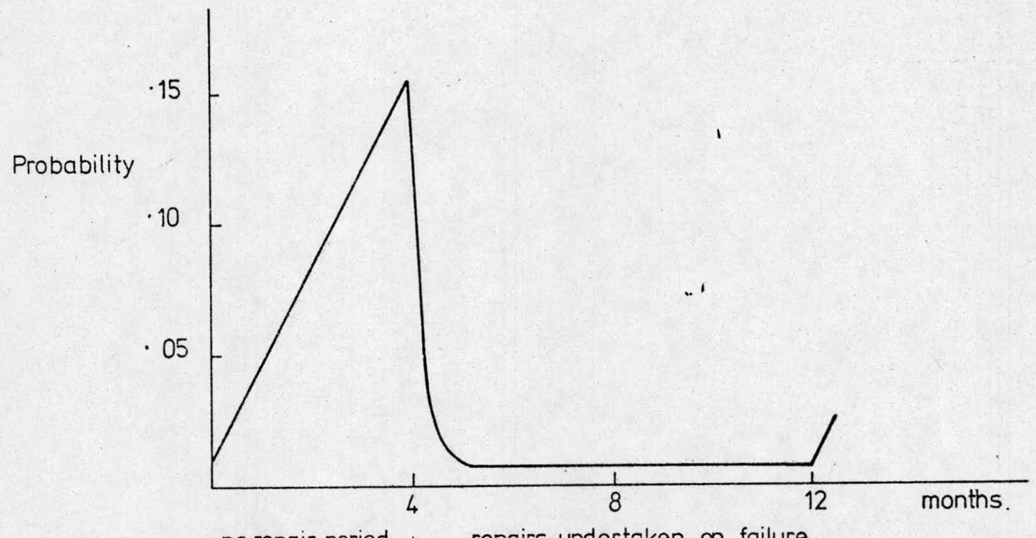
Firstly, the effect of the assumed four month period in which no repairs can be carried out is considerable. The average proportion of power that is lost due to component failure is about 17% at the start of this period and rises to 49% by the end. These figures, however, refer to the base case and when standby cables are installed on both submarine cable runs the equivalent figures are 7% and 32%. These figures are still on the high side as they refer to times when the system is under full load, i.e. when 2,000 MW would be delivered to Perth if all the components in the system were functioning correctly. When under half load the average proportion lost would be 5% and 26%. Much of these losses can be attributed to components on the devices themselves. If some repairs can be made to these during brief intervals of calm weather during our assumed no-repair period, this would increase the power output.

It is important to note that our analysis is based on a notional scheme with floating devices generating power which is transmitted to platforms and thence to the shore. Thus it does not cover the HRS device. It is assumed that this will be more reliable as components will



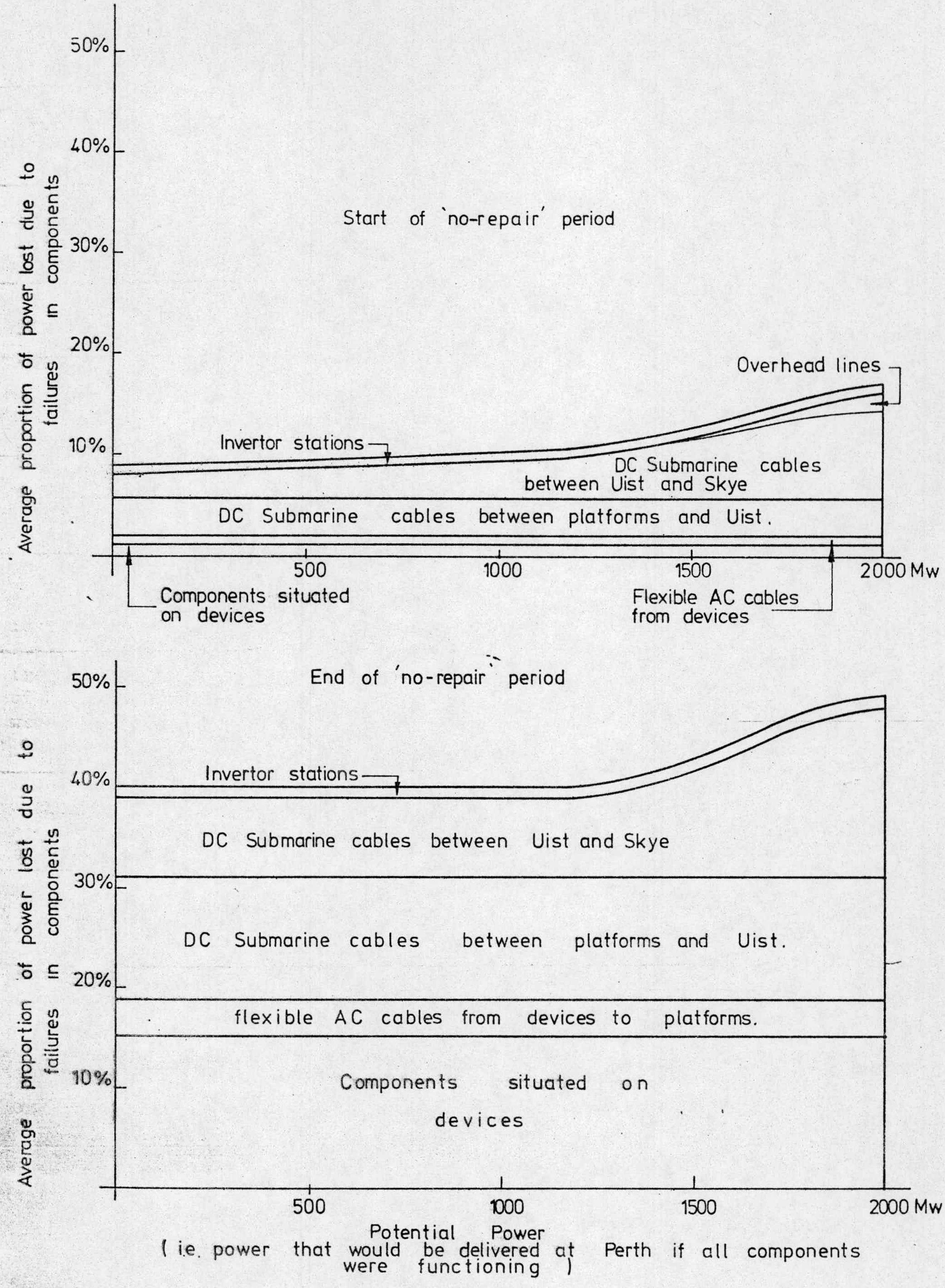
THE PROBABILITY DISTRIBUTIONS OF POWER DELIVERED AT PERTH ASSUMING THAT 2GW WOULD BE DELIVERED IF ALL COMPONENTS IN THE SYSTEM WERE FUNCTIONING

FIGURE 12·3



THE PROBABILITY THAT A DEVICE IS NOT FUNCTIONING

FIGURE 12·2



THE AVERAGE POWER LOST IN VARIOUS COMPONENTS OF THE SYSTEM UNDER DIFFERENT LOAD CONDITIONS.

(THIS REFERS TO THE BASE CONFIGURATION, THAT IS, BEFORE ANY REDUNDANCY IN CABLES IS INTRODUCED.)

FIGURE 12·4

System Configuration	At end of 'no-repair period		At start of 'no-repair period	
Potential power (i.e. assuming all components functioning)	2000MW	1000MW	2000MW	1000MW
'Base' configuration	1030MW	600MW	1660MW	910MW
With cables between adjacent platforms	1120MW	690MW	1720MW	950MW
With one redundant set of cables on each route of Uist-Skye run	1210MW	650MW	1800MW	920MW
With buried cables on Uist-Skye run	1280MW	670MW	1770MW	920MW
With cables between platforms and redundant cones between Uist and Skye	1360MW	740MW	1860MW	950MW
With cables between platforms and buried cables on Uist-Skye run	1440MW	760MW	1830MW	950MW

Table 12.2 Mean power delivered at Perth under full and half load for various tranmission configurations

be more accessible for repair in the winter months. In addition, the equipment on this device will operate in a fixed environment and there will be no need for flexible A.C. cables.

Our analysis does not effectively cover the SEA device either as the design of the ducks is such that replacing components even during the summer months, may not be possible. This leads to a rather different design philosophy with added redundancy or highly reliable equipment, which on failure, will not be replaced until the whole string is towed away for maintenance.

12.7 FURTHER WORK

Systems analysis and particularly reliability studies, will play an important role as the design process continues. In this respect Device Teams may consider using the sort of methods outlined in this report. Such calculations need not entail modelling the whole system but can be used to compare different types and configurations of equipment installed upon devices. There will possibly be scope for optimisation techniques to establish the most economic system and thus to set reasonable standards for manufacturers and designers of equipment.

The chief limitation of the work described here is that the analysis is a static one considering only the availability of components in the steady state situation. The next step is to consider the system dynamically. This would enable the assessment of the duration and frequency of various types of outage which in turn would indicate the sort of maintenance effort that will be necessary and also the way in which a wave system would be incorporated into the national electricity grid.

Apart from refining the models, the quality of the data needs to be improved. This will be an ongoing activity, reflecting changes in equipment as well as new operating experience gained in other offshore areas and HVDC transmission systems.

CHAPTER 13 - ANNUAL PRODUCTIVITY OF WAVE POWER DEVICES

13.1 INTRODUCTION AND SUMMARY

In this Chapter the Consultants' assessment of the productivity of each Device is given. As far as possible this is intended to represent the total energy produced in a typical year from a long string of devices of the form of the 1978 Reference Designs. A location off the West coast of the Outer Hebrides is assumed in water 50 m or deeper, or as appropriate for bottom sitting devices. The line of the devices is assumed to run approximately North-South.

In the final section 13.5 the variation of productivity with size and its bearing on cost effectiveness is discussed.

The main factors affecting productivity are as follows:-

a) Wave climate - power in the sea and its distribution with respect to wave period and wave height.

b) Direction from which the wave power comes.

c) Efficiency of the device in capturing wave power, in various sea states, coming from various directions.

d) Efficiency and maximum capacity of the power chain which converts and transmits the energy captured.

e) Reliability of devices and plant.

Previously no assessment has been made taking all of these factors into account, partly because of the lack of basic information on each subject. However the Consultants believe that in spite of the incompleteness of some of this information, some reasonably well-founded statements can now be made concerning the productivity of most of the devices. A two stage approach has been adopted using computer analyses. Firstly detailed calculations were made of the annual output of the Reference Designs operating in the Reference Climate on the basis that the wave direction was perpendicular to the line of the devices. These computations were based on the best currently available laboratory data and estimated characteristics of each link of the power chain. The device response and plant mean power levels were considered for each sea state and the results accumulated over a one year period. In the second stage of the analysis, further factors were introduced to take account of other effects (such as directionality) which modified and refined the results from the first analysis. At the same time, estimated bounds were introduced for all the parameters and the factors were combined using a simple probabalistic model. The results are given in Table 13.1.

13.2 WAVE CLIMATE DATA

13.2.1 BASIC DATA

Early U.K. wave power studies generally referred to mid-Atlantic Station India data. TAG 2 recognised that this data was recorded too far from the U.K. coast to be reliable for predictive purposes, and a wave recording buoy was commissioned and installed off South Uist in 40 m of water 15 km offshore (see Drawing WP78/OWC/2). Data collection commenced in November 1976. So far two years data have been analysed by the Institute of Oceanographical Sciences. However, wind records show that both years were untypically mild. A weighted sample of the records was therefore prepared by IOS from the first year's data, this being referred to as the 76-77 South Uist Selected Spectra (reference IOS Report No.1). Shortly before writing this report, the second year's data also became available and another set of spectra was selected from the full set by Mollison using a different method. The various annual average power levels, measured and predicted, are compared below.

Data from	Annual Av. Power Level	Source
Nov.'76 - Oct.'77	31 kW/m	IOS data from buoy
Nov.'77 - Oct.'78	40 kW/m	IOS data from buoy
Nov.'76 - Oct.'77	42 kW/m	Selected set - IOS
Nov.'76 - Oct.'78	38 kW/m	Selected set - Mollison

*plus perhaps 4 kW/m to correct for most severe storms

It can be seen that the two corrected results are very close and it is hoped that the average power for the site is fairly reliably established. The most likely errors are the prediction for the power in the most severe storms. These would tend to make extrapolations from data for mild years slight underestimates of the true value, but in all storms above a certain level devices produce power at maximum capacity. Therefore predictions of device productivity will change very little due to these errors.

It should be emphasised therefore that the Uist climate appears to be very much less severe than Station India - about 42 kW/m annual average compared with about 75-80 kW/m.

The most important question remaining seems to be how site specific the South Uist data is, and whether the climate in adjacent waters of 60-100 m depth (for the floating devices) is significantly more favourable. The site of the buoy may be untypical of the deeper water sites for the floating devices for the following reasons:

a) Energy losses due to bed friction.

b) Shelter from the North by the Monach Islands.

c) Refraction in the shallower water will affect wave direction for the longer period waves.

However, even at the shallow depth there will not be a significant loss of energy due to depth-induced wave breaking.

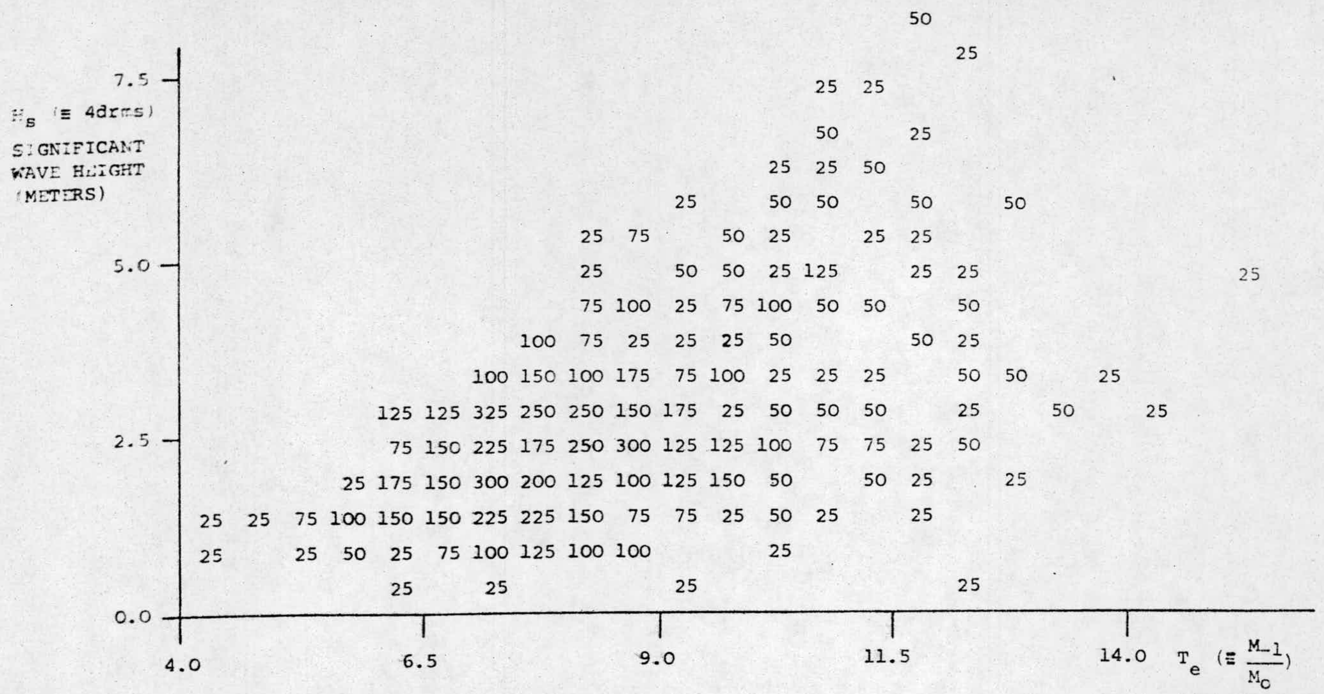
Concerning a), data on the rate of loss of wave energy due to bed friction in shelving waters in the context of the previous exercise is not available. It is commonly disregarded in engineering design for transitional water depths.

The second and third points, b) and c) are discussed in 13.4.

The Reference Climate scatter diagram, based on the IOS 76-77 selected spectra is given in Figure 13.1.

13.2.2 WAVE DIRECTIONS

No directional wave data has been collected off the west coast of Scotland. Ideally for each sea state the mean direction of the local wind generated and swell components are required, together with



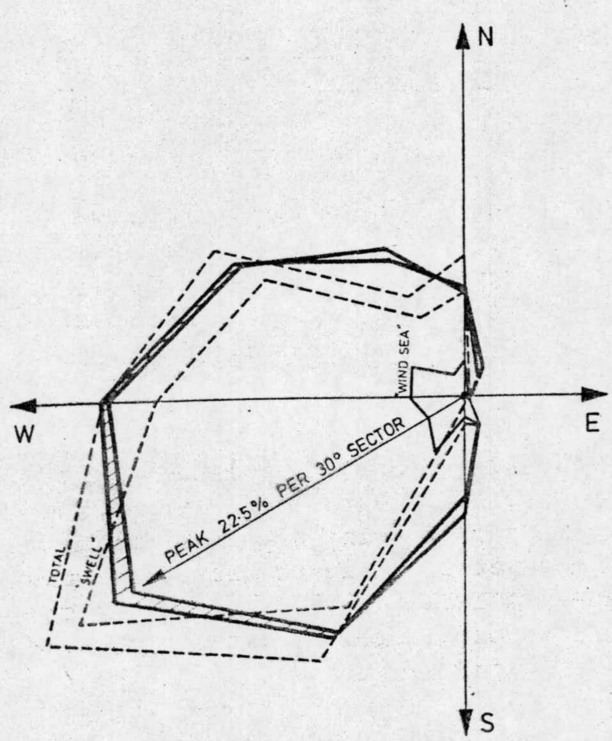
Data from IOS report 1

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

Fractional occurences in parts per 10,000.

REFERENCE CLIMATE SCATTER DIAGRAM

FIGURE 13·1.

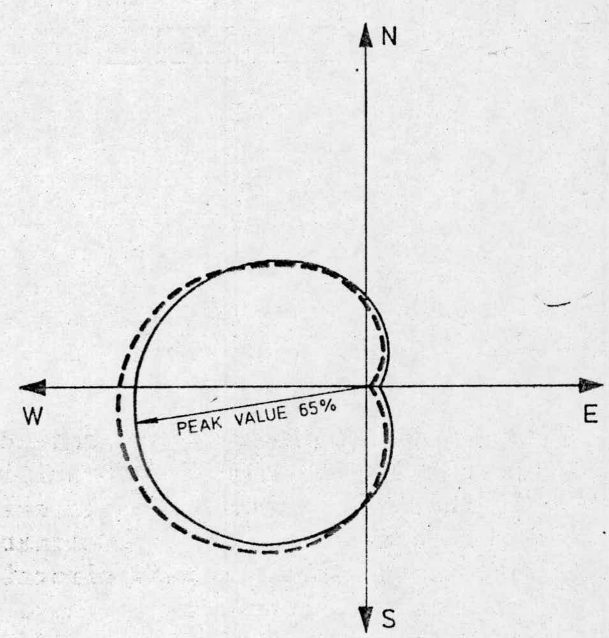


---- UNIDIRECTIONAL WAVES ASSUMED

—— SPREADING FUNCTION* $\cos^4$ & $\cos^7$ ASSUMED

BREAKDOWN OF TOTAL WAVE POWER AS A FUNCTION OF DIRECTION – MET. OFFICE SIMULATION NOV. 77 - FEB. 78

FIGURE 13·2.



--- UNIDIRECTIONAL WAVES ASSUMED

—— SPREADING FUNCTION INCLUDED

PERCENTAGE OF ANNUAL WAVE ENERGY AVAILABLE TO A LONG STRING OF DEVICES AS A FUNCTION OF DEVICE HEADING

FIGURE 13·3.

information on the directional spread of each component. In practice very few records have been analysed in such detail anywhere in the world. In engineering design, wave direction is commonly associated with wind direction and directional spread is ignored. For the South Uist site, with negligible fetch to the east, these assumptions are very questionable.

The only rational information currently available is that produced by the large scale computer model of the North Atlantic prepared by the Meteorological Office using finite difference methods. This model simulates the generation and radiation of wave fields through time and space using daily wind records and a very simplified coastline model. This work is still in the experimental stage and the absolute values of particular sea states are not accurate. However, there is reason to hope that the long term average of the distribution of power from various directions should be reasonably representative. The model differentiates between swell and wind sea components, but the distinction may not be identical to that which would be used in describing a monitored sea state. Mollison (reference WESC/78) has calculated the power distribution from the results of the M.O. program for the four months November 1977 to February 1978. These are plotted in Figure 13.2, firstly taking the results as they stand, and secondly assuming that each component will, in fact, have been associated with a directional spreading function. The results are seen not to be relatively insensitive to the form of the spreading function used.

The incorporation of this directional information into the productivity assessment is described in 13.4. Due to the siting of the S. Uist buoy, it has been assumed that the majority of the 6 to 8% of power coming from the north did not reach the buoy.

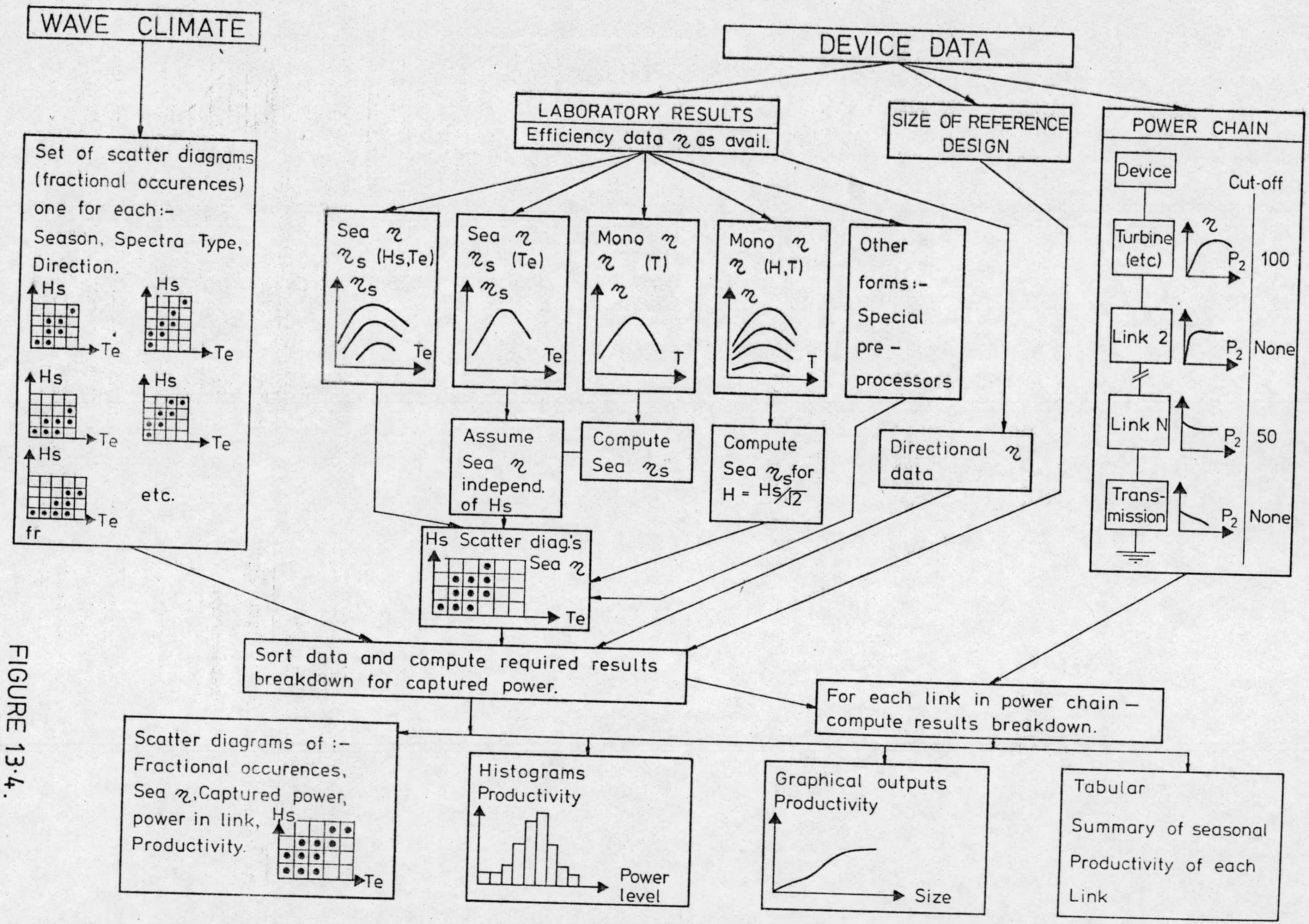
13.3 DETAILED CALCULATIONS FOR THE REFERENCE DESIGN OPERATING IN THE REFERENCE CLIMATE - FIRST STAGE ANALYSIS

13.3.1 GENERAL

The procedures used are best described by the simplified flow-chart, Figure 13.4, which is the basis of a computer program written to make the best use of the data available. The type and extent of the data varied considerably between Device Teams. It was necessary to use several computational procedures, particularly in constructing the full set of sea efficiencies required to cover the Reference Climate scatter diagram (see 13.3.2)

Because of the absence of data in several areas, full use cannot yet be made of the facilities built into the program as described in the flow-chart. A single scatter diagram of fractional occurrences was used to describe the wave climate. It is not yet possible to differentiate between seasons, compass directions and spectra types, although sensitivity studies have been made in these areas. One important result established by Mollison (reference WESC/78/) is that for a given set of numerical spectra, the annual productivity predicted using Pierson-Moskowitz spectra with the correct values of Hs (defined here as 4x d_{rms}) and Te, is nearly identical to that obtained from the original spectra. The Consultants have therefore used this procedure in their assessment.

The lack of data regarding the ability of long strings of devices to accept energy from various directions was a further reason for not including directional sea data in the first stage of the analysis (see also 13.4.2).



PROGRAMME FOR ASSESSMENT OF POWER LEVELS AND PRODUCTIVITY STAGE 1 ANALYSIS

FIGURE 13·4

Only very simple models of the power chain characteristics were used on most devices.

The input device data is summarised for each device in Figures 13.5 (a) to (f) together with the results.

13.3.2 CALCULATION OF SEA EFFICIENCIES

These have had to be derived from different sorts of test data for the different devices. Depending on the type of device and data available, this was done as follows:

a) <u>From monochromatic efficiency data (linear devices)</u> - Random sea efficiencies for linear devices can be calculated by numerical integration - (reference). The sea efficiency is then independent of wave height. No device is truly linear, but some are nearly so within the most significant areas of the wave climate scatter diagram.

b) <u>From monochromatic efficiency data (non linear devices)</u> In the absence of alternative data, the sea efficiencies can be estimated from families of curves of monochromatic efficiencies against period for various wave heights by using the above procedure and the curve for $H = Hs/\sqrt{2}$.

c) <u>From sea efficiency data</u> - Obviously this is the most satisfactory data and is directly applicable provided an appropriate wave spectra type was used during testing.

d) <u>Special cases - non resonant devices.</u> Particularly for non-resonant devices, e.g. the French Flexible Bag and Russell Rectifier, efficiency data is not primarily a function of wave period. If random tests are not available only approximate estimates of sea efficiency can be made. The particular procedures used for the Russell Rectifier are described in Figure 13.6.

13.4 <u>SECOND STAGE OF ANALYSIS - INTRODUCTION OF ADDITIONAL INFLUENCES AND PROBABILITY ANALYSIS</u>

13.4.1 SUMMARY

This section describes the modifications made to the first stage analysis to account for a number of additional effects. The modifications derive from three factors fs, fd, and fr, which are now defined.

Overall it is clear that there is a considerable degree of uncertainty in the data used in predicting productivity. Hence the results must be qualified with estimates of their reliability.

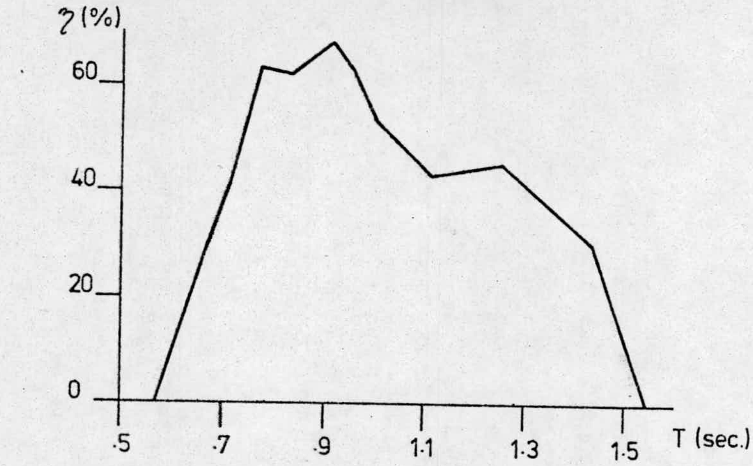
To a reasonable approximation the productivity of a device can be represented by the following product of uncorrelated factors.

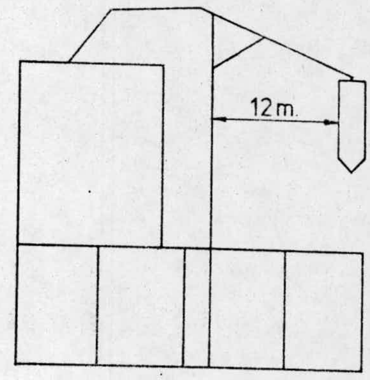
$$P = S(s.u.) \times fs \times \eta d \times fd \times \eta p \times fr$$

where

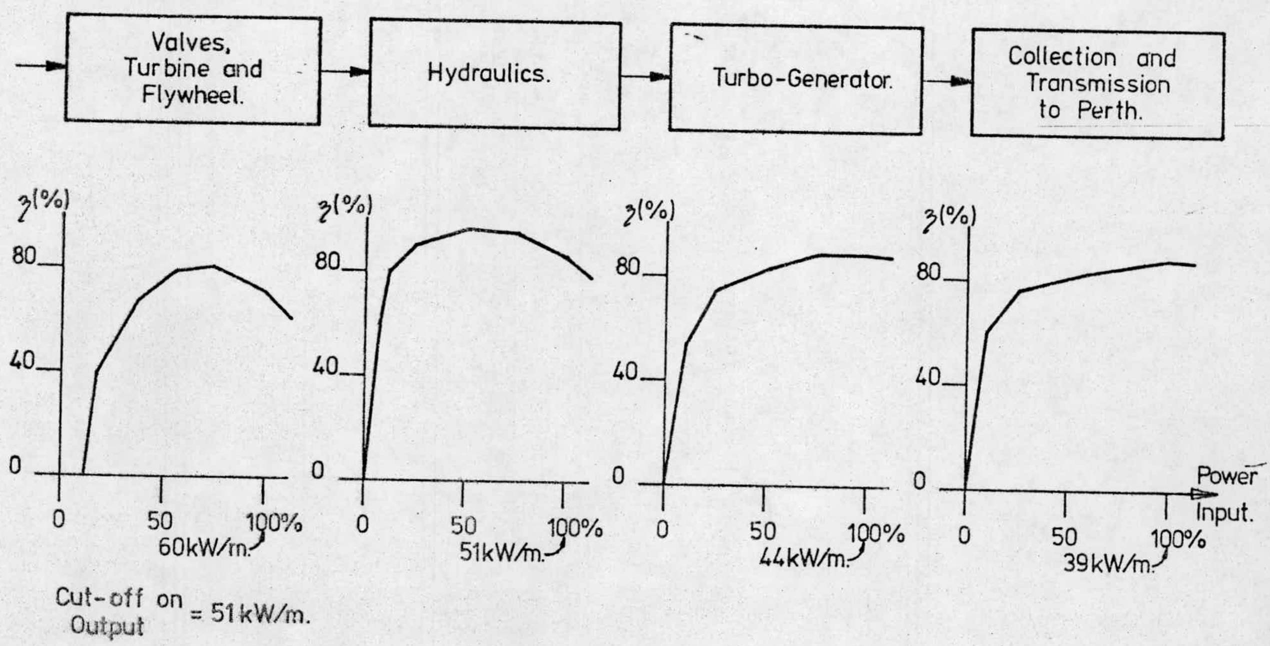
P = Device annual productivity in kW/m.
S(s.u.) = Average annual power at the South Uist wave buoy
fs = factor to correct the power level to that at the device site
ηd = global device capture efficiency (see 13.3)

MONOCHROMATIC EFFICIENCY (·12m)





POWER CHAIN



ANNUAL AVERAGE OUTPUTS AT ALL LINKS IN kW/m

BEFORE CORRECTION

LINK	OUTPUT
AVAILABLE POWER	42.3
CAPTURED POWER	16·6
VALVES, TURBINE AND FLYWHEEL	9·0
HYDRAULICES	7·9
TURBO - GENERATOR	6.3
COLLECT AND TRANSMIT TO PERTH	5·0

	ANNUAL kW/m WAVE POWER $S_{s.u.}$	SITE FACTOR f_s	DEVICE CAPTURE η_d	DIRECTIONALITY f_d	POWER CHAIN η_p	RELIABILITY f_r
HIGH ESTIMATE	48.0	1.4	·44	·75.	·65	·92
MOST PROBABLE	42.3	1.1	·39	·65	·30	·87
LOW ESTIMATE	39.0	1.0	·35	·50	·25	·80

ANNUAL MEAN POWER DELIVERED TO PERTH

UPPER BOUND 95% CONFIDENCE

— MEAN —

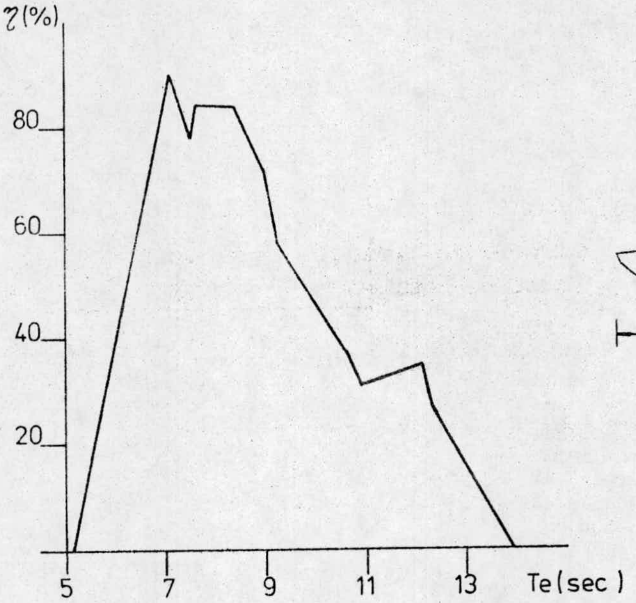
LOWER BOUND 95% CONFIDENCE

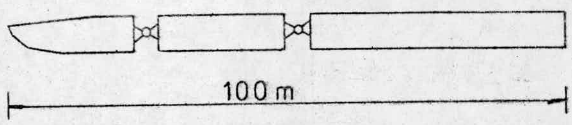
PER M WORKING FACE OF DEVICE	PER 2GW RATED INSTALLATION
5·8 kW/m	·32 GW
— 3·7 kW/m —	*— ·20 GW —*
2·4 kW/m	·13 GW

OSCILLATING WATER COLUMN
PRODUCTIVITY OF REFERENCE DESIGN
DATA AND RESULTS

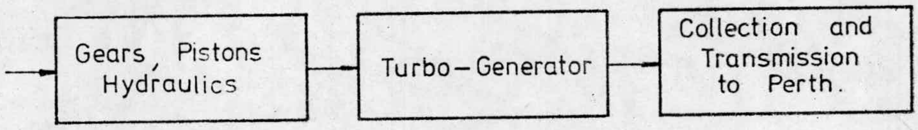
FIGURE 13·5a

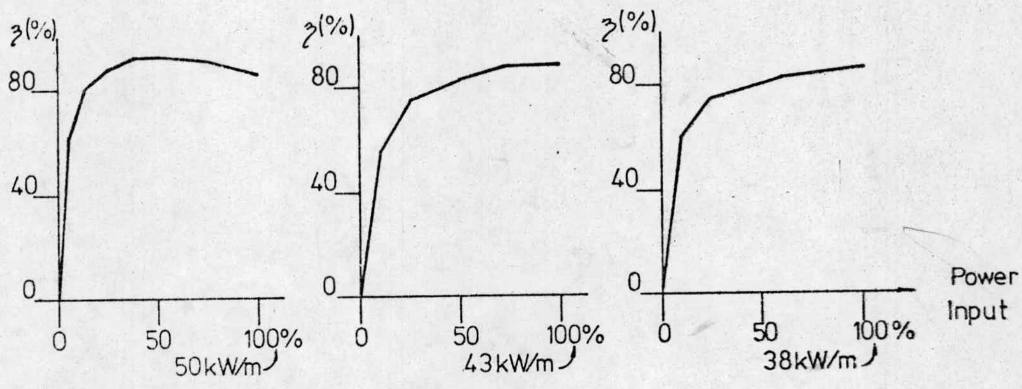
SEA EFFICIENCY (100 m)





POWER CHAIN





Cut-off on Output = 43 kW/m

ANNUAL AVERAGE OUTPUTS AT ALL LINKS IN kW/m

BEFORE CORRECTION

LINK	OUTPUT
AVAILABLE POWER	42.3
CAPTURED POWER	21·3
GEARS PISTONS AND HYDRAULICS	16·6
TURBO - GENERATOR	13·6
COLLECT AND TRANSMIT TO PERTH	11·0

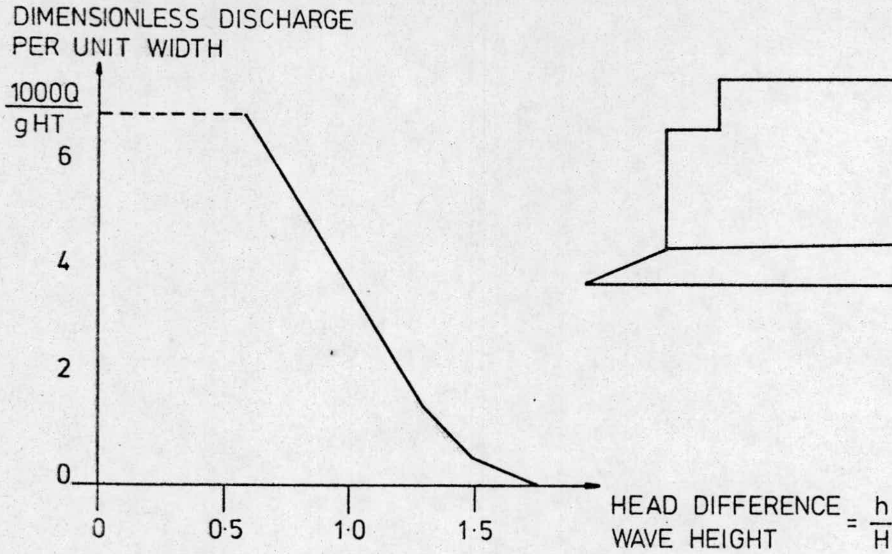
	ANNUAL kW/m WAVE POWER $S_{s.u.}$	SITE FACTOR f_s	DEVICE CAPTURE η_d	DIRECTIONALITY f_d	POWER CHAIN η_p	RELIABILITY f_r
HIGH ESTIMATE	48.0	1·4	·6	·75	·60	·92
MOST PROBABLE	42.3	1·1	·5	·65	·52	·87
LOW ESTIMATE	39.0	1·0	·3	·45	·35	·80

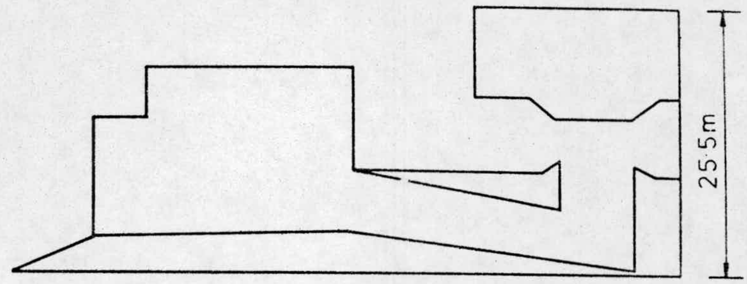
ANNUAL MEAN POWER DELIVERED TO PERTH	PER M WORKING FACE OF DEVICE	PER 2GW RATED INSTALLATION
UPPER BOUND 95% CONFIDENCE	8·9 kW/m	·51 GW
— MEAN —	*— 6·4 kW/m —*	*— ·37 GW —*
LOWER BOUND 95% CONFIDENCE	4·0 kW/m	·23 GW

COCKERELL RAFTS
PRODUCTIVITY OF REFERENCE DESIGN
DATA AND RESULTS

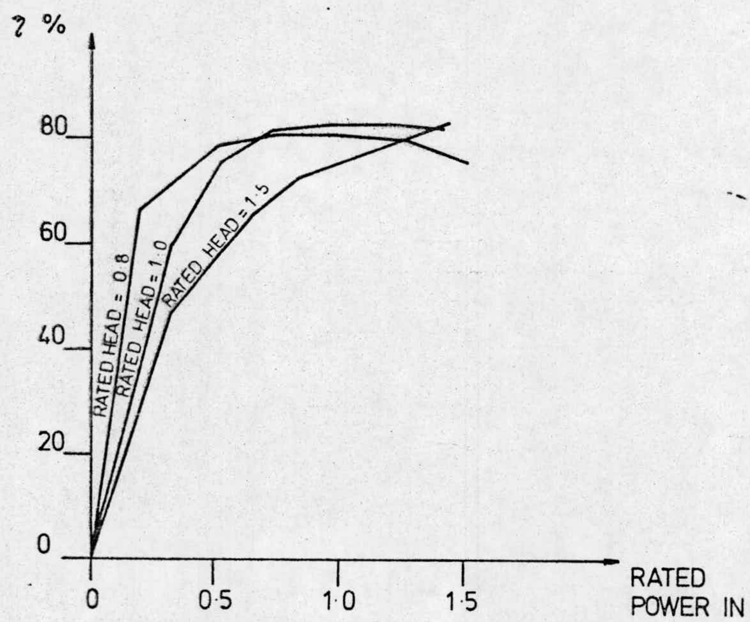
FIGURE 13·5b

FLOW CHARACTERISTICS

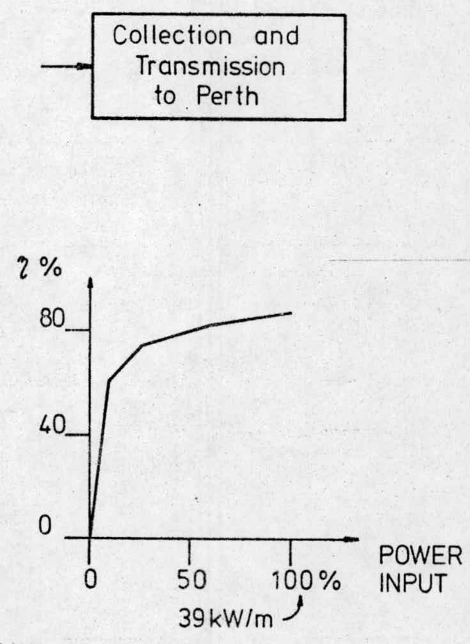




TURBINE AND GENERATOR EFFICIENCIES



POWER CHAIN



No. 1 UNIT : RATED HEAD = 2m; RATED POWER = 10kW/m

No. 2 UNIT : RATED HEAD = 3m; RATED POWER = 25kW/m

Nos.1&2 UNITS : RATED HEAD = 3m; RATED POWER = 35kW/m

ANNUAL AVERAGE OUTPUTS AT ALL LINKS IN kW/m

BEFORE CORRECTION

LINK	OUTPUT
AVAILABLE POWER	42.3
‡ CAPTURED POWER	13·9
‡ TURBINE(S) & GENERATOR	6·30
COLLECT & TRANSMIT TO PERTH	4·21

‡ NOTE - THESE LINKS WERE CONSIDERED SIMULTANEOUSLY IN DELIVERY OUTPUT FROM THE TURBINE. HERE CAPTURED POWER IS THE OUTPUT ASSUMING 100% EFFICIENT TURBINE.

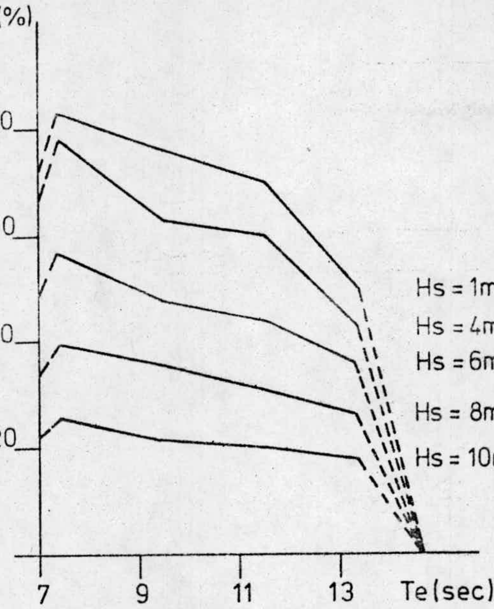
	ANNUAL kW/m WAVE POWER $S_{s.u.}$	SITE FACTOR f_s	DEVICE CAPTURE η_d	DIRECTIONALITY f_d	POWER CHAIN η_p	RELIABILITY f_r
HIGH ESTIMATE	48.0	1·05	·40	·70	·50	·95
MOST PROBABLE	42.3	0·9	·33	·65	·30	·92
LOW ESTIMATE	39.0	0·65	·20	·55	·20	·83

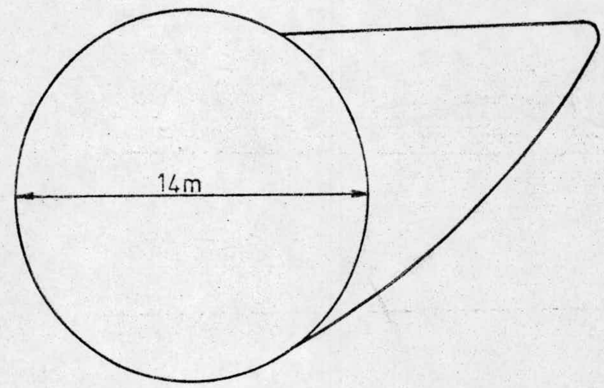
ANNUAL MEAN POWER DELIVERED TO PERTH	PER M WORKING FACE OF DEVICE		PER 2GW RATED INSTALLATION	
UPPER BOUND 95% CONFIDENCE	3·4	kW/m	·23	GW
— MEAN —	*— 2·2	kW/m —*	*— ·15	GW —*
LOWER BOUND 95% CONFIDENCE	1·2	kW/m	·08	GW

RUSSELL RECTIFIER
PRODUCTIVITY OF REFERENCE DESIGN
DATA AND RESULTS

FIGURE 13·5c

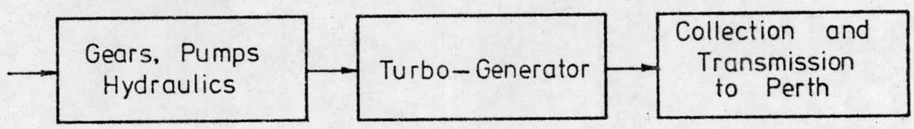
SEA EFFICIENCY – 15m DUCK (D0019)

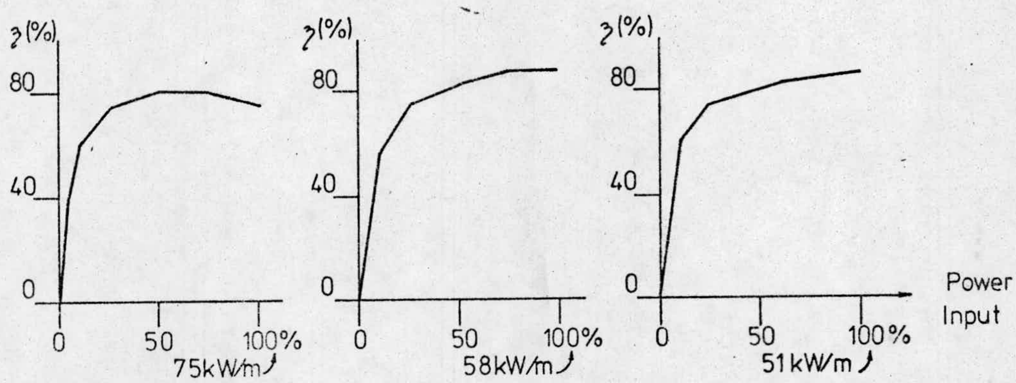




Notes 1 Results were re-scaled to 14m Ø

POWER CHAIN.





Cut-off on Output = 58 kW/m

ANNUAL AVERAGE OUTPUTS AT ALL LINKS IN kW/m
BEFORE CORRECTION

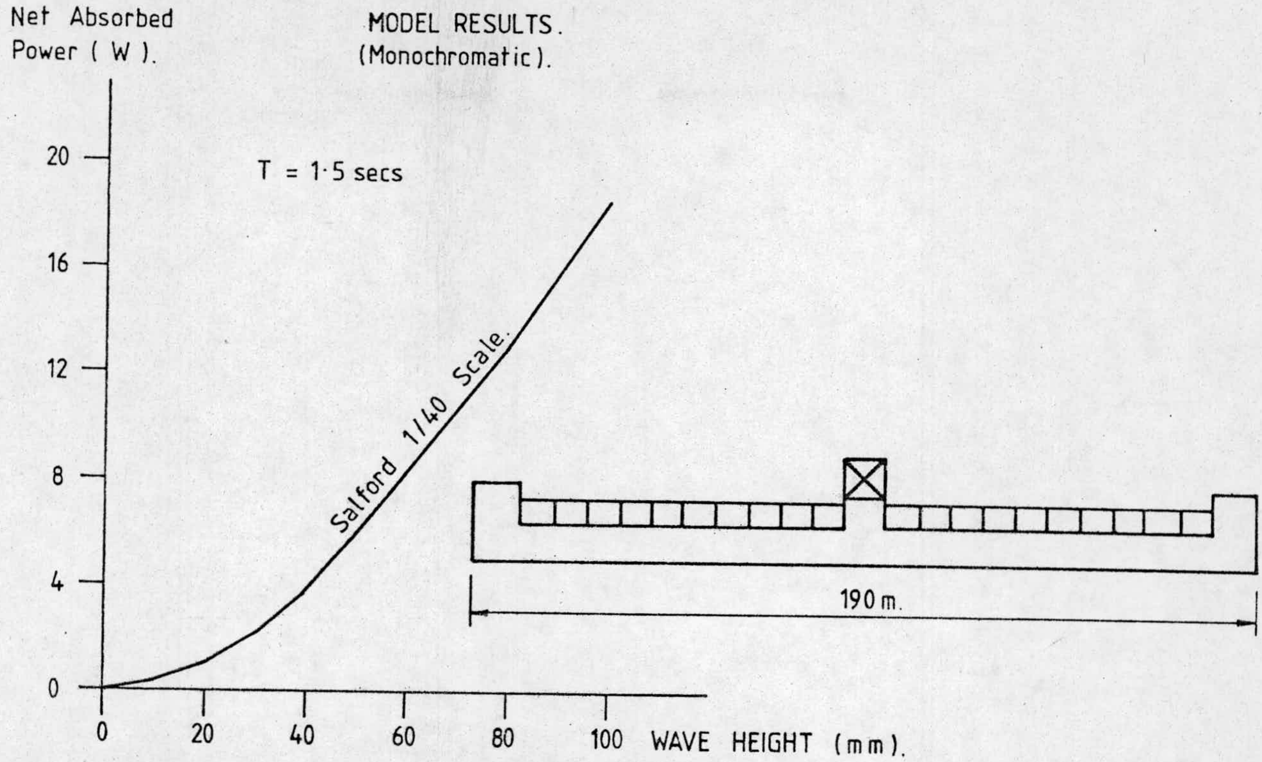
LINK	OUTPUT
AVAILABLE POWER	42.3
CAPTURED POWER	23·0
GEARS PUMPS AND HYDRAULICS	16·9
TURBO – GENERATOR	13·4
COLLECT AND TRANSMIT TO PERTH	10·5

	ANNUAL kW/m WAVE POWER $S_{s.u.}$	SITE FACTOR f_s	DEVICE CAPTURE η_d	DIRECTIONALITY f_d	POWER CHAIN η_p	RELIABILITY f_r
HIGH ESTIMATE	48.0	1·4	·60	75	60	·85
MOST PROBABLE	42.3	1·1	54	65	·46	·70
LOW ESTIMATE	39.0	1·0	45	·50	30	·50

ANNUAL MEAN POWER DELIVERED TO PERTH	PER M WORKING FACE OF DEVICE	PER 2GW RATED INSTALLATION
UPPER BOUND 95% CONFIDENCE	7·4 kW/m	·31 GW
* —— MEAN —— *	* —— 5·2 kW/m —— *	* —— ·22 GW —— *
LOWER BOUND 95% CONFIDENCE	3·1 kW/m	·13 GW

SALTER DUCKS
PRODUCTIVITY OF REFERENCE DESIGN
DATA AND RESULTS

FIGURE 13·5d



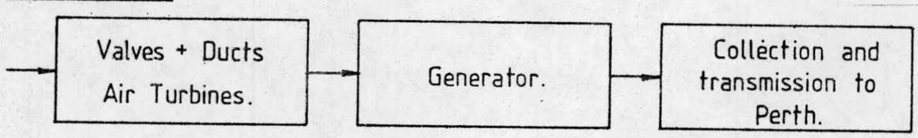
Notes. 1. Results were factored to compensate for 4 bags which did not work.

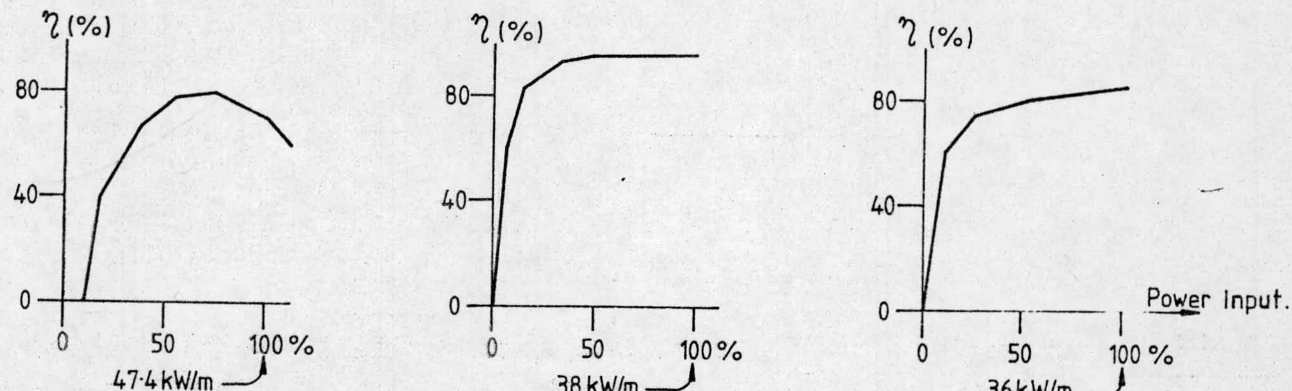
2 Assume that power from random sea (H_S, Te) = power in monochromatic wave ($H = H_S/\sqrt{2}$, T = Te).

3. Power captured was found to be independent of T for $1{\cdot}2 \leq T \leq 2{\cdot}1$. Outside range efficiency tailed off.

4. Power levels in kW/m below are (power per device) / 190 m.

POWER CHAIN





Cut off on output = 38 kW/m.

ANNUAL AVERAGE OUTPUTS AT ALL LINKS IN kW/m
BEFORE CORRECTION

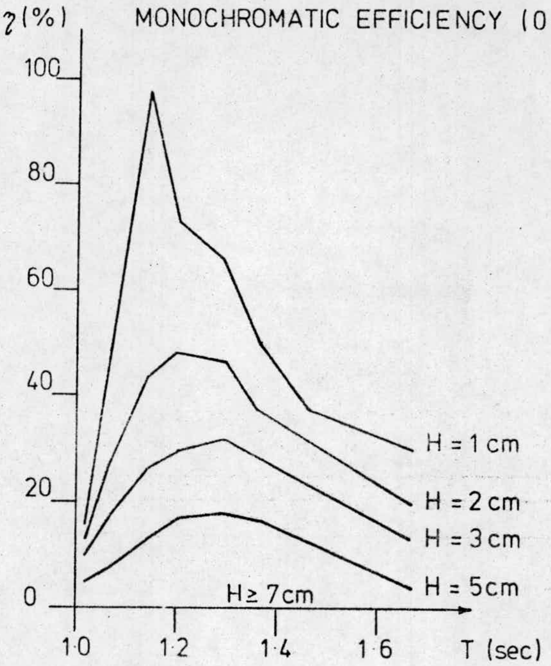
LINK	OUTPUT
AVAILABLE POWER	42.3
CAPTURED POWER	12·9
VALVES, DUCTS & AIR TURBINES.	7·4
GENERATOR.	6·7
COLLECT & TRANSMIT TO PERTH.	5·1

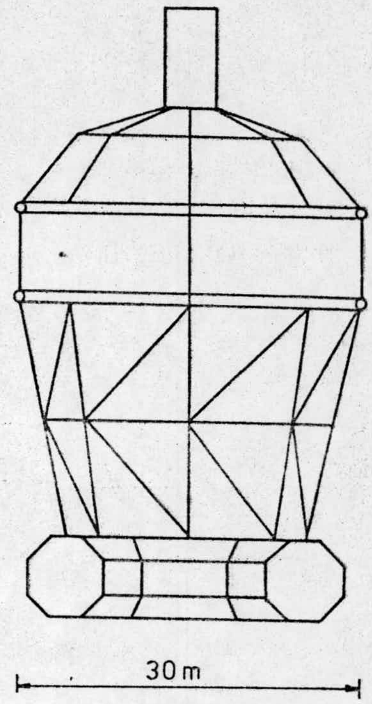
	ANNUAL kW/m WAVE POWER $S_{s.u.}$	SITE FACTOR f_s	DEVICE CAPTURE η_d	DIRECTIONALITY f_d	POWER CHAIN η_p	RELIABILITY f_r
HIGH ESTIMATE	48.0	1·4	0·40	0·85	0·65	0·92
MOST PROBABLE	42.3	1·1	0·30	0·65	0·40	0·82
LOW ESTIMATE	39.0	1·0	0·10	0·55	0·30	0·70

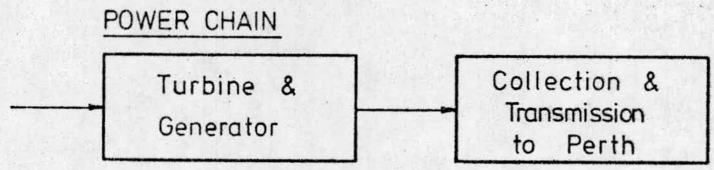
ANNUAL MEAN POWER DELIVERED TO PERTH	PER M GROSS LENGTH OF DEVICE.	PER 2GW RATED INSTALLATION
UPPER BOUND 95% CONFIDENCE	4·9 kW/m	0·29 GW
— MEAN —	*— 3·1 kW/m —*	*— 0·18 GW —*
LOWER BOUND 95% CONFIDENCE	1·5 kW/m	0·09 GW

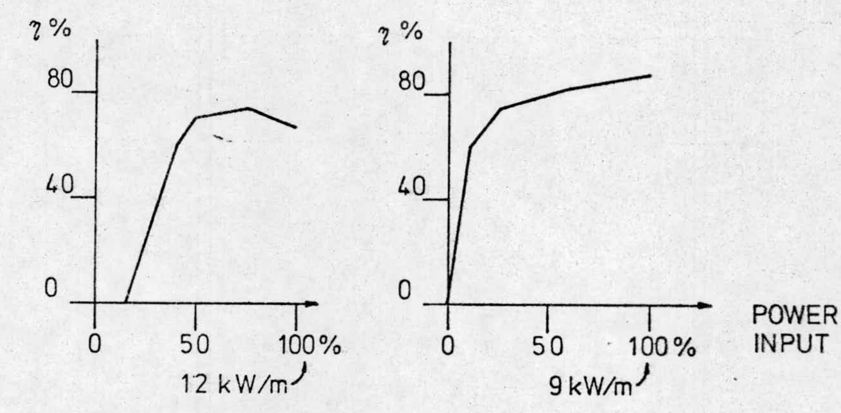
FRENCH FLEXIBLE BAG
PRODUCTIVITY OF REFERENCE DESIGN
DATA AND RESULTS

FIGURE 13·5e









Cut-off on output = 9kW/m

ANNUAL AVERAGE OUTPUTS AT ALL LINKS IN kW/m
BEFORE CORRECTION

LINK	OUTPUT
AVAILABLE POWER	42.3
CAPTURED POWER	5 9
TURBINE GENERATOR	3·7
COLLECT & TRANSMIT TO PERTH	3·0

	ANNUAL kW/m WAVE POWER $S_{s.u.}$	SITE FACTOR f_s	DEVICE CAPTURE η_d	DIRECTIONALITY f_d	POWER CHAIN η_p	RELIABILITY f_r
HIGH ESTIMATE	48.0	1·4	·30	·80	·65	·92
MOST PROBABLE	42.3	1·1	·14	·65	·51	·87
LOW ESTIMATE	39.0	1·0	·10	·55	·40	·80

ANNUAL MEAN POWER DELIVERED TO PERTH

	PER M OF DIAMETER	PER 2GW RATED INSTALLATION
UPPER BOUND 95% CONFIDENCE	3·5 kW/m	·42 GW
* — MEAN — *	* — 2·2 kW/m — *	* — ·26 GW — *
LOWER BOUND 95% CONFIDENCE	1·2 kW/m	·14 GW

WELLS OSCILLATOR
PRODUCTIVITY OF REFERENCE DESIGN
DATA AND RESULTS

FIGURE 13·5f

For sea state H_S, T_e

Power available $= \frac{\rho g^2}{64\pi} H_S^2 T_e$

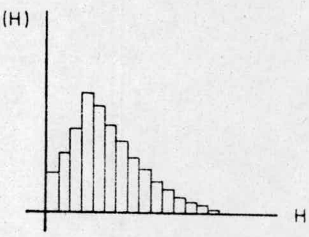
Note: Cutoff characteristic dimension = Height of device above mean sea level

Procedure: Replace random sea with wave height distribution for constant T_e

Probability of wave height $< H$ = Rayleigh function(H, H_S)

$= 1 - e^{-2(H/H_S)^2}$

Note: Device performance is insensitive to wave period, hence it is reasonable to calculate just one "effective" period. (See below for proof that $\sum$ power in these waves = power available.)



RAYLEIGH DISTRIBUTION OF WAVE HEIGHTS BEFORE CUTOFF

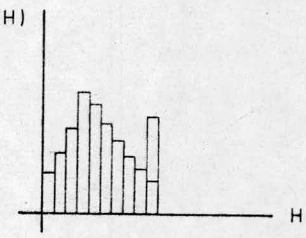
Procedure: Apply cutoff to waves

Maximum wave height = 2*Height of device above mean sea level

For $H = H_{largest}$ to $H_{smallest}$

If H > Cutoff height Then $p(H_-) = p(H_-) + p(H_0)$; $p(H_0) = 0$

Else Cutoff has no effect



RAYLEIGH DISTRIBUTION OF WAVE HEIGHTS AFTER CUTOFF

Procedure: Define target turbine head for sea state

Note: It is assumed that the control system for the turbo-generator is set such as to minimise head fluctuations in a given sea state. The 'target' head, h, is chosen to optimise overall efficiency as follows:

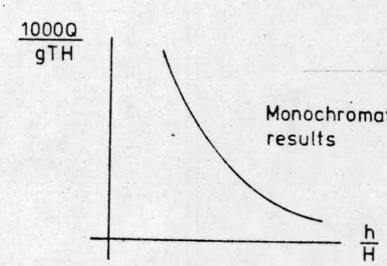
Target turbine head = $k*H_S$ If turbine head < 2*k*height of device above mean sea level

Else 2*k*height of device above mean sea level

Tests indicate k optimum ≑ 0.8

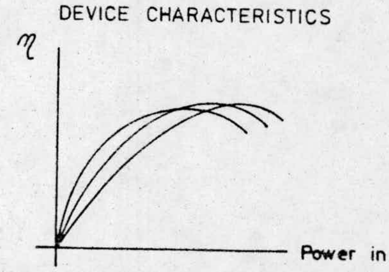
Procedure: Obtain flow through turbine from device characteristics based on test results

Note: This curve will be taken as independent of wave period (not an essential assumption but experimental data is too sparse to allow differentiation). This also assumes response for each wave ≡ response in a train. This can be justified partly by the assumption of constant h which ideally makes the acceptance of a wave independent of previous waves.



DEVICE CHARACTERISTICS

Procedure: Obtain turbine/generator efficiency for known flow Q and known target turbine head



TURBINE CHARACTERISTICS

Procedure: Calculate device efficiency before and after turbine by summation of power captured over all waves

For $H_{smallest}$ to $H_{largest}$

Power after flow characteristics = $\rho g Q * \text{Head}$

Power after turbine = $\eta_{turbine}$ * Power after flow characteristics

$$\text{Device sea efficiency} = \frac{\sum p(H) * \text{Power after flow characteristics}}{\text{Power available}}$$

$$\text{Device sea efficiency after turbine} = \frac{\sum p(H) * \text{Power after turbine}}{\text{Power available}}$$

Note: The above procedure is repeated for all sea states in the wave climate scatter diagram

<u>PROOF THAT POWER IN A SEQUENCE OF WAVES DISTRIBUTED ACCORDING TO THE RAYLEIGH DISTRIBUTION AND ALL WITH PERIOD Te, EQUALS THE POWER IN THE ORIGINAL SEA STATE (Hs, Te)</u>

POWER IN SEA STATE (Hs, Te) $= \frac{\rho g^2}{64\pi} H_s^2 T_e$

POWER IN SEQUENCE OF WAVES WITH PERIOD T' (CONSTANT) $= \frac{\rho g^2}{32\pi} \int_0^\infty p(H) . H^2 T' \, dH$

RAYLEIGH DISTRIBUTION - p.d.f. FOR WAVE HEIGHT $\quad p(H) = \frac{4H}{H_s^2} e^{-2\left(\frac{H}{H_s}\right)^2}$

$$\frac{\rho g^2}{32\pi} \int_0^\infty p(H) H^2 T' \, dH = \frac{\rho g^2}{64\pi} H_s^2 T'$$

$$\therefore \quad T' = T_e$$

CALCULATION OF SEA EFFICIENCY FOR THE RUSSELL RECTIFIER

fd = directionality correction factor (see 13.4.2)
ηp = global power chain efficiency (see 13.3)
fr = reliability factor to allow for losses due to breakdowns.

For each of the above variables, and for each device the most probable value and likely bounds (with a notional 95% confidence level) have been estimated. Skew distributions have been fitted to the data and Monte Carlo methods used to predict the probability distribution of the final Device Productivity. From this, corresponding mean and bounding values have been calculated. The estimated values and results are summarised in Figure 13.5 (a) to (f). Further description of the derivation of each variable are given below.

S(s.u.) see 13.2.

fs see 13.2. Station India in Mid Atlantic provides an absolute upper bound to the wave climate ($\simeq$ 75 kW/m). However this will include significant energy from the east. Furthermore no major energy loss mechanisms has been identified for the S. Uist buoy site relative to adjacent sites in 60-100 m of water, except for the $\simeq$ 7% of shelter from the north (see 13.2). The high estimate is therefore most unlikely to exceed 1.30. The low estimate must be greater than 1.0. The most likely estimate is 1.07 (sheltering) x 1.10 (for energy loss).

ηd Derived from 13.3
Detailed subjective assessment of high and low values for each device depending on -
1. Type of data (monochromatic vs random etc.)
2. Realism in modelling of Reference Design.
3. Quality of data.
4. Possibility for improvements in model results without significant change to the Reference Design.

fd See 13.4.2

ηp As for ηd

fr Assessed from reliability studies plus subjective judgement (see Chapter 12).

13.4.2 DIRECTIONALITY FACTOR fd

The derivation of a suitable power rose is given in 13.2. The next step to be considered is the ability of devices to capture power from various directions. Line devices, if isolated, can absorb energy from inclined waves and even from waves travelling along the device in most cases. Isolated point absorbers are clearly able to accept energy from any direction. However, if such devices are placed in a long array the energy available to them from certain directions is much more restricted. This is limited in a very long string to the energy flux, equal to the power in the sea times the cosine of the "angle of inclination". Elsewhere in this report it is shown that for reasonable power generation capacities devices will need to be deployed in very long strings indeed, with a minimum of space between devices. Only for a few devices at the ends of the string will a greater power level be available. As a first step the Consultants have taken the power rose and calculated the energy available to lines of devices at various angles. The results are plotted in Figure 13.3. as a percentage of the total annual wave energy at the site. It can be seen that the best direction is facing just south of west, with 65% available energy.

A correction should be applied to this estimate to allow for the different directional properties of the various devices. No test data is available except for an isolated NEL device and it is not known how to interpret this information for a long string of devices.

However, in a separate exercise the Consultants have found a remarkable insensitivity of the variable fd to a wide range of assumptions with the notable exception of the assumed wave power rose.

13.5 PRODUCTIVITY OF DEVICES OF VARIOUS SIZES

(a) In the same location -

The results from model tests can be applied to a wide range of full-size devices by using Froude scaling. This is valid up to the point where the predominant sea wave heights and periods lie outside the range anticipated in the tests. Figure 13.7 shows the results of such an exercise for the Cockerell Rafts, the NEL oscillating water column, and the Salter Ducks. Also plotted is the productivity per unit gross volume of device. For a given device this can be considered to be a simple first approximation to cost effectiveness, particularly if structural costs are predominant. This comparison is not valid between different devices. The indications are, therefore, that for cost effectiveness, the optimum devices may well be significantly smaller than the Reference Designs, but unfortunately this implies a very large drop in the total power captured per kilometre of device.

(b) Smaller devices in less energetic locations -

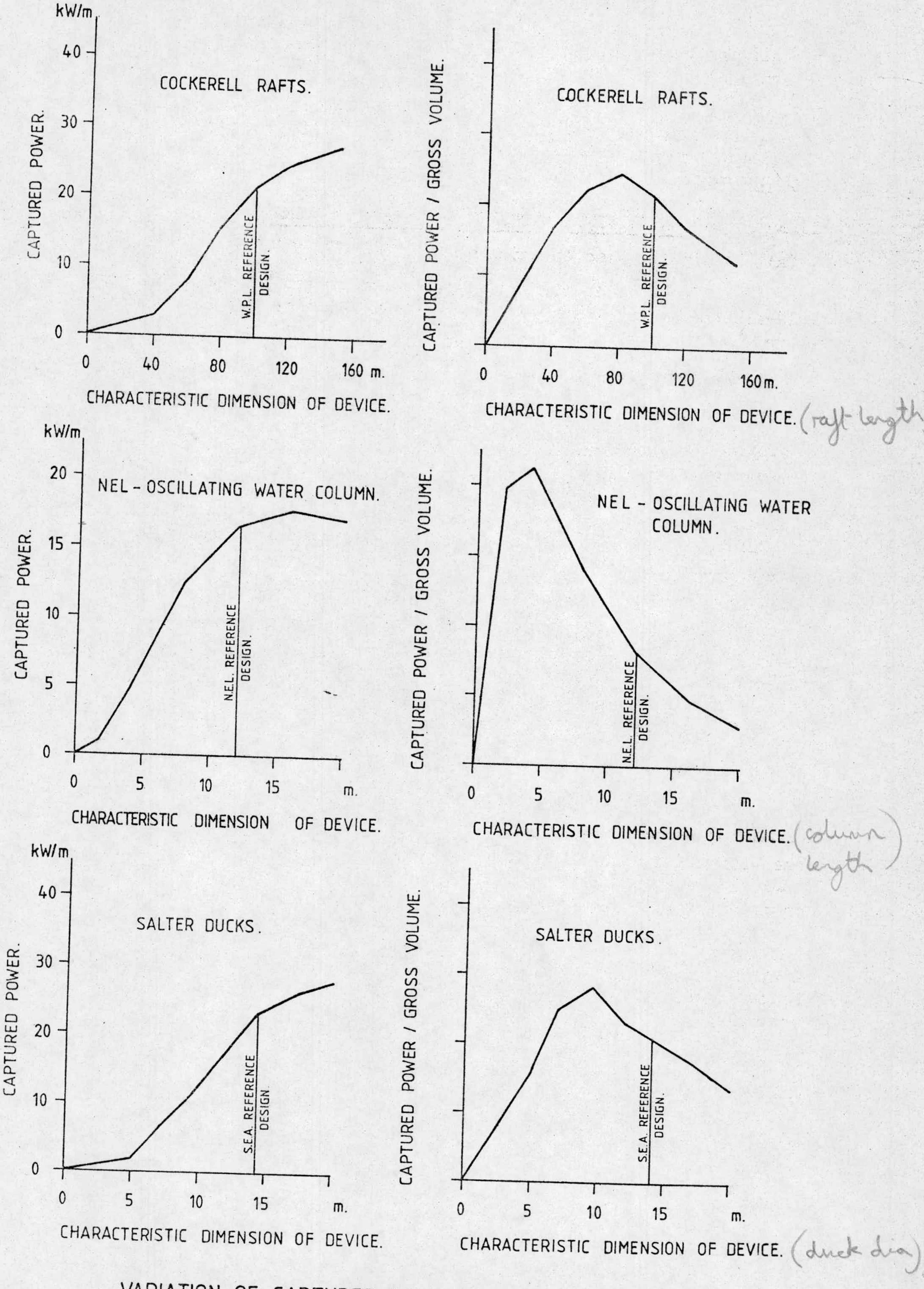
An important question remaining is how cost effective devices would be in other climates, perhaps less energetic than South Uist. If the device size for various climates is 'optimised' for maximum power per unit volume as above the following relationships hold.

Optimum size	$\propto (PCL)^{2/5}$
Power produced per kilometre of device	$\propto (PCL)$
Power produced per unit volume of device	$\propto (PCL)^{1/5}$

where PCL = power in the wave climate per kilometre of coastline. (It has been assumed that the breakdown of the wave climate follows Froude scaling laws, a not unreasonable first approximation). As an example, if the power on the East Coast of Scotland were half of that of the Hebrides, the optimum device size would be reduced to 76% and the 'cost effectiveness' to 87%, but the power produced per kilometre of coastline would be only 50%. Overall, this is encouraging as the 'cost effectiveness' while apparently better in the most energetic seas, is not very sensitive to available power levels.

Consideration of the cost effectiveness of optimised mechanical and electrical plant in the two cases also suggests an insensitivity to wave climate. The tentative conclusion from this is that it may well be reasonable to exploit the wave power resource available at a wide range of sites around the U.K. without an unacceptable drop in economic performance.

As a footnote, extrapolating the above logic perhaps beyond its limits of applicability, the 'cost' of power produced by 1/10 scale models in scale seas would be of the order of three times that for the full scale device, a surprisingly small ratio.



VARIATION OF CAPTURED POWER WITH SIZE OF DEVICE.

FIGURE 13·7

	Annual Average Output in KW/m			Annual Average Output of the 2GW Reference Scheme in GW			(see drawings) (WP 78 series)
	Lower Bound (95% confidence) level	Mean	Upper Bound (95% confidence) level	No. Devices per 2GW scheme	Lower Bound (95% confidence) level	Mean	Upper Bound (95% confidence) level
NEL Oscillating Water Column	2.4	3.7 per metre working face	5.8	513	.13	.20	.32
Cockerell Rafts	4.0	6.4 per metre working face	8.9	1143	.23	.37	.51
Russell Rectifier	1.2	2.2 per metre working face	3.4	667	.08	.15	.23
Salter Ducks	3.1	5.2 per metre working face	7.4	1770	.13	.22	.31
French Air Bag	1.5	3.1 per metre gross length	4.9	312	.09	.18	.29
Wells Oscillator	1.2	2.2 per metre diameter	3.5	4000	.14	.26	.42
Vickers	-	Not known -	-	Not known	-	Not known	-

SUMMARY OF ESTIMATES AND PROBABLE RANGE OF UNCERTAINTY FOR ANNUAL AVERAGE OUTPUT OF REFERENCE DESIGN SCHEMES IN A TYPICAL YEAR.

VOLUME 1 TABLE S 1
VOLUME 2 TABLE 13.1

CHAPTER 14. - MOORINGS

14.1 INTRODUCTION

Moorings have been identified as a major cost centre for wave power devices. The duty performed by the mooring system is not entirely novel and in the offshore industry there are many examples of very large vessels being moored in the roughest of seas for long periods. However, it is believed that none of the mooring systems used in the past are entirely suitable for wave power devices. In particular existing systems appear to be very expensive, ineffective in their usage of material, lacking in durability and not suited to close mooring of separate devices.

It is generally hoped that improved systems can be developed, but the Teams are at a very early stage of developing their ideas. Some progress has been made recently by TAG 4 in clarifying the theoretical aspects and defining the problems to be solved, but for the immediate future tank testing will remain the main tool for investigation.

14.2 THE MOORING SPECIFICATION

Clearly the specification for a mooring will vary from device to device but the following general principles are applicable to all schemes.

a) A device must be held on station, but not necessarily in a fixed position, for all possible waves, currents and tides.

b) Separate device units must be restrained sufficiently to avoid collision of the devices themselves or their mooring lines.

c) The mooring must be sufficiently compliant to the waves to reduce the forces acting on anchors, moorings and the device itself to a minimum.

d) All components must have adequate strength, fatigue life and durability.

e) Mooring lines for a device must not be able to touch each other.

f) Removal of mooring lines for inspection and maintenance must be possible.

g) A degree of redundancy is highly desirable for individual devices, and essential for schemes which link devices.

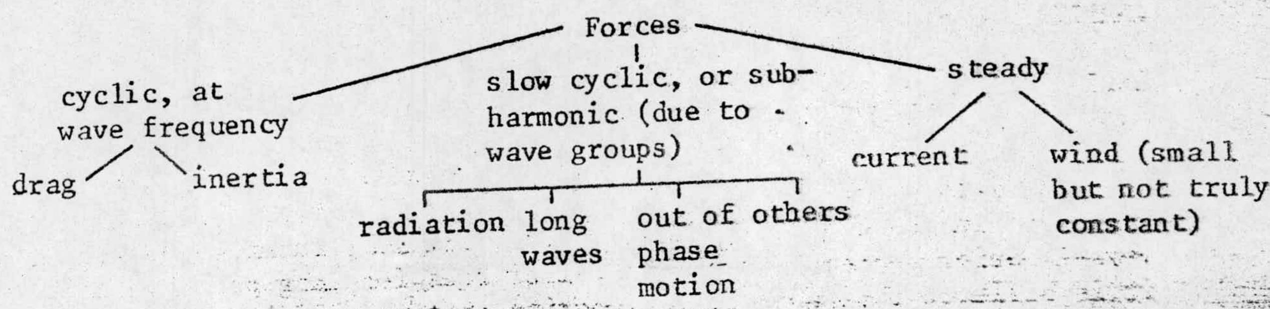
h) The system as a whole should be capable of lasting for 30 or more years, with replacement of particular components at not less than, say, 5 year intervals.

i) The mooring should not adversely affect the efficiency of the device.

j) The mooring system should allow the removal of single devices without affecting the mooring of adjacent devices.

14.3 FORCES AND EXCURSIONS, THE THEORETICAL BACKGROUND

The forces acting on a device can be summarised as follows:-



For rigidly held devices the cyclic forces at wave frequency would totally dominate all other forces, being perhaps twenty to one hundred times greater. Fortunately these forces can be reduced to an acceptable level by allowing the device to move freely in each wave, following the orbital water particle motions. This is the philosophy behind compliant moorings.

The subharmonic forces are second order effects and are imperfectly understood for random seas, particularly with regard to their variation with different degrees of compliance, and to the significance of subharmonic resonances. The latter are possible as the excursions of a device with compliant moorings will of course have a long natural period. Even without resonance, subharmonic forces are likely to govern mooring design.

The various phenomena causing subharmonic forces have been described by Bowers (ref.) and an abridged version of this description is given below.

"It has been observed in physical model studies that mooring loads in irregular or random seas are generally very much greater than loads measured in regular waves. To understand how non-linearities due to random waves influence the motions of moored vessels it is necessary to appreciate that moored vessels have natural periods of horizontal oscillation that are generally far longer than the periods of wind generated surface waves. For this reason a typical regular wave is unable to excite these resonances. In an irregular sea, however, non-linearities give rise to small forces that will excite resonant horizontal movements (they are smaller than forces at the wave period by approximately the wave amplitude over the wave length). Since these movements are generally lightly damped, these small non-linear forces are able to build up large excursions of the vessel, leading to large mooring loads. Three well known effects that lead to slowly varying forces in random seas are described below.

a. Radiation pressure - wave grouping

A vessel floating in regular waves will be subject to a steady force when the wave height in front of the vessel is greater than the wave height behind. This force arises because there is a steady flux of momentum in a regular wave which is proportional to the square of the wave height. This effect is sometimes called radiation pressure. Because the wave height is not constant in an irregular or random sea this momentum flux will vary with the wave envelope. In other words, a vessel moored in random waves will be subject to a force that varies with the periodicity of wave groups. For typical sea conditions wave groups will excite resonant motions of vessels with periods in the range of 20 seconds to 3 minutes".

Longuet-Higgins (reference) has extended this concept to wave absorbing devices and has derived the following formula for a line device in a regular wave train

$$F = \frac{\rho g H^2}{16} \text{ (1 +(proportion of power reflected) - (proportion of power transmitted))}$$

"b. Out of phase motion of vessels

The second effect is caused when the motions of a vessel in waves are out of phase with the periodic forces due to the wave motion. When heaving and pitching movements of a vessel in head seas are out of phase with the force and couple due to a regular wave motion then the vessel will be subject to a steady force proportional to the movement of the vessel times the wave height. In an irregular sea the product of the vessel's movement with the wave height will contain a slowly varying component and so the vessel will be subject to a slowly varying force capable of exciting resonant horizontal movements. Observations indicate that for a regular wave system the steady drifting force in a head sea becomes most prominent when the vessel's natural pitch and heave periods (these are usually similar) coincide with the wave period. On this basis it is to be expected that in an irregular sea the slowly varying force under discussion in this paragraph will dominate the slowly varying force due to radiation pressure, discussed in the last paragraph, when the vessel's resonant periods of vertical motion coincide with the wave period.

c. Long wave effect

The third effect is due to the direct excitation of resonant movements of a moored vessel by long wave motions. Two recent articles describe mooring difficulties in a port on the Pacific Coast. These problems are due to long waves with periods that generally lie in the range of 50 seconds to 3 minutes. Spectral analyses taken of wave recordings inside the harbour showed that wave energy was concentrated in the two distinct wave period ranges of Pacific swell (10 to 20 seconds) and long waves (50 seconds and above) with little or no energy in between. Given the narrow band nature of the swell spectra this is the type of long wave energy distribution that one would expect to find if the source of the long waves is to be found in phenomena associated with wave grouping.

Set-down - One such phenomenon is 'set-down' beneath wave groups. This effect is due to water particle velocities being higher in groups of large waves than in between the groups. This means the water pressure is slightly lower (by a term proportional to the square of the orbital wave velocity) beneath these groups than the pressure between groups. When the assumption of constant air pressure is made this leads to a small depression in the mean water level beneath wave groups and a small rise in mean level between groups. This surface pertubation then induces a wave-like flow beneath the surface which will act on the submerged section of a vessel to produce a slowly varying force. It is interesting to note that because a depression accompanies groups of large waves the slowly varying forces due to 'set-down' will be 180° out of phase with the force due to radiation pressure. Thus, the two effects will tend to cancel each other. It can be expected that for vessels in deep water the force due to radiation pressure will be greater than the force due to 'set-down' with the opposite being true in shallow water. The only feature distinguishing 'set-down' from an ordinary long wave is that it propogates at the group velocity whereas an ordinary wave always travels faster than the group velocity."

Vickers(reference) have suggested that a fourth effect should be added to this list.

d. "Wave forces on compliant structures must be calculated in their instantaneous displaced positions. Modifications to the forces are proportioned to the displacements and appear therefore as time-dependent stiffness components. These have the potential of producing instabilities and/or large amplitude response components at other than the wave excitation frequency."

Calculation procedures do not exist to reliably predict the above phenomena, with the exception of the constant radiation pressure in regular waves. Tank testing will therefore be necessary, but it has yet to be confirmed that the second order wave effects are correctly represented in tanks.

14.4 TYPES OF MOORINGS

These can be categorised as follows:-

a) dynamic positioning by propulsion - this possibility can be disregarded for wave power devices on grounds of cost, reliability and power consumption;

b) dynamic positioning by active moorings - this suffers most of the disadvantages of a) above, but may conceivably be suitable for devices which use taut seabed moorings for power extraction. This possibility is not considered further for the devices in this report;

c) catenary moorings - the traditional mooring, most commonly using heavy chain. A catenary has the advantage of providing a purely horizontal force at the anchor point which suits the traditional forms of drag anchor;

d) weighted moorings - these have the same action as catenary moorings but the added weights provide additional energy storage when lifted from the at-rest position - normally on the sea bed;

e) submerging "floats" - an inversion of d). The advantage is that the problem of impact of the weight on the sea bed is eliminated and purely horizontal forces are applied to the vessel, but the anchor must be uplift resistant;

f) taut moorings - the elastic properties of synthetic ropes are increasingly being used as the means of storing energy in a compliant mooring;

g) tension leg mooring - the vessel is connected by vertical cables to a gravity base or piled sea bed anchorage. The mooring is compliant horizontally, acting as an inverted pendulum, but is stiff vertically, the cables always being held in tension by the excess buoyancy of the vessel. The provision of this excess buoyancy makes the use of this system unattractive for all of the current wave power devices. It is interesting to note that several early proposals for tension leg oil production platforms with inclined cables of steel or parafil to the sea bed are now not favoured and are unlikely to be adopted. Being semi-rigid these moorings would attract the full cyclic forces, probably magnified by the dynamic responsiveness of the whole system.

14.5 SELECTING A SUITABLE MOORING SYSTEM FOR WAVE POWER

For reasons explained previously, the mooring for the devices in this report is likely to be compliant, and either be a catenary, weighted, sinking buoy or taut elastic mooring. The disadvantage of the first three systems are in their very unfavourable load-deflection characteristics. For small and moderate waves the stiffness of the system is very low, and excursions unnecessarily large. In larger waves the stiffness of the mooring suddenly increases as the slack in the system is taken up, and the forces in the mooring increase dramatically. In extreme cases snatch or impact loadings occur. For exposed locations, adequate compliance and strength can only be achieved by the extravagant use of materials, and even so, the movements of the vessel under combined drifting and cyclic action will be larger than would be necessary with an elastic system. The lack of stiffness in moderate seas is a particularly important disadvantage for groups of closely moored devices. In conclusion, although catenary and similar systems are technically feasible, at least for isolated devices, the Consultants preliminary studies suggest that they will be prohibitively expensive.

14.6 FURTHER INVESTIGATION OF COST EFFECTIVE ELASTIC CONFIGURATIONS

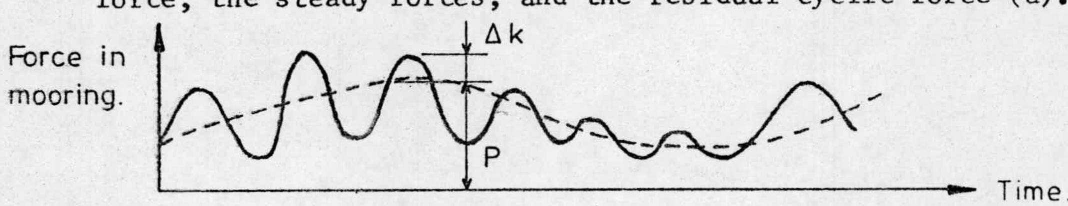
14.6.1 MATERIALS FOR THE RODES

It is important to note that both load and extension must be considered in optimising a compliant mooring rope.

For the purposes of arriving at a first design for moorings, the following simplified model of mooring action is proposed.

a) Cyclic wave forces are irresistable - for large waves devices will follow the orbital water particle motion and the cyclic force in the mooring is determined by the stiffness of the mooring times the excursion.

b) The total force in the mooring is the sum of the subharmonic force, the steady forces, and the residual cyclic force (a).



P = maximum subharmonic + steady force

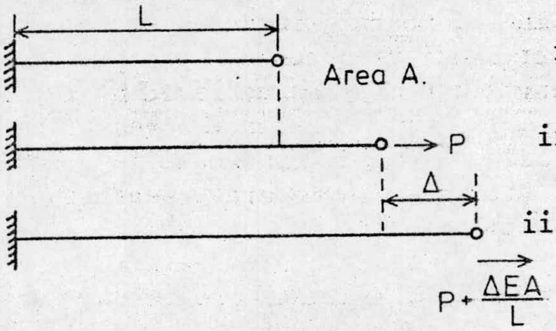
 = maximum cyclic excursion at wave frequency

k = stiffness of mooring

Maximum force in mooring = P + x k.

For comparative purposes, a simple horizontal mooring has been studied. For a given material the mooring can be made either very long and very compliant with low forces and hence small area, or shorter, stiffer and with greater area carrying larger forces. Minimising the volume of material produces the lengths, areas and comparative costs for the mooring material shown in Figure 14.1. It should be noted that the ranking of results is independent of both the values of P and Δ assumed. It appears that a very short, thick rubber mooring is most "cost effective", followed by man-made fibres; with the more rigid forms of parafil and all forms of steel impracticably long.

Model - mooring line subject to a steady force P plus an imposed cyclic extension of



i) unloaded mooring line

ii) constant drift force on line

iii) additional extension due to cyclic wave force. Design load for mooring line.

Material properties of mooring line : $E, \sigma ult$, (for cylic loadings)

governing equation:- $\frac{P}{A} + \frac{\Delta . E}{L} = \frac{\sigma ult}{\lambda}$ (λ = factor of safety)

hence values for A and L, for minimum volume of mooring line are:-

$A = \frac{2P\lambda}{\sigma ult}$, $L = \frac{2\Delta E\lambda}{\sigma ult}$, Minimum volume = $(4\Delta P\lambda^2)\ \frac{E}{\sigma^2 ult}$

Material		L (m.)	A(mm^2)	Rate (Pence)/(T.m.)	£ Cost per m. width
High yield steel bars		14,290	1,286	8.4	43,244
High tensile steel wire	Conventional	4,689	439	7.1	12,057
	Dyform	4,343	407	11.1	17,412
Filled rubber IRHD 65		8	24,489	196	563
Parafil Type A		557	834	21.4	4,294
Parafil Type F		1,394	322	38.1	19,130
Viking Nylon braidline		906	2,857	30.6	9,956
Viking Nylon squareline		411	3,522	26.9	3,971
Viking polypropylene squareline		461	4,718	14.9	2,464

Loading parameters used in example - (note these do not affect the ranking)

Δ = 10 m, P = 180 $\frac{KN}{m.width}$ Factor of safety λ = 1.43

COST COMPARISON OF MATERIALS FOR A COMPLIANT ELASTIC MOORING - SIMPLIFIED MODEL

TABLE 14.1

It is interesting that this ranking is almost a complete reversal of that for cost effectiveness in carrying a known load for a known distance. Looking at the highest ranking options, rubber has the advantage of durability, comparatively well known fatigue resistance, abrasion resistance and ease of manufacturing special end details for attachment. However, the length required suggest that it would need to be combined with some other material for the mooring to reach the sea bed. The latter might be either Parafil A or steel wire, to be chosen on the basis of cost effectiveness per tonne force carried per metre, durability to match that of the rubber, and finally to meet any special requirements appropriate to the areas adjacent to the splash zone and near the sea bed anchorage. A final advantage of this mooring may be in allowing compact mooring arrays in shallower waters (see Figure 14.1)

It is also interesting that for minimum volume the maximum force in the moorings is independent of the mooring material and is two times the starting load P. It is true that the value of P is not independent of the stiffness of the mooring if subharmonic dynamic magnification occurs. However, it so happens that the effective stiffness of all of the optimised mooring lines in the Table is identical and the dynamic response of each should be similar. This adds validity to the results, if used for comparative purposes. The main limitations are in choosing the correct allowable maximum stresses and the effective modulus of elasticity for the material after many cycles of loading, particularly in the absence of any explicit consideration of fatigue life.

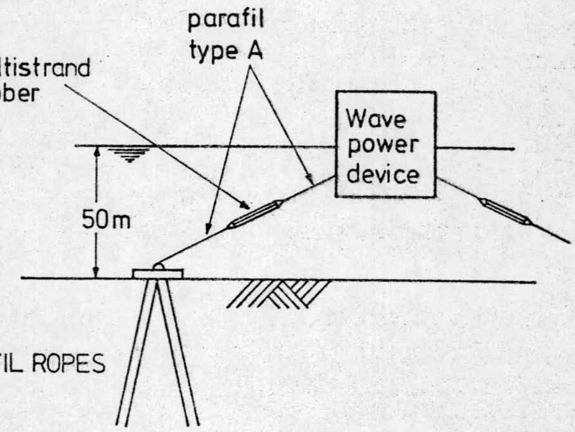
The fact that the stiffness of the minimum volume mooring is independent of the material chosen means that a formula can be derived for the natural period of the device in surge which depends only on the design value of P and Δ These are plotted in Figure 14.2 for the NEL, WPL, and SEA Reference Designs. It can be seen that these periods are within the range which may be excited by subharmonic resonance (see 14.3).

14.6.2 ANCHORAGES

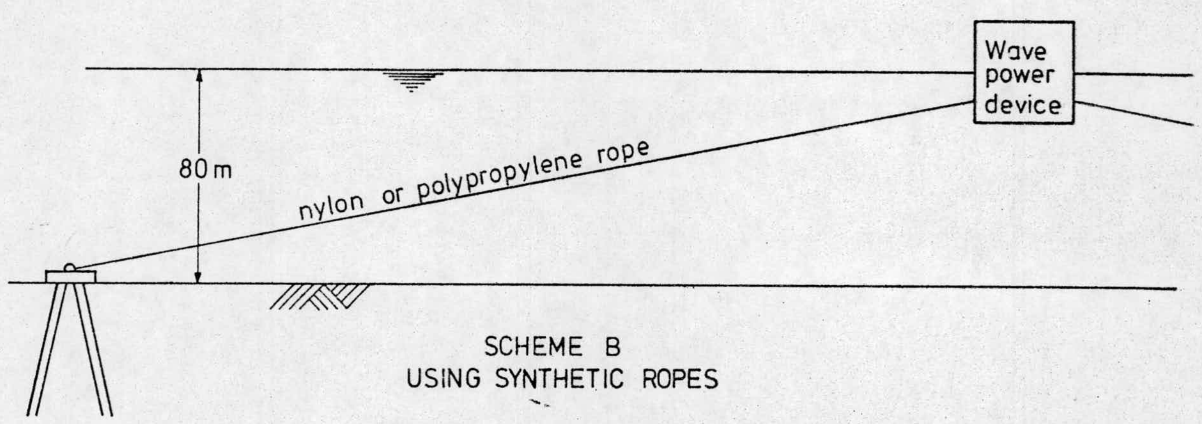
It is quite possible that the anchorages will be more expensive than the rodes. The various rode types considered in 14.7.1 all resulted, at the optimum design point, in the same peak mooring force. This indicates that rode material selection and anchor selection can be largely independent. However, the shorter the rode the more acute the inclination and the larger the vertical component of the anchorage force. This can be overcome however, by moving the device to shallower water, which may have the additional advantage of lower installation costs, and lower electric transmission costs.

The anchor types available are drag anchors, mass anchors, self-buring anchors, piled anchors and rock bolted anchors.

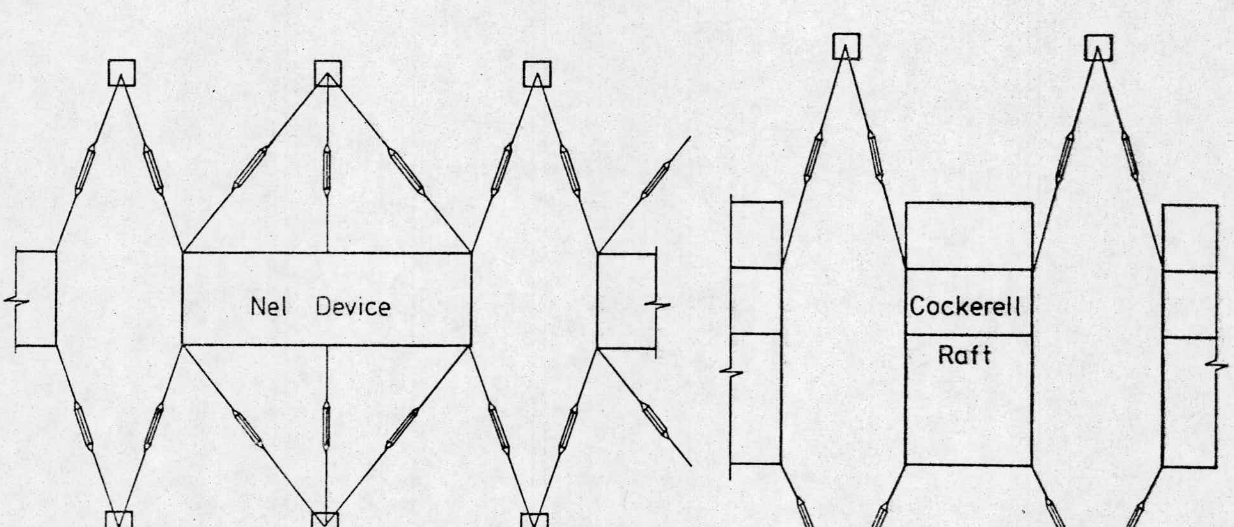
Drag anchors are the traditional form of anchor. These can be cost effective in sand and are very cheap to install. The disadvantages are the uncertainty in predicting their final position, their inability to take uplift forces, and the absence of an accessible attachment point for periodic replacement of rodes. For these reasons these anchors are likely to be combined with heavy concrete blocks, to which the rodes proper will be attached. There is a fairly low limit on the maximum possible capacity of drag anchors.



SCHEME A
USING MIXED RUBBER / PARAFIL ROPES



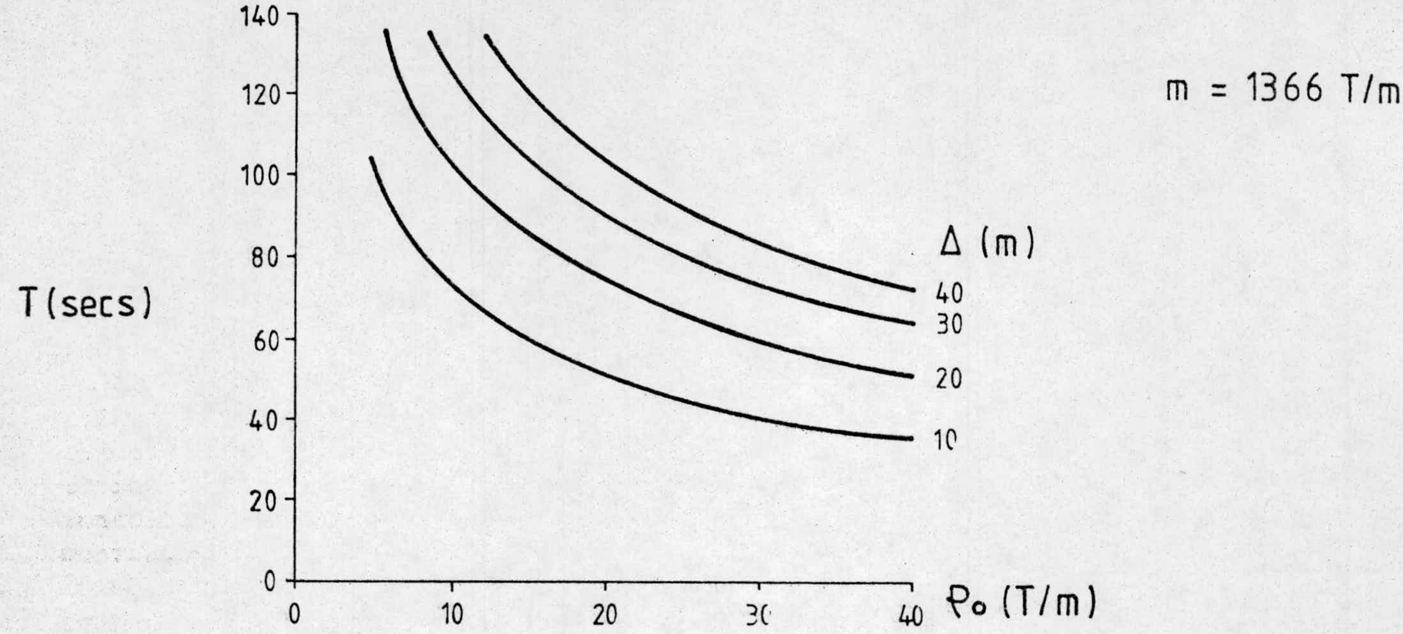
SCHEME B
USING SYNTHETIC ROPES



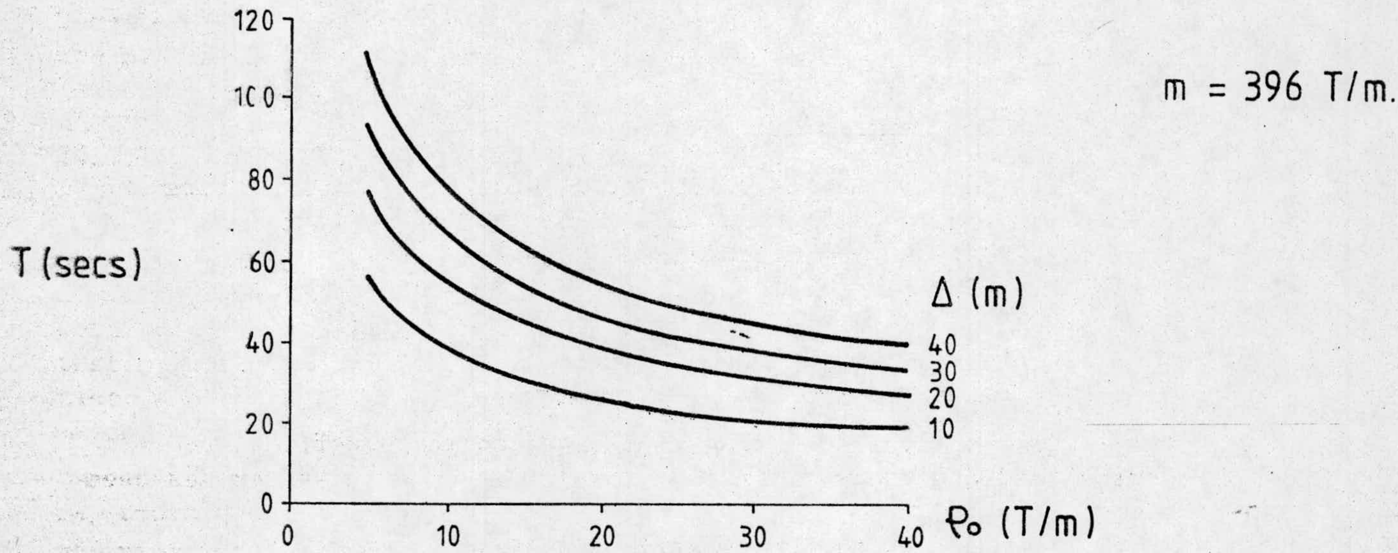
Compact Mooring Arrays Using Scheme A

ALTERNATIVE ELASTIC MOORINGS

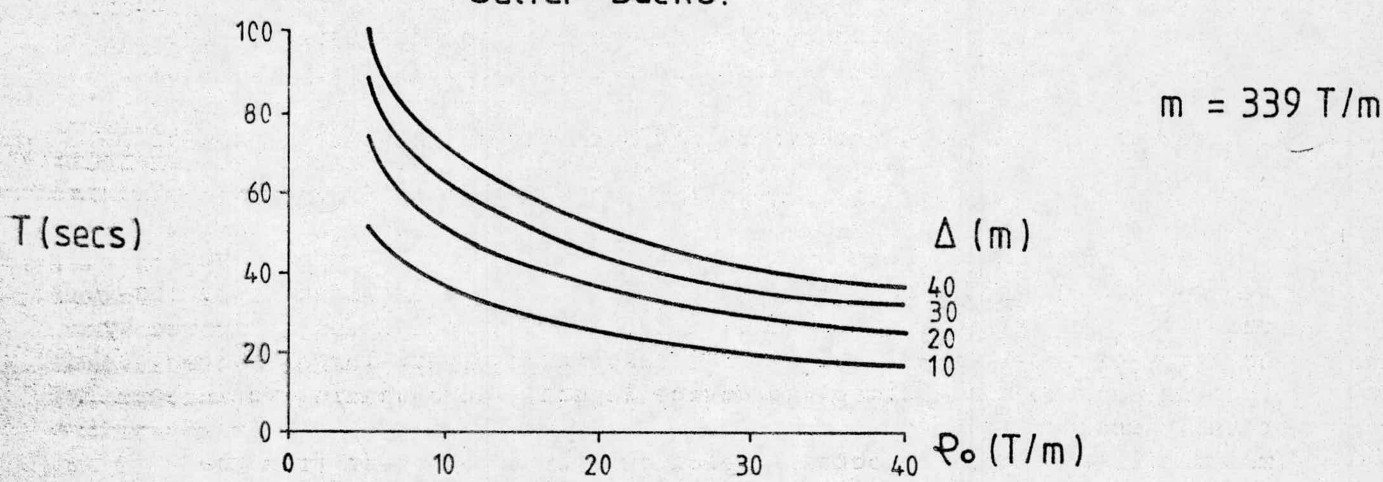
FIGURE 14·1



NEL Oscillating Water Column.



Salter Ducks.



Cockerell Rafts.

Notes.

1. Results are independent of material – see text.
2. ρ_o = design maximum drift force.
3. Δ = design imposed cyclic excursion at wave frequency.
4. m = mass including added mass.

NATURAL PERIOD OF VIBRATION OF SINGLE LINE MOORING SYSTEM OF MINIMUM VOLUME.

FIGURE 14·2

Mass anchors rely only on friction for holding horizontal forces and therefore use large volumes of material. At the sizes required for wave power, installation costs will be significant. A likely form would be a hollow concrete caisson, floated to site, sunk and filled with dredged material.

Self burying anchors are not dissimilar to drag anchors in action, but are capable of taking uplift forces due to their mode of placing. Unfortunately large scale versions of these have yet to be developed.

Piled anchors (using driven piles) are more versatile than drag anchors, being suitable for any form of sea bed except rock and capable of resisting very large forces at one point in any direction. The principle costs are likely to be in installation.

Rock bolted anchors are the equivalent of the piled anchor for rock foundation.

14.7 DEVICE TEAM PROPOSALS

Only NEL have made detailed first proposals for a mooring system. WPL have made a preliminary review of the problem but have not prepared a design for a full scale device.

14.7.1 NEL REFERENCE DESIGN MOORING

Refer to Drawing WP78/OWC/3.

NEL have given a mooring specification which defines the peak mooring load and the maximum excursions. An elastic system has been chosen, and designed to meet this specification. There are two reasons however, to believe that the rodes as designed are neither strong enough nor long enough. Firstly, late tank tests indicated somewhat higher loads and excursions in the mooring as modelled. Secondly, the first load static extension curve has been used in the design of the nylon ropes. Under cyclic loading the effective flexibility of nylon ropes is only one half, approximately, of the former value. For these reasons the Consultants have increased both the number and lengths of the rodes for the Reference Design in this report, but quite possibly not sufficiently to correct the design.

The Device Team mooring design as for a small wave power scheme (100 MW) and no account was taken of maximum utilisation of the resource. An array was adopted with each device independently moored by an array of radial moorings. This necessitated a very large device spacing, about four times the device length. Such spacing would be totally unacceptable for a major wave power scheme for which close mooring is essential to obtain useful quantities of power from the available lengths of coastline. The possibility of mooring devices in lines parallel to the coast with devices staggered in the lines is not a favoured alternative due to the degredation of performance of the leeward devices, especially for directional seas. The Consultants have therefore adopted a revised mooring array for the 2GW wave power scheme. This reduces the problems of close mooring, but it is suspected that it may not have solved them. In particular the array will present formidable problems for installation, maintenance and inspection.

The Team's preferred anchorages have been adopted - drag anchors plus weights.

To summarise, the Consultants have found it necessary to modify the NEL proposals for the 2GW scheme. The resulting scheme is at the limits of credibility, and would rapidly become completely unrealistic if the lengths of the mooring lines had to be further increased. There are some indications that the latter may be necessary. The Consultants agree with the Device Team's preferences for elastic moorings, independent device moorings, and schemes minimising installation costs. The Consultants would propose however, that shorter, but equally compliant moorings described in 14.6 would give very great advantages, particularly in allowing triangulation of the lines in plan without crossover. Piled or rock bolted anchors may be necessary to accommodate the large forces in a manageable number of anchor points. This Team are now facing design problems which require solution by all the Teams with isolated devices. There may be a pay-off in increasing the device length, which reduces the problems of close mooring, but incurs other operational disadvantages (see Chapter 4).

14.7.2 WPL REFERENCE DESIGN MOORINGS

The WPL Team have looked at a variety of systems but have not developed any of these into a mooring design. The mooring array on Drawing WP/78/RAFT/3 was proposed by the Team. They have not chosen any particular material for the rodes. Most of their sketches and tank testing have indicated mooring lines with a catenary form. It is not clear whether the Team are intending to provide some compliance by this means, or whether they will rely entirely on the flexibility of the rodes.

In the Consultants' opinion the characteristics of a catenary mooring would be particularly ill suited to the mooring array proposed, and mixtures of catenary and elastic moorings are unlikely to be beneficial. For this reason in the Reference Design the moorings are shown with taut rodes, the rodes assumed to be neutrally buoyant or nearly so.

The Team have conducted tank tests on moorings and have shown that peak forces reduce with increasing compliance. The Team have concluded from these tests that the peak mooring force will be of the order of 30 tonnes per metre of working face of device. It is interesting to compare this with the NEL early estimate of 21 tonnes per metre, which subsequent testing has shown to be an underestimate. At this stage it appears that the peak forces are similar for the two devices, but much more tank testing is needed. This will need to concentrate on correct representation of random seas, and on correct modelling of mooring characteristics. In the absence of more detailed information, the WPL Reference Design rope lengths, rope sizes, and anchorages have been chosen to match that of the NEL design.

The array proposed forms a space frame with undersea connection points. By present day standards such an array would not be regarded as feasible due to the problems of installation, adjustment, inspection and replacement. Further problems are that although nominally redundant, in practice if any one component fails the stiffness of the mooring for the worst affected raft will be so reduced that it would be likely to swing round and collide with adjacent rafts. This tendency is reinforced by the fact that the moorings are only effective in tension, and moorings on one side, being slack or nearly so will not contribute to the stiffness of the system. A domino effect is then likely to occur.

To summarise, the proposed mooring array typifies the problems associated with close mooring of narrow devices. Experience suggests that the proposed system is not likely to be feasible, and the problem remains a challenge to the Team's ingenuity. The Consultants would propose that the Team should reconsider using individual moorings for each device with short but compliant rodes.

14.7.3 SEA REFERENCE DESIGN MOORINGS

The SEA Team have not made any proposals for full scale moorings. The Edinburgh Team have made extensive measurements of the mean surge forces on ducks on a rigidly held spine in a narrow tank. The maximum value of this force for all likely sea states is 30 kN/m (3 tonnes/m), full scale. This will be very much less than the instantaneous peak force in the mooring, even for very compliant moorings. For the Reference Design the Consultants have multiplied this figure by two to correct the peak slowly varying drift force, and by two again to correct for the variations in force at wave frequency in an optimised elastic mooring system (see 14.6). This gives a figure of 12 tonnes/m of device. For simplicity and fair comparison the design of the rodes is again based on the NEL design. As the mooring for the spine is at 250 m centres a large number of ropes is required at each attachment point. It would not be possible to use many drag anchors, and rock bolted anchors have been adopted.

14.7.4 FRENCH AIR BAG

Drafting note - Comments pending - relatively favourable comments anticipated.

14.8 CONCLUSIONS

a) Close mooring of many separate vessels has never before been attempted for exposed locations and presents formidable problems.

b) None of the present proposals for close mooring appear satisfactory.

c) Rigid moorings are not feasible for the current floating devices, the moorings need to be compliant.

d) Catenary moorings, and moorings using weights or sinking buoys to store energy appear to be both unacceptably expensive and have very unfavourable stiffness characteristics.

e) Moorings using material strain to store energy appear to be the only feasible proposal. Materials suitable for this duty are nylon, polypropylene, and rubber. The last mentioned has the advantage of providing a compact mooring which will be essential in mooring arrays.

f) In deriving a mooring specification it will be necessary for loads and deflections to be considered simultaneously. Cost effectiveness of moorings in terms of load carrying characteristics only, is very misleading.

g) In designing high strain mooring lines the cyclic load-deflection curve must be considered rather than the static curve.

h) Elastic rodes should be approximately neutrally buoyant and taut to avoid 'slack'.

i) Future designs must consider installation and adjustment, reliability, redundancy, maintenance, and replacement as priority topics. Only very simple systems are likely to be feasible.

j) It is obvious that more tank testing, of a fairly sophisticated nature, is required. Less obviously, it is essential that this testing is fully integrated with appropriate design studies. Only an iterative programme of investigation will provide a feasible and proven solution.

k) Devices with long spines will almost certainly be easier to moor than many short devices. However, the consequences of failure of one line could be catastrophic, unless the system has a suitable degree of redundancy.

CHAPTER 15 - MAINTENANCE AND MANNING

Short Chapter in course of preparation

CHAPTER 16 - WAVE DATA

Short Chapter in course of preparation

CHAPTER 17 - ENVIRONMENT

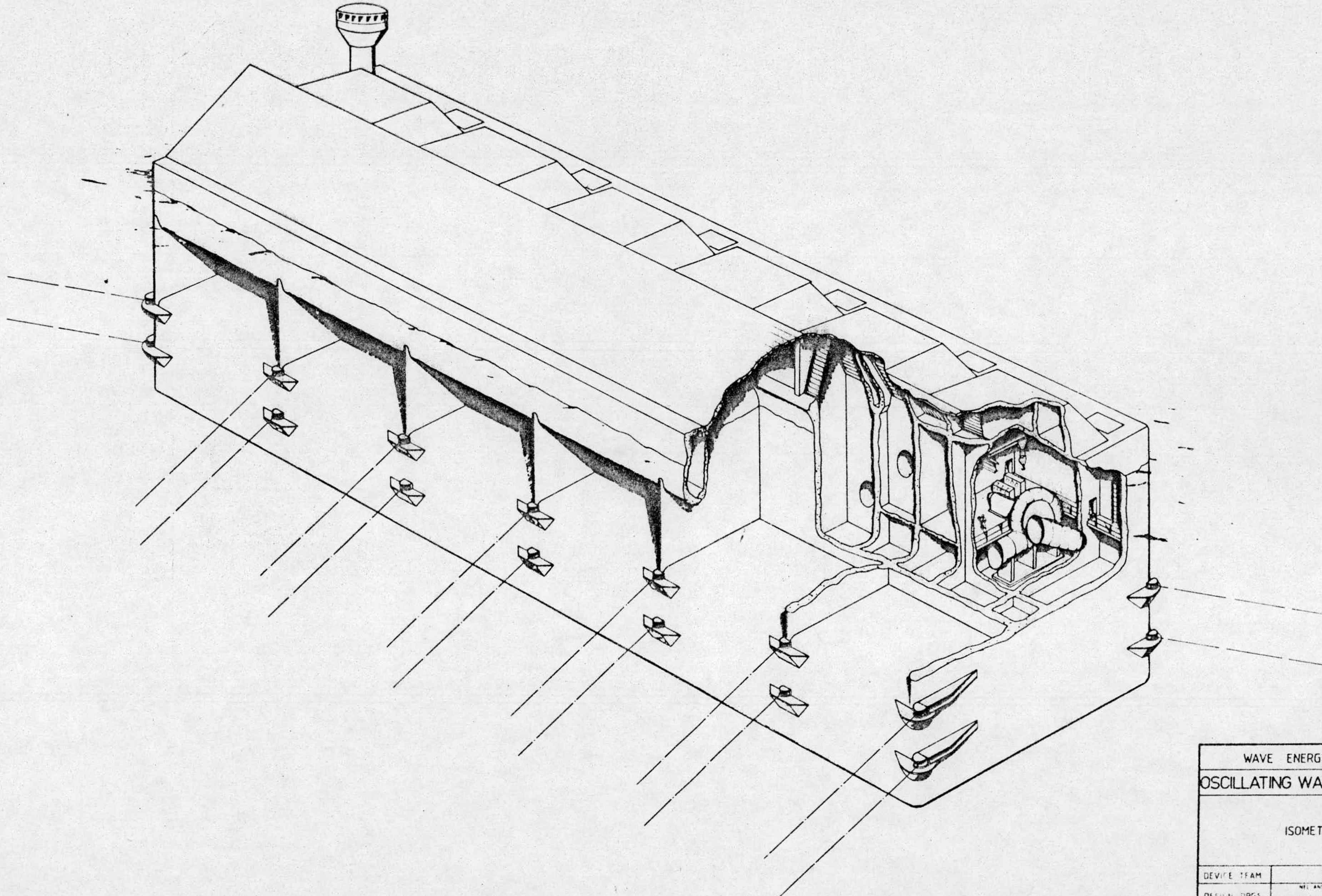
Short Chapter in course of preparation

CHAPTER 18 - ECONOMICS

Short Chapter in course of preparation

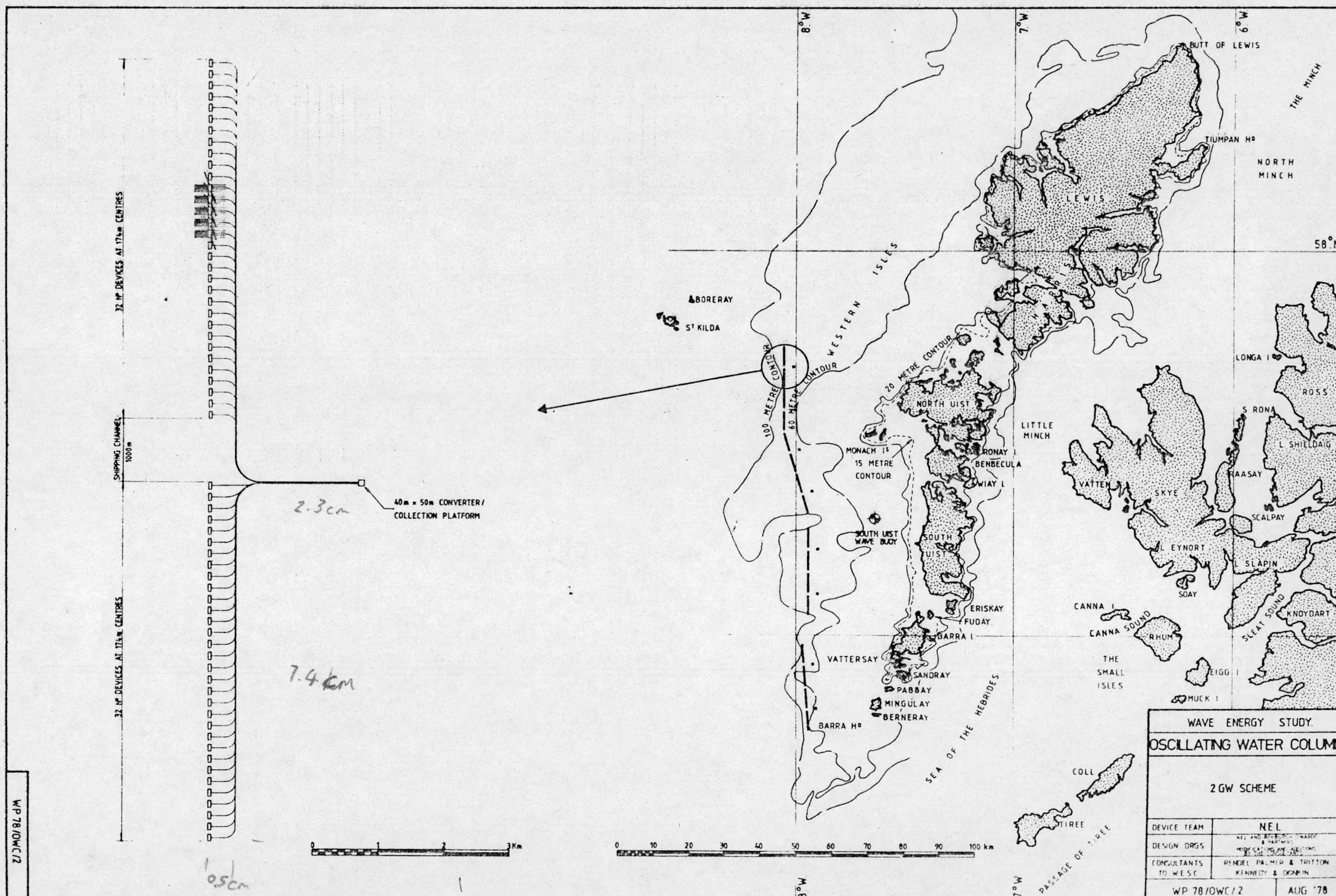
ACKNOWLEDGEMENTS

Currently in course of preparation



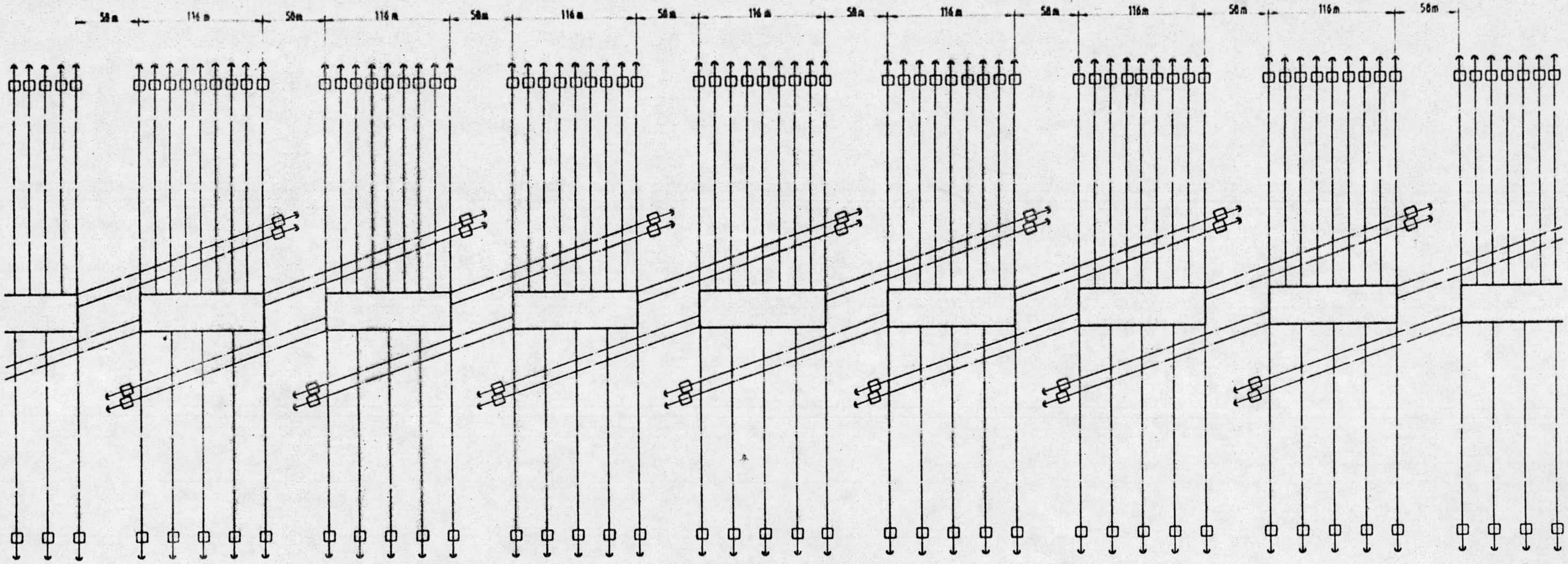
WP 78/OWC/1

WAVE ENERGY STUDY	
OSCILLATING WATER COLUMN	
ISOMETRIC	
DEVICE TEAM	N.E.L
DESIGN DRGS	NEL AND [illegible] & PARTNERS MODIFICATIONS AND ADDITIONS BY THE CONSULTANTS
CONSULTANTS TO W.E.S.T.	RENDEL PALMER & TRITTON KENNEDY & DONKIN
WP 78/OWC/1	AUG '78

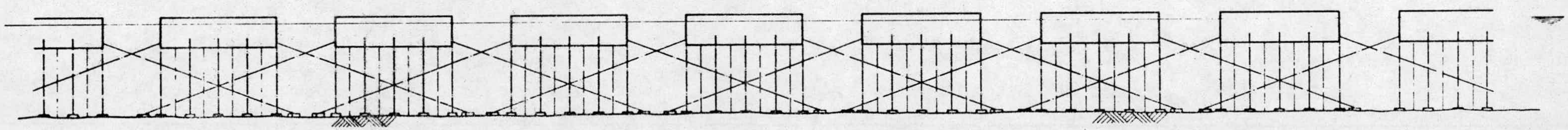


AV = 6.5cm = 5km each

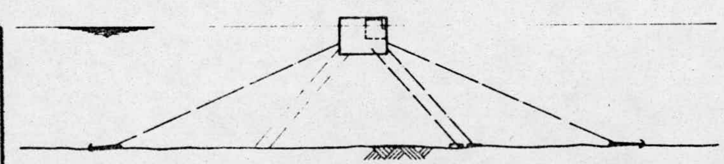
512 devices



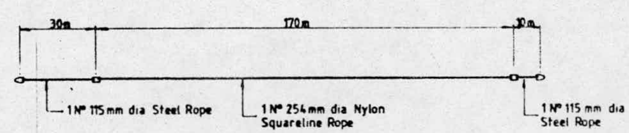
PART PLAN ON A LINE OF DEVICES
SHOWING MOORING



ELEVATION



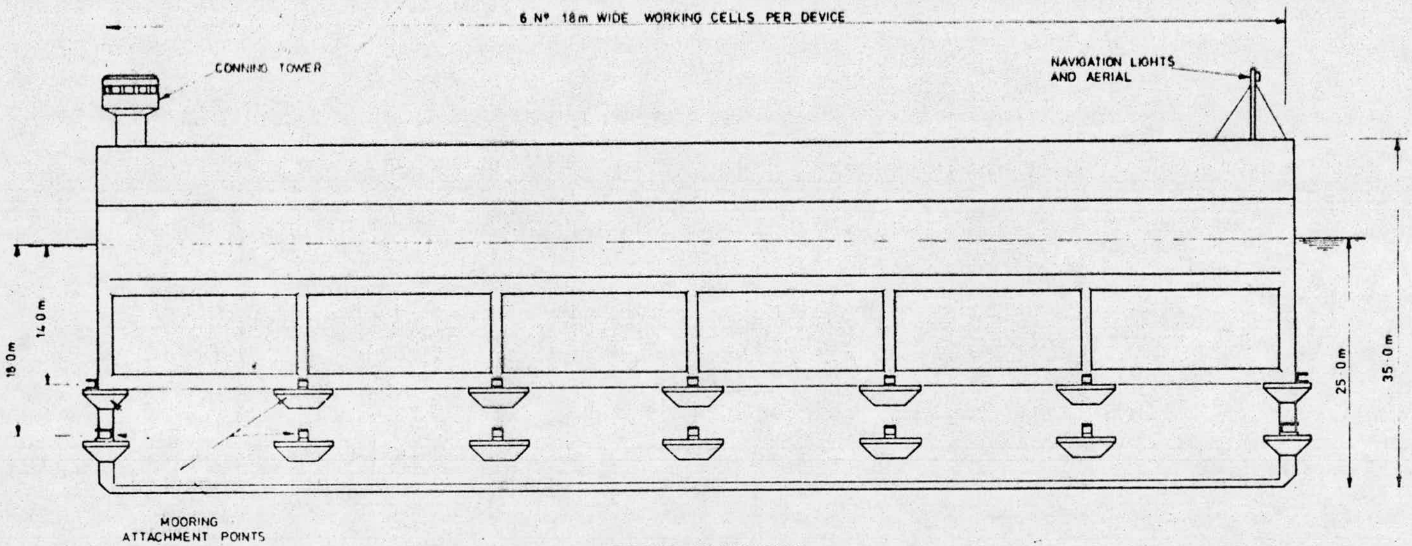
END ELEVATION



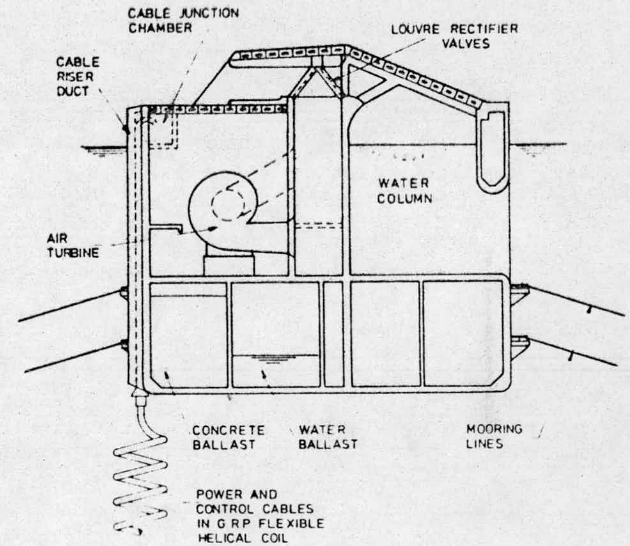
MOORING RODE DETAIL

WP 78/OWC/3

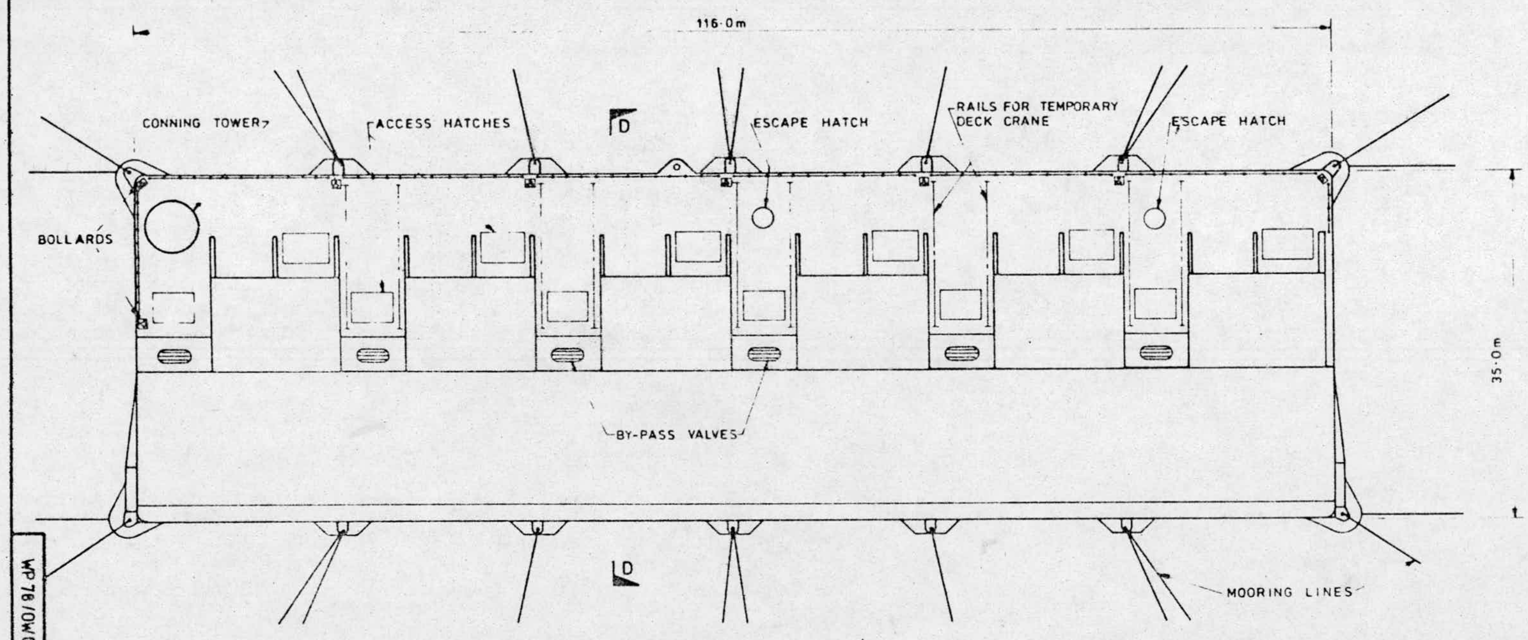
WAVE ENERGY STUDY.	
OSCILLATING WATER COLUMN	
MOORING	
DEVICE TEAM	N.E.L
DESIGN DRGS	NEL AND ROXBURGH DINARDO & PARTNERS MODIFICATIONS AND ADDITIONS BY THE CONSULTANTS
CONSULTANTS TO W.E.S.C.	RENDEL, PALMER & TRITTON KENNEDY & DONKIN
WP 78/OWC/3	AUG '78.



FRONT ELEVATION



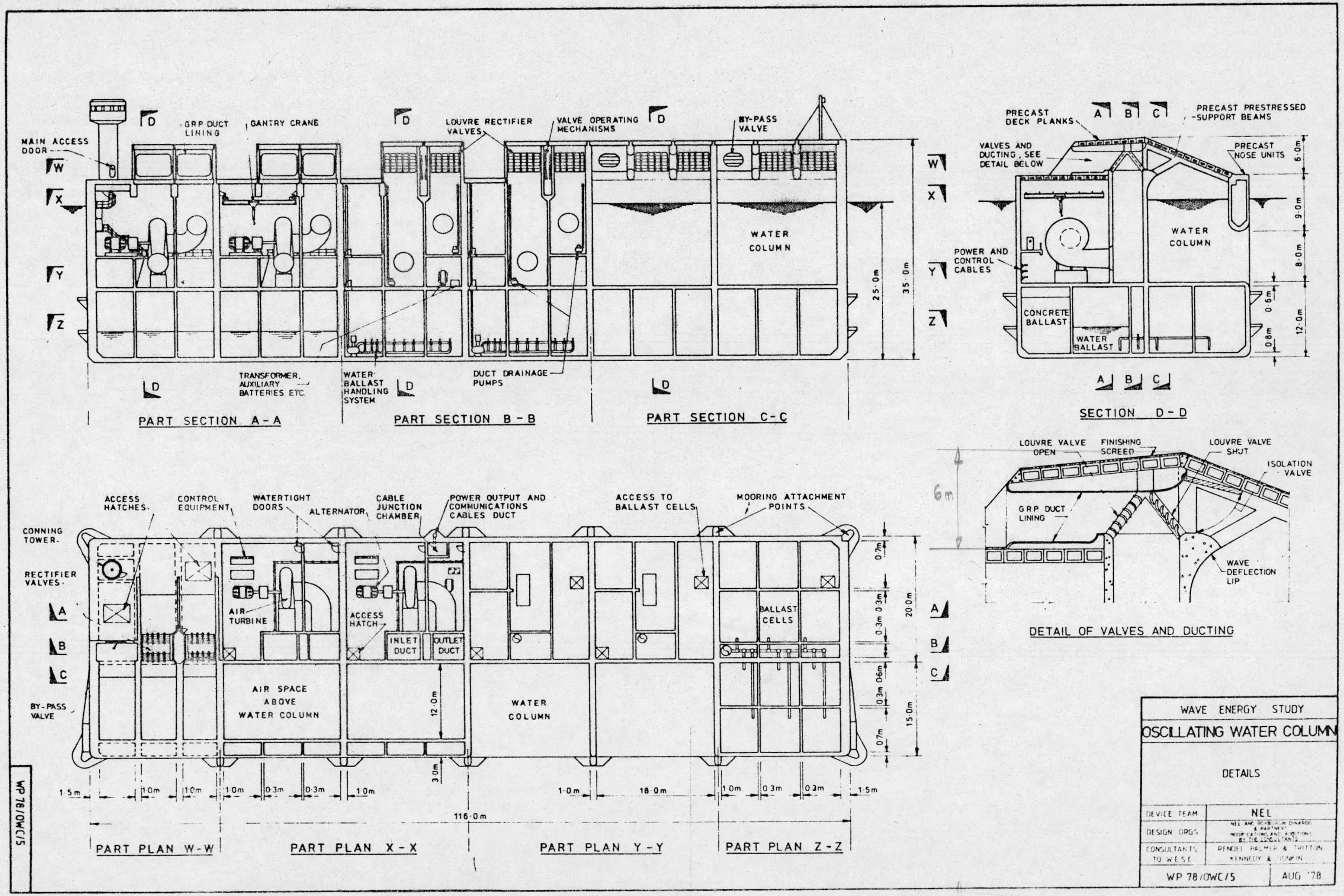
SECTION D-D

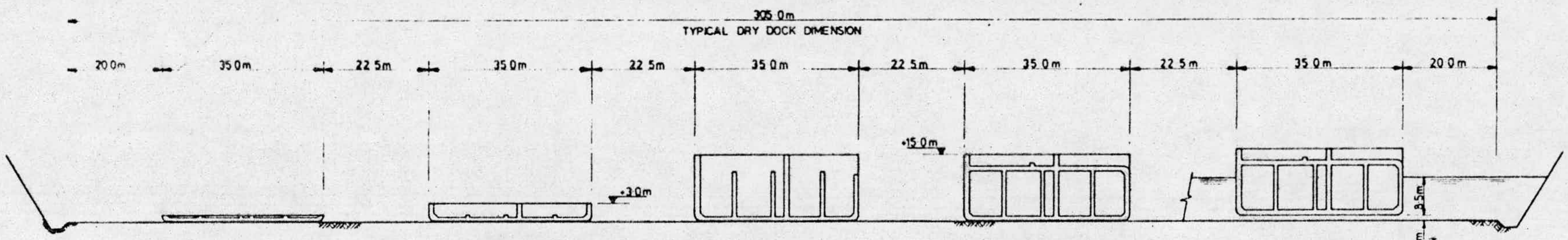


PLAN

WP 78/OWC/4

WAVE ENERGY STUDY	
OSCILLATING WATER COLUMN	
GENERAL ARRANGEMENT	
DEVICE TEAM	NEL
DESIGN DRGS	[illegible]
CONSULTANTS	RENDEL PALMER & TRITTON / KENNEDY & DONKIN
WP 78/OWC/4	AUG '78


MAIN ACCESS DOOR
GRP DUCT LINING
GANTRY CRANE
LOUVRE RECTIFIER VALVES
VALVE OPERATING MECHANISMS
BY-PASS VALVE
WATER COLUMN
TRANSFORMER, AUXILIARY BATTERIES ETC.
WATER BALLAST HANDLING SYSTEM
DUCT DRAINAGE PUMPS
25·0m
35·0m
PART SECTION A-A
PART SECTION B-B
PART SECTION C-C
PRECAST DECK PLANKS
PRECAST PRESTRESSED SUPPORT BEAMS
VALVES AND DUCTING, SEE DETAIL BELOW
PRECAST NOSE UNITS
POWER AND CONTROL CABLES
WATER COLUMN
CONCRETE BALLAST
WATER BALLAST
6·0m
9·0m
8·0m
12·0m
0·6m
0·8m
SECTION D-D
LOUVRE VALVE OPEN
FINISHING SCREED
LOUVRE VALVE SHUT
ISOLATION VALVE
GRP DUCT LINING
WAVE DEFLECTION LIP
6m
DETAIL OF VALVES AND DUCTING
ACCESS HATCHES
CONTROL EQUIPMENT
WATERTIGHT DOORS
ALTERNATOR
CABLE JUNCTION CHAMBER
POWER OUTPUT AND COMMUNICATIONS CABLES DUCT
ACCESS TO BALLAST CELLS
MOORING ATTACHMENT POINTS
CONNING TOWER
RECTIFIER VALVES
BY-PASS VALVE
AIR TURBINE
ACCESS HATCH
INLET DUCT
OUTLET DUCT
BALLAST CELLS
AIR SPACE ABOVE WATER COLUMN
WATER COLUMN
12·0m
3·0m
20·0m
15·0m
0·7m
0·3m
0·6m
1·5m
1·0m
0·3m
18·0m
116·0m
PART PLAN W-W
PART PLAN X-X
PART PLAN Y-Y
PART PLAN Z-Z
WP 78/OWC/5
WAVE ENERGY STUDY
OSCILLATING WATER COLUMN
DETAILS
DEVICE TEAM
NEL
DESIGN DRGS
CONSULTANTS TO W.E.S.C.
RENDEL PALMER & TRITTON
KENNEDY & DONKIN
WP 78/OWC/5
AUG '78



STAGE 1
FORM BASE SLAB

STAGE 2
POUR STARTER WALLS FOR SLIPFORMED WALLS

STAGE 3
SLIPFORM MAIN WALLS TO 15m POUR OTHER WALLS IN-SITU

STAGE 4
FORM INTERMEDIATE SLAB

STAGE 5
FLOAT-OUT

CONSTRUCTION SEQUENCE

STAGE 1 PREPARE DOCK FLOOR (116m × 35m PER DEVICE) AND FORM BASE SLAB AND KICKERS.

STAGE 2 FORM 3m HIGH STARTER WALLS FOR ALL EXTERNAL AND FULL HEIGHT WALLS TO BE SLIPFORMED

STAGE 3 SLIPFORM THESE WALLS TO A HEIGHT OF 15m AND CONVENTIONALLY SHUTTER AND POUR OTHER WALLS TO THE SOFFIT LEVEL OF THE INTERMEDIATE SLAB.

STAGE 4 FORM INTERMEDIATE SLAB AND KICKERS TO INTERNAL DIAPHRAGMS.

STAGE 5 BALLAST UNIT TO PREVENT PREMATURE FLOAT- OFF. FLOOD DOCK. DE-BALLAST AND FLOAT-OUT IN SEQUENCE. TOW TO CALM WATER CONSTRUCTION SITE.

STAGE 6 MOOR UNIT. ERECT TEMPORARY STEEL BULKHEADS TO WATER COLUMN OPENING. COMPLETE SLIPFORMING OF MAIN WALLS AND IN-SITU CONCRETE WORK ON INTERNAL WALLS AND FLOORS.

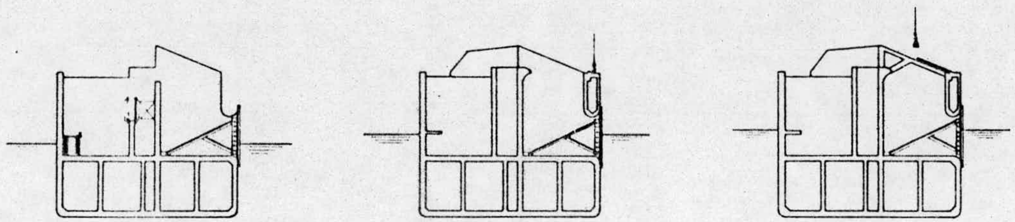
STAGE 7 POSITION PRECAST NOSE UNITS AND STRESS THEM TOGETHER.

STAGE 8 POSITION PRECAST PRESTRESSED ROOF SUPPORT BEAMS OVER WATER COLUMN AREA. PLACE PRECAST DECK BEAMS ON THESE AND CONCRETE IN POSITION.

STAGE 9 PLACE PERMANENT CONCRETE BALLAST IN REAR CELLS AND TEMPORARY WATER BALLAST IN FRONT CELLS TO MAINTAIN TRIM.
INSTALL MACHINERY. VALVES. DUCT LININGS. ETC.

STAGE 10 CONSTRUCT CONNING TOWER. PLACE FINAL PRECAST DECK AND ROOF PLANKS. CONSTRUCT ACCESS AND ESCAPE HATCHES AND APPLY FINISHING SCREEDS TO ROOFS.

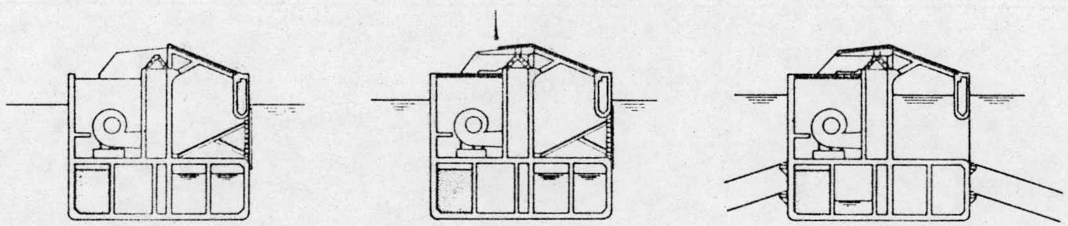
STAGE 11 TOW OUT TO OPERATIONAL LOCATION AND MOOR. REMOVE TEMPORARY BULKHEAD. ADJUST WATER BALLAST TO TRIM.



STAGE 6
ERECT TEMPORARY BULKHEADS CONTINUE SLIPFORMING AND IN-SITU CONCRETE POURS

STAGE 7
PLACE P.C. NOSE UNITS

STAGE 8
PLACE P.C. SUPPORT BEAMS AND DECK PLANKS



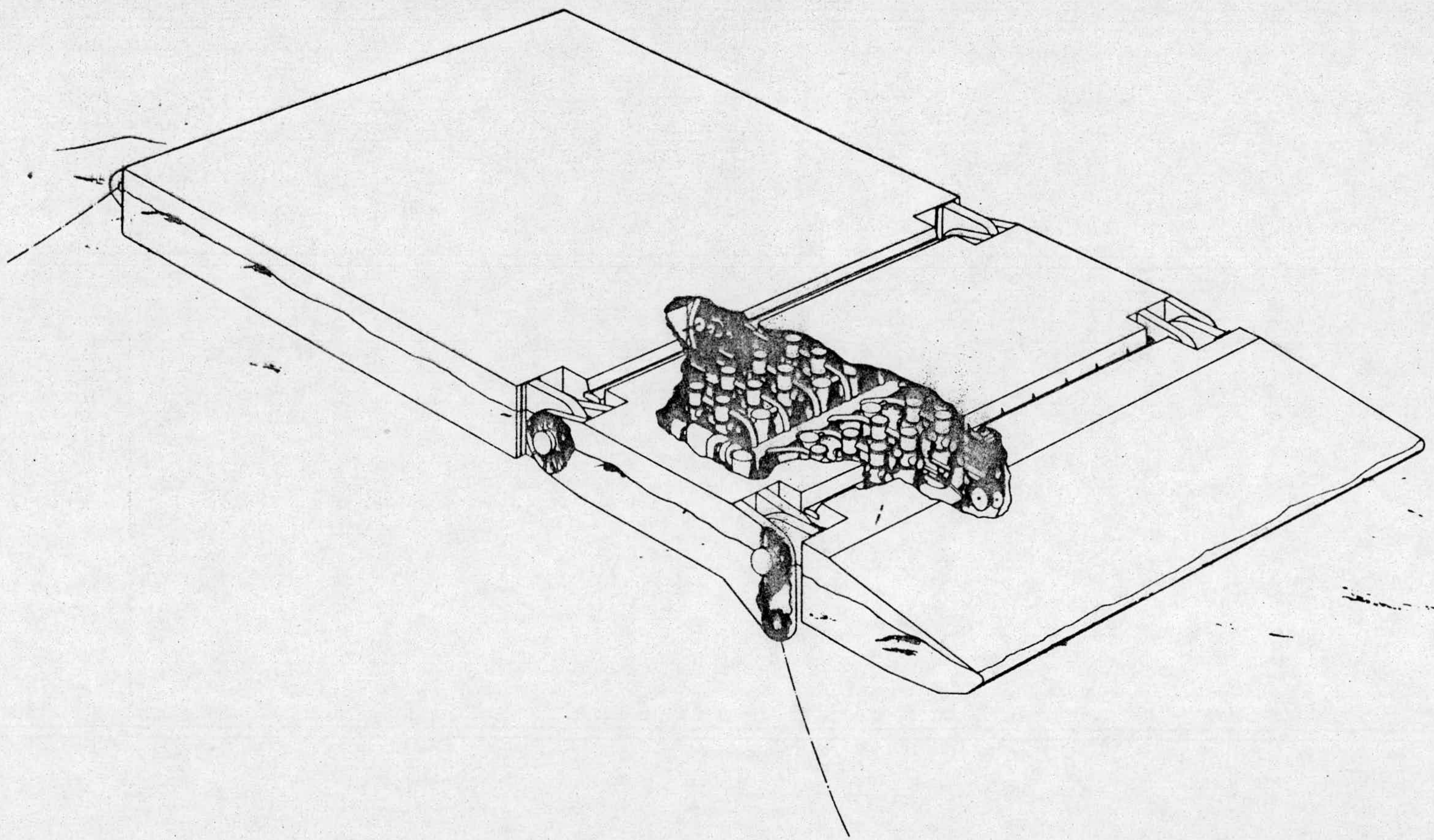
STAGE 9
PLACE CONCRETE BALLAST AND INSTALL MACHINERY

STAGE 10
FINISH OFF DECKS AND ROOFS

STAGE 11
TOW-OUT AND INSTALLATION

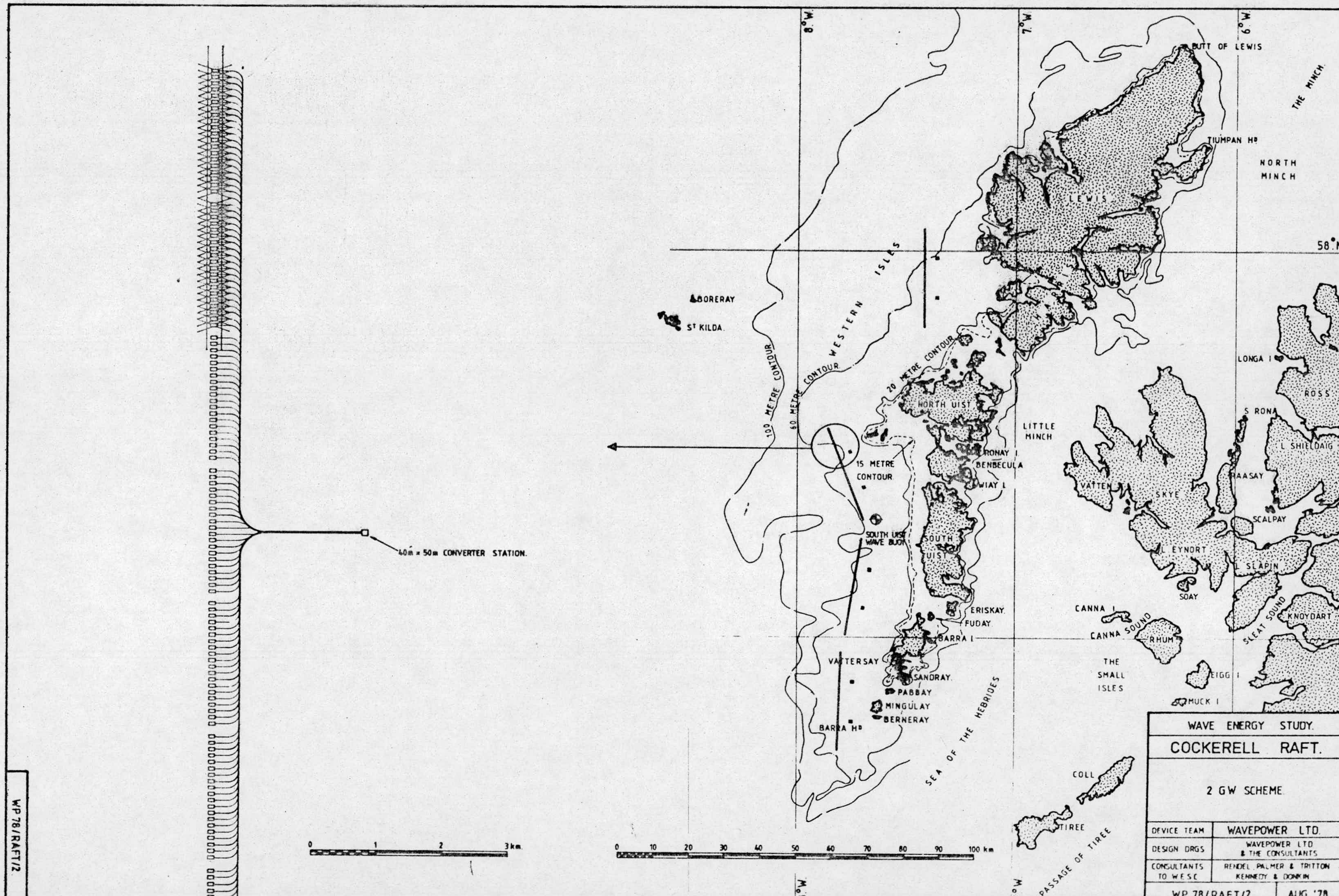
WP 78/OWC/6

WAVE ENERGY STUDY.	
OSCILLATING WATER COLUMN	
CONSTRUCTION & FLOTATION	
DEVICE TEAM	NEL
DESIGN ORGS	[illegible]
CONSULTANTS TO W.E.S.C.	RENDEL PALMER & TRITTON / KENNEDY & DONKIN
WP 78/OWC/6	AUG '78

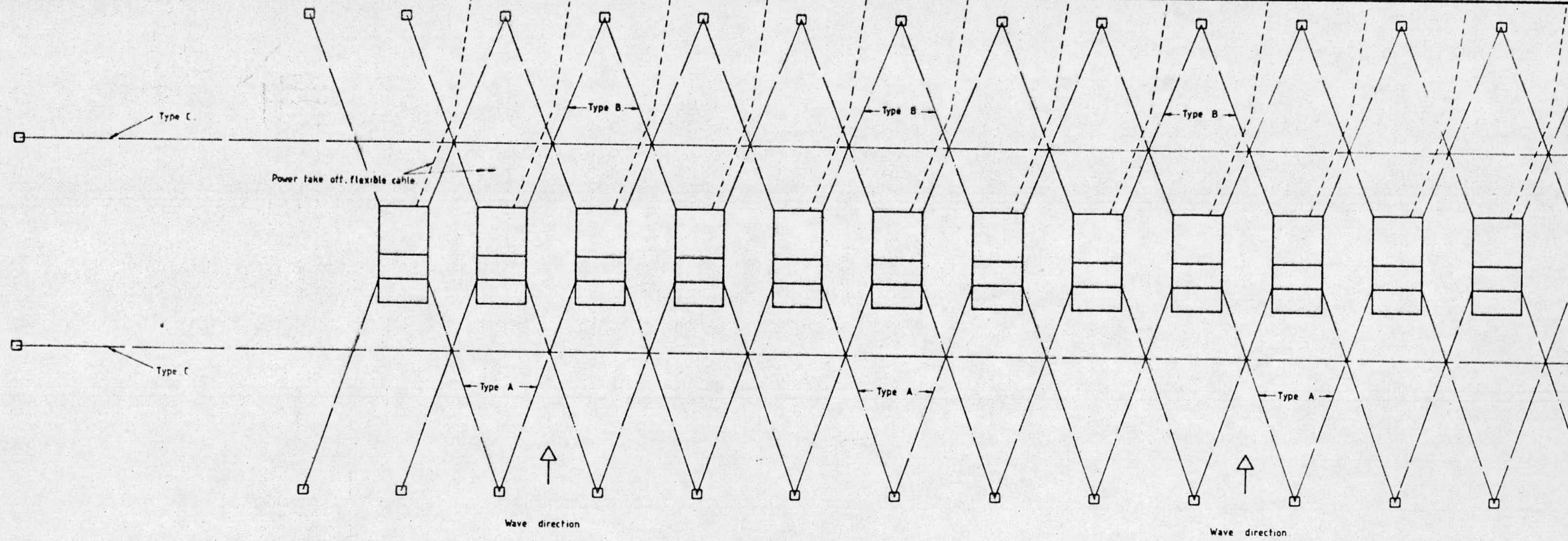


WP 78/RAFT/1

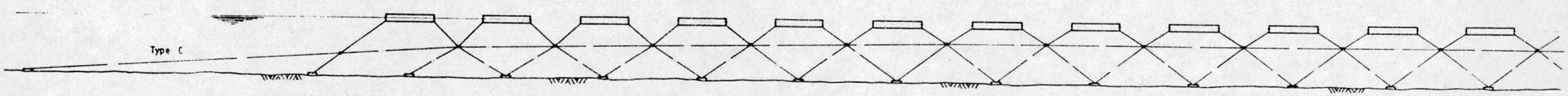
WAVE ENERGY STUDY.	
COCKERELL RAFT	
ISOMETRIC	
DEVICE TEAM	WAVE POWER LTD
DESIGN DRGS	DRAWN BY THE CONSULTANTS BASED ON IDEAS BY WAVEPOWER LTD
CONSULTANTS TO W.E.S.C.	RENDEL PALMER & TRITTON KENNEDY & DONKIN
WP 78/RAFT/1	AUG '78



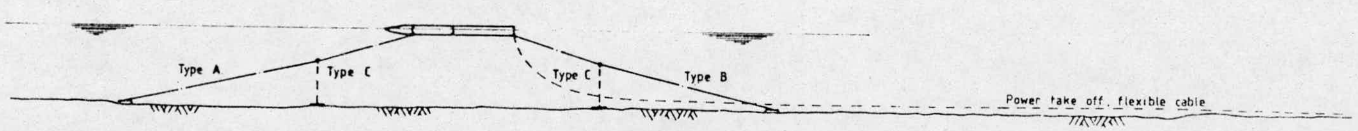
WAVE ENERGY STUDY.
COCKERELL RAFT.
2 GW SCHEME.
DEVICE TEAM
WAVEPOWER LTD.
DESIGN DRGS
WAVEPOWER LTD & THE CONSULTANTS
CONSULTANTS TO W.E.S.C.
RENDEL, PALMER & TRITTON
KENNEDY & DONKIN
WP 78/RAFT/2
AUG '78
WP 78/RAFT/2
40m x 50m CONVERTER STATION.
0
1
2
3 km.
0
10
20
30
40
50
60
70
80
90
100 km
8°W.
7°W.
6°W.
58°N.
BUTT OF LEWIS
THE MINCH.
TIUMPAN Hd
NORTH MINCH
LEWIS
HARRIS
BORERAY
St KILDA.
WESTERN ISLES
100 METRE CONTOUR
60 METRE CONTOUR
20 METRE CONTOUR
15 METRE CONTOUR
NORTH UIST
LITTLE MINCH
RONAY I
BENBECULA
WIAY I
SOUTH UIST WAVE BUOY
SOUTH UIST
ERISKAY.
FUDAY.
BARRA I
VATTERSAY
SANDRAY.
PABBAY
MINGULAY
BERNERAY
BARRA Hd
SEA OF THE HEBRIDES
LONGA I
ROSS
S. RONA
L. SHIELDAIG
RAASAY
VATTEN
SKYE
SCALPAY
L. EYNORT
L. SLAPIN
SOAY
CANNA I
CANNA SOUND
RHUM
KNOYDART
SLEAT SOUND
THE SMALL ISLES
EIGG I
MUCK I
COLL
TIREE
PASSAGE OF TIREE



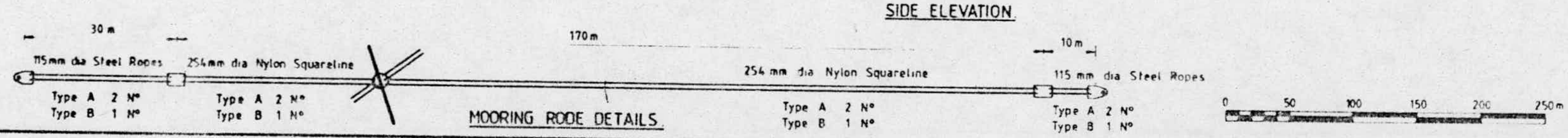
PLAN ON A LINE OF RAFTS.
SHOWING MOORINGS.



FRONT ELEVATION.



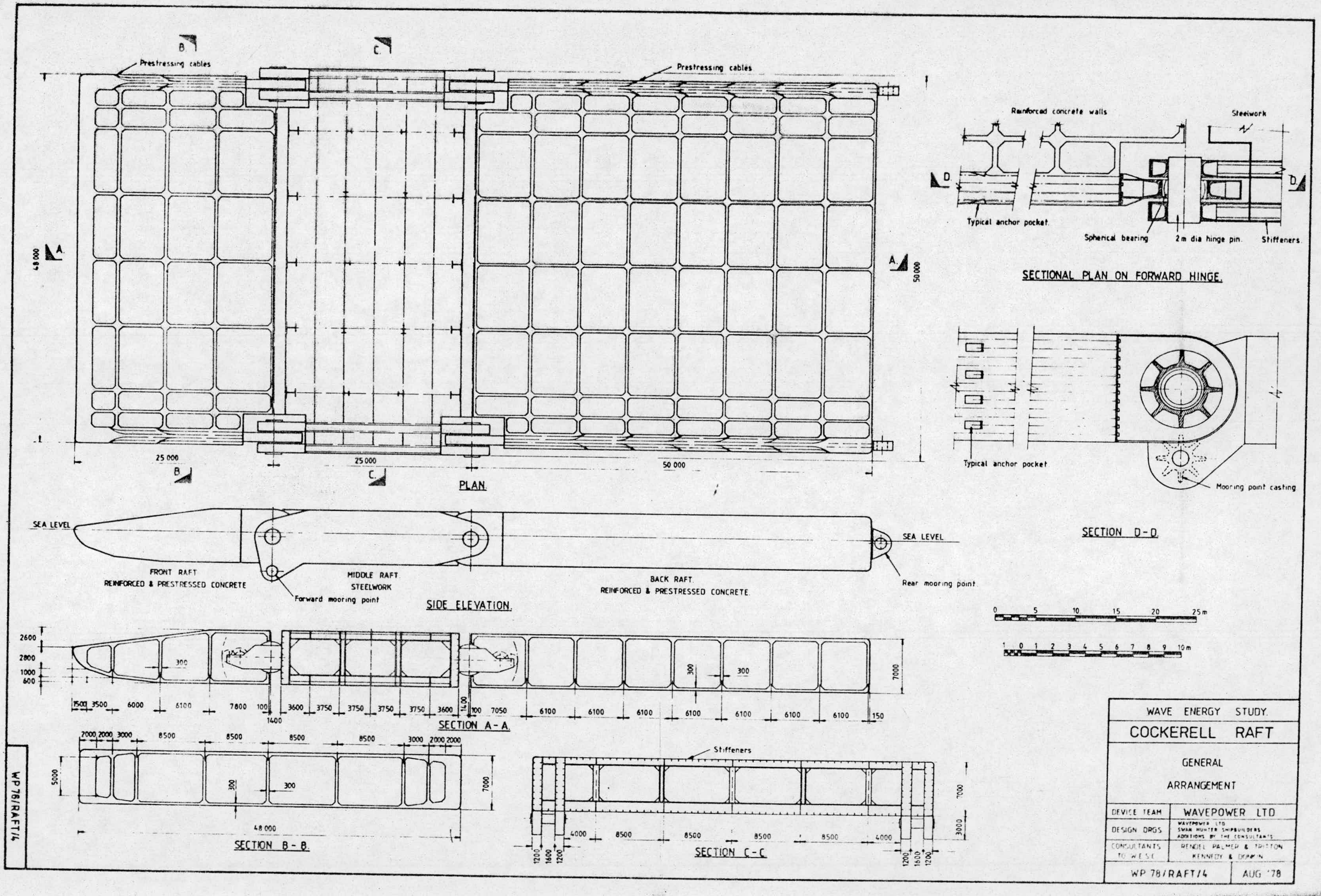
SIDE ELEVATION.



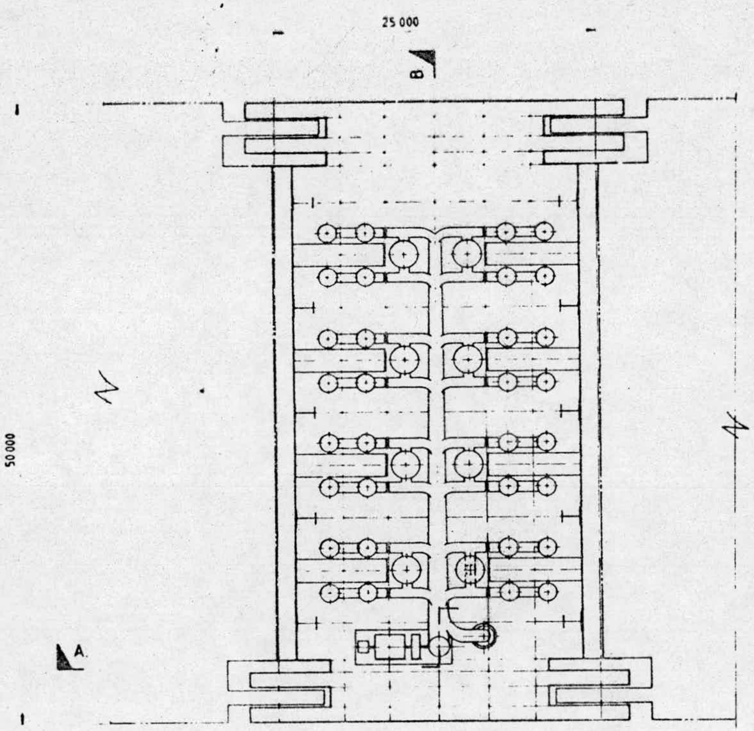
MOORING RODE DETAILS.

WP 78/RAFT/3

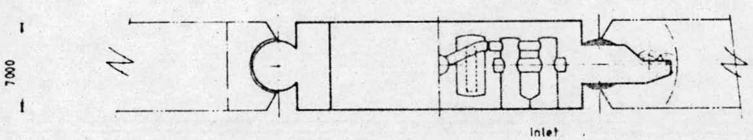
WAVE ENERGY STUDY.	
COCKERELL RAFT.	
MOORING	
DEVICE TEAM	WAVEPOWER LTD
DESIGN DRGS	SCHEME PROPOSED BY WAVEPOWER LTD REDRAWN BY CONSULTANTS
CONSULTANTS TO W.E.S.C.	RENDEL PALMER & TRITTON KENNEDY & DONKIN
WP 78/RAFT/3	AUG '78



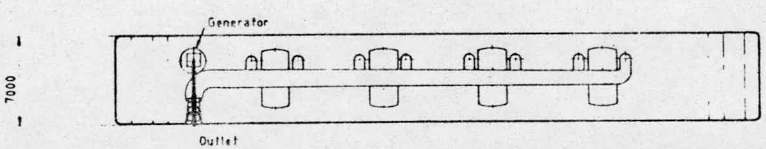
Prestressing cables
Prestressing cables
PLAN
25 000
25 000
50 000
48 000
50 000
Reinforced concrete walls
Steelwork
Typical anchor pocket
Spherical bearing
2m dia hinge pin
Stiffeners
SECTIONAL PLAN ON FORWARD HINGE
Typical anchor pocket
Mooring point casting
SECTION D-D
SEA LEVEL
SEA LEVEL
FRONT RAFT
REINFORCED & PRESTRESSED CONCRETE
MIDDLE RAFT
STEELWORK
Forward mooring point
BACK RAFT
REINFORCED & PRESTRESSED CONCRETE
Rear mooring point
SIDE ELEVATION
0 5 10 15 20 25m
1 0 1 2 3 4 5 6 7 8 9 10m
SECTION A-A
SECTION B-B
Stiffeners
SECTION C-C
WAVE ENERGY STUDY
COCKERELL RAFT
GENERAL
ARRANGEMENT
DEVICE TEAM
WAVEPOWER LTD
DESIGN DRGS
WAVEPOWER LTD
SWAN HUNTER SHIPBUILDERS
ADDITIONS BY THE CONSULTANTS
CONSULTANTS TO W.E.S.P.
RENDEL PALMER & TRITTON
KENNEDY & DONKIN
WP 78/RAFT/4
AUG '78
WP 78/RAFT/4



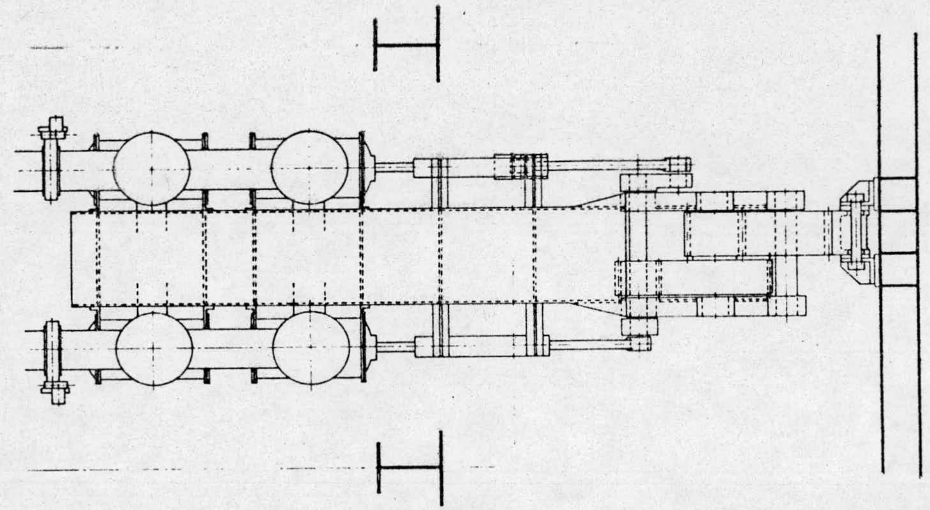
PLAN SECTION



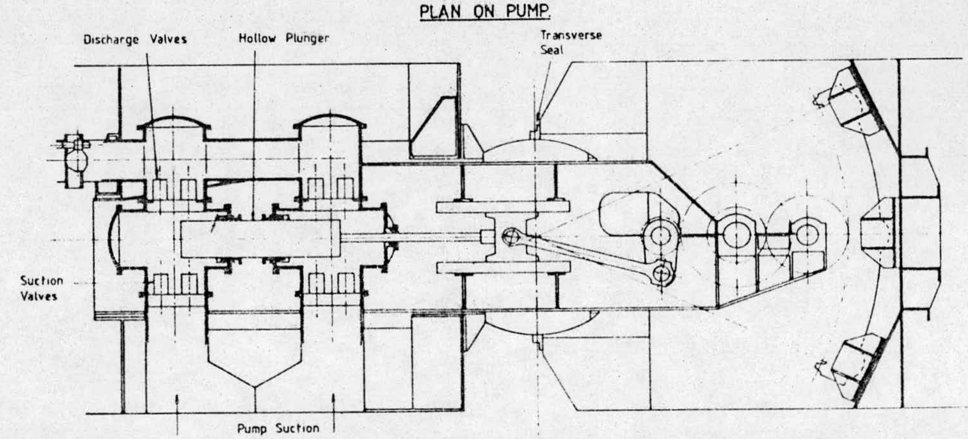
SECTION A-A.



SECTION B-B.



PLAN ON PUMP.



SECTION THROUGH PUMP.

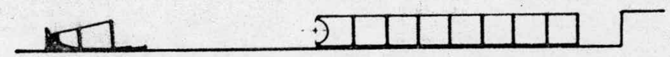
0 5 10 15 20 25 m

1 0 1 2 3 4 5 m

WAVE ENERGY STUDY.	
COCKERELL RAFT	
DETAILS OF POWER TAKE-OFF	
DEVICE TEAM	WAVEPOWER LTD
DESIGN DRGS	WAVEPOWER LTD
CONSULTANTS TO W.E.S.G.	RENDEL PALMER & TRITTON KENNEDY & DONKIN
WP 78/RAFT/5	AUG '78

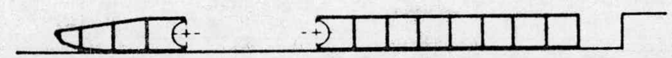
WP 78/RAFT/5

STAGE 1
Cast base slab with wall starter bars.
Centre section in steelwork being fabricated elsewhere.
Work in dry dock or on slipway.

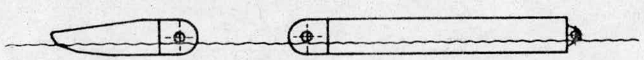


STAGE 2.
Cast diaphragm walls.

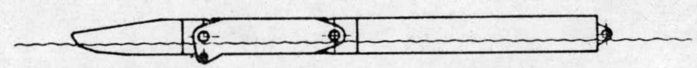
STAGE 3
Rotate front section and cast remaining base slab
Shutter and cast top slabs



STAGE 4.
Complete front section.

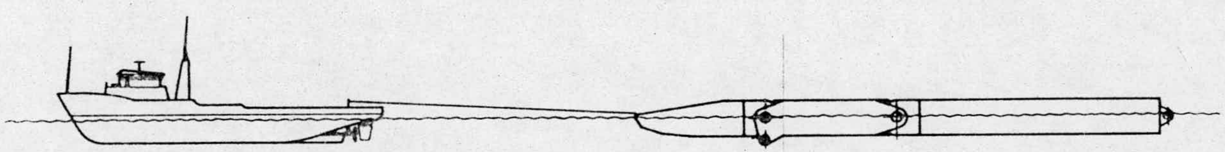


STAGE 5
Launch or float out to vacate casting site
Moored awaiting linking up with centre section



STAGE 6.
Sections enter fitting out berth for splicing of hinge assemblies, fitting of hinge trunnions, mating of gears in racks and fitting of joint seal assemblies.

N.B. The shipyard construction sequence diagram for the central section is not shown.

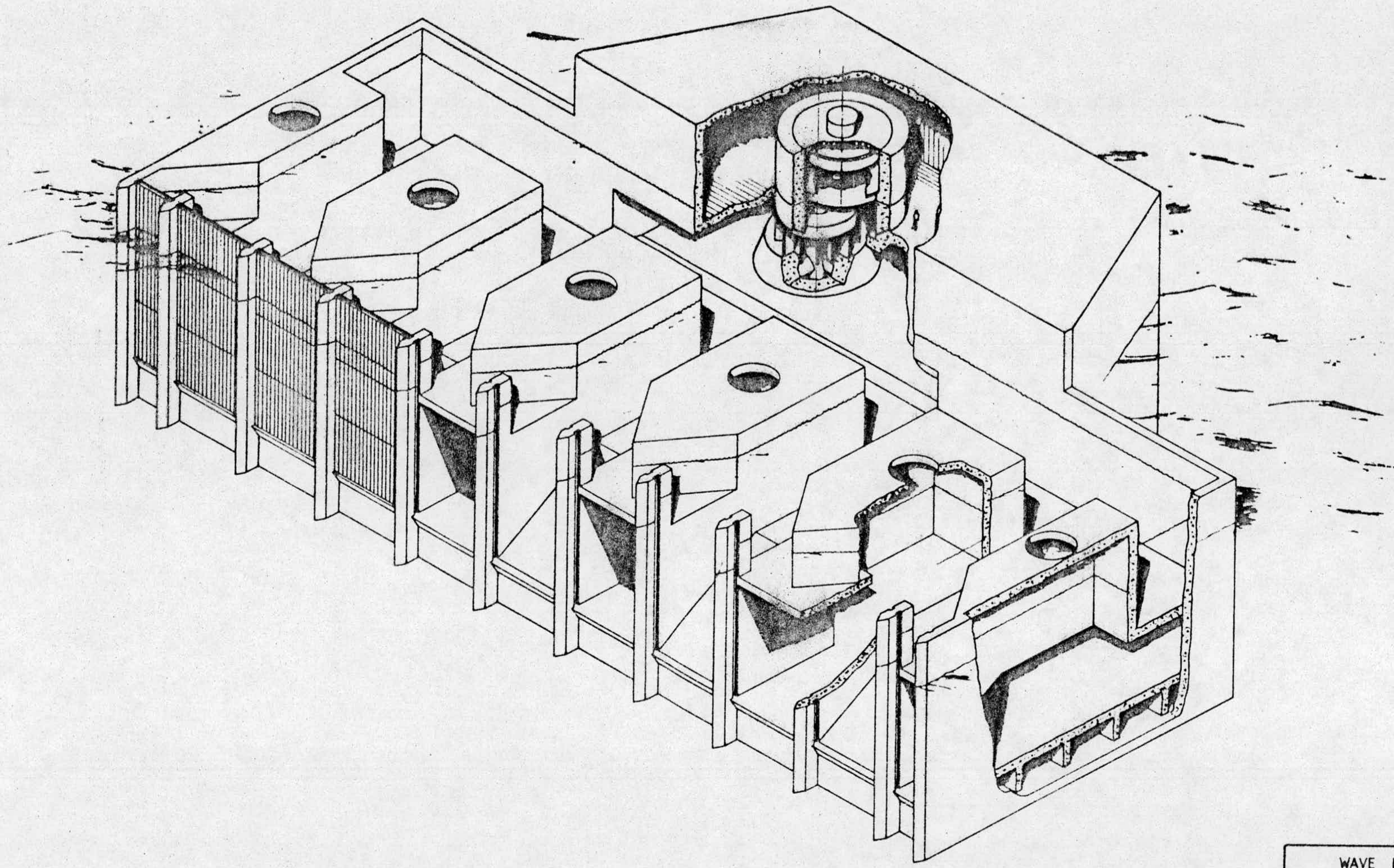


STAGE 7
Tow to site and moor

10 0 10 20 30 40 50m

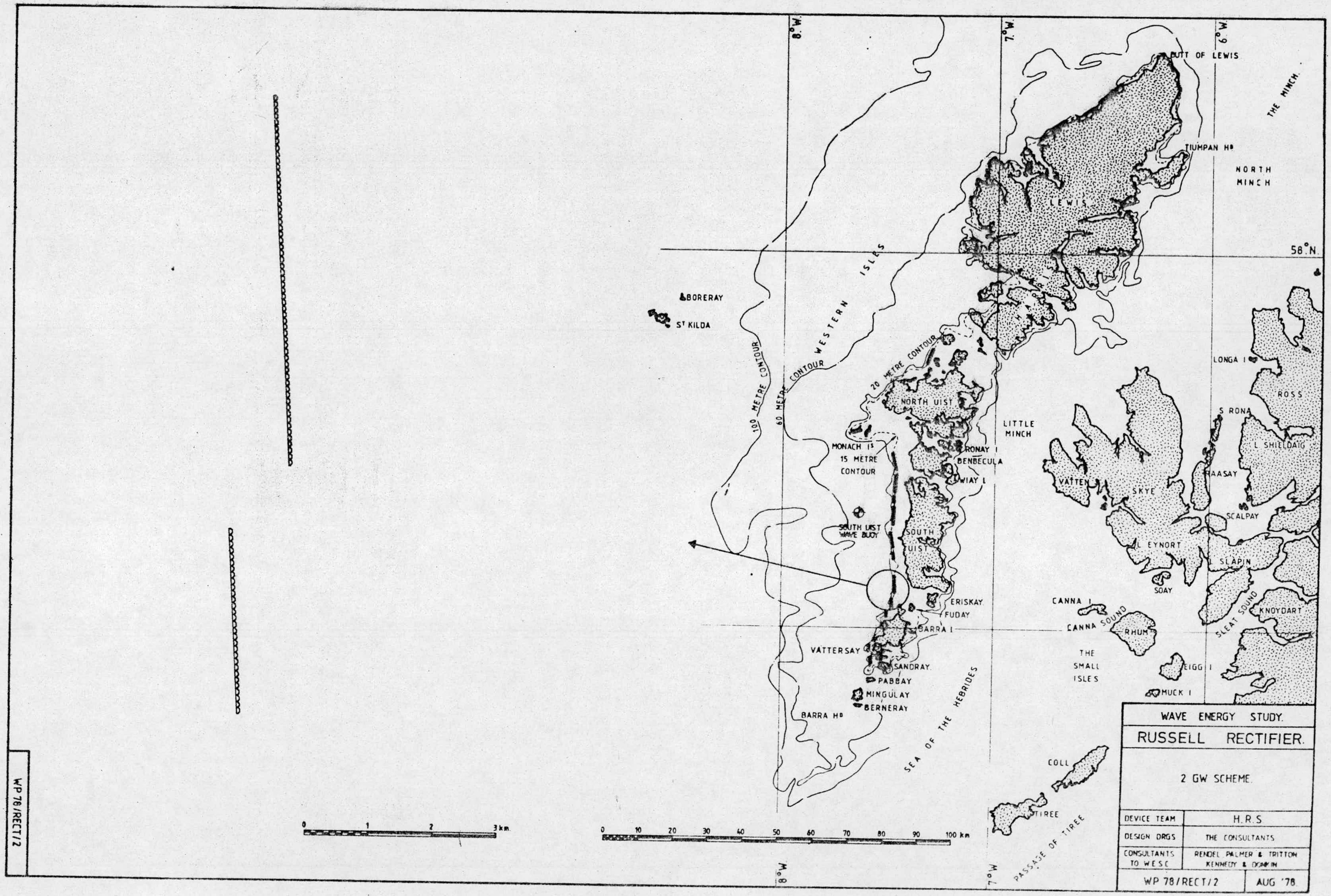
WAVE ENERGY STUDY.	
COCKERELL RAFT	
CONSTRUCTION & FLOTATION	
DEVICE TEAM	WAVEPOWER LTD.
DESIGN DRGS	DRAWN BY THE CONSULTANTS BASED ON IDEAS BY WAVEPOWER LTD.
CONSULTANTS TO W.E.S.C.	RENDEL, PALMER & TRITTON KENNEDY & DONKIN
WP 78/RAFT/6	AUG '78.

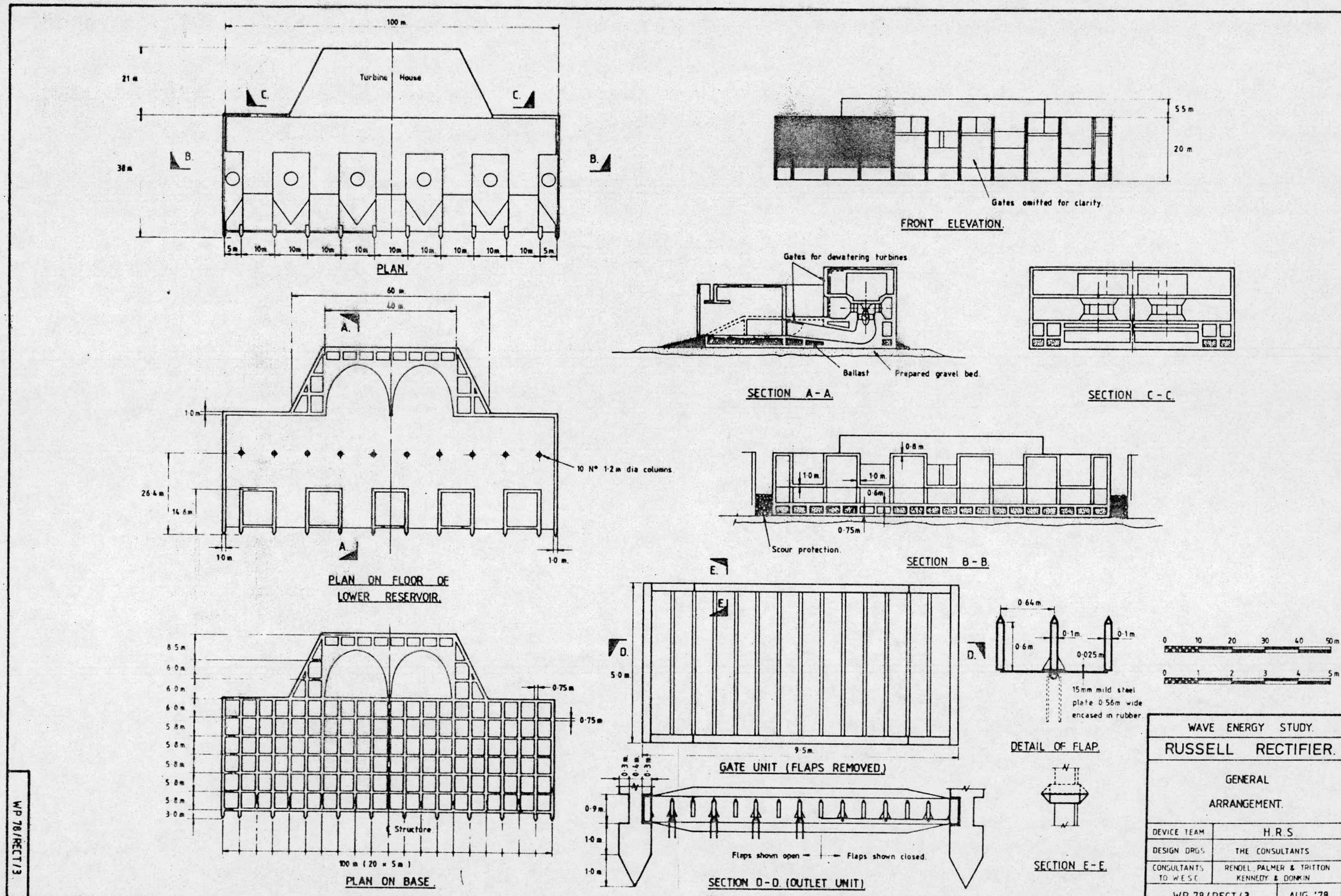
WP 78/RAFT/6



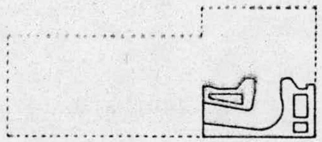
WP 78/RECT/1

WAVE ENERGY STUDY.	
RUSSELL RECTIFIER	
ISOMETRIC	
DEVICE TEAM	H.R.S.
DESIGN DRGS	THE CONSULTANTS
CONSULTANTS TO W.E.S.C.	RENDEL PALMER & TRITTON KENNEDY & DONKIN
WP 78/RECT/1	AUG '78

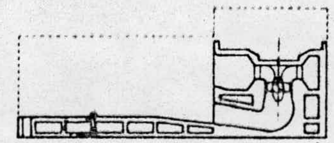

BUTT OF LEWIS
THE MINCH
TIUMPAN Hd
NORTH MINCH
LEWIS
58°N
8°W
7°W
6°W
WESTERN ISLES
BORERAY
St KILDA
100 METRE CONTOUR
60 METRE CONTOUR
20 METRE CONTOUR
NORTH UIST
LITTLE MINCH
MONACH Is
15 METRE CONTOUR
RONAY I
BENBECULA
WIAY I
SOUTH UIST WAVE BUOY
SOUTH UIST
ERISKAY
FUDAY
BARRA I
VATTERSAY
SANDRAY
PABBAY
MINGULAY
BERNERAY
BARRA Hd
SEA OF THE HEBRIDES
LONGA I
ROSS
S RONA
L SHIELDAIG
RAASAY
SKYE
SCALPAY
L EYNORT
SLAPIN
SOAY
CANNA I
CANNA SOUND
RHUM
SLEAT SOUND
KNOYDART
THE SMALL ISLES
EIGG I
MUCK I
COLL
TIREE
PASSAGE OF TIREE
0 1 2 3 km
0 10 20 30 40 50 60 70 80 90 100 km
WAVE ENERGY STUDY.
RUSSELL RECTIFIER.
2 GW SCHEME.
DEVICE TEAM H.R.S
DESIGN DRGS THE CONSULTANTS
CONSULTANTS TO W.E.S.C. RENDEL PALMER & TRITTON KENNEDY & DONKIN
WP 78/RECT/2 AUG '78
WP 78/RECT/2



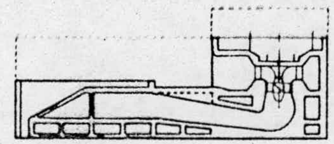
PLAN.
Turbine House
100 m.
21 m
38 m
5m 10m 10m 10m 10m 10m 10m 10m 10m 10m 5m
FRONT ELEVATION.
Gates omitted for clarity.
5.5 m
20 m
PLAN ON FLOOR OF LOWER RESERVOIR.
60 m.
40 m.
10 N° 1·2 m dia columns.
1·0 m
26·4 m
14·6 m
SECTION A - A.
Gates for dewatering turbines.
Ballast
Prepared gravel bed.
SECTION C - C.
SECTION B - B.
0·8 m
1·0 m
0·6 m
0·75 m
Scour protection.
PLAN ON BASE.
100 m (20 × 5 m)
℄ Structure
8.5 m
6.0 m
5.8 m
3.0 m
0·75 m
GATE UNIT (FLAPS REMOVED)
5.0 m
9.5 m.
SECTION D-D. (OUTLET UNIT)
Flaps shown open
Flaps shown closed.
0.3 m
0.4 m
0.9 m
1.0 m
DETAIL OF FLAP.
0·64 m
0·1 m
0·6 m
0·025 m
15mm mild steel plate 0·56m wide encased in rubber.
SECTION E - E.
0 10 20 30 40 50 m
0 1 2 3 4 5 m
WAVE ENERGY STUDY.
RUSSELL RECTIFIER.
GENERAL ARRANGEMENT.
DEVICE TEAM H.R.S.
DESIGN DRGS THE CONSULTANTS
CONSULTANTS TO W.E.S.C. RENDEL, PALMER & TRITTON KENNEDY & DONKIN
WP 78/RECT/3
AUG '78
WP 78/RECT/3



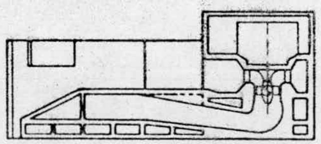
STAGE 1.
Turbine Module commences in advance of other areas.



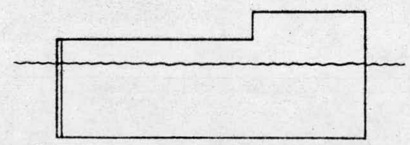
STAGE 2.
Formation of Torsion box and kickers to vertical walls. Turbine installation.



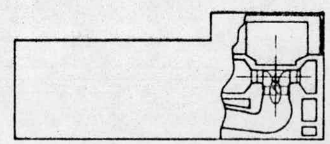
STAGE 3.
Formation of side walls, sloping ramp and horizontal slab. Machinery installation.



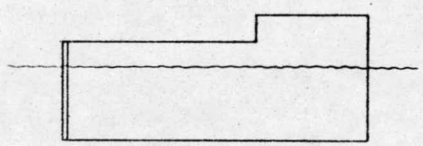
STAGE 4.
Formation of upper walls of outlet reservoir and completion of Turbine house after machinery installed.



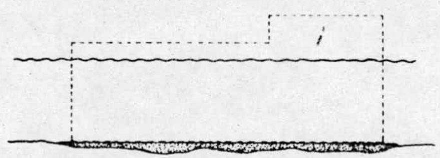
STAGE 5.
Flotation with blank front panels positioned.



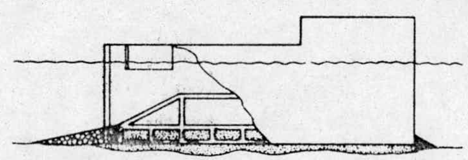
STAGE 6.
Formation of outlet reservoir roof.



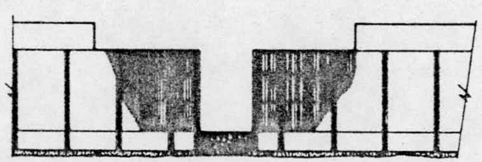
STAGE 7.
Tow out to site



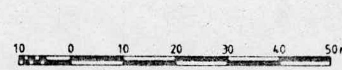
STAGE 8.
Preparation of gravel bed completed.



STAGE 9.
Device in position under working conditions, gate flaps installed.

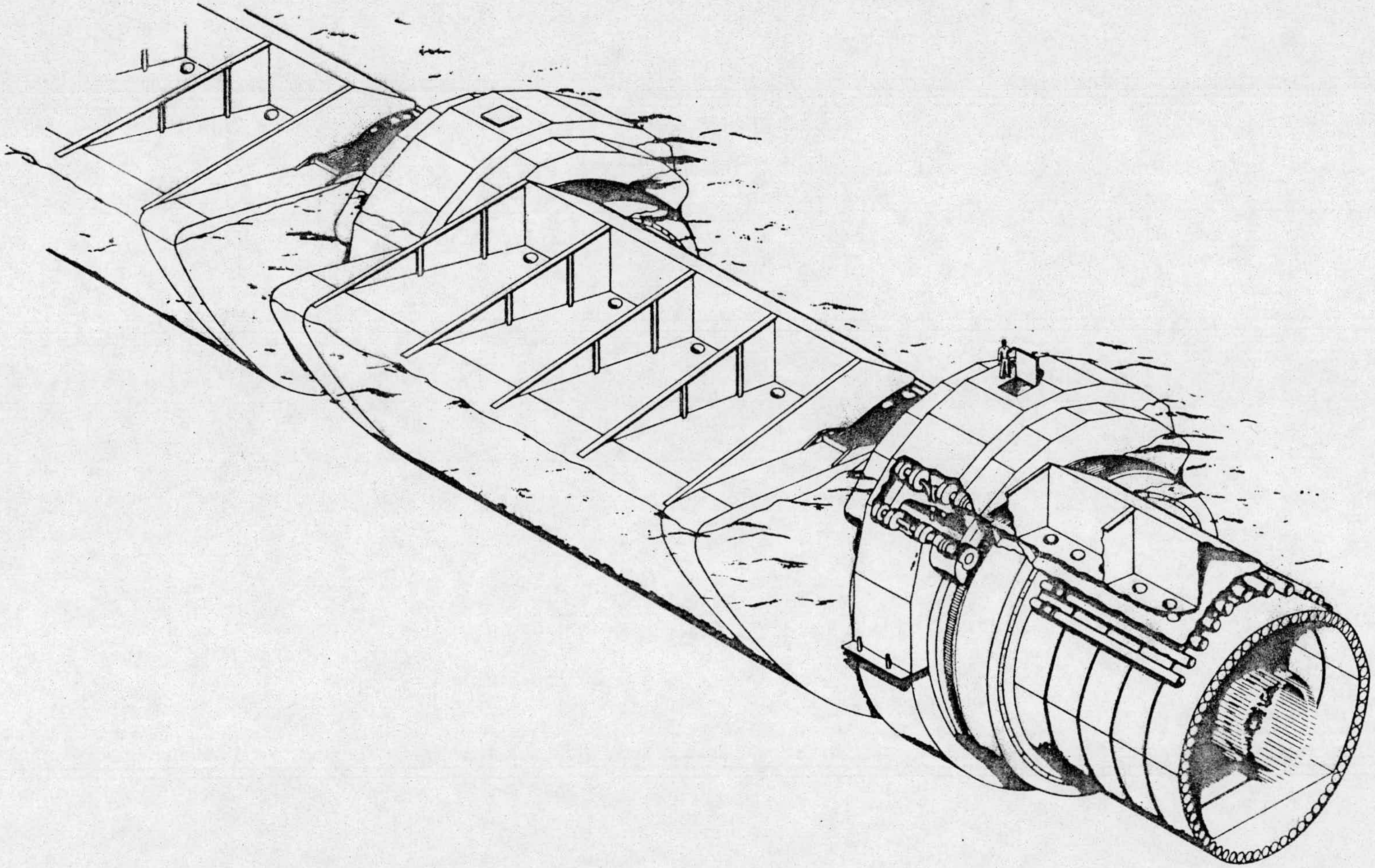


STAGE 10
Dumping scour protection between adjacent units



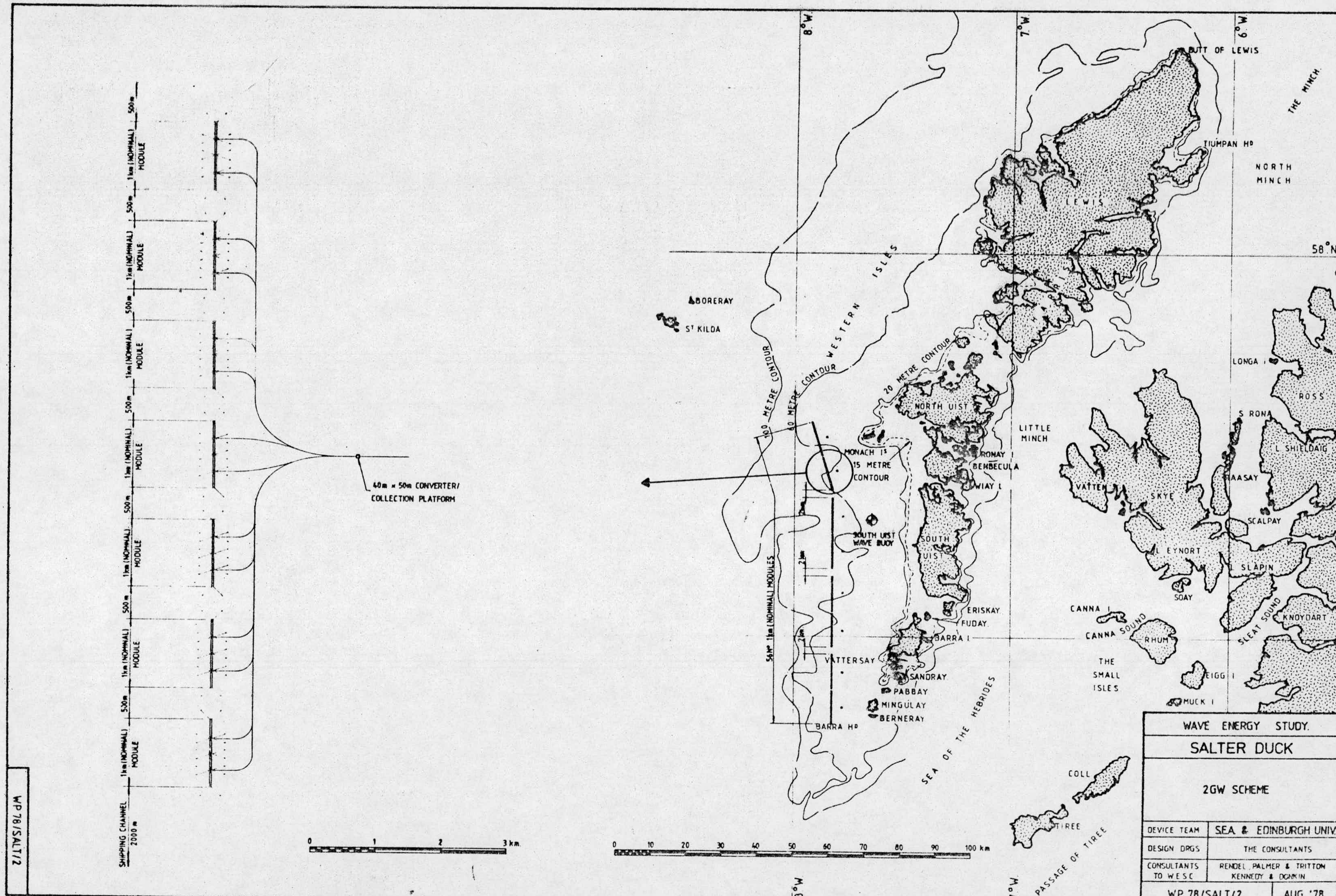
WAVE ENERGY STUDY.	
RUSSELL RECTIFIER	
CONSTRUCTION & FLOTATION.	
DEVICE TEAM	H.R.S.
DESIGN DRGS	THE CONSULTANTS
CONSULTANTS TO W.E.S.C.	RENDEL, PALMER & TRITTON KENNEDY & DONKIN
WP 78/RECT/4	AUG '78.

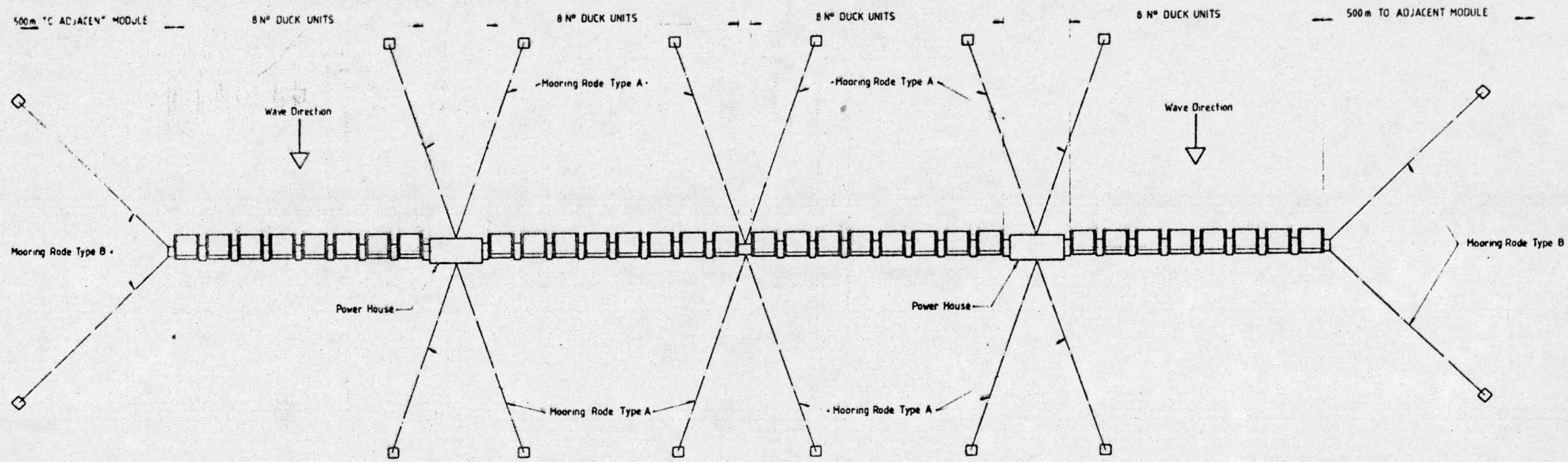
WP 78/RECT/4.



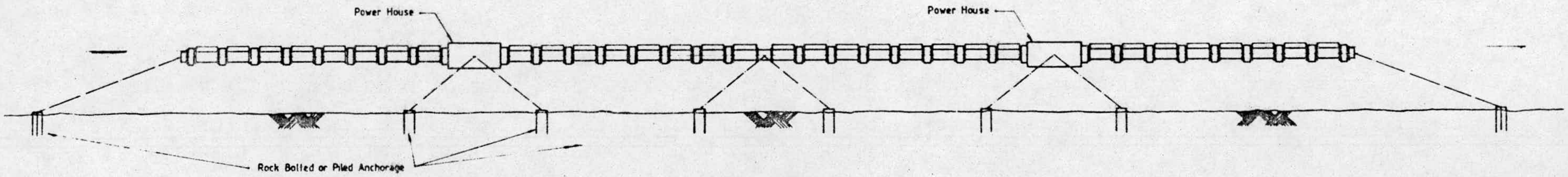
WAVE ENERGY STUDY.	
SALTER DUCK	
ISOMETRIC	
DEVICE TEAM	S.E.A. & EDINBURGH UNIV.
DESIGN DRGS	THE CONSULTANTS
CONSULTANTS TO W.E.S.C.	RENDEL, PALMER & TRITTON KENNEDY & DONKIN
WP 78/SALT/1	AUG '78.

WP 78/SALT/1

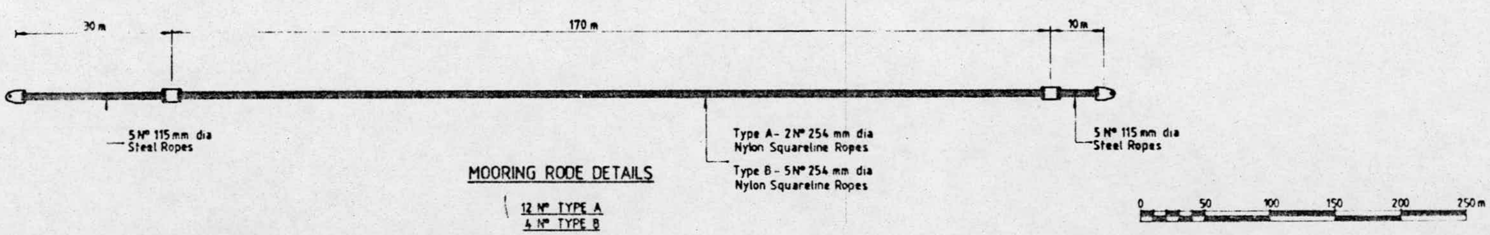

WAVE ENERGY STUDY.
SALTER DUCK
2GW SCHEME
DEVICE TEAM
SEA & EDINBURGH UNIV.
DESIGN DRGS
THE CONSULTANTS
CONSULTANTS TO WESC
RENDEL PALMER & TRITTON
KENNEDY & DONKIN
WP 78/SALT/2
AUG '78
WP 78/SALT/2
40m x 50m CONVERTER/
COLLECTION PLATFORM
1km (NOMINAL) MODULE
500m
SHIPPING CHANNEL 2000m
0 1 2 3 km
0 10 20 30 40 50 60 70 80 90 100 km
8°W
7°W
6°W
58°N
BUTT OF LEWIS
THE MINCH
TIUMPAN Hd
NORTH MINCH
LEWIS
HARRIS
BORERAY
St KILDA
WESTERN ISLES
20 METRE CONTOUR
50 METRE CONTOUR
100 METRE CONTOUR
NORTH UIST
MONACH Is
15 METRE CONTOUR
RONAY
BENBECULA
WIAY I.
LITTLE MINCH
SOUTH UIST WAVE BUOY
SOUTH UIST
56 No 1km (NOMINAL) MODULES
ERISKAY
FUDAY
BARRA I.
VATTERSAY
SANDRAY
PABBAY
MINGULAY
BERNERAY
BARRA Hd
SEA OF THE HEBRIDES
LONGA I.
ROSS
S RONA
L. SHIELDAIG
RAASAY
VATTEN
SKYE
SCALPAY
EYNORT
SLAPIN
SOAY
CANNA I.
CANNA SOUND
RHUM
THE SMALL ISLES
EIGG I.
MUCK I.
SLEAT SOUND
KNOYDART
COLL
TIREE
PASSAGE OF TIREE



PLAN ON 1KM (NOMINAL) MODULE
SHOWING MOORINGS
(56 Nº THUS)



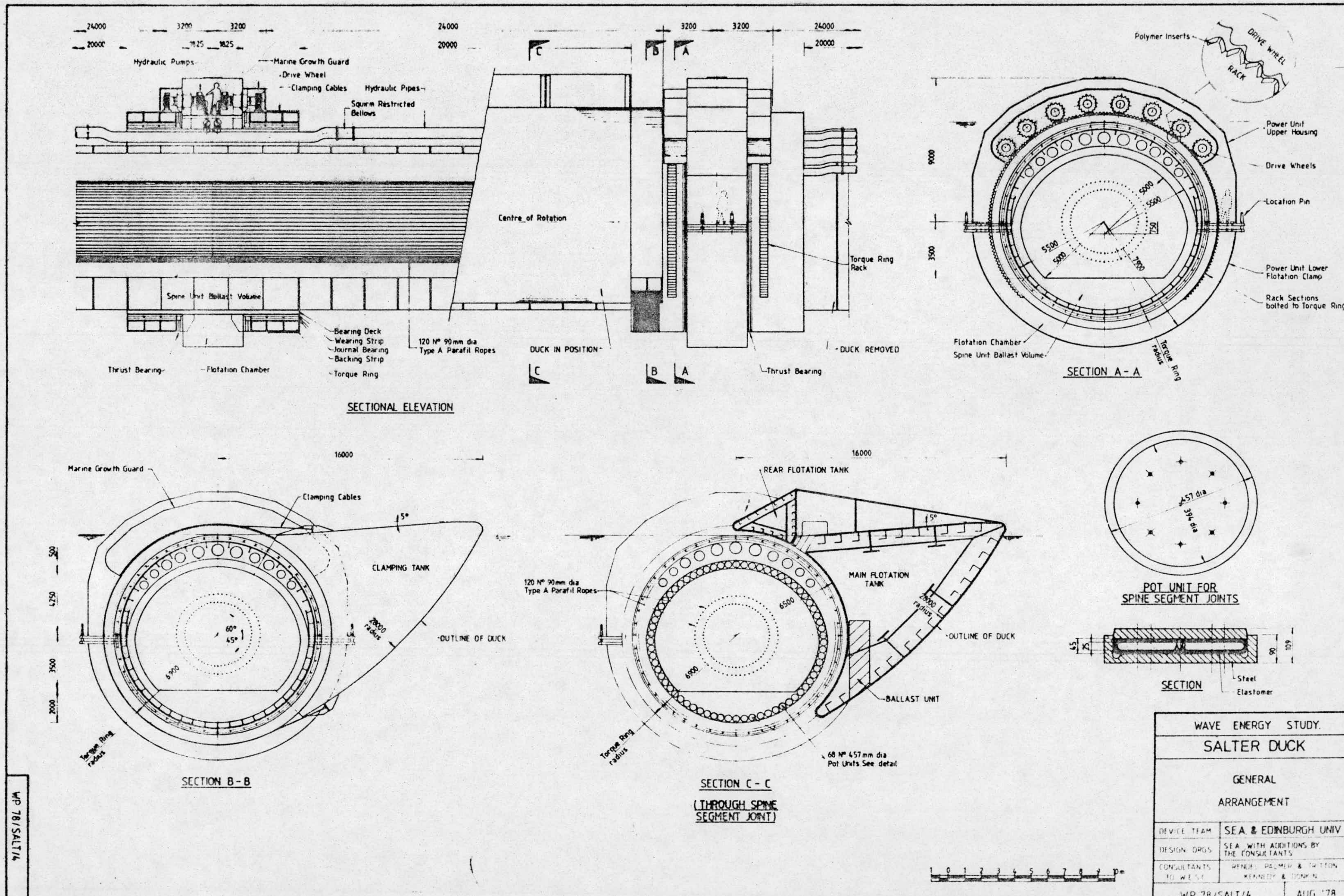
REAR ELEVATION



MOORING RODE DETAILS
12 Nº TYPE A
4 Nº TYPE B

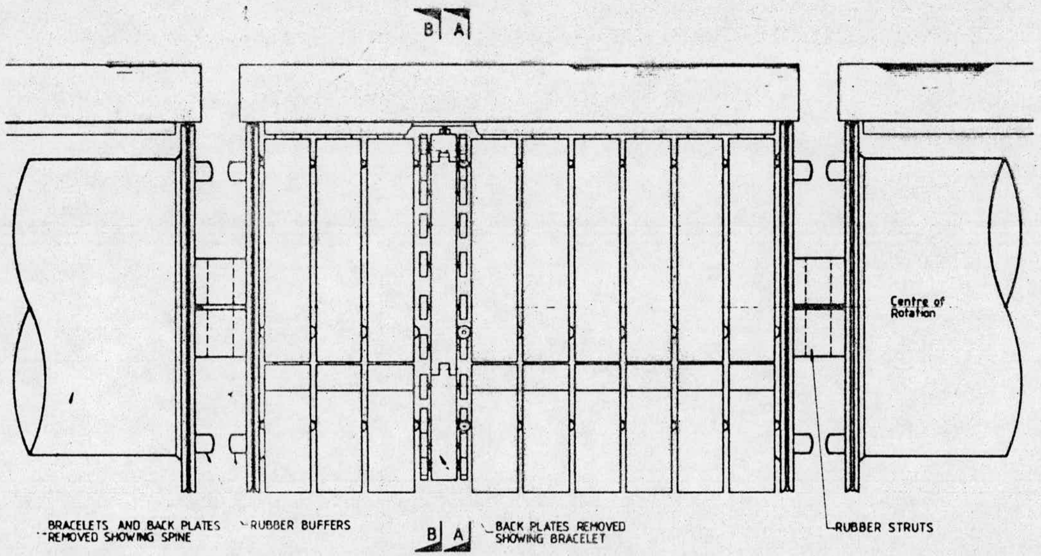
WAVE ENERGY STUDY	
SALTER DUCK	
MOORING	
DEVICE TEAM	SEA & EDINBURGH UNIV
DESIGN DRGS	THE CONSULTANTS
CONSULTANTS TO W.E.S.C.	RENDEL PALMER & TRITTON KENNEDY & DONKIN
WP 78/ SALT/3	AUG '78

WP78/SALT/3

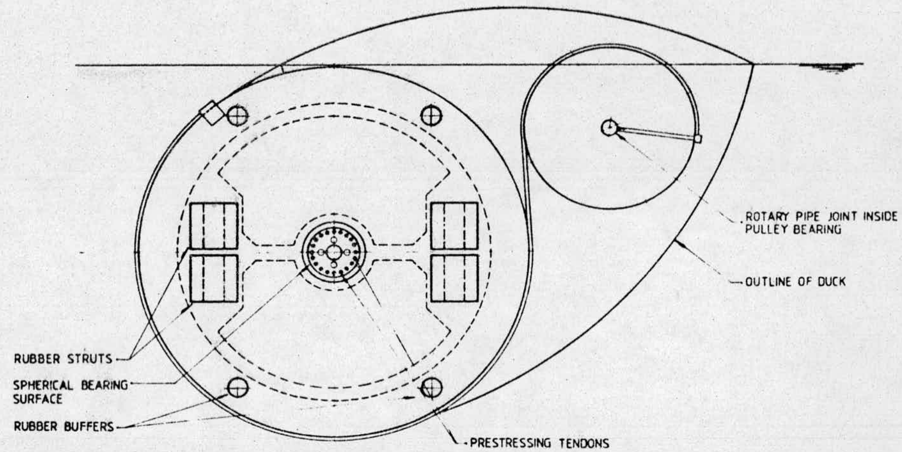


Hydraulic Pumps
Marine Growth Guard
Drive Wheel
Clamping Cables
Hydraulic Pipes
Squirm Restricted Bellows
Centre of Rotation
Spine Unit Ballast Volume
Bearing Deck
Wearing Strip
Journal Bearing
Backing Strip
Torque Ring
120 Nº 90mm dia Type A Parafil Ropes
DUCK IN POSITION
DUCK REMOVED
Torque Ring Rack
Thrust Bearing
Flotation Chamber
SECTIONAL ELEVATION
Polymer Inserts
DRIVE WHEEL
RACK
Power Unit Upper Housing
Drive Wheels
Location Pin
Power Unit Lower Flotation Clamp
Rack Sections bolted to Torque Ring
Flotation Chamber
Spine Unit Ballast Volume
Torque Ring radius
SECTION A - A
Marine Growth Guard
Clamping Cables
CLAMPING TANK
OUTLINE OF DUCK
Torque Ring radius
SECTION B - B
REAR FLOTATION TANK
MAIN FLOTATION TANK
120 Nº 90mm dia Type A Parafil Ropes
OUTLINE OF DUCK
BALLAST UNIT
68 Nº 457mm dia Pot Units See detail
Torque Ring radius
SECTION C - C
(THROUGH SPINE SEGMENT JOINT)
POT UNIT FOR SPINE SEGMENT JOINTS
457 dia
394 dia
SECTION
Steel
Elastomer
WAVE ENERGY STUDY.
SALTER DUCK
GENERAL ARRANGEMENT
DEVICE TEAM
SEA & EDINBURGH UNIV
DESIGN DRGS
SEA WITH ADDITIONS BY THE CONSULTANTS
CONSULTANTS TO W.E.S.T.
RENDEL PALMER & TRITTON
KENNEDY & DONKIN
WP 78/SALT/4
AUG '78

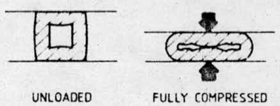
WP 78/SALT/4



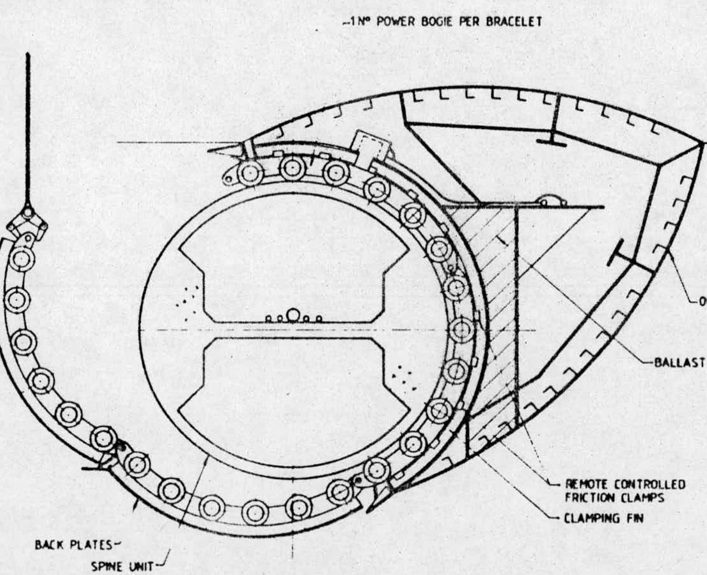
ELEVATION ON BACK OF SPINE



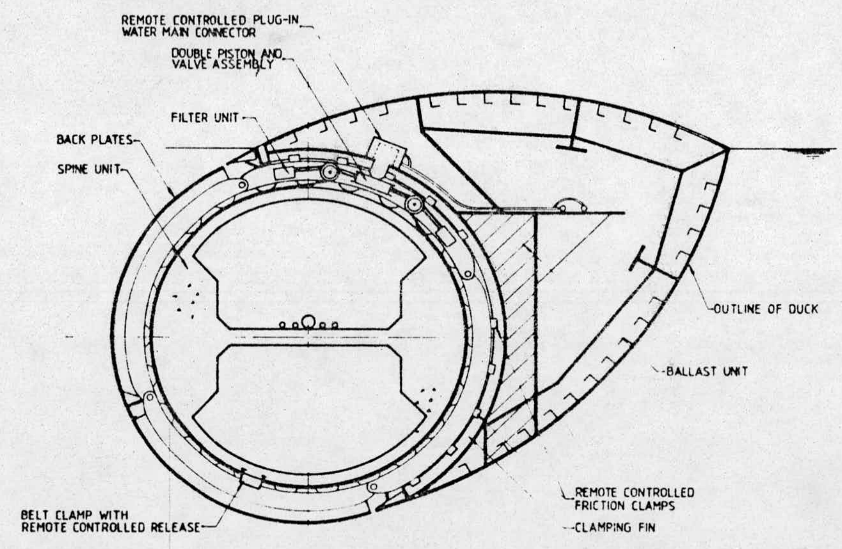
END VIEW ON 20m DUCK AND SPINE UNIT



PLAN ON RUBBER STRUTS



SECTION A—A
(SHOWING BRACELET BEING REMOVED)



SECTION B—B
(SHOWING PRIMARY POWER TAKE OFF BOGIE)

WAVE ENERGY STUDY

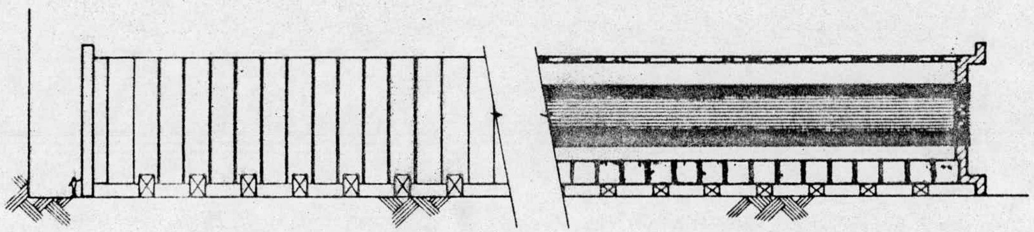
SALTER DUCK

PROPOSAL FOR FULL SCALE DEVICE

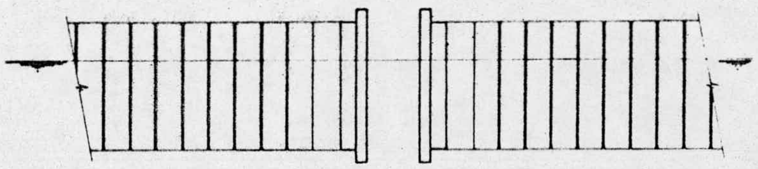
EDINBURGH UNIVERSITY

DEVICE TEAM	SEA & EDINBURGH UNIV
DESIGN DRGS	THE CONSULTANTS
CONSULTANTS TO W.E.S.C.	RENDEL PALMER & TRITTON KENNEDY & DONKIN
WP 78/SALT/5	AUG '78

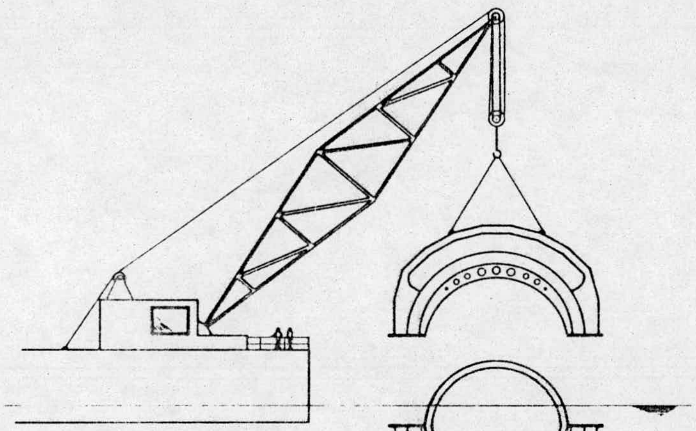
WP 78/SALT/5



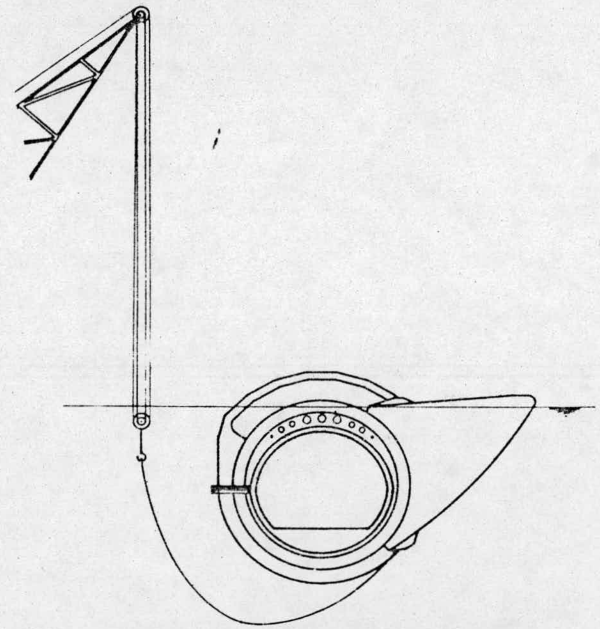
1. Precast Sections tensioned together in dry dock into lengths using Parafil cables between end plates.



2. m long sections floated to calm water site and connected by divers into appropriate lengths. Joints provide location points for power houses and moorings.



3. Upper and lower parts of power collar including hydraulic pumps, drive wheels and torque ring positioned from floating crane, and bolted together from the inside. Slave flotation tanks placed around the outside of the spine, raising it by 2m and enabling fitters to connect hydraulic pipes between adjacent modules.



4. Ducks offered to torque rings by means of floating crane, and secured by the clamping cables which must be hauled under the spine and reconnected to the top of the duck from the back

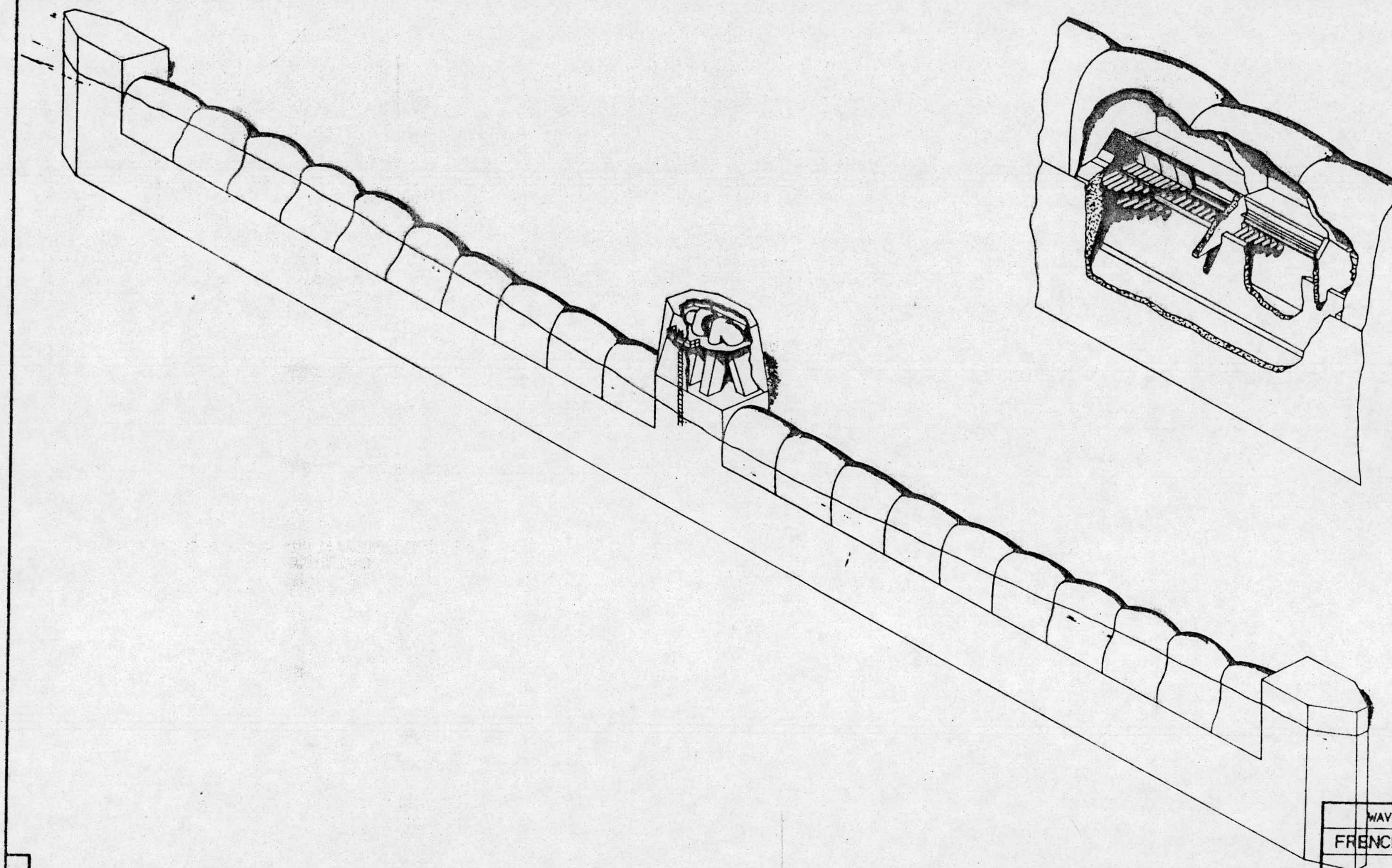
WAVE ENERGY STUDY.

SALTER DUCK

CONSTRUCTION & FLOTATION

DEVICE TEAM	S.E.A. & EDINBURGH UNIV.
DESIGN DRGS	S.E.A., WITH ADDITIONS BY THE CONSULTANTS
CONSULTANTS TO W.E.S.C.	RENDEL, PALMER & TRITTON KENNEDY & DONKIN
WP 78/SALT/6	AUG '78.

WP 78/SALT/6



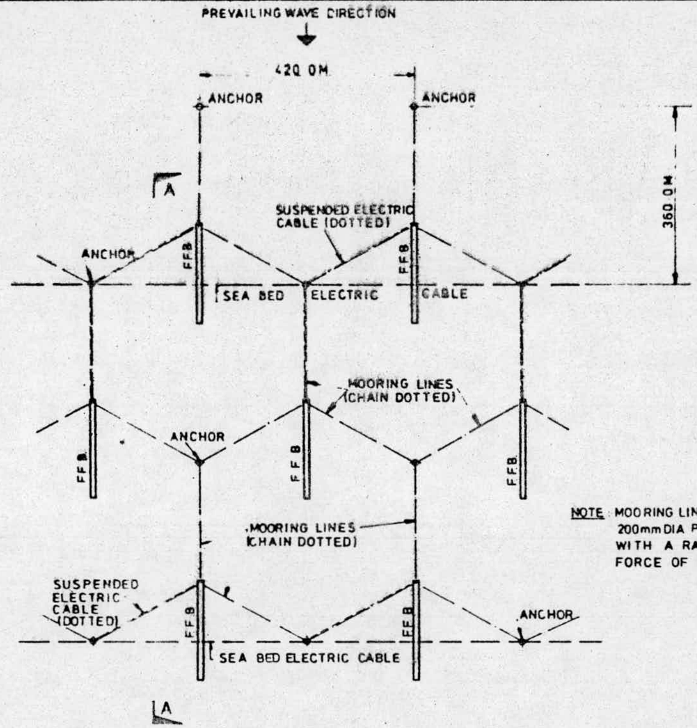
WAVE ENERGY STUDY.

FRENCH FLEXIBLE BAG

ISOMETRIC

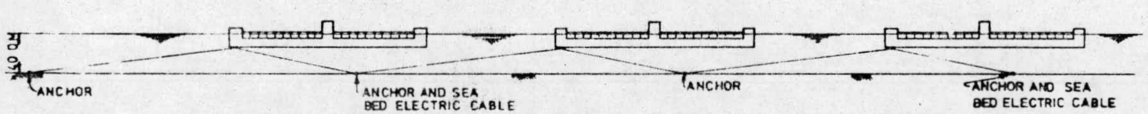
DEVICE TEAM	LANCASTER UNIVERSITY
DESIGN DRGS	THE CONSULTANTS
CONSULTANTS TO W.E.S.C.	RENDEL PALMER & TRITTON KENNEDY & DONKIN
WP 78/FREN/1	AUG '78

WP 78/FREN/1

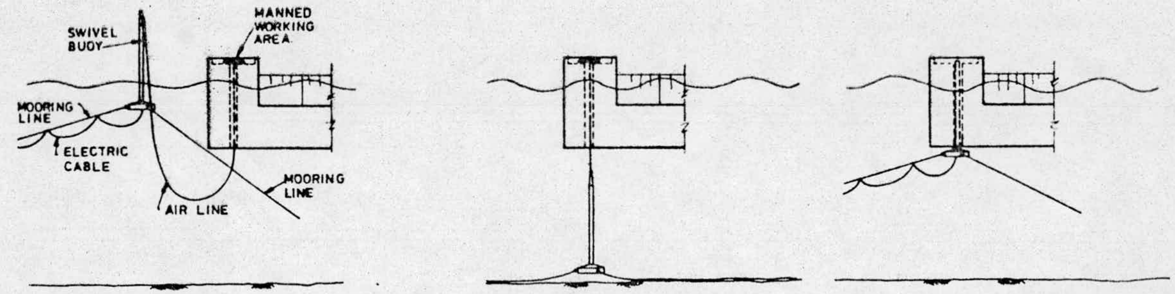


NOTE: MOORING LINES TO BE 200mm DIA PARAFIL CABLE WITH A RATED BREAKING FORCE OF 1000 TONNES

PLAN SHOWING MOORING LINES AND ELECTRIC CABLES FOR THREE BANKS OF CONVERTERS

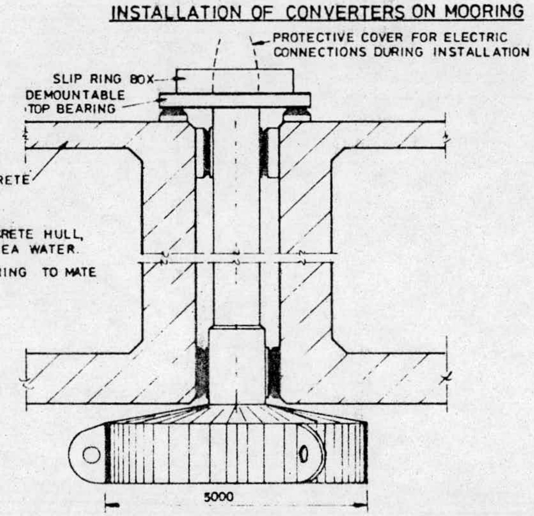


ELEVATION A–A



STAGE 1 STAGE 2 STAGE 3

INSTALLATION OF CONVERTERS ON MOORING



NOTE
1) BEARING FIXED TO CONCRETE HULL, AND SEALED AGAINST SEA WATER.
2) INNER SLEEVE OF BEARING TO MATE WITH TUBE ON BUOY.

SWIVEL BUOY INSTALLED IN HULL

SEQUENCE FOR INSTALLATION OF CONVERTER ON MOORING

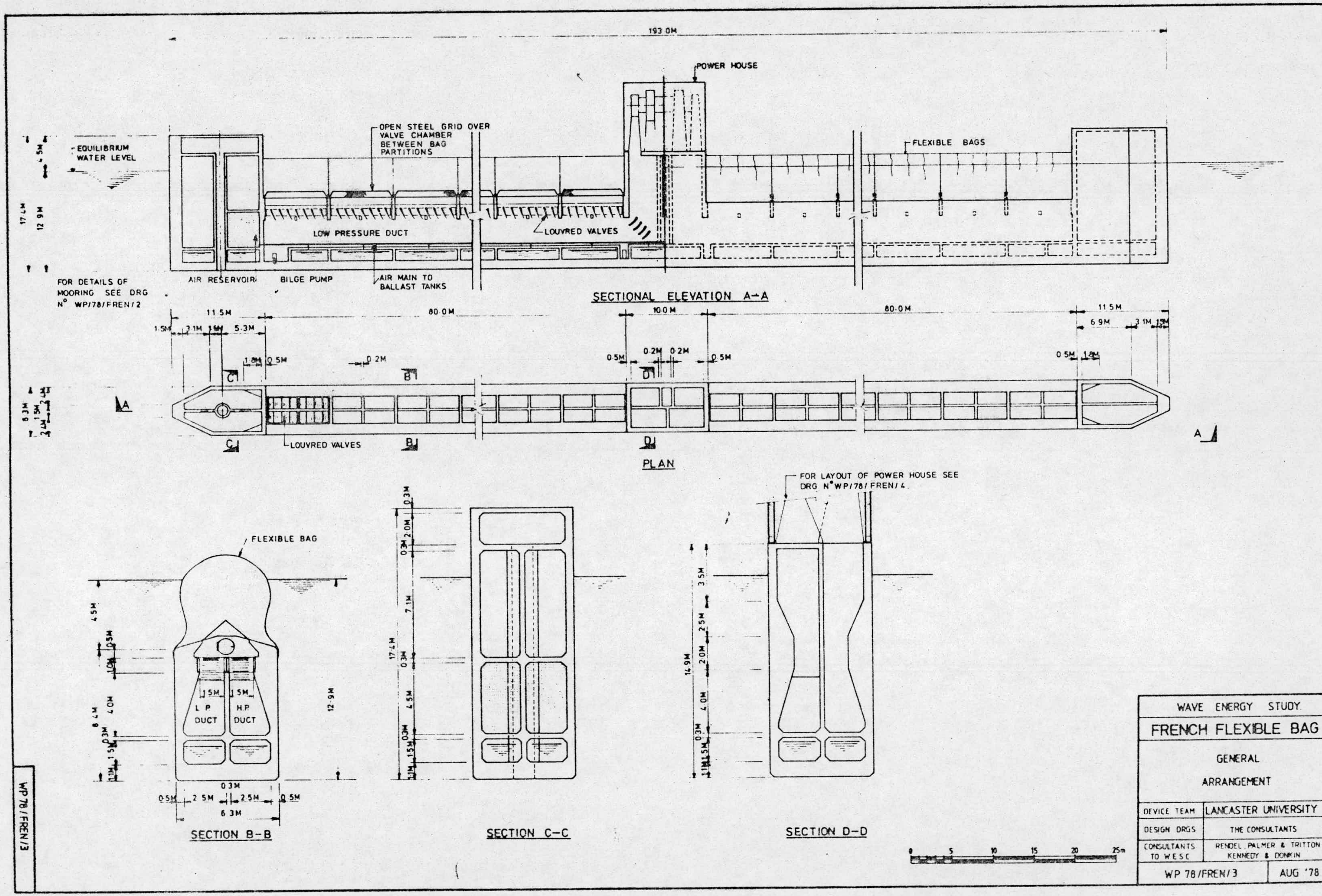
STAGE 1 SWIVEL BUOY FLOATS ALONE, WITH PROTECTIVE COVER. BOW OF DEVICE BROUGHT TO BUOY. MOORING LINE AND AIR LINE ATTACHED.

STAGE 2 BUOY SUNK AND THE DEVICE FLOATED OVER.

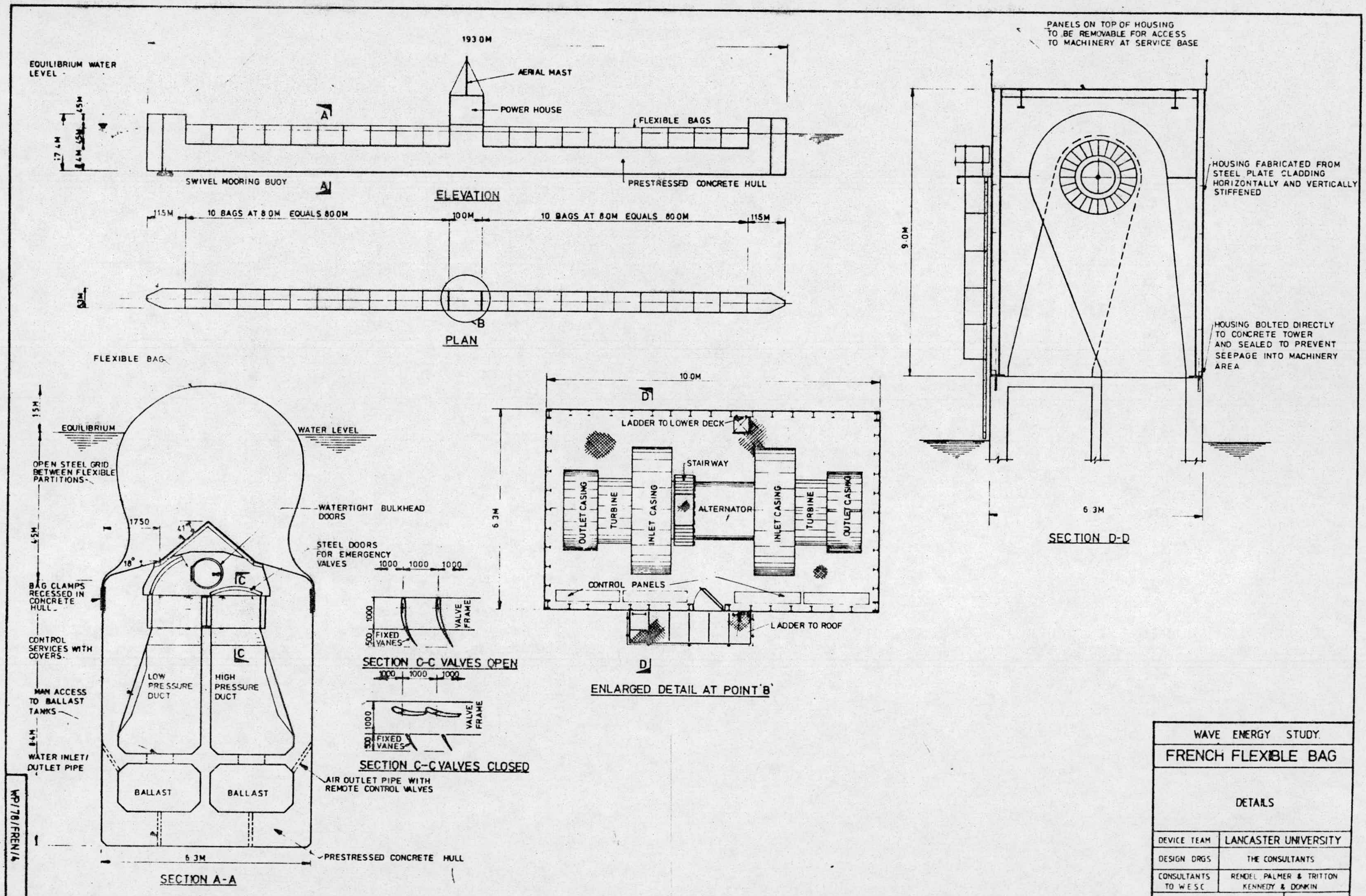
STAGE 3 BUOY PUMPED AND LIFTED TO MATE WITH BEARING IN THE DEVICE. THE PROTECTIVE COVER REMOVED. THE TOP BEARING CLAMPED AND ELECTRICAL CONNECTION MADE.

WP 78/FREN/2

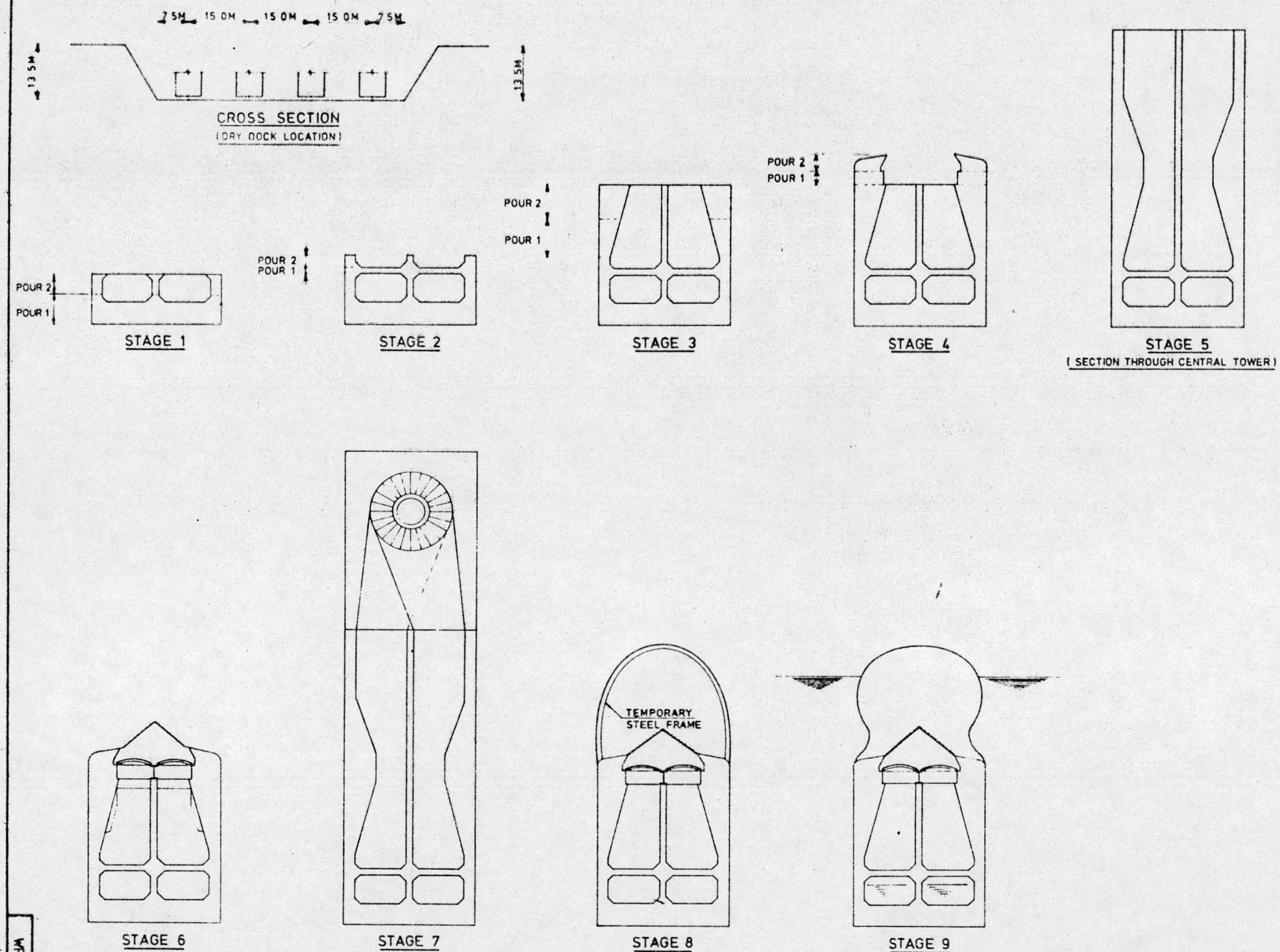
WAVE ENERGY STUDY.	
FRENCH FLEXIBLE BAG	
MOORING	
DEVICE TEAM	LANCASTER UNIVERSITY
DESIGN DRGS	THE CONSULTANTS
CONSULTANTS TO W.E.S.C.	RENDEL, PALMER & TRITTON KENNEDY & DONKIN
WP 78/FREN/2	AUG '78.



193.0M
POWER HOUSE
OPEN STEEL GRID OVER VALVE CHAMBER BETWEEN BAG PARTITIONS
FLEXIBLE BAGS
EQUILIBRIUM WATER LEVEL
LOW PRESSURE DUCT
LOUVRED VALVES
AIR RESERVOIR
BILGE PUMP
AIR MAIN TO BALLAST TANKS
FOR DETAILS OF MOORING SEE DRG N° WP/78/FREN/2
SECTIONAL ELEVATION A–A
11.5M
80.0M
10.0M
80.0M
11.5M
PLAN
LOUVRED VALVES
FLEXIBLE BAG
L.P. DUCT
H.P. DUCT
SECTION B–B
SECTION C–C
FOR LAYOUT OF POWER HOUSE SEE DRG N° WP/78/FREN/4.
SECTION D–D
WP 78/FREN/3
WAVE ENERGY STUDY
FRENCH FLEXIBLE BAG
GENERAL ARRANGEMENT
DEVICE TEAM
LANCASTER UNIVERSITY
DESIGN DRGS
THE CONSULTANTS
CONSULTANTS TO W.E.S.C
RENDEL, PALMER & TRITTON
KENNEDY & DONKIN
WP 78/FREN/3
AUG '78



193.0M
EQUILIBRIUM WATER LEVEL
AERIAL MAST
POWER HOUSE
FLEXIBLE BAGS
17.4M
8.4M
4.5M
SWIVEL MOORING BUOY
PRESTRESSED CONCRETE HULL
ELEVATION
A
11.5M
10 BAGS AT 8.0M EQUALS 80.0M
10.0M
10 BAGS AT 8.0M EQUALS 80.0M
11.5M
6.3M
B
PLAN
FLEXIBLE BAG
1.5M
EQUILIBRIUM
WATER LEVEL
OPEN STEEL GRID BETWEEN FLEXIBLE PARTITIONS
4.2M
1750
41°
18°
WATERTIGHT BULKHEAD DOORS
STEEL DOORS FOR EMERGENCY VALVES
BAG CLAMPS RECESSED IN CONCRETE HULL
C
CONTROL SERVICES WITH COVERS
LOW PRESSURE DUCT
HIGH PRESSURE DUCT
MAN ACCESS TO BALLAST TANKS
8.4M
WATER INLET/ OUTLET PIPE
BALLAST
BALLAST
AIR OUTLET PIPE WITH REMOTE CONTROL VALVES
6.3M
PRESTRESSED CONCRETE HULL
SECTION A-A
1000 1000 1000
1000
500
FIXED VANES
VALVE FRAME
SECTION C-C VALVES OPEN
1000 1000 1000
1000
300
FIXED VANES
VALVE FRAME
SECTION C-C VALVES CLOSED
10.0M
D
LADDER TO LOWER DECK
STAIRWAY
OUTLET CASING
TURBINE
INLET CASING
ALTERNATOR
INLET CASING
TURBINE
OUTLET CASING
6.3M
CONTROL PANELS
LADDER TO ROOF
ENLARGED DETAIL AT POINT 'B'
PANELS ON TOP OF HOUSING TO BE REMOVABLE FOR ACCESS TO MACHINERY AT SERVICE BASE
HOUSING FABRICATED FROM STEEL PLATE CLADDING HORIZONTALLY AND VERTICALLY STIFFENED
9.0M
HOUSING BOLTED DIRECTLY TO CONCRETE TOWER AND SEALED TO PREVENT SEEPAGE INTO MACHINERY AREA
6.3M
SECTION D-D
WP/78/FREN/4
WAVE ENERGY STUDY
FRENCH FLEXIBLE BAG
DETAILS
DEVICE TEAM
LANCASTER UNIVERSITY
DESIGN DRGS
THE CONSULTANTS
CONSULTANTS TO W.E.S.C.
RENDEL PALMER & TRITTON
KENNEDY & DONKIN
WP 78/FREN/4
AUG '78.



CONSTRUCTION SEQUENCE

STAGE 1	PREPARE CONSTRUCTION BED AND FORM BASE SLAB AND KICKERS FOR EXTERNAL, INTERNAL, AND TRANSVERSE WALLS UP TO SOFFIT LEVEL OF BALLAST COMPARTMENTS / AIR DUCT DIVISION SLAB IN TWO SEPARATE POURS.
STAGE 2	FORM DIVISION SLAB BETWEEN BALLAST COMPARTMENTS / AIR DUCT AND KICKERS FOR EXTERNAL, INTERNAL, AND TRANSVERSE WALLS TO LOWER LEVEL OF SLOPING PART OF EXTERNAL WALLS IN TWO SEPARATE POURS.
STAGE 3	FORM EXTERNAL SLOPING AND INTERNAL WALLS TO TOP LEVEL OF SLOPING WALL IN TWO POURS.
STAGE 4	COMPLETE MAIN CROSS SECTION OF HULL EXTERNAL WALLS IN TWO POURS AND FORM KICKERS FOR WALLS IN BOW, STERN AND CENTRAL TOWER.
STAGE 5	FORM WALLS IN BOW, STERN AND CENTRAL TOWER TO REQUIRED HEIGHT. PREPARE AND PRESTRESS DEVICE.
STAGE 6	INSTALL VALVES OVER DUCTS AND SERVICES TO EACH AIR DUCT COMPARTMENT.
STAGE 7	INSTALL MECHANICAL PLANT AND POSITION AND FIX STRUCTURAL STEELWORK.
STAGE 8	ERECT FLEXIBLE BAG (TEMPORARILY FRAMED) COMPLETE WITH SEPTA STARTING FROM FIXED FRAME ON CENTRAL TOWER AND PROGRESSIVELY TOWARDS BOW / STERN, CLAMPING EDGES AND AT EACH SEPTUM SEAL PERIPHERY OF BAG TO PRE-FORMED FRAME ON BOW / STERN.
STAGE 9	FLOOD THE DRY DOCK INFLATE BAGS AND ADD WATER BALLAST TO ACHIEVE THE REQUIRED WATER TRIM. TOW TO WORKING LOCATION.

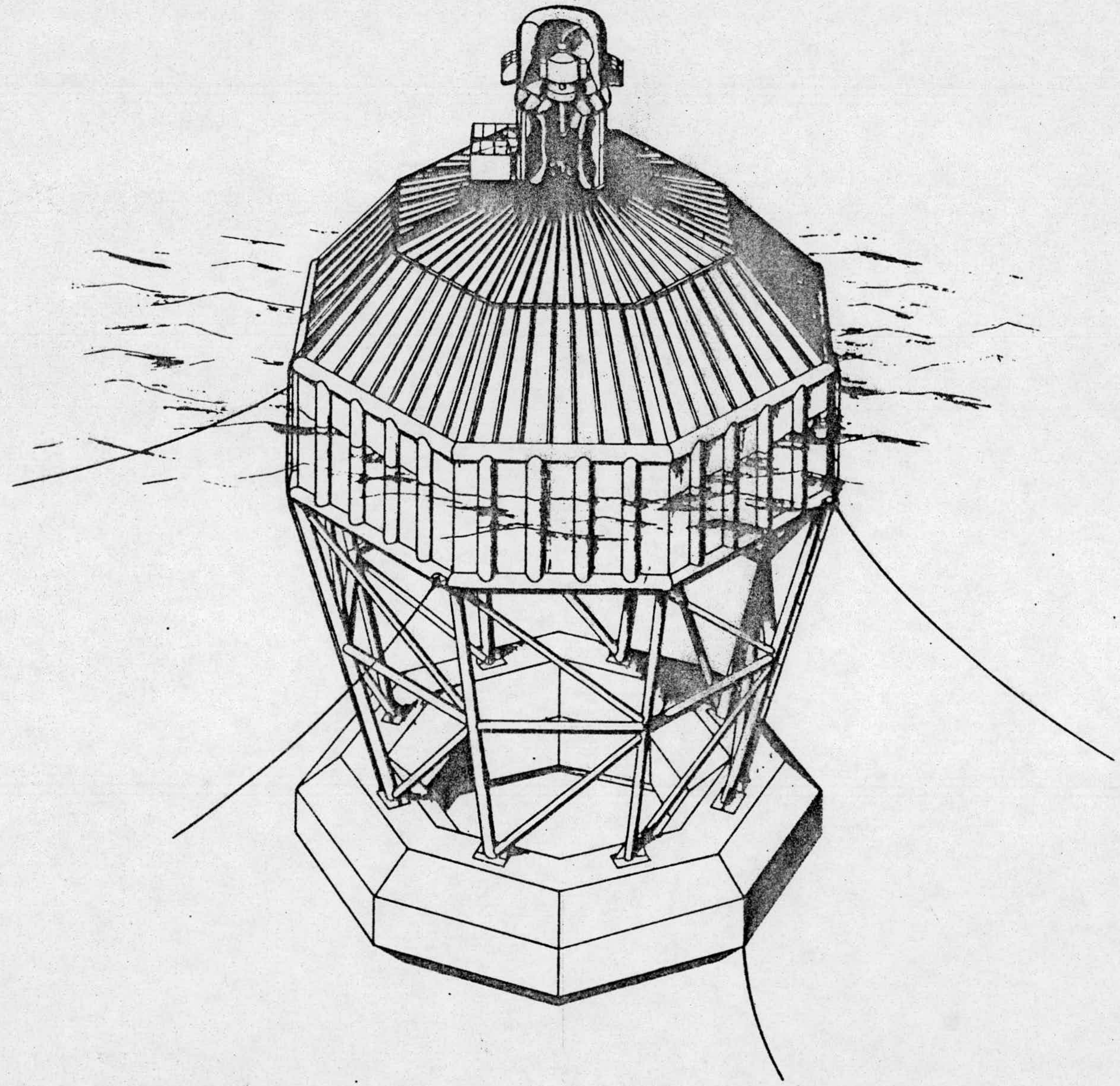
ALTERNATIVE TO STAGE 9 IF CONSTRUCTION CARRIED OUT ON LAND AND THE DEVICE IS LAUNCHED

STAGE 9	INFLATE BAGS AND ADD WATER BALLAST TO ACHIEVE THE REQUIRED WATER TRIM. LAUNCH ON SUBMERSIBLE BARGE AND ADJUST BALLAST AS NECESSARY AND TOW TO WORKING LOCATION.

1 0 1 2 3 4 5 6 7 8 9 10m

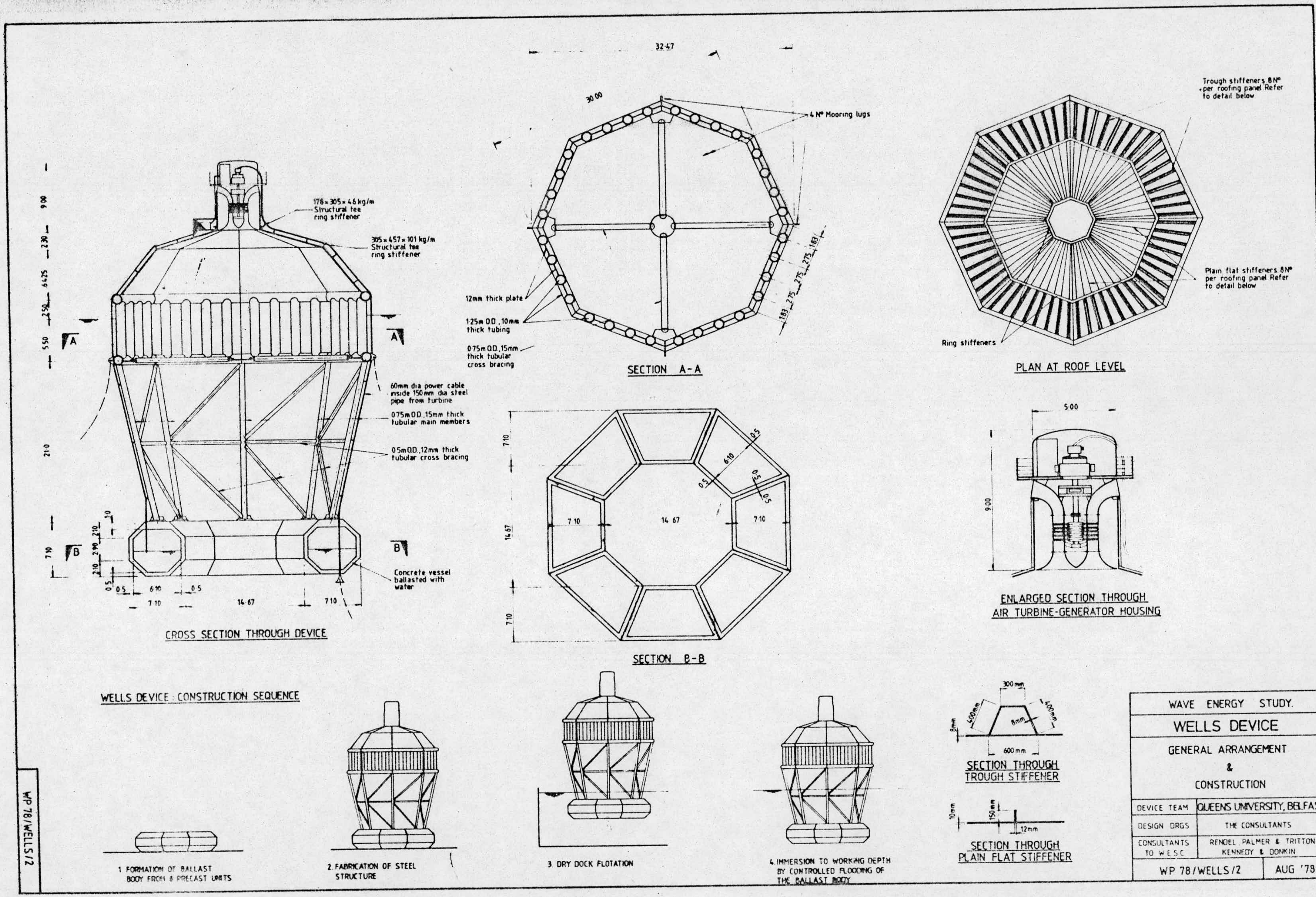
WAVE ENERGY STUDY.	
FRENCH FLEXIBLE BAG	
CONSTRUCTION & FLOTATION	
DEVICE TEAM	LANCASTER UNIVERSITY
DESIGN DRGS	THE CONSULTANTS
CONSULTANTS TO W.E.S.C.	RENDEL, PALMER & TRITTON KENNEDY & DONKIN
WP 78/FREN/5	AUG '78

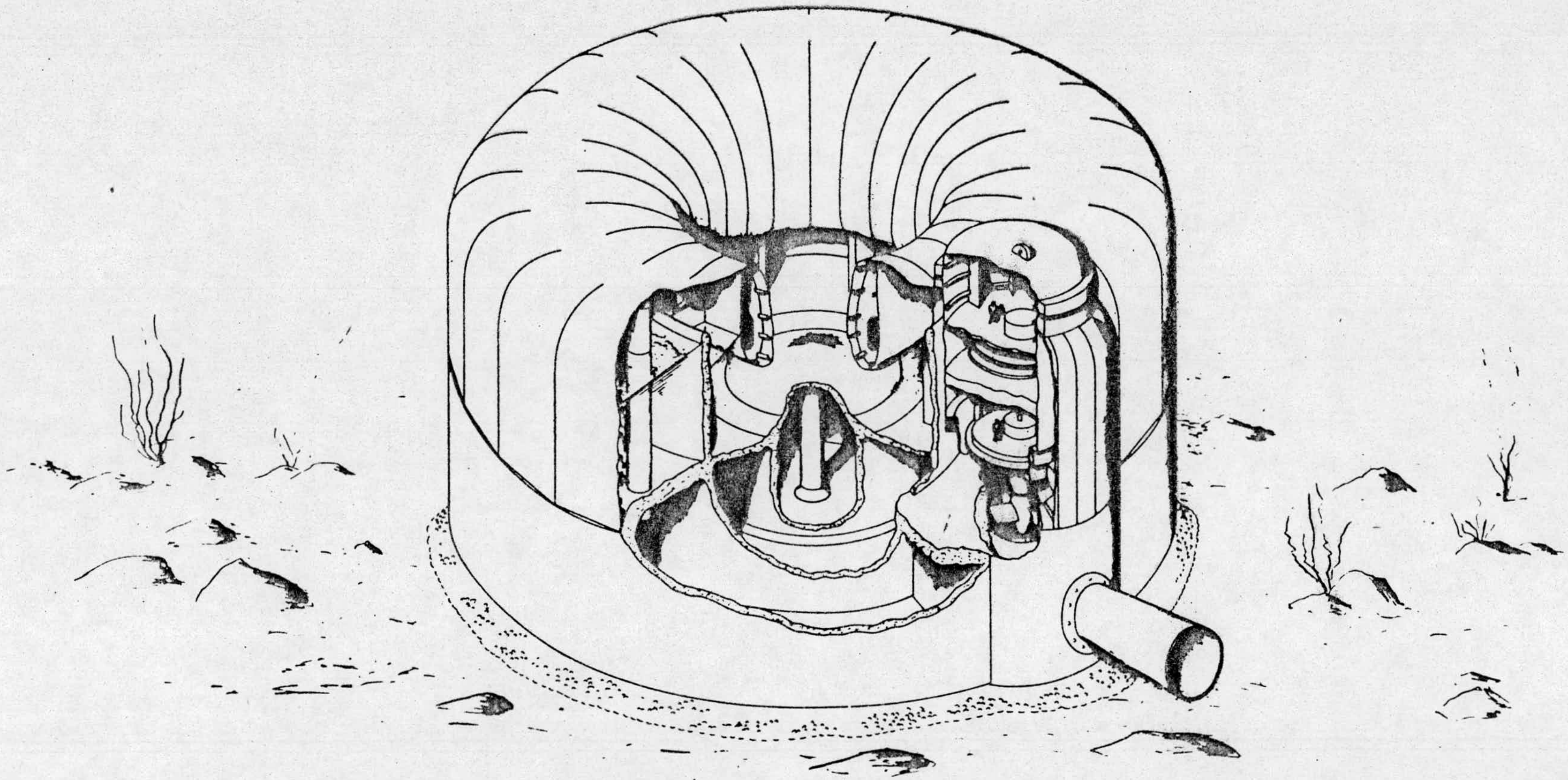
WP 78/FREN/5



WAVE ENERGY STUDY	
WELLS DEVICE	
ISOMETRIC	
DEVICE TEAM	QUEENS UNIVERSITY, BELFAST
DESIGN DRGS	THE CONSULTANTS
CONSULTANTS TO WESC	RENDEL, PALMER & TRITTON KENNEDY & DONKIN
WP 78/WELLS/1	AUG '78

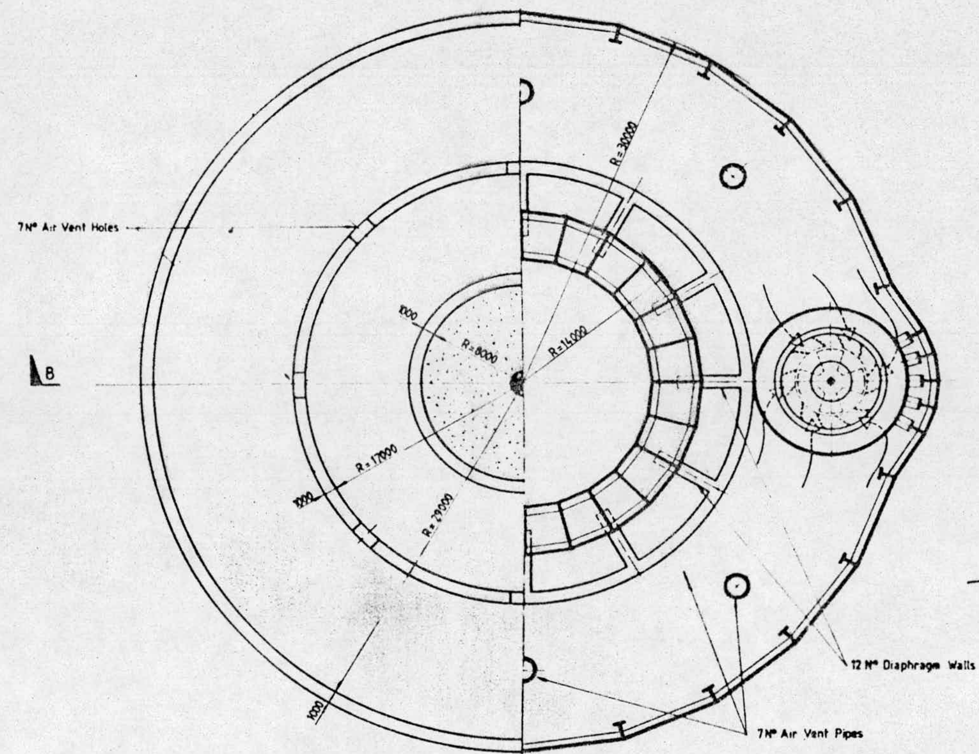
WP 78/WELLS/1


32·47
30·00
4 Nº Mooring lugs
Trough stiffeners 8Nº per roofing panel Refer to detail below
Plain flat stiffeners 8Nº per roofing panel Refer to detail below
Ring stiffeners
178 × 305 × 46 kg/m Structural tee ring stiffener
305 × 457 × 101 kg/m Structural tee ring stiffener
12mm thick plate
1·25m O.D., 10mm thick tubing
0·75m O.D., 15mm thick tubular cross bracing
60mm dia power cable inside 150mm dia steel pipe from turbine
0·75m O.D., 15mm thick tubular main members
0·5m O.D., 12mm thick tubular cross bracing
Concrete vessel ballasted with water
9·00
2·30
6·425
2·50
5·50
21·0
7·10
14·67
6·10
0·5
A
B
CROSS SECTION THROUGH DEVICE
183
2·75
SECTION A-A
PLAN AT ROOF LEVEL
SECTION B-B
5·00
ENLARGED SECTION THROUGH AIR TURBINE-GENERATOR HOUSING
WELLS DEVICE: CONSTRUCTION SEQUENCE
1. FORMATION OF BALLAST BODY FROM 8 PRECAST UNITS
2. FABRICATION OF STEEL STRUCTURE
3. DRY DOCK FLOTATION
4. IMMERSION TO WORKING DEPTH BY CONTROLLED FLOODING OF THE BALLAST BODY
300mm
400mm
8mm
600mm
SECTION THROUGH TROUGH STIFFENER
10mm
150mm
12mm
SECTION THROUGH PLAIN FLAT STIFFENER
WAVE ENERGY STUDY.
WELLS DEVICE
GENERAL ARRANGEMENT & CONSTRUCTION
DEVICE TEAM QUEENS UNIVERSITY, BELFAST
DESIGN DRGS THE CONSULTANTS
CONSULTANTS TO W.E.S.C. RENDEL PALMER & TRITTON KENNEDY & DONKIN
WP 78/WELLS/2
AUG '78.
WP 78/WELLS/2

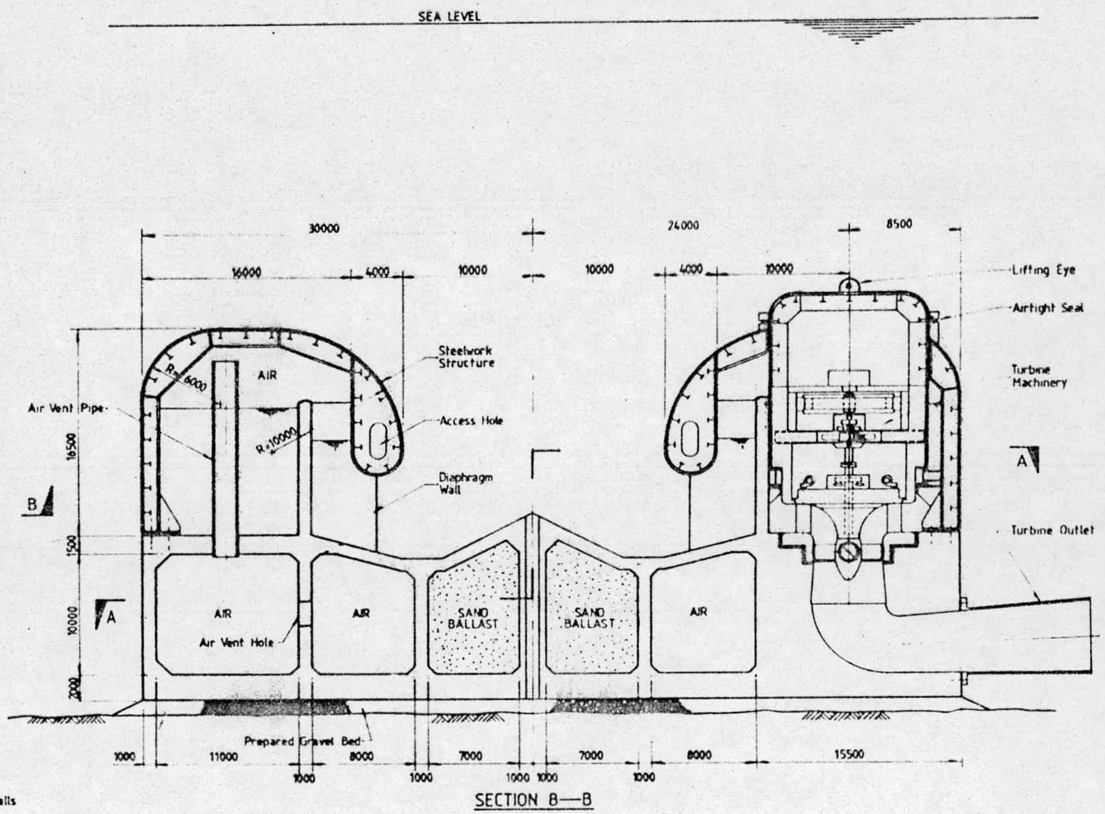


WAVE ENERGY STUDY.	
VICKERS DEVICE.	
ISOMETRIC.	
DEVICE TEAM	VICKERS LTD.
DESIGN DRGS	THE CONSULTANTS
CONSULTANTS TO W.E.S.C.	RENDEL, PALMER & TRITTON KENNEDY & DONKIN
WP 78/VICK/1.	AUG '78.

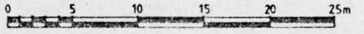
WP 78/VICK/1.



SECTIONAL PLAN A—A



SECTION B—B



WAVE ENERGY STUDY.	
VICKERS DEVICE	
PROVISIONAL VISUALISATION	
DEVICE TEAM	VICKERS LTD
DESIGN DRGS	THE CONSULTANTS
CONSULTANTS TO W.E.S.C.	RENDEL PALMER & TRITTON KENNEDY & DONKIN
WP 78/VICK/2	AUG '78

WP 78/VICK/2