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WAVE ENERGY IN THE UNITED KINGDOM
A REVIEW OF THE PROGRAMME
JUNE 1975 – MARCH 1982

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Author's Foreword

The responsibility for the views expressed is mine alone; I do in fact know that much of what I have said is agreed by most of the UK wave energy community. I have tried to set out a complex technical development so that you can see what actually happened. It may be that I was too close to the heat to make unbiased judgements, history alone will decide.

Abstract

The paper sets out the need for an inexhaustible supply of energy and describes the management system established to examine wave energy as one of the contenders for that role. It then describes the work which has been done in the UK, setting out the various costing figures obtained and the decision making processes which controlled the funding. It concludes that the work is very close to reaching a valuable result and should not be stopped until a prototype has been built.

1. Introduction

Modern Western civilisation has developed into a consuming society and one of the goods which it consumes is energy. We are fast approaching a time when there will not be enough energy to meet the demands of all groups and worst of all we are consuming our sources of energy much more rapidly than Nature is replenishing them. Something must be done.

Hundreds of thousands of years ago, early man faced a similar dilemma. At that time he was operating a life style which archaeologists call "Food gathering" and as the human populations grew in numbers they needed more and more land upon which to forage for their sustenance. They were consuming the food faster than Nature was replenishing it. Something had to be done. It was:

they developed agriculture. Thus was ensured, give or take the odd drought, an everlasting supply of food.

We have to ensure an inexhaustible supply of energy.

For some people the source which will provide that exhaustible supply of energy is Nuclear power. Others recognise that the thermal nuclear power station is also consuming fuel, at a slower rate perhaps but inexorably for all that. People have proposed a reduction in consumption of energy; hence the current popularity of Energy Conservation schemes. Certainly these are valuable but really they only postpone the dreaded time; they do not remove it.

Of course the fast breeder nuclear reactor is an inexhaustible energy source and the present generations of thermal reactors might provide mankind with the energy he needs while the complex engineering problems of the FBR are overcome. But then again the problems might take longer to solve safely than thermal systems could cover. And there might just possibly be serious safety problems arising from the use of large numbers of thermal reactors which have not so far become apparent with only small numbers of stations built by highly expert engineers working to the highest standards of safety and inspection.

When he was Chief Scientist of the UK Department of Energy, Sir Hermann Bondi enunciated the "Insurance Philosophy" which viewed the "renewable energy sources" as insurance against the unlikely failure of the Nuclear programme to deliver a safe and inexhaustible supply of energy. Such a philosophy seemed reasonable when it was assumed that the R&D for each of the renewable energy sources would be fully explored before the insurance was considered valid.

Under the financial constraints of political economists that philosophy has been somewhat distorted and the analogy has been pushed too far. Now questions are being asked about the "premium" to be paid for the insurance, ie how much does the R&D cost. A situation is developing in which research is likely to be cut back just when the final questions are about to be answered. This would be a mistake and in the case of wave energy, a costly and possibly fatal one.

To see how much progress wave energy has made in the past nine years and how near we are to the final answers, I want to take you back to 1973. At that time the recent oil crisis had concentrated people's minds on the instability of our energy supply and our complete dependence on a small number of countries for the oil we needed.

During the preceding 100 years, there had been work on a wide variety of electric generators which were driven by sea waves. Indeed there is a story told of a wave energy device which was used to light the lamps on the Pier at Atlantic City in 1926. Many and various were the gadgets which were patented; one of the more bizarre was a giant self-winding water movement. Figure 1 shows some of them. The most popular type was a float attached to the sea bed by a line whose changing length was used to drive various mechanical systems. Most of them would have worked in the sense of generating electricity and that was what their inventors claimed of them. None was likely to be economic as an electricity generator on a large scale.

There is, of course, one man who spans the time between small power units and the search for economic large size power stations. Our well loved friend Commander Yoshio Masuda who patented and built a wave-powered navigation buoy in 1947 and who is today one of the world's leading authorities on full-scale wave power systems. We shall hear about his recent work on Thursday.

What the early pioneers had failed to recognise was, what I call, the first law of wave energy:

"Any properly designed system will generate electricity: the trick is to do it economically".

The first of the modern inventor/designers had come into the wave energy business because of the economic pressures on energy prices. Thus you will find that the earliest papers by Sir Christopher Cockerell and Stephen Salter were well sprinkled with £/kW installed and p/kWh generated. It is no shame to them that their early estimates were later believed to be too optimistic; it is more likely to be the sceptics who will be proved wrong in the end.

Sir Christopher Cockerell's wave contouring raft and Stephen Salter's oscillating vane which later become universally known as the Salter Duck, were the first two in the UK to receive official recognition; somewhat grudging recognition, however, and by later standards a ridiculously small amount of funding. The Department of Energy commissioned our National Engineering Laboratory to carry out a techno/economic survey of wave energy, and the British Government's "Think Tank" wrote a report saying that sea waves could be a valuable energy source for the UK.

The combined effect of those two documents was to stimulate Dr Walter Marshall who was, at that time, both Chief Scientist of Department of Energy and Director of Harwell. The stimulation resulted in a suggestion that the Department of Energy should fund a study of the feasibility of wave energy generation and that Harwell's Energy Unit should put together and manage a programme to do that work.

Now why, you may well ask, should a Nuclear Research Establishment like Harwell be given the job of managing a very non-nuclear feasibility study. I have even heard remarks about putting Dracula in charge of a Blood Bank.

The reason was that Harwell was then and still is earning half its funds by selling its expertise as contract R&D. A whole infrastructure of supporting services and people were available to the Energy Unit and the senior staff of that Unit was drawn largely from the entrepreneural research managers whom Harwell had trained over many years in widely ranging different disciplines.

The principal theme of the management style of these people was to give the the research teams the maximum freedom to innovate but to keep them moving in the desired general direction. We wanted to engage people to apply their minds to the problems not just to act as additional hands to the plough. It is a style of management which calls for a close rapport between all the parties and it is one whose delicate balance can easily be upset by heavy handed bureaucracy.

It was this style of management which Harwell was called upon to apply to the new technology of wave energy which Dr Marshall wanted us to develop.

2. The Work Up to 1977: A Technology Led Development

Following from Dr Marshall's initiative, Harwell put together the outline of a first step towards a feasibility study. There was to be work on four different wave energy systems and a supporting programme of more basic studies.

Those first four systems, which became known as "Devices" were:

- The Salter Duck
- The Cockerell Raft
- The Russell Rectifier
- The NEL Oscillating Water Column

These basic studies which became known as the Generic Programme consisted of the following:

- Wave data collection and analysis;
- Studies of structural behaviour;
- Investigation of methods of electricity generation and transmission;
- The effects of wave energy conversion on the Natural environment;
- The search for new system concepts.

The programme of work on these devices and the generic work was submitted to the Department of Energy in January 1976 and the first tranche of funding (£1 Million) was announced at a Press Briefing in April.

A set of illustrations was prepared for that briefing and these are shown as Figures 2, 3, 4 and 5.

In the terminology which we have since developed, the Cockerell Raft in the picture would probably be classified as an "attenuator" and the Duck as a "terminator". Both would be said to have "mechanical" power take-off.. The Russell Rectifier would now be called a sea-bed passive system and the NEL/OWC was an early example of one of the most promising and versatile systems which are covered by the general title of "open oscillating water columns".

Around each of these devices was built a team of researchers whose style of working and skills were different and to a very large measure complementary.

At that time the main drive of those "Device Teams" was to get the maximum capture efficiency from their device.

There was not a great deal known about the real wave climate close to the UK and most of the early estimates of power and cost which were presented to Harwell by the Device Teams were based upon wave data from Ocean Weather Station India, 250 miles out into the Atlantic where a mean annual value of 80-90 kW/m was recorded (Figure 6).

Device capture efficiencies were based upon small scale experiments in narrow tanks or flumes and were in many cases in excess of 70%.

All of this led to the belief that a 1000 km stretch of Western UK coast could produce 60,000 MW of electricity. Even if an allowance of 50% efficiency was made for the generation and transmission systems, the figure of 30 GW, which was equal to the annual output of the UK generating system, was huge.

I always tried to be on the cautious side in the hope that the future surprises would be pleasant ones and I worked on the "three fifties" basis:

50 kW/m in the sea

50% Device capture efficiency

50% Generation and transmission efficiency

This calculation led to a figure of 12 GW for 600 miles of coast and to the claim that wave energy would easily be able to supply half of the UK's electricity needs.

The optimum which arose from this type of estimate was certainly a contributing factor in obtaining funds and in ensuring the interest of highly creative engineers.

I can recall that the Select Committee on Science and Technology of the UK Parliament criticised us for not spending money fast enough and on all sides the Press sought to have us go faster. We had to explain that we were still an infant technology, very much in the research phase and not yet ready for huge engineering works. The Select Committee was not very impressed and one member suggested that we were a "cosy little group" lacking drive and industrial advice.

Although Harwell had a prime responsibility for the content and management of the programme, it was being steered by a group known as the Wave Energy Steering Committee (WESC) which was chaired at first by Dr Lewis Roberts, who later became Director of Harwell. The main members of the group were: Dr John Wright of the CEGB, Mr Roger Hancock of NEL, Mr Don Gore of the DEn and me as Secretary.

As we got down to the detailed study of the programme we felt a lack of specialist input on two important topics, data about the wave climate, and the behaviour of structures at sea. To fill these gaps we persuaded Mr Robert Russell of Hydraulics Research Station and Dr Charles Smith of Naval Construction Research Establishment, to join the group.

Another significant change to the group occurred in the Summer of 1976 when Dr Freddy Clarke took over as Chairman.

Following Freddy's appointment, we did a number of things to take note of some of the external criticism. We appointed two engineers from industry to WESC; Mr Pat Wyman of GEC and Mr Don Townend from BP. We also engaged a firm of Civil Engineering Consultants to examine the estimates of the cost of power, believing that it was structural cost which would always be dominant. In order to let the main Steering Committee concentrate its time on important policy decisions and on direct interaction with the device teams, we set up a series of expert groups each chaired by a member of the Steering Committee who had specialist knowledge in that field. Thus Robert Russell chaired the Wave Data Group, Charlie Smith the Structures Group, John Wright the Generation and Transmission Group, etc. These Groups became known as the Technical Advisory Groups or TAGs, and although they caused me personally some aggravation, they did a splendid job in ensuring that all the many parts of this multi-facetted technology were fully examined.

The main themes of the programme in the first years were:

- maximise device efficiency;
- collect and analyse wave data;
- examine structural behaviour;
- estimate the cost of power.

Under Freddy's enthusiastic leadership, the Steering Committee began the pattern which it was to follow for many years; it visited the Device Teams in their Laboratories and listened not only to the science and engineering but also to the people themselves. For we believe that it is only from a full understanding of the people that you can make successful judgements about what to fund and what to stop.

This period saw the beginnings of 1/10th scale sea trials, of the multi-wave wide tank in Edinburgh, of the wave rider buoys off South Uist, and of the involvement of Rendel Palmer and Tritton as Consultants.

3. The 1977 Workshop in Oxford

Recognising that with a widely scattered community and with many new groups and devices being added to the teams originally funded, we decided in late 1977 to have a workshop/conference. The idea was to get everyone together for a few days and to exchange ideas, report progress and discuss the costing exercise which RPT had carried out on the four original devices.

Each of the device teams and the TAGs were given an opportunity to report and there was a full discussion of these reports.

I came away from the Workshop with some very clear impressions. I list them here though not necessarily in order of their importance.

(1) The costing prospects looked encouraging, and although at that time they were expressed in terms of capital cost per kilowatt installed, I give them here in the units we later came to use, viz pence/kWh delivered.

Raft	3 p/kWh
Duck	2.6 p/kWh
Rectifier	5.6 p/kWh
OWC	4.2 p/kWh

The calculation is based on the then assumed mean annual output of 65% of installed capacity and an annual cost of 10% of capital. The latter figures is based on capital costing 7% and maintenance costing 3%.

(2) Much more work was going to be needed on all topics than I had previously estimated. And in particular that there were likely to be considerable problems with structural costs, mooring systems and the engineering of power take-off systems particularly the mechanical ones (Raft and Duck).

(3) We should encourage development work on some of the new devices which had appeared; notably the flexible bag invented by Professor Michael French at Lancaster University and the Oscillating submerged cylinder invented by Dr David Evans of Bristol University.

(4) The 1/10th scale trials were likely to be very revealing and should be pursued with vigour.

(5) The Department of Energy should be asked to fund a three year development programme costing £3M per year.

(6) There should be another workshop in 12 months time and at least part of it should be open to the public and the Press.

(7) Finally we had been very fortunate to have brought together such an enthusiastic, dedicated and creative group of people.

Early in 1978 we presented our progress report and future plans to the DEn's Advisory Council on Research and Development (ACORD). Although the Council did not give us the three year funding which we had requested, they did under Sir Hermann Bondi's skilled management give us the first years funds and an indication that if the prognosis continued to be favourable they would continue funding. They also reminded us that a near full scale sea trial was an essential step and that we should be reducing the number of device options with that in view. Sir Hermann Bondi himself always emphasised the importance of "green-sea" experience.

Throughout 1978 the Device Teams continued to improve their understanding of the complex relationship between the power in the sea and the proportion of it which the devices could land. This involved changes of shape for some devices, different methods of damping to obtain maximum output and the effect which multi-frequency mixed direction seas would have on device output.

During this time also, the team at RPT started to do a very much more detailed study of the engineering designs and to carry out more detailed costings.

The data from the South Uist buoys started to become available this year in analysed and usable form.

4. The 1978 Heathrow Conference and Workshop

The 1978 Heathrow Conference was seen by many as a major set back (with the hindsight of 1982 it was a very minor one!).

The situation in November 1978 can best be expressed in the words Freddy Clarke used in his introduction to the Conference:

> "There is usually a stage in the research and development of technology at which the problems loom larger than the solutions and things appear to change from month to month and possibly from week to week. Wave energy is currently at that stage".

We had had a very thorough evaluation of the engineering designs and concepts, we had had a close analysis of the South Uist wave data and had taken full account of the effect of wave direction on devices fixed in a line predominantly to accept waves from the West.

Figures 7, 8, 9, and 10 show the 1978 devices which were: Duck, Raft, Rectifier, and the Oscillating Water Column.

The sea energy input to the devices had been reduced from the 80-90 kW/m previously obtained at OWS India to 48 kW/m at the new location in 40 m of water off the Outer Hebrides. So we had "lost" half the energy in one step. The effect of direction reduced it by a further 25%; and estimates of device capture efficiency when applied over the whole scatter diagram had averaged out at 40-50%. Estimates of the power chain efficiency and reliability were in the region of 50% and 80% respectively.

The values for the five devices costed at the Heathrow Conference are set out in Table 1 where the original four devices (cost of energy) was in the range 20-50p/kWh with the then little known Lancaster Flexible Bag at below 10p/kWh.

The reasons for this dramatic increase in the cost estimates are really three in number:

Energy available in the sea decreased by 50%
Load Factor for device output down from 65% to 25 or 30%
Capital Cost estimates increased by 2 to 4 times.

So the UK wave energy community had problems, but it also had the important ingredients of:

- high engineering and scientific quality
- great dedication
- an enormous capacity for hard work
- a management that believed in its ability to crack the problems.

Once again we reported to ACORD early in 1979. We spelt out the problems and outlined the means by which we expected to solve them. Our funding for the ensuing year was approved and again we were advised of the importance which the Council attached to a sea trial at near full-scale.

We set about the task of reducing costs and improving device output with the objective of reaching a magic figure of 10p/kWh.

5. The 1979 Reference Designs and the Maidenhead Conference

Each of the Device Teams tackled the cost reduction problem in a different way and in each case much of what was learned could be of value in reducing the cost of other device systems.

Before I describe the successful ones however, I must talk briefly about the unsuccessful one. The HRS Rectifier had in the 1978 reference design been a massive concrete structure and although its total capital cost was lower than the others, so also was its output. A study was initiated early in 1979 to try to find the means of either reducing cost or increasing output. It was found that while a modest increase in output could be achieved, the sheer size of the concrete structure kept the cost high. The main reason for this is that the distance from front opening to back wall must be a minimum of a quarter of a wave length to prevent the reflected wave from closing the valves against the incoming one. It is interesting to note here that the passive lagoon type of wave energy device is believed by Mr Bott and the Crown Agents to be cost effective in some locations. This is because, although it does have many of the features of the HRS Rectifier which would tend to make it costly, it does not require the massive concrete containment structure: that is provided "free" by the lagoon. All things being considered, we decided that there was no possible future for the Rectifier type of device in the conditions we had specified and accordingly work was stopped.

The Cockerell Raft designs shown in Figure 11 are the result of a design philosophy called "design for production". The people at Wavepower Limited had discussions with a firm of shipyard designs, A&P Appledore. Basically the principle is that all the parts of the raft structure should be fabricated from a single type of stiffened steel plate which itself could be mass produced in great quantities in a fully automated yard. All the sections of the structure are so designed that it is possible to make them from this standard plate. Figures 12 and 13 show in outline how this production process would be organised. Comparison of the man hours per tonne achieved in the best Swedish ship yards indicated that the targets proposed were achievable. The result of these studies was to reduce the capital cost by a massive £10,000M and with virtually the same annual output the cost of energy was estimated to be reduced by 3 times to 12p/kWh.

The Duck problems were in the main associated with two features of the 1978 design: the wheel motor power take-off and the torque transmitting spine. The new 1979 design removed these two features and used instead precessing gyroscopes in a vacuum sealed pod in the nose of the Duck. Figure 14 shows this now well known diagram. The result of these changes was to reduce the estimated capital cost by £7000M to £4,200M and with a 30% improvement in the output the cost of energy estimates for this system were reduced to 10p/kWh.

The NEL's Oscillating Water Column 1979 design was one of the most radical changes since it went from a massive floating structure to one fixed to the sea bed (Figure 15). There were as a consequence of this change, a whole sequence of other changes which had not been fully worked out by the time of the 1979 review. Many of the improvements resulted from detailed engineering studies by Roxburgh and Partners for the NEL. The main ones however were that the capital costs were reduced by £10,000M to £8,000M and because of the higher capture efficiency obtained with a fixed system the output was increased by 60% to give a load factor of 36% and a mean annual output of 6.3 TWh/year with a consequent reduction of the cost of energy estimate from 48p/kWh to 13p/kWh.

The changes brought about in the Lancaster Flexible Bag (Figure 16) by construction studies carried out by WPL and Gifford and Partners were not so dramatic as in some other devices because it had started later than the rest in its engineering studies and had as a consequence been able to take advantage of the work done on the earlier studies. The engineering work on this device was at this time being undertaken by Sir Christopher Cockerell's team at Wavepower Limited. The capital cost estimates at this time were some 60% less than the previous estimates and with no reduction in the estimated value of annual output the cost of energy figure was 6p/kWh.

A new device made its first official appearance in our costing tables at this time. This was the Bristol Cylinder (Figure 17) invented by Dr David Evans. The engineering work had been undertaken by Sir Robert McAlpine and Sons Limited under the guidance of Dr Tom Shaw previously of Bristol University. This device was very much at the early research stage and the designers were keen not to be too optimistic in their cost estimates, but rather to leave room for some later improvement. Their estimates of cost of energy were 14p/kWh.

The break down of these cost figures and the previous years designs are given in the Proceedings of the Mainhead Workshop and are reproduced here for easy reference as Tables II and III.

There were many shortcomings of the figures produced for the 1979 reference designs, most of which were associated with the short time scale on which the work had been done. Most important of these was the lack of really substantial wide tank test data to give the output figures some real credibility and also that there had not been time for the costing figures produced by the Device Teams and those of RPT to be reconciled.

Other events had occurred during 1979/80 (including the start of work on a second wide tank at the WPL site at Cadnam), which were mostly associated with a wide variety of new device concepts which had emerged previously and were now approaching the stage when they had to be given careful study.

6. The March 1980 ACORD Meeting

We approached the March 1980 ACORD meeting with an optimistic progress report and a request for funding a wider range of device types than at any previous occasion. The funding request, which was basically at about the same level as previous years (£3-4M) also included some £500k to be spent on developing the hydraulic machinery and gyros for the Duck.

Remembering that the Council had from the very beginning been asking us to reduce the number of options and move towards a near full scale sea trial, it is not surprising that at this point they said NO. What they did do however was to invite me to come back to their June 1980 meeting with a programme concentrating on a much smaller number of devices, (two was suggested), and indicating which one should be taken to a sea trial prototype. Quite specifically the Council did not believe that the prospects for the Duck were sufficiently encouraging for it to be worth spending such a substantial sum on developing the power take-off system.

In order to achieve what ACORD had asked, we set about a fundamental reassessment of the programme methods. We realised that what we had been doing was to use devices and the teams associated with them to investigate the various design principles; for example the work on Ducks investigates spines; the work on Clams by SEA was investigating mooring systems; the work on Rafts was investigating design for production. Re-examined in this way we were able to present a different programme to ACORD in June 1980.

7. June 1980 ACORD and the Two Year Programme

The programme which we submitted for funding in June 1980 was really for three basic device types:

- the open oscillating water column
- the membrane closed water column
- the mechanical power systems.

The selected vehicles for these studies were the sea-bed mounted OWC, the Lancaster Flexible Bag and the Bristol Cylinder. It did not escape notice that the last two were also the most recent designs, there by reinforcing the second law of wave energy that "The device you last thought of is the most attractive".

This programme was to last two years and would culminate in a recommendation of which device (if any) should be taken to prototype sea trials. Funding was approved and was in fact slightly more than had been requested in March. This in my view adds credence to the view that ACORD were at that time keen to have the work done thoroughly and to bring it to a sensible conclusion, they were not then seeking a means of shutting down the wave energy programme.

In late 1980 and early 1981 the Wave Energy Programme suffered its worst blows. Sir Hermann Bondi retired from his post as Chief Scientist at the Department of Energy and Dr Freddy Clarke left his position as Chairman of the Wave Energy Steering Committee. Later he was to leave the Renewable Energy scene completely which made matters worse. With the loss of these two great men we lost that intellectual perception of the problems of managing an innovative group and the scientific grasp of the significance of what we were trying to do.

The programme which we set out was to include a very thorough investigation of costs and to ensure, we hoped, that these would be easily agreed, we set out basic costing data for all the device teams to use. These cost data were produced by groups of experts in the various fields under the general guidance of RPT. As it turned out the Civil Engineering or Structural Costs were reasonably easy to agree, but in the fields of installation, power transmission and generating/power take-off, there were considerable difference of view between equally respected experts.

In the fields of maintenance and reliability we found that we were really having to cover completely new ground. Dr Roy Taylor will be telling you all about this work this afternoon.

8. The "Mid-Term" Report in March 1981

To obtain our funding for the second year of the two year study we had to return to ACORD and report. I had expected this to be something of a formality as we had already set out the two years of work and were really only a few months into the first year.

Two things happened which were ill omens for the future:

- there was a significant bid to shut down the work then and there;
- we were required to return with our final recommendations the following March (1982) thus reducing the time available to do the work by 3-4 months.

We were, after some discussion, granted the money needed but I was given the strongest possible warning that the March 1982 report must contain a definitive recommendation about which device should be taken to a prototype if the costings looked encouraging. In answer to my specific question, what figure would be considered encouraging, I was told about 5p/kWh, a figure which was given further support by the Department of Energy spokesman at the Nairobi Conference in August 1981.

9. The March 1982 Report

We pushed on with the studies, introducing considerable refinements into the tank work by the use of a representative set of 46 sea spectra which could be reproduced in both tanks and which could subject the model to a very realistic recreation of North Atlantic sea climates.

In addition to this improvement in the quality of the tank results we had also produced the basic costing data to be used by all teams.

These sets of information led in many cases to the need for redesign to overcome the problems revealed by the new data and with the March 1982 dead-line fast approaching it was not possible to have all the different figures produced by the device teams and RPT fully reconciled. And even more importantly there was not time to carry out the optimisation studies and cross fertilisation from one team to another which could have led to a truly representative device design which was as close to economic viability as possible.

Recognising these problems I prepared a paper comparing the costing figures of RPT with those of the device teams looking towards what might be achieved in the future. The Device Teams' estimates of cost of energy were in many cases close to the 5p/kWh figure and five of them believed there was reason to think they could get below that figure. The figures are all given as Tables IV and V of this paper and the discussion document is issued as an appendix to this paper.

I also had prepared detailed artists impressions of the various devices so that ACORD would be able to see exactly what we were talking about (Figure 18-24). I had estimated that we would need a further 12 months of work in order to be able to recommend the details of a prototype although it was clear that it was likely to be some version of a sea bed mounted oscillating water column.

The Department of Energy has not yet made its recommendations fully available for discussion. However press reports of a D.En. briefing suggest that further funding for work on wave energy is likely to be very limited.

10. The future of Wave Energy

Having spent £15M and a huge amount of intellectual input into this work for the past seven years, it seems to me to be a criminal waste to stop now when we are within months of being able to specify a prototype.

My first reason for this is that we cannot be sure what the shape of future energy needs will be and must pursue any goal which could lead in the future to an inexhaustible source of energy. In his foreword to the Severn Tidal Barrage Report, Sir Hermann Bondi referred to an "Act of Faith" for the future. That is certainly what is needed in Wave Energy.

My second reason is much more immediate and concerns the island and coastal communities of the Third World. Many of these people are at present paying very high costs for their electricity and for that reason have very little of it. But give such a community large amounts of power at 10-15p/kWh and their whole way of life could be changed dramatically. Wave power could be valuable to them particularly because in the construction of, for example, a sea bed mounted OWC, there would be much use made of local skills, people and materials with only a relatively small proportion of capital cost being imported.

What this project needs is funding for a further 9-12 months so that a prototype can be defined and then a commitment to build a 2-4 MW sized module from which the Third World customers can see what the product could do for them.

To make such a decision requires imagination, foresight and courage. It also requires some £10-20M and Governments tend to be short on these things.

<u>References</u>

Heathrow Conference Proceedings

Maidenhead Workshop Proceedings

<u>Annex</u>

Comparison of the cost of energy from RPT and the Device Teams.

TABLE I - 1978 DEVICE COSTS

Device	Capital Cost of 2 GW £M	Device efficiency %	Power chain effic %	Reliability %	Direction-ality factor ,%	Mean annual output TWh/y	Cost of Energy* p/kWh	Load factor %
Raft	14,500	50	59	87	65	4	36	22
Duck	11,200	54	53	70	65	2.9	39	17
Rectifier	8,900	33	41	92	65	1.6	56	9
OWC (NEL)	18,000	39	37	87	65	3.8	47	22
LFB†	41,000	30	64	82	65	4.3	9.5	25

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†

*different from RPT

TABLE II

COSTS OF 1978 REFERENCE DESIGNS OF A 2 GW STATION

	NEL/ OWC	DUCK	RAFT	LFB	HRS
NUMBER OF UNITS	1000	2200	1200	560	576
STRUCTURAL COST £1000M	5.8	4.7	5.3	1.0	3.7
MECHANICAL COMPONENTS £1000M	3.6	3.6	4.3	1.3	2.7
MOORING ETC. £1000M	5.6	0.9	2	0.6	0.84
POWER COLLECTION £1000M	1.0	0.65	1	0.8	0.23
20% CONTINGENCY £1000M	1.9	1.4	1.9	0.4	1.5
TOTAL CAPITAL £1000M	18	11.2	14.5	4.1	8.9
COST OF OWNERSHIP 10% OF CAPITAL	1.8	1.12	1.45	0.4	0.89
MEAN OUTPUT IS A TYPICAL YEAR MW	430	330	460	470	180
MEAN ANNUAL OUTPUT TWH	3.8	2.9	4.0	4.3	1.6
COST PER KWH IN PENCE = COST OF OWNERSHIP / MEAN ANNUAL OUTPUT	47	39	36	9.5	56

} ?

TABLE III

COSTS OF 1979 REFERENCE DESIGNS OF A 2 GW STATION

	NEL/ OWC FIXED	DUCK	RAFT	LFB	BOC
NUMBER OF UNITS	1400	1500	930	435	930
STRUCTURAL COST £1000M	4.4	0.3	* 2.0	0.6	0.2
MECHANICAL COMPONENTS £1000M	1.9	2.6	0.5	1.0	2.4
MOORING ETC. £1000M	0.3	0.4	0.76	0.25	1.0
POWER COLLECTION £1000M	0.4	0.45	0.7	0.5	0.6
20% CONTINGENCY £1000M	1.0	0.46	0.6	0.3	0.8
TOTAL CAPITAL £1000M	8.0	4.2	4.6	2.6	4.2
COST OF OWNERSHIP 10% OF CAPITAL	0.8	0.42	0.46	0.26	0.42
MEAN OUTPUT IS A TYPICAL YEAR MW	720	470	450	480	410
MEAN ANNUAL OUTPUT TWH	6.3	4.1	3.9	4.2	3.6
COST PER KWH IN PENCE = COST OF OWNERSHIP / MEAN ANNUAL OUTPUT	13	10	12	6	14

* it looks like concrete raft used for costings

TABLE IV - PRESENT COSTS

	DUCK		BOC		LFB		SEA C		NEL B/W		VIC ATT		[illegible]	
	RPT	DT	RPT	DT	RPT	DT	RPT	DT	RPT	DT	RPT	DT	RPT	DT
Structure £M	1554	1296	488	480	2456	1677	1841	1641	1358	1232	1814	1664	2850	2074
M & E £M	843	635	1199	378	961	1571	849	559	793	576	529	531	1520	540
INST&MRG £M	211	123	1776	2242	783	625	273	271	1018	630	983	962	2090	1849
PC & T £M	460	230	710	409	1068	740	1015	519	603	264	832	807	760	270
TOT CAP £M	3068	2284	4173	3509	5268	4613	3978	2990	3772	2702	4158	3964	7220	4733
MAINT/Annum £M	68	9	35	90	47	54.5	61	30	46	41	48	33	104	7.3
η D %	39	38	46	385	17.4	16.7	23	37.4	55	55	15	32	57	25
η PTO/AV %	83/80	73/92	66/80	68/90	71/84	73/89	65/83	65/87	72/89	78/89	71/87	71/91	67/88	67/95
Power in kW/m	54	59.3	47.8	47.8	51	52	51.3	50	29.6	29.6	36.2	36.2	41.7	41.7
Depth m	100	100	42	45	75	75	90	80	21	21	25	25	30	30
Inst Cap GW	2.39	2.25	2.16	2.95	2.85	2.69	3.41	3.41	2.74	2.63	3.18	3.18	2.85	2.34
No of Devices	956	864	444	444	356	336	341	320	589	589	756	756	1900	1500
MAO TWh	5.21	5.75	3.37	4.16	4.2	4.35	5.28	5.55	3.56	3.55	4.23	4.96	4.18	5.25
G-P COE p/kWh	5.5	3	9.8	8.2	10	8.9	6.5	4.4	8.8	6.6	8.1	6.3	14.7	6.4
COE p/kWh	5.6	3.3	10.2	8.6	10.4	9.1	6.7	4.4	9.3	6.3	8.7	6.3	15.5	7.3

TABLE V - DEVELOPMENT POTENTIAL

	NEL B/W		LFB		DUCK		BOC		CLAM					
		DT		DT		DT		DT		DT				
Structure		1232		1677		1296		555		1641				
M & E		283x2		157		635		378		559				
I & M		630		625		123		1074		271				
PCT		135		740		230		372		519				
TOT C		2563		3199		2284		2379		2990				
MAINT		24		545		9		90		30				
η D		55		30		38		50.6		37.4				
η P & A		72/89		77/89		73/92		68/90		65/87				
Power in	-	29.6		52		59.3		47.8		54				
Depth		21		75		100		45		80				
Inst Cap		2.63		3.69		2.25		2.95		3.41				
No of D		589		336		864		300		320				
MAO TWh		4.6		8.7		5.75		4.58		6.0				
G-P COE		3.5		3		3		4		4				

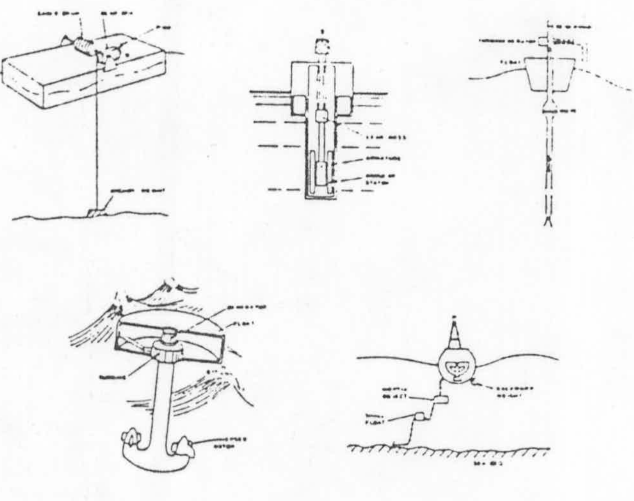
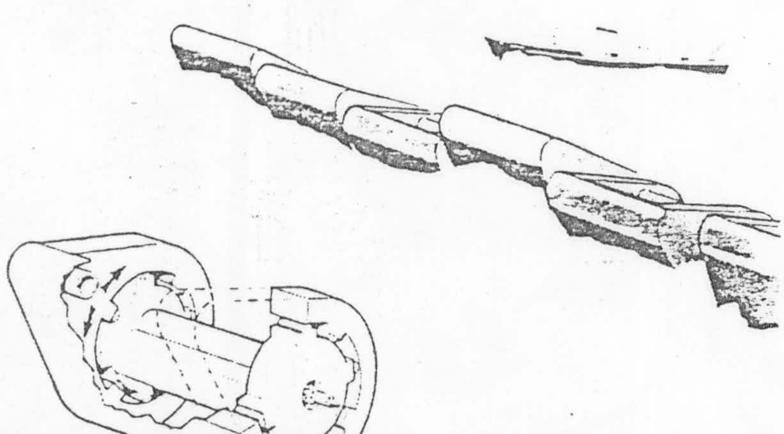


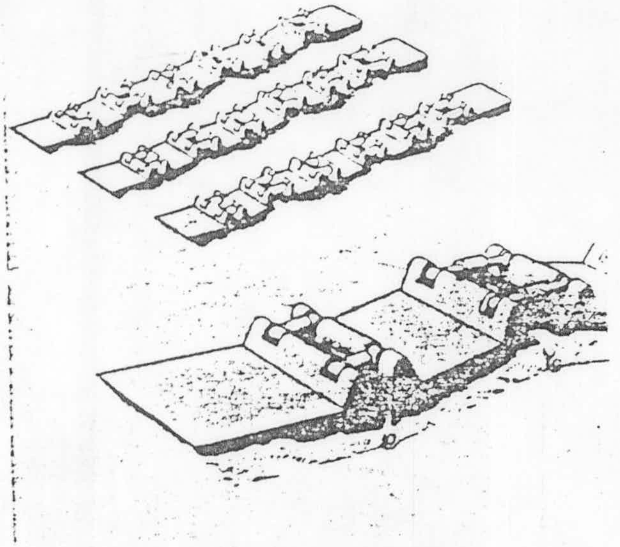
FIG 1



ENERGY FROM SEA WAVES

Salter's Ducks

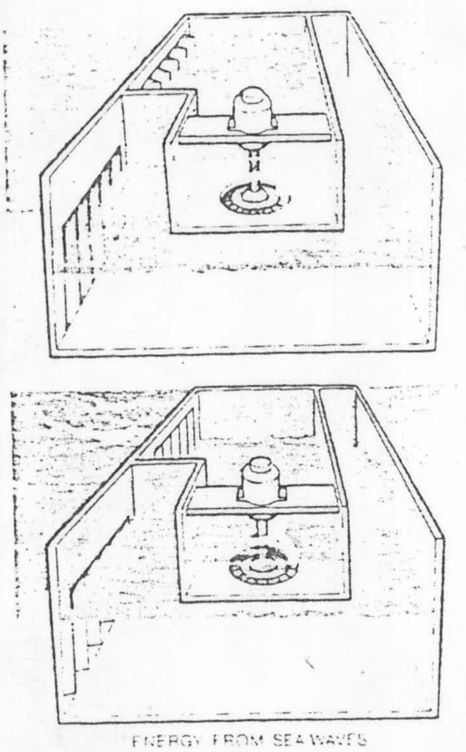
FIG 2



ENERGY FROM SEA WAVES

Wave Contouring Raft

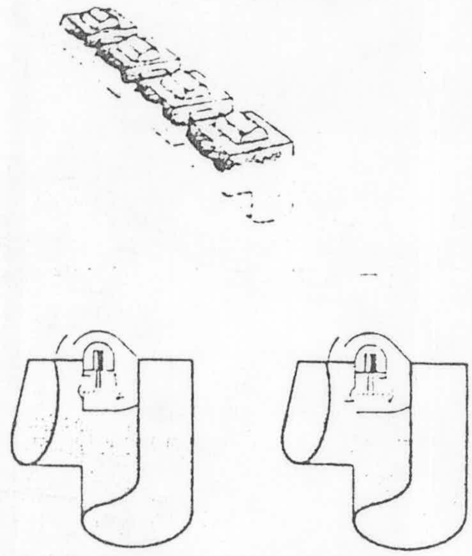
FIG 3



ENERGY FROM SEA WAVES

The Russell Rectifier

FIG 4



ENERGY FROM SEA WAVES

FIG 5

FIG 6

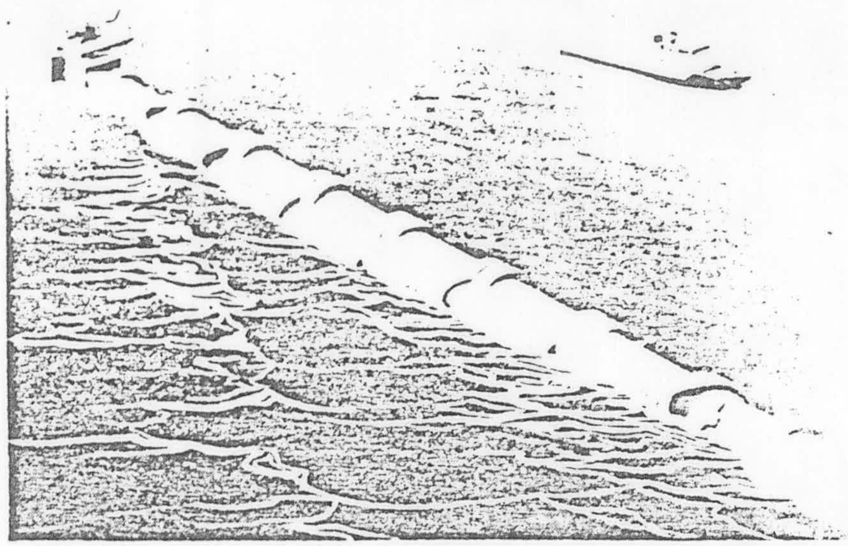


FIG 7

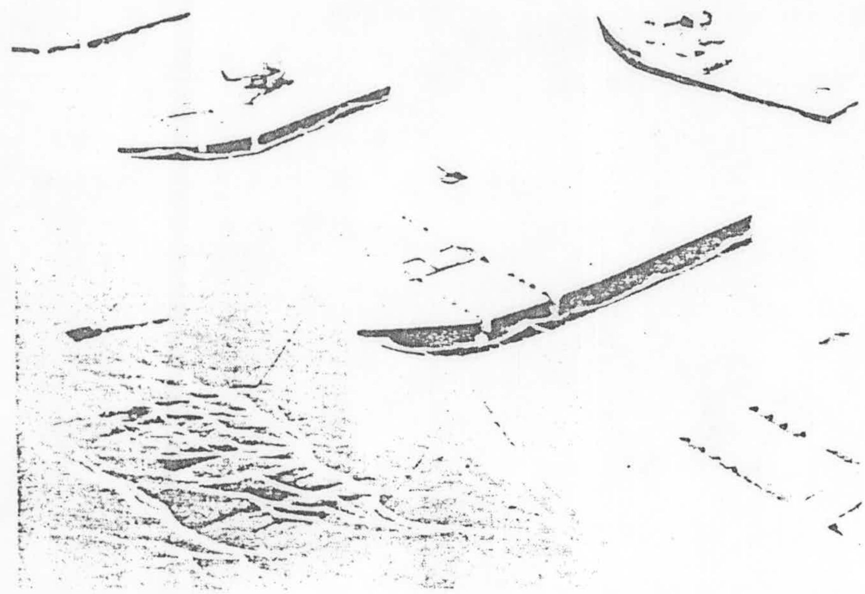


FIG 8

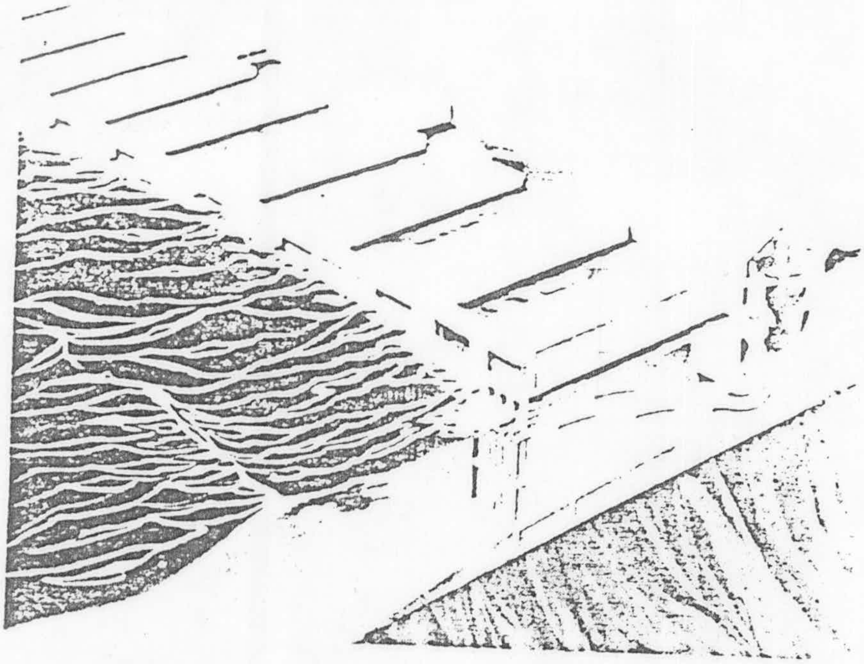


FIG 9

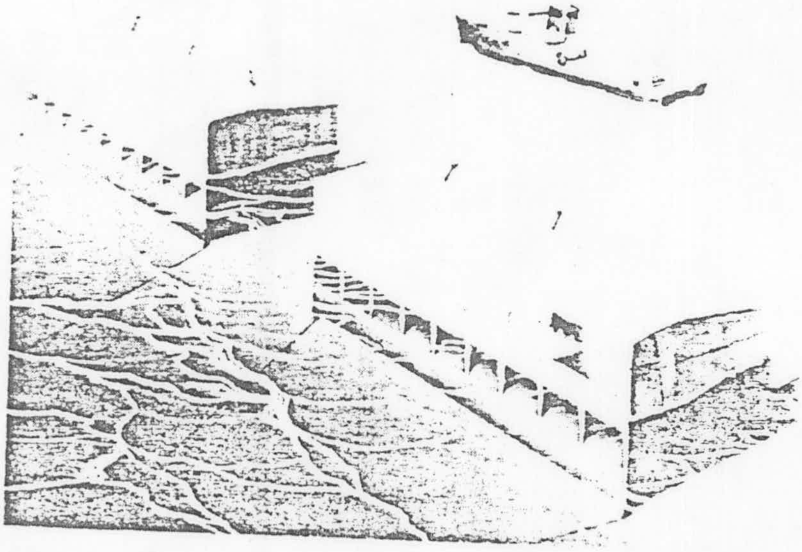


FIG 10

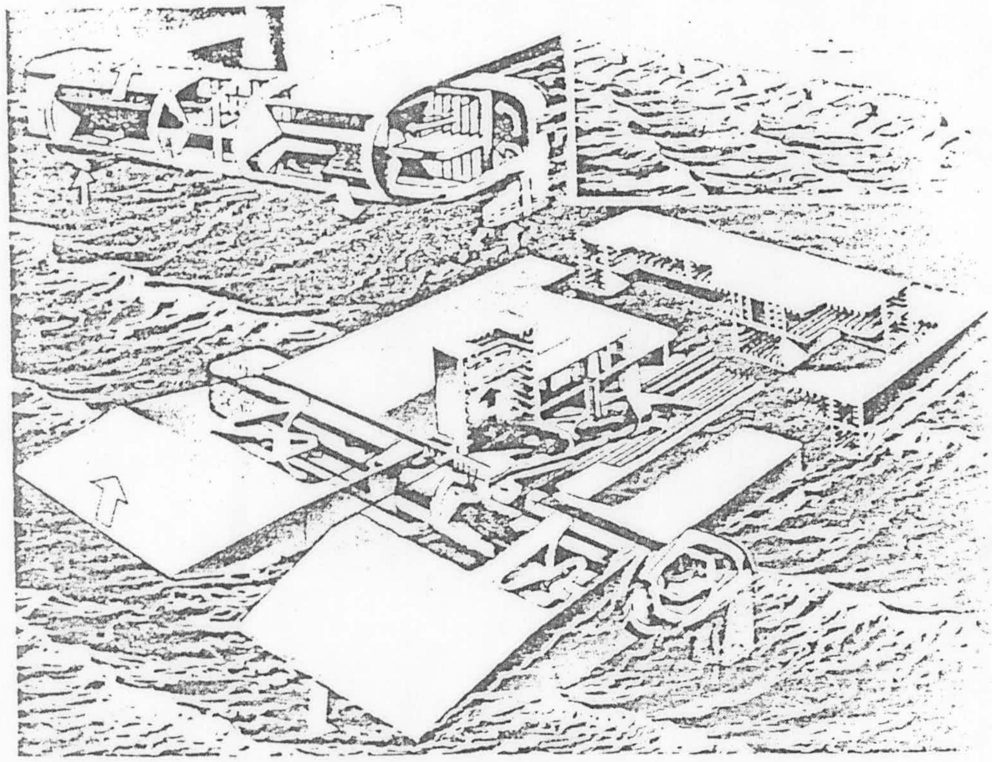


FIG 11

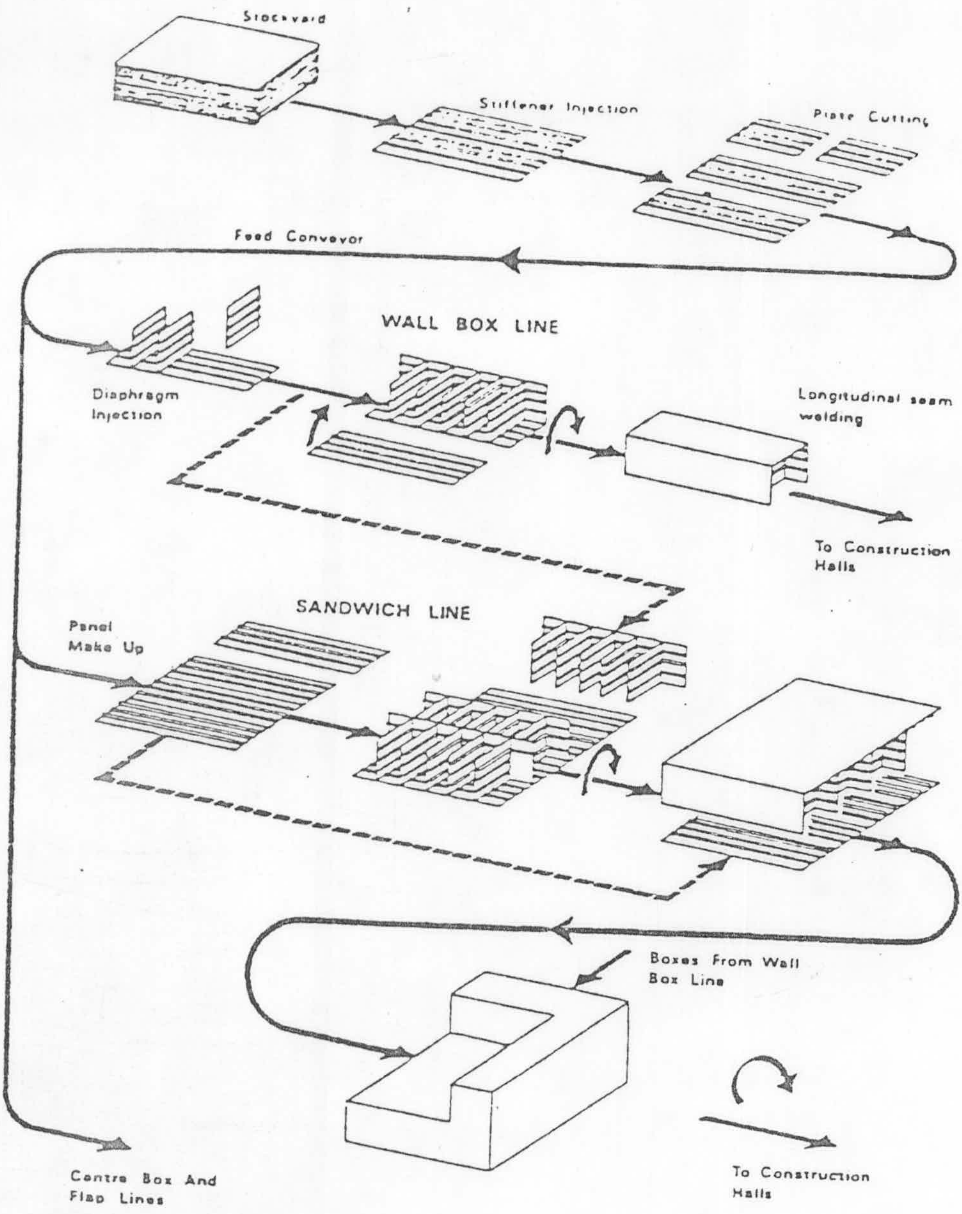


FIG. 12 : Steel Hull Production
Preparation and Assembly

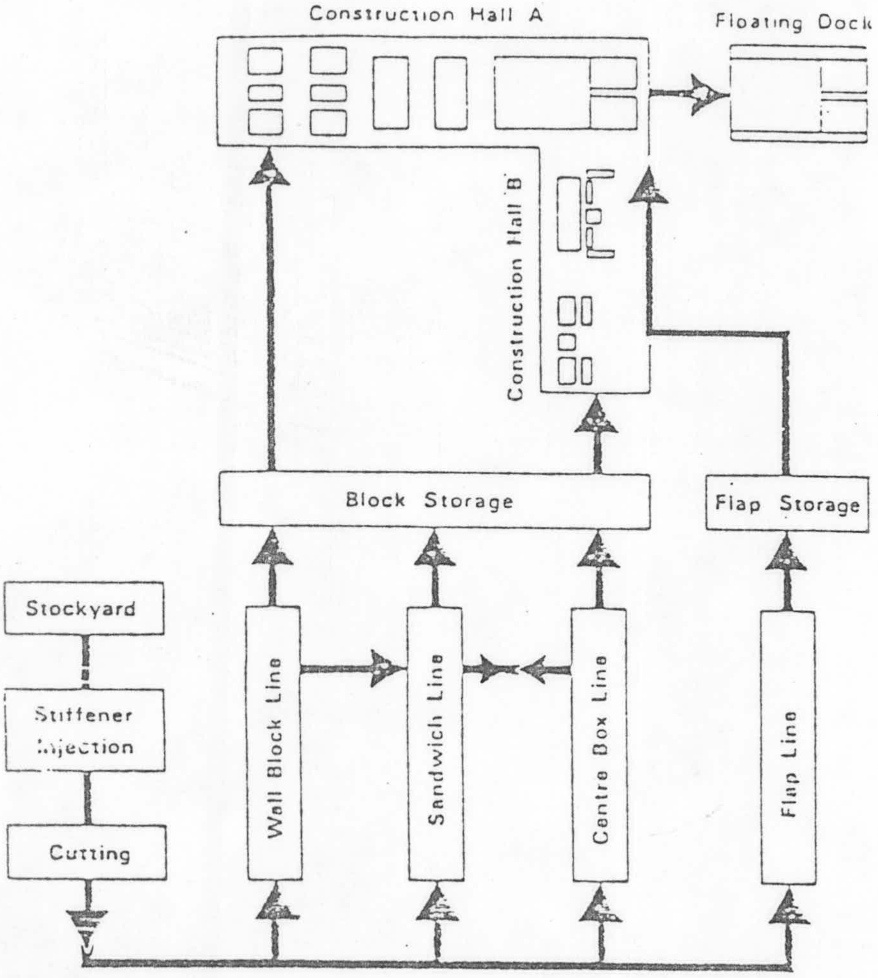


FIG 13 : Steel Hull Production
Diagram of Facility

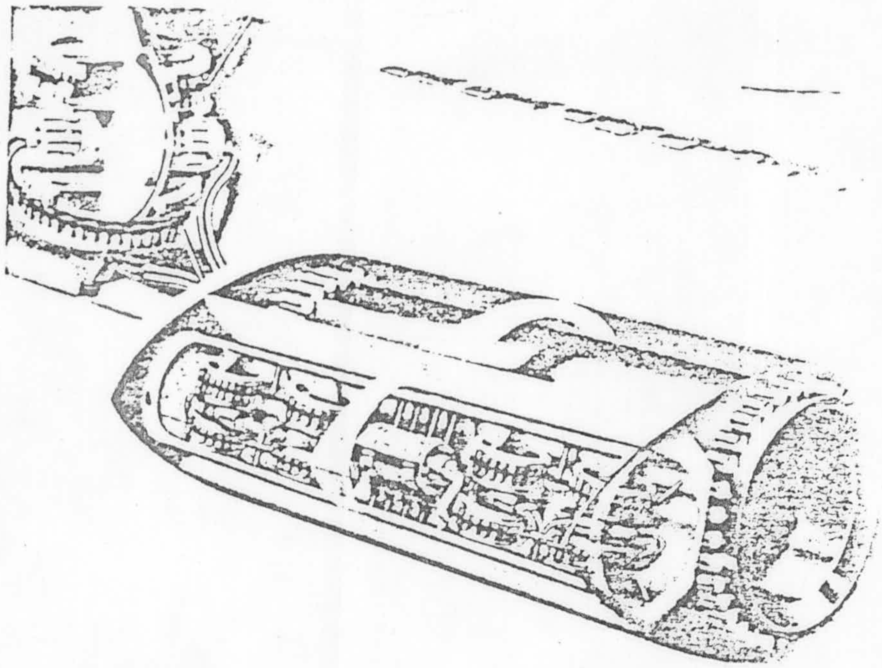


FIG 14

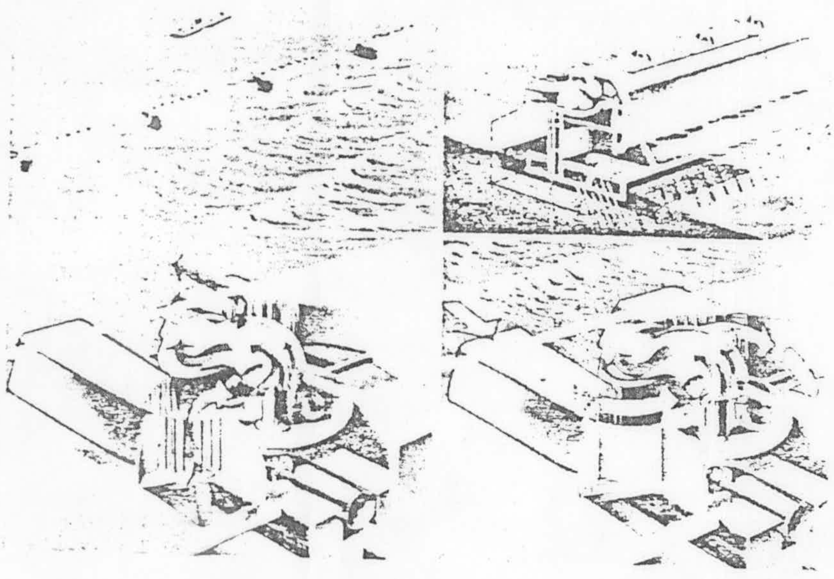


FIG 15

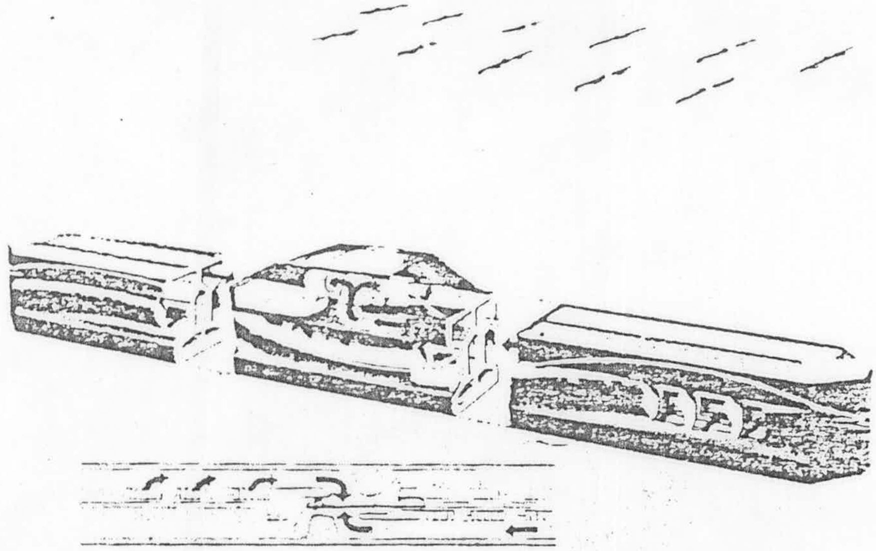


FIG 16

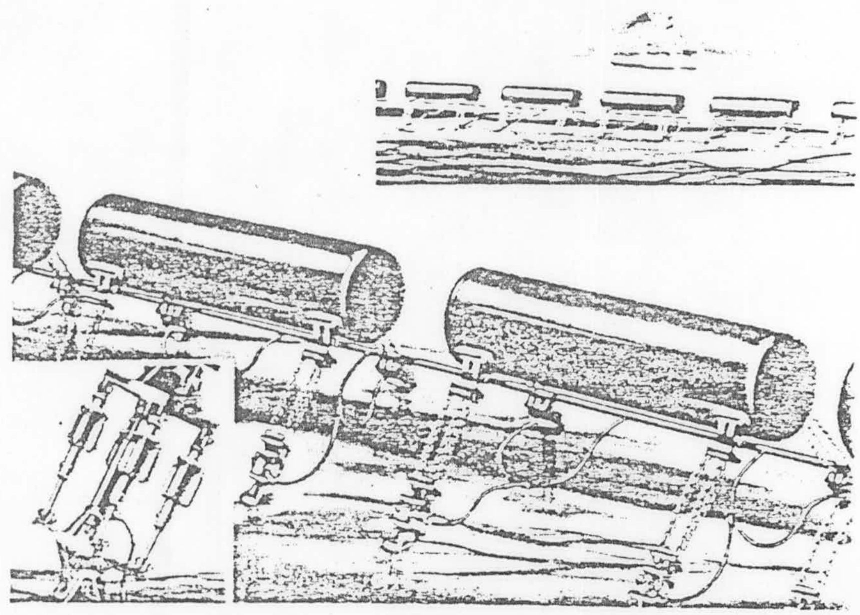


FIG 17

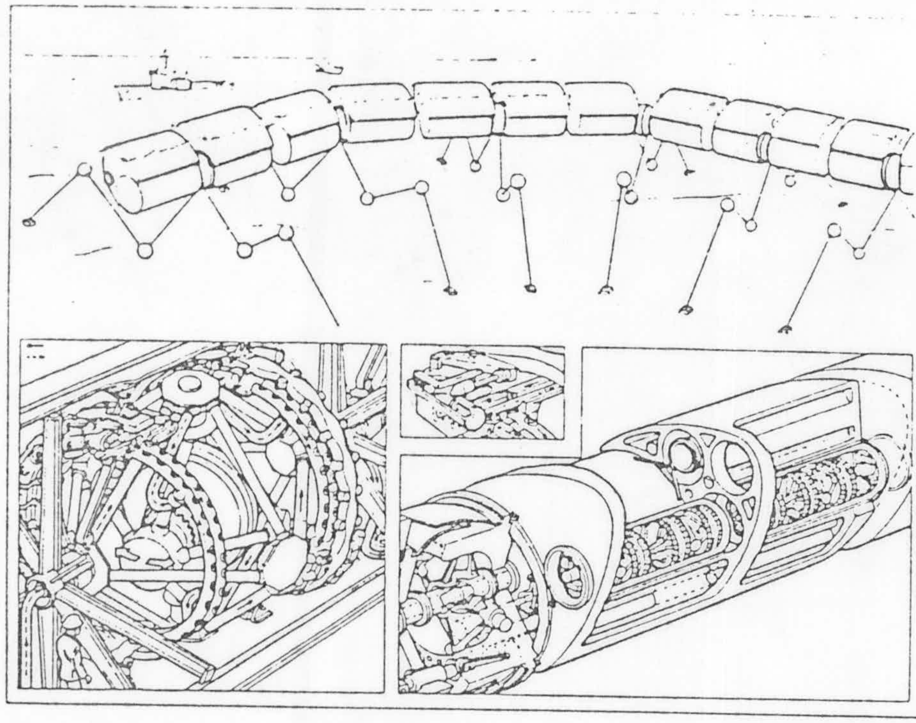


FIG 18

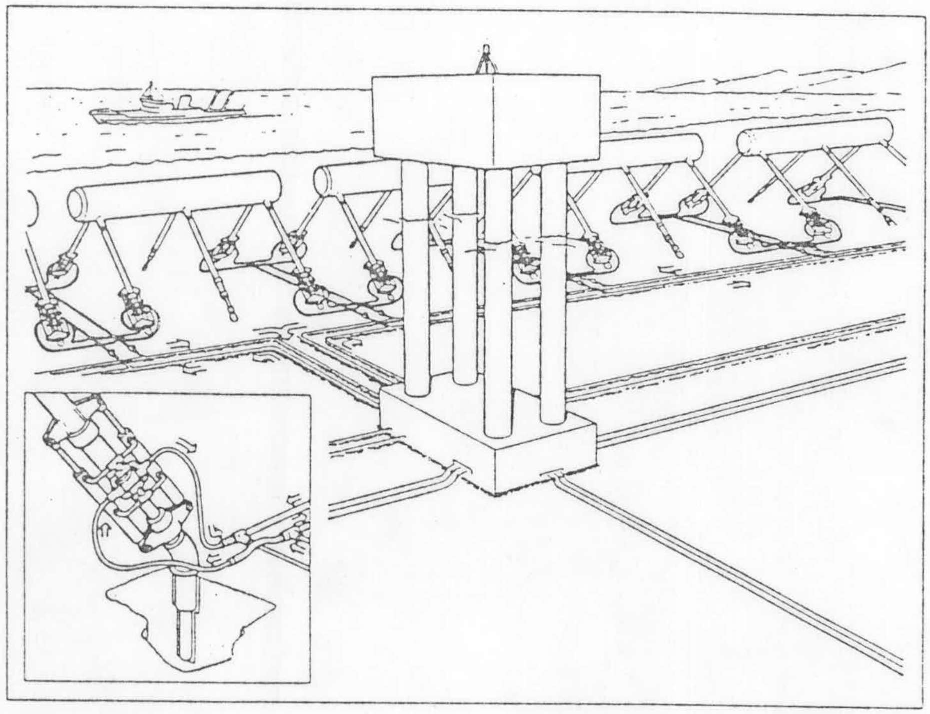


FIG 19

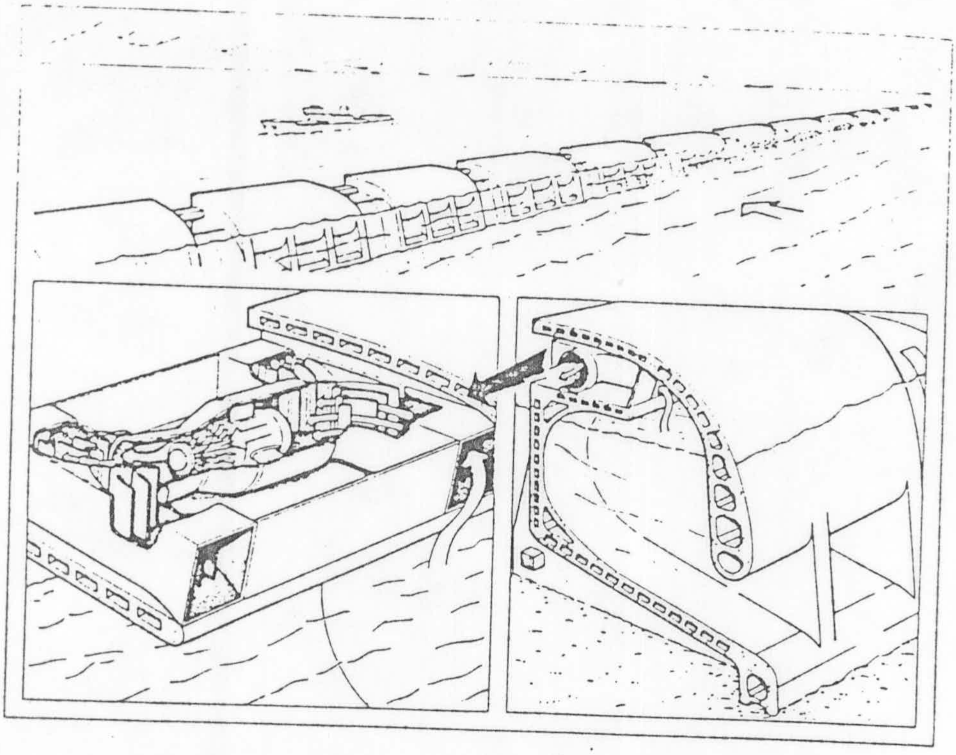


FIG 20

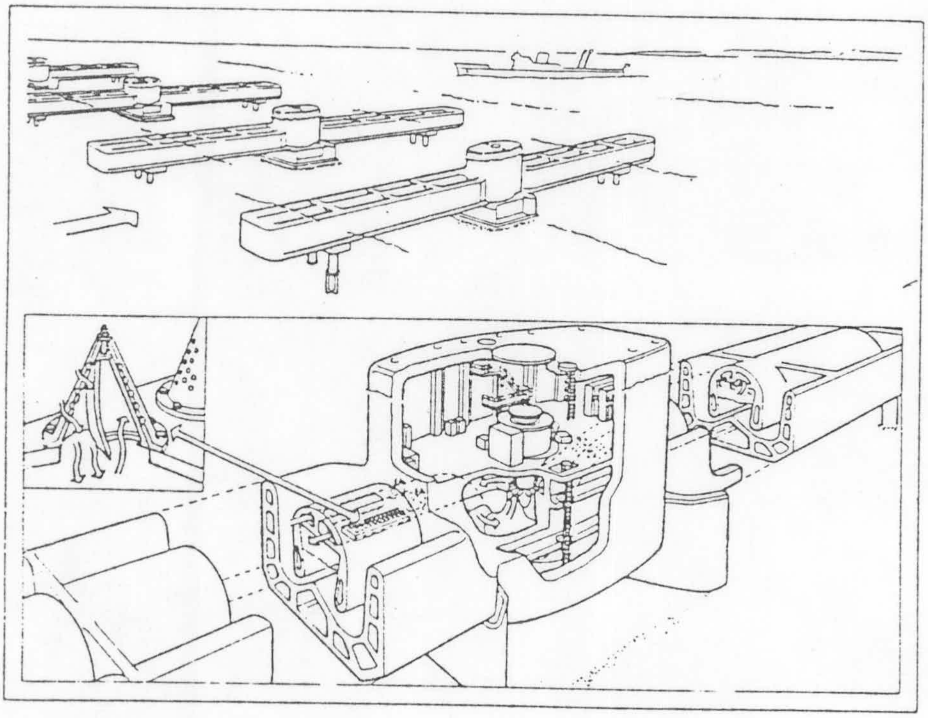


FIG 21

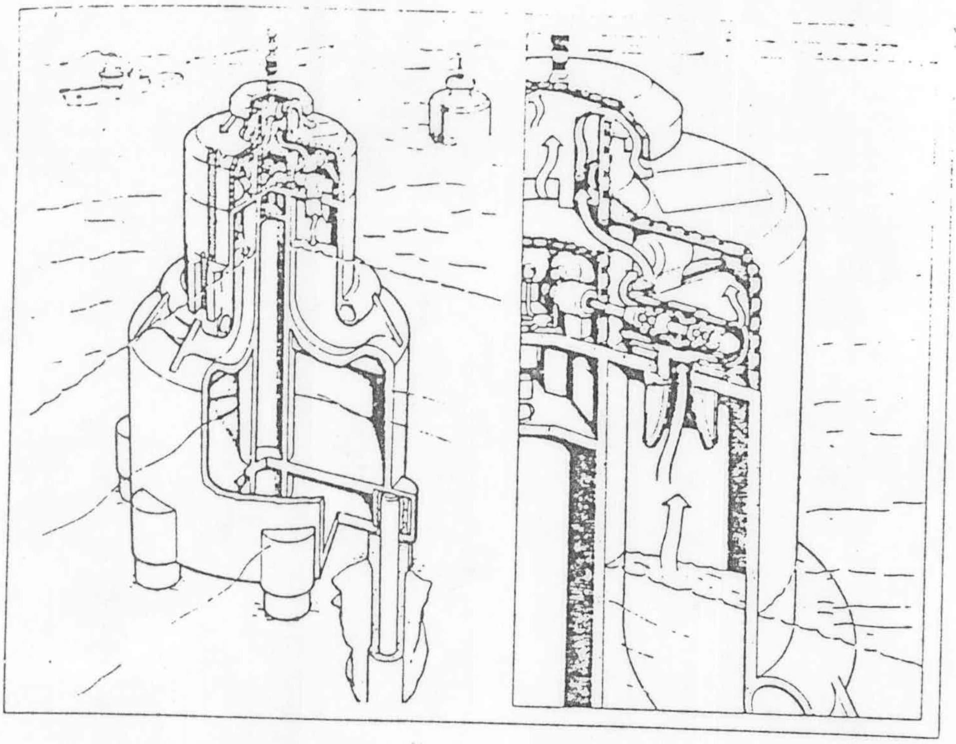


FIG 22

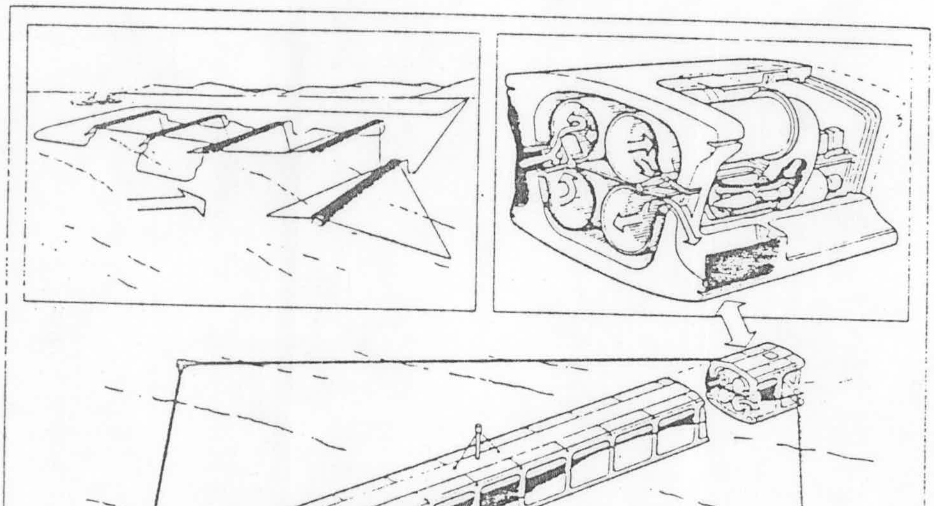


FIG 23

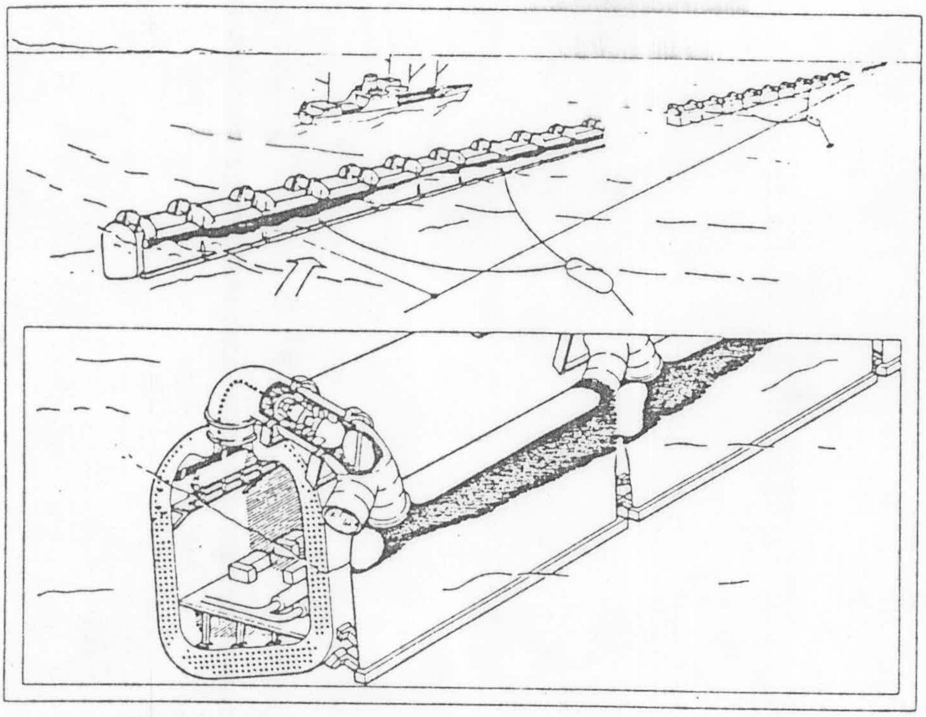


FIG 24