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# FURTHER DEVELOPMENT OF THE SEA-CLAM WAVE ENERGY CONVERTER

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## INTRODUCTION

The Department of Energy assessment programme drew to a close in 1982 with no real prospects of the immediate development of a large scale wave energy scheme and the apparent decision to greatly reduce wave energy funding in the United Kingdom. Up to that time the main research effort was aimed at designing and evaluating the prospects for a nominal 2 GW wave energy power station operating off the Outer Hebrides and linked to the UK national grid. Thus the SEA-Clam, a freely floating wave energy device previously described in a paper to the Energy Options Conference of 1982 (1), has been further developed for operation in such a scheme. Approximately 240 spines, each 290 m long supporting 10 air bags and rated at 10 MW, would be required for the 2 GW power station delivering electricity at between 4 and 8p/kWh. At the time of writing the Department of Energy is awaiting the final assessment report but initial indications are that the SEA-Clam device is the most cost effective with the greatest potential for further development.

However in the light of the present overcapacity of the generating system and the ACORD recommendations it is unlikely that the Department of Energy will be prepared to commit over £15 M, over a 5 year period, needed to construct and test a nominal 10 MW prototype SEA-Clam wave energy device. The SEA-Lanchester research group believes that the way ahead lies in the development of 250 kW to 1000 kW rated devices suitable for use, singly or in small groups, by remote island and coastal communities in order to provide, replace or supplement electricity which would otherwise be generated expensively by diesel sets. Thus since September 1982 the group, with the backing of its industrial sponsors, the RMC group p.l.c., Cawoods Ltd. and the Fairclough Construction Group p.l.c., have carried out work on the development of the SEA-Clam for this use. This has included the investigation of factors affecting the construction, operation and generating costs of a range of sizes of single devices and extrapolation of existing productivity information, derived from wide tank and Loch Ness test results, together with outline costing, indicates that, in suitable wave climates, costs between 4 and 8p/kWh could reasonably be achieved with such devices. At the present time the SEA-Lanchester group are commencing a 3½ year programme, partially funded by the Department of Energy, aimed at the construction and testing of an 80 m long prototype, rated at about 650 kW. The initial 18 months would be to carry out the detailed design and productivity testing required to prepare for the construction and testing in the following 2 year period.

## THE SEA-CLAM DEVICE FOR A 2 GW SCHEME

Since 1981 this device has undergone considerable design improvements including the removal of the flaps, modifications to air bag shape and optimisation of spine shape. Extensive performance testing has been carried out on a series of operational models at both 1/55th scale in the Cadnam wide tank and at 1/11th scale in Loch Ness.

The principle of operation of the SEA-Clam is to use the wave induced displacement of air, to and from a series of flexible bags, to extract energy from sea waves. A long floating spine acts as the main structural element and provides a stable frame of reference for the attachment of the air bags, as well as a suitable passage for the exchange of air between bags. The power conversion system employs "Wells", self-rectifying, air turbines (2) situated in the ducting between each bag outlet and the spine.

Figure 1 illustrates one of the SEA-Clam units proposed for the 2 GW power station off the Outer Hebrides, with 10 soft-fronted, flexible, air bags, each driving a single stage, self-rectifying, turbo-generator unit. A self-aligning single buoy mooring arrangement, with an unequal rode "V" yoke between the leading buoy and the spine, allows the whole system to move round the single anchor point, automatically adjusting to any change in the principal direction of the oncoming waves. Careful choice of the "V" yoke length controls the spine mooring angle to about 35$^0$ to the approaching wave fronts which, together with the randomness of sea wave patterns, allows phased operation of the air bags with the spine acting as a nearly stable frame of reference. Extensive mooring force measurements, for both passive and active device tests, show that the maximum peak forces will not exceed 250 tonne, at North Atlantic full scale. The flexible rubber air bags, reinforced with cross-corded Kevlar plies, act as the wave to air interface, allowing a direct water to air power transfer whilst retaining the benefits of enclosed air buoyancy and a closed circuit air system. The rectangular shaped bags are attached to the spine at their lower edge and supported by ductings at the top corners.

Figure 2 shows a cutaway section of the spine with a flexible bag and its associated turbo-generator module. The wave action causes air to be exchanged between bag and spine, through ducting attached to the upper trailing corner of the bag and an air port in the top of the spine. The turbo-generator module is contained in the ducting which can be closed by a butterfly valve in the event of failure of the bag. The air turbines are of the self-rectifying, "Wells" design with a single stage, 3.5 m diameter, 8 bladed rotor directly coupled to a 1.3 MW rated alternator. Fixed stator blades on each side of the rotor ensure axial alignment of the air flow from both directions. Turbine performance tests, carried out at 1/10th scale, confirm that the machine can be designed to be efficient over a broad power range, to be self-starting at low energy levels and to present the controlled linear load to the bag-water interface which is necessary for high energy absorption efficiencies. The Clam spine consists of a post-tensioned reinforced concrete, hollow floating beam, 15 m high, 13 m wide and designed to withstand the wave induced bending moments and hydrostatic forces. A rigorous series of bending moment measurements on a wide range of cross-sectional shapes, carried out at both 1/10th scale in Loch Ness and at 1/50th scale in a local reservoir, has led to the development of a quasi-static analysis method (3). Thus for any defined sea state, the maximum wave induced loadings can be predicted for any floating spine structure.

Overall device productivity is a function of energy capture efficiency, power chain efficiency and the effects of equipment reliability. The capture efficiency of the proposed SEA-Clam device has been determined by extensive testing of fully instrumented air system models, with representative linear damping characteristics, at both 1/55th scale in a wide, directional wave tank and 1/11th scale in Loch Ness. Figure 3 shows a 20 tonne model on test in Loch Ness during the Summer of 1982. Performance optimisation tests have investigated the sensitivity of absorption efficiency to the many variables that influence device performance, such as spine length, spine alignment to principal wave direction, damping characteristics and system operating pressure. The likely capture productivity for the proposed North Atlantic location of the 2 GW power station has been assessed from tests carried out in the 46 sea states deemed to represent the average yearly wave climate. These results were combined with the power chain efficiency predicted by mathematical simulation of the Clam power system and used in conjunction with a detailed costing exercise and reliability study to predict the overall average cost/kWh of electricity for a 25 year operational life.

## SMALL SCALE APPLICATIONS OF WAVE ENERGY

Wave energy for small scale markets has long been recognised as an alternative goal to the supply of power on a national scale. In the present energy climate there is no demand for 2 GW wave energy stations particularly in view of the present uncompetitive costs and risks involved. Therefore, attention can be concentrated on defining the smaller scale markets where the economics may be much more attractive and the technological step forward much less demanding.

Examination of the UK and overseas markets shows a possible requirement for small scale, 250-1000 kW wave energy installations, provided they could generate electricity at below local diesel fuel cost. Communities relying on local diesel powered generators of more than 100 kW rating use electricity which is produced at a cost of between 8 and 20p/kWh depending on their remoteness and whether the type of oil used is residual or distillate. Fuel costs often account for more than half of the generating costs with maintenance making up a significant proportion of the remainder.

Many of the potential wave energy markets have existing diesel power stations. Integration of wave energy with diesel driven power systems should result in overall firm power and the maximum use of the wave energy capacity available. A 650 kW rated wave energy unit with 250 kW annual average output would integrate well with a 1 MW system on a small island whereas several 650 kW units could be used to advantage for larger community networks.

## THE SEA-CLAM FOR SMALL INSTALLATIONS

For major schemes, such as the 2 GW power station, it is necessary to use large units moored close together in order to maximise the conversion of the available wave power and to utilise the coastline efficiently with a minimum length of undersea transmission cable from devices to shore stations. Increasing spine length to improve stability and maximise capture efficiency brings the penalty of greatly increased wave induced bending moments and hence necessary structural costs. In a particular wave climate the maximum expected spine bending moment is proportional to the cube of the spine length. However single, small SEA-Clam units, still operating in the high energy wave climates, would have such a local surplus of energy available that maximising absorption capacity would no longer be an overriding requirement. The substantial structural cost benefits brought about by length reduction can help to balance the effect of considerable reduced absorption efficiencies. Also as wave induced bending moment is directly proportional to device height, the effective utilisation of wave depth can be maintained at little structural cost. Thus the design of the small SEA-Clam unit is likely to be proportionally shorter and deeper than the 10 MW rated unit, to be closer inshore with much shorter transmission distances and to have an overall load factor of as much as 40% of its peak rating.

The extensive absorption efficiency data obtained from both the Cadnam and Loch Ness tests has been extrapolated to cover the proposed range of small device sizes and combined with the turbo-generator operational characteristics to allow prediction of annual productivity in any appropriate wave climate. Using the considerable costing experience gained from the 2 GW scheme deign and assessment process, a 12 cost centre model has been developed for a steel spine, SEA-Clam device. Figure 4 shows a plot of estimated cost/kWh for a range of device depths and for lengths between 50 m and 120 m, derived from the combined application of the productivity and costing models to a typical Outer Hebrides scatter diagram. Because of device response to wave period and to upper rating limitations, the overall power output in less energetic wave climates is not necessarily greatly reduced, particularly if the energy periods are generally lower.

The costs presented in Figure 4, although based on considerable past experience, are, of necessity, simplified estimates being dependent on prediction of availability, site specific variables such as transmission, installation and maintenance costs, and on productivity extrapolation outside the range of past model measurements. Thus a major early part of the present 3½ year, small prototype development programme will be specific performance testing, site identification and detailed design costing.

CONCLUSION

The final design of the SEA-Clam as a unit for a large 2 GW scheme has been described. This is the leading wave energy device arising out of the UK National Wave Energy Programme and is seen as having the greatest potential for further development particularly for smaller scale applications.

The small scale market for wave energy is examined and the design and cost parameters evaluated for the 250 kW to 1000 kW range of SEA-Clam units. Building a demonstration prototype rated at 650 kW and producing an annual average output of 250 kW is identified as the next step towards the commercial exploitation of wave energy.

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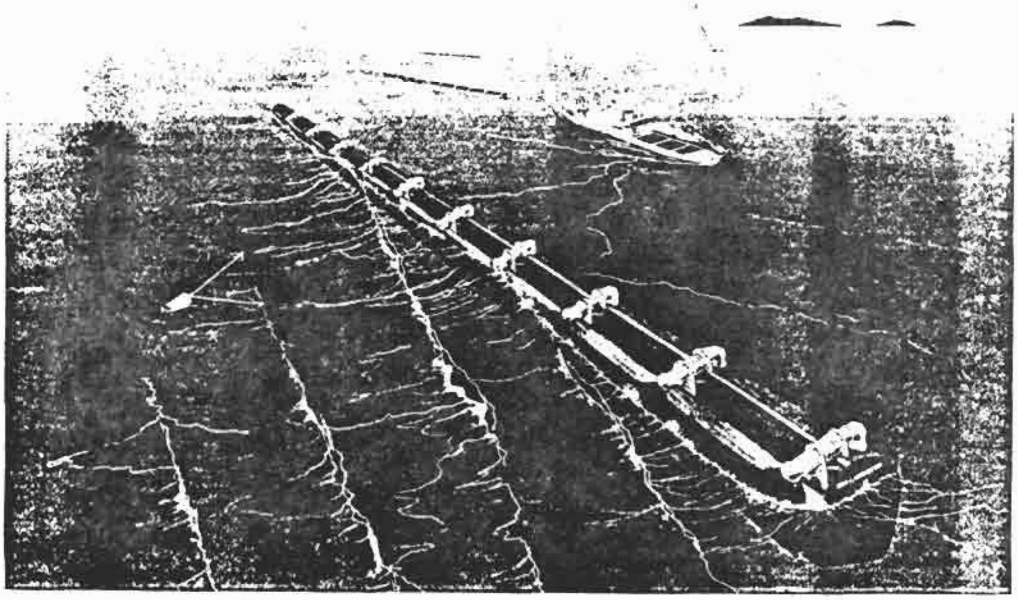

Figure 1 Artists Impression of a SEA-Clam Unit in a 2 GW Wave Energy Station.

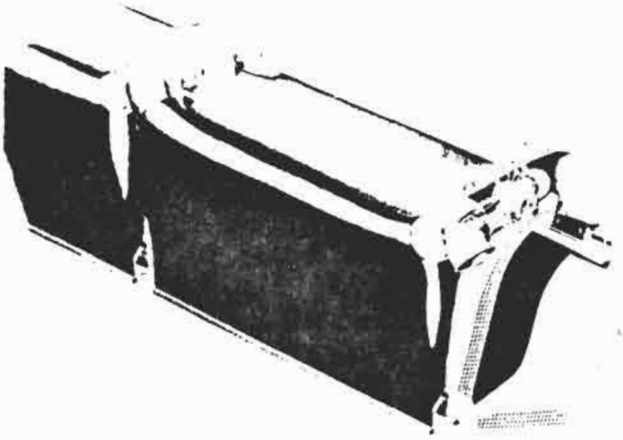

Figure 2 Cutaway View Showing Spine Structure, Flexible Air Bag and Turbo-Generator.

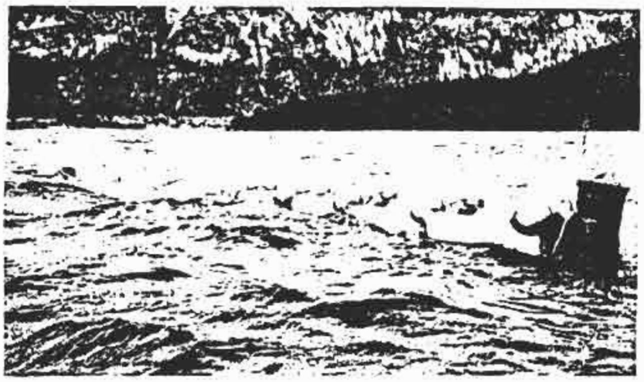

Figure 3 Tests of a 1/10th Scale SEA-Clam on Loch Ness

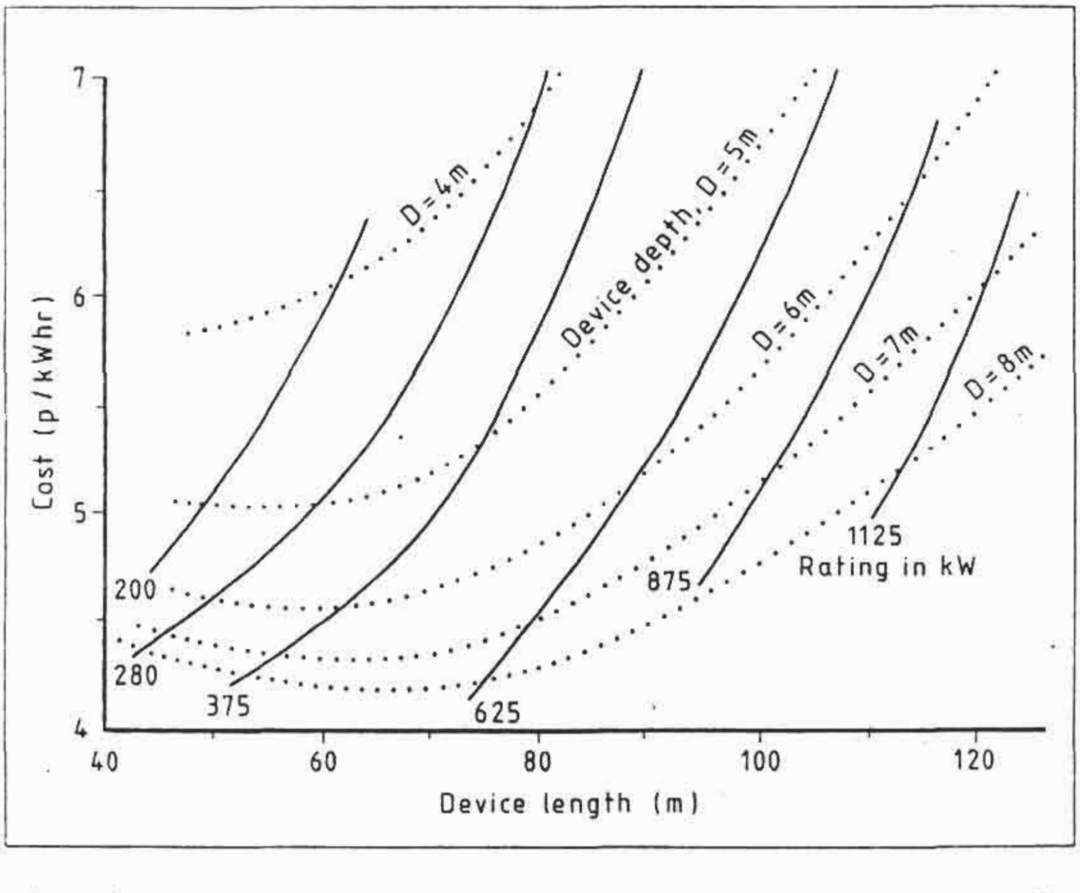


Figure 4 Estimated Cost of Electricity Produced by Small Scale SEA-Clams of Varying Dimensions.