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A SECOND GENERATION WAVE ENERGY DEVICE - THE CLAM CONCEPT

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INTRODUCTION

Wave energy is an evolving technology with an urgent need for continuing innovation. Since 1975 new ideas and concepts useful in the extraction of energy from sea waves have been put forward at an almost embarrassing rate causing problems to those assigned to assess the potentialities. How can a young and inexperienced wave energy community decide on the relative merits of individual contributions to the national programme, bearing in mind that up to ten devices are already in serious competition? This paper presents one device concept which has arisen from a system approach adopted by a research group with considerable experience in the discipline of wave energy. The Clam is deemed to be a second generation wave energy device in that it tries to utilise system components already identified as attractive, whilst at the same time avoiding known problem areas.

A research group based at Lanchester Polytechnic, Coventry, and funded by Sea Energy Associates and the Department of Energy worked on the development of the Salter Duck (1) for four years. This group designed, built and tested a working model of this wave power device at an engineering scale for trials in real waves. The work, and supporting full scale design studies has placed the SEA-Lanchester group in a good position to identify and pursue the most fruitful lines of investigation and development. The Clam evolved from this experience.

THE LOCH NESS DUCK TRIALS

At the last conference, a paper was presented by the author (2) on the wave power experiments at Loch Ness on the Salter duck device. These trials have now been concluded, analysed and conclusions drawn. Some remarkable film is available which demonstrates clearly how well the device concept works and its ability to survive storm conditions. The experience and data gained from the trials should be of great value to other researchers and add significantly to the accumulated knowledge on wave energy.

The Loch Ness experiments produced the following conclusions.

1. The Loch Ness test site is ideal for 1/10th scale model work in a natural wave environment. It avoids the tidal, corrosion and logistical problems of equivalent sea sites.
2. The Salter duck is a most elegant device concept which performs well and efficiently. It demonstrates the advantages of spine-based terminators in extracting a significant proportion of the wave energy flux crossing a given line.
3. High capture efficiency and low mooring forces with a relatively good structural utilisation were confirmed in real waves. It is the capture efficiency which strongly influences overall productivity and efficient use of structural material which determines capital costs.
4. Power conversion from the nodding action of the ducks to a suitable electrical output through intermediate hydraulics proved to be unsatisfactory. Full scale power conversion needs a different approach.
5. The single point restrained mooring system performed extremely well. The model automatically aligned itself to the predetermined optimum angle of 20° to the wave front required to give maximum efficiency.
6. Reliability and maintenance of active wave energy devices is a problem. Fatigue and wear are ultimately more destructive than other more obvious dangers such as storms.
7. Testing at 1/10th scale separates functional designs from those of a more speculative nature. Any design weakness is soon highlighted in the natural environment.

It may be some time before large scale testing of selected wave energy devices is attempted in the U.K. again. Two indoor 1/150th scale tanks are now available where models can be tested in simulated wave conditions. These will enable device capture efficiency, structural and hydrodynamic forces to be measured. However, power conversion, the prime function of wave energy converters, will still have to be carried out at a larger scale.

THE CLAM WAVE ENERGY CONVERTER

The Clam can be classified as a spine-based pneumatic terminator. Devices utilising spines, that is long narrow structures, have been shown to be structurally efficient and, as such, featured in the three most cost-effective devices in a 1979-80 assessment exercise. Of the three fluids available for wave energy conversion - air, water and oil - air is generally accepted as the most desirable. Closed circuit air is an additional advantage in that damage from water ingress is prevented. Terminator is the name given to devices which face the wave front and extract the energy by terminating the wave in a matched load. Therefore, one can argue with some justification that a practical wave energy converter can be conceived as a floating spine terminator with a pneumatic wave absorbing front face.

Briefly, the Clam is based on the reversal of a simple concept normally used in the laboratory for efficient wave making. It comprises flaps hinged to a floating spine with air bags sandwiched between. Ocean waves dissipate their energy as they impinge upon the flaps and move them in and out. This causes air in the bags to be forced through self-rectifying turbines into an enclosed duct running the length of the spine, allowing interchange of air between Clam elements. The randomness of sea wave patterns allows phased operation of the Clam elements, enabling the spine to act as a stable reference body. Typically, a 10 MW generator unit would feature ten Clam elements on a 300m long spine moored to face the waves, as illustrated in Figure 1.

The cutaway view in Figure 2 shows the Clam spine with the flap, bag and turbine equipment. Each Clam element has only two moving parts the flap itself and the turbine-alternator rotor. It is this simplicity which enhances reliability and aids maintenance. The following paragraphs detail the design consideration for each component part which are necessary to meet the system requirements.

The spine is the principal structural component and accounts for about a third of the total generating and transmission costs. Its prime function is to act as a frame of reference in the form of a floating beam that is capable of withstanding induced bending moments and hydrostatic loads. Both device productivity and cost increase with spine length and, as a result, the optimum length of spine is not easy to calculate, particularly when dealing with the random excitation of waves.

With three million waves a year in the Atlantic, fatigue tends to be more important than ultimate strength and hence dictates the choice of materials and the method of construction. A study of the limited knowledge available on the fatigue life of concrete suggests that a suitably designed post-tensioned concrete spine structure should last for at least 50 years. The [illegible] x 10m rectangular spine design shown is slipformed in 30m sections with lateral reinforcement and ten sections post-tensioned together to make the 300m length. Hydrostatic loading on the external walls has to be [illegible] by internal supporting walls and special attention is needed to reduce local stress concentration around the holes necessary for air intake or access hatches. Launching of each 30,000 tonne spine structure would be broadside down a purpose-built slipway.

The flap is 30m long and 15m deep and varies in width up to 1m. In its present form it would be fabricated from 25mm steel plate with outer skins stiffened by internal webs. The flaps would be buoyant and filled with foam to restrict ingress of water in the event of damage. Along the bottom edge of each flap would be approximately 60 individual hinges of the type used as rollers on the tracks of heavy earth-moving equipment. The life of these sealed hinges should exceed the [illegible] year flap life and, in any case, there is adequate redundancy to cover individual failures.

It is the flap which has to extract the energy from the waves. Evans (3) has analysed the simple vertical hinged plate and confirms its efficient operation if it is tuned and damped correctly. Simple experiments in the laboratory also demonstrate its broadband efficiency, although it is not immediately obvious how to engineer its desirable features into a device. The Clam solution is to support and damp the flap operation by air in a flexible bag which itself acts as a spring due to its rolling action changing the bag-flap contact area. Suitable design enables the spring rate to neutralise the flap inertia and added mass over the frequency range of desired operation.

The air bag is speculative in the sense that no fabrication for a similar duty exists. There is no doubt that the bag can be manufactured with present techniques and would work for a short time. The question is how long would a well designed bag work before fatigue or wear induced failure. Five years is considered a satisfactory life before replacement would have to be carried out during general refurbishing periods. Only extensive development and testing of bags in laboratory and then in real conditions could answer this question. Needless to say, certain vehicle tyres withstand duty cycles akin to those expected of Clam bags.

The design of bags from flexible fabric materials has to follow certain rules for long life. These rules primarily ensure that all regions of the material operate within defined stress or strain limits. For instance, creasing or bending of the fabric over small radii would drastically reduce the 10-20 million cycles of operation which can be achieved with careful design. The Clam bag tries to avoid these problems by allowing the bag fabric to roll tangentially on the structural surfaces of the spine or inner flap and to confine all fabric distortion to the top two corners of the rectangular shaped bags. These corners can be of a special ribbed construction fanning out in a quadrant from a central point.

There are two air systems which could be utilised to convert the reversing air flow from each bag into a uni-directional shaft drive required for electrical generation. First, rectifying valves could be used to draw air from a low pressure duct and feed it into a high pressure duct to drive one turbine for the whole spine unit. This method would require large and very reliable rectifying valves and also present a constant pressure load to the wave driven flap instead of the ideal linear damping. The second and more favoured air system is to use one self-rectifying air turbine at each bag orifice and interchange the air by means of a common duct running the full length of the spine. Self-rectifying turbines have some very desirable characteristics. They are simple, reasonably efficient, present a linear load and have a low drag loss when running free. However, it is not yet clear whether the large dynamic range of power input into 10 individual turbines will reduce overall efficiencies as compared with a single large turbine working with the integrated power input from 10 air bags.

The Clam has a unique 'close down' mode. By venting the air system, the flaps automatically close onto internal fenders under the influence of external water pressure. Maintenance and inspection can then be carried out at sea with the moving parts static. In the event of malfunction, the device can be closed down partially or completely to limit progressive damage.

Bag failure, with the possibility of spine flooding through the air ports, has to be anticipated. Several designs for sealing the spine which incorporate buoyancy valves or inflatable bags have been suggested, but are not shown on the artist's impressions. Obviously, whatever system is used has to be automatic and failsafe.

The mooring system follows the design used on the Loch Ness duck tests. The proposed 2000MW scheme consists of a single line of 200 spine units, each 300m long and spaced at 400m centres. The front mooring for each spine comprises a single anchor point situated in some 60m of water and connected by chain to a leading buoy of 200 tonne displacement and then by two wire rodes to the spine in a V-yoke configuration. Rear restraining moorings allow the spines to swing through ±40° to face the principal wave direction and, hence, increase the directional capture efficiency by an estimated 5%. Piled rock anchors will have to be used at the majority of the wave power sites down the coast of the Hebrides.

d.c. electrical transmission to land is dictated by the availability of high voltage flexible cables for connection to the sea bed. 35kV flexible single core cables can be used to interconnect spine units in series to give 250MW groups before transmission to land converters. Hence generator outputs on each spine unit will have to be transformed and rectified to give about 3kV d.c.

PRODUCTIVITY ESTIMATES

Productivity is the measure of the power delivered to the national grid compared to that available at the wave site. Deriving productivity is a complex calculation which has to take account of the variable energy source, load factor, reliability and a long power chain. Other factors, such as the matching of supply and demand during winter and summer, plus the need for back-up generating capacity to cover calm conditions, depend on national generating strategies and, therefore, have not been taken account of. For the Clam the on-board power chain is relatively simple and can be analysed with some certainty. Transmission is a common problem shared with all wave devices and is particularly expensive in the U.K. context where the wave energy sites are remote in relation to the population centres.

The following productivity estimates were made for the Clam during a 1979 U.K. assessment of current wave energy converters.

Productivity Parameters	
Available sea energy	52.3 kW/m
Directional factor	0.83
Capture efficiency	37%
Power chain efficiency	63%
Reliability factor	0.82
Power to the grid	8.3 kW/m
Average output of 2GW scheme	0.54GW

The overall efficiency of 16% for generation and transmission is very low by any standard. However, this is typical of present wave energy devices and is largely due to the difficulty in coping with the random nature of waves. Since productivity is proportional to generating costs, development effort in improving the overall system efficiency would be very rewarding. Even now, it is not too difficult to see certain improvements which would lead to an overall efficiency of 25% or the equivalent of 13 kW/m delivered to the grid.

COST ESTIMATES

The large structures associated with wave energy converters naturally lead to high capital costs. Any high technology components can add significantly to the basic structure costs and incur extra operating costs through maintenance and reliability problems. The Clam is designed as a simple structure with the minimum of high technology components. Operating costs should be low between the five year refurbishing periods when wear components such as moorings, air bags and possibly hinges are changed.

The 1979 U.K. assessment exercise derived the following costs for one Clam spine unit.

	£M
Structure	7.6
Power Plant	2.0
Moorings	1.4
Transmission	1.7
Sundries	1.2
Contingencies	1.3
TOTAL	15.2

From the productivity and cost estimates, the capital cost per kilowatt generated is £6,500 and the cost per kilowatt hour is 6p, taking into account depreciation, interest and operating costs. This latter figure is roughly twice that of future conventional generating stations when costed on the same basis. Here again, further development should reduce capital costs by at least 25%, which, if coupled with the improved productivity discussed earlier, should make the Clam competitive with conventional energy sources.

FUTURE WORK

A 1/50th scale Clam model has been tested in natural waves and in a laboratory wide tank. It performs remarkably well and behaves exactly as anticipated. The spine is surprisingly stable in normal operational waves and rides well in survival conditions. Each Clam element responds to its immediate wave front and exchanges air with its neighbours through the spine duct in a most effective manner. The next step is to calibrate the porous plugs, which simulate the air turbines, and the losses in the system associated with small scale work in order to measure the model's capture efficiency.

The spine design of the Clam is at an advanced stage, having been studied by structural consultants. The air system and turbines are also well defined and should be easy to engineer. It is the flap and bag mechanism where further innovation is required and ideas for an integral flap-bag arrangement are being studied. Full development in this direction would eliminate the expensive steel flap and mechanical hinges and lead to the idealised soft fronted Clam.

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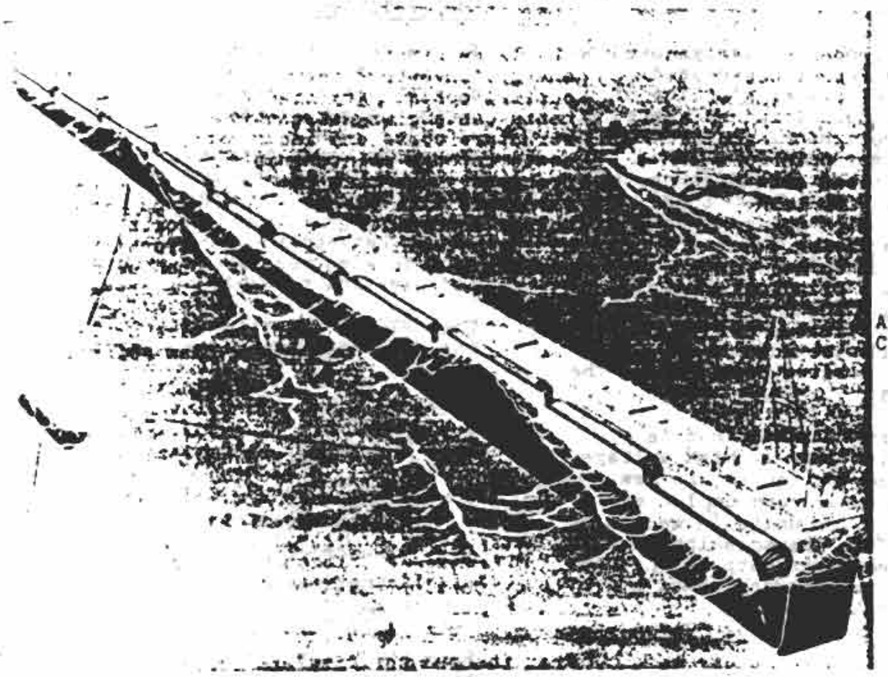

Figure 1.
Artist's impression of the Clam Wave Energy Converter.

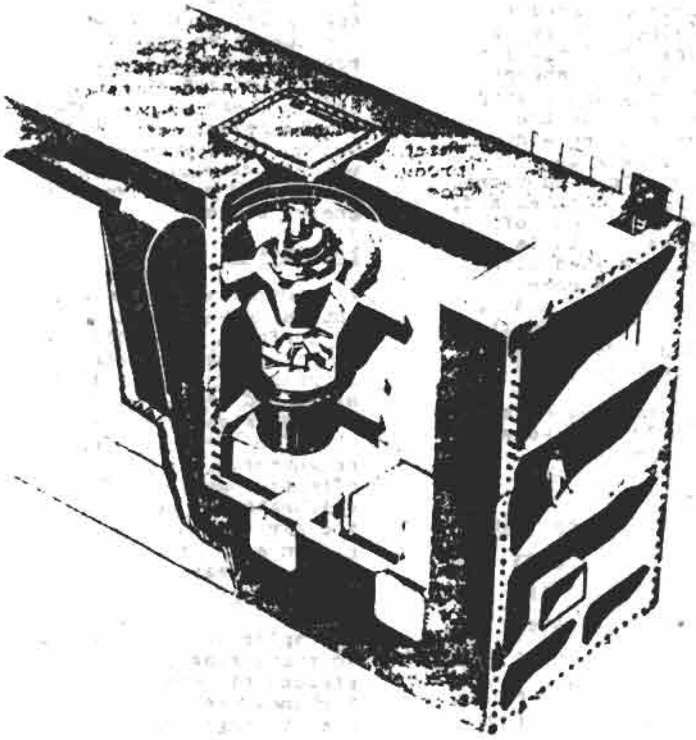

Figure 2.
Cutaway view of the spine showing flap, air bag and turbine equipment.