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Consultancy on a Review of the SEA Clam

Contractor

Coventry Polytechnic Enterprises Ltd

Report No. ETSU (to be advised)

The work described in this report was carried out under contract as part of the Department of Energy's Renewable Energy Research and Development Programme managed by the Energy Technology Support Unit (ETSU). The views and judgements expressed in this report are those of the Contractor and do not necessarily reflect those of ETSU or the Department of Energy.

SUMMARY

Three principal aspects of the development of the Circular SEA Clam wave energy device by the Energy Systems Group at Coventry Polytechnic are reviewed, in support of the assessment of the SEA Clam as part of the current Wave Energy Review for the Department of Energy by AEA Technology.

Firstly, developments in the mathematical modelling of the overall system performance and availability are reviewed and used to evaluate the likely effects on unit cost of electricity generation of variations in device design, power chain characteristics and operational water depth. The resulting predicted cost of electricity from a suitably sited array of SEA Clam devices are in the range 3.5 to 6.0 p/kWh.

Secondly, the development of the flexible membranes, (whose role is essentially to interface the air system driving the generator turbines to the incident waves), is reviewed. It is recognised that the membranes probably constitute the largest risk element of the Clam device. Nevertheless, the results of testing to date, (including practical experience with the Borrowash low head hydro electric system), lead the Energy Systems Group to conclude that membranes for the less demanding wave energy application can be designed to survive for an economically attractive lifetime - a view supported by the Group's industrial collaborator.

Success in this respect will. however, depend on the further development of mathematical models of the membrane and, in particular, on testing of a full-size cell with a working membrane.

Finally, work world-wide on the Wells turbine is reviewed. The Wells turbine, because of its simplicity and linear pressure drop/flow characteristic, is eminently suited to wave energy applications. Its characteristics are now well understood by the Energy Systems Group and a series of programmes is available to predict, with some confidence, the starting and energy conversion performance of a Wells turbine of a particular geometry.

Given appropriate attention to the aerodynamic design of the approach ducts to the rotor and to the geometry and surface finish of the rotor blades, a peak efficiency of up to 80% can be expected from an economically viable design with guide vanes, resulting in a yearly mean efficiency of over 70% in appropriate wave climates. Again, some further work will be required to improve the accuracy of performance prediction, particularly near the point of stall and in the areas of 3-dimensional rotating cascade effects and blade profile optimisation.

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INTRODUCTION,

AIMS,

OBJECTIVES

and PROGRAMME of WORK

INTRODUCTION

In September 1990, the Energy Systems Group at Coventry Polytechnic was invited to provide technical assistance to AEA Technology and AEA Technology's representatives, (Advanced Mechanics and Engineering Ltd), in support of the assessment of the SEA Clam as part of the current Wave Energy Review for the Department of Energy.

The Group was requested to provide technical assistance byway of a presentation to the Department of Energy's Wave Power Steering Group, (which took place at Coventry on 24th September 1990), together with informal meetings, telephone consultations and correspondance with Advanced Mechanics and Engineering Ltd and with the Project Officer, Mr T W Thorpe, including comments and discussion on reports produced as part of the Wave Energy Review. In particular, the Group was required to provide to AEA Technology a Report on three particular aspects of the development of the Circular SEA Clam i.e.

(a) to assess the SEA Clam's overall systems performance and availability

(b) to summarise the design and development work on the flexible bag and to assess its implications for the likely performance of the Clam

(c) to collate data relating to the performance of Wells turbines and to produce an assessment of their likely performance in the Clam.

These three aspects of Clam development are reported in the Sections which follow. Since the three issues are largely independent, each Section is complete in itself, containing the text of the report, together with related Tables, Figures, References and Appendices within the relevant Section.

As well as overall supervision of the work as Project Manager, Mr A M Peatfield was resonsible, in collaboration with Dr F P Lockett for Section 1 of the Report. Sections 2 and 3 were mainly the work of Dr L J Duckers and Dr P R S White respectively.

Mr B W Loughridge was responsible for overall co-ordination of the Contract and Report on behalf of the Contractor.

SECTION 1

ASSESSMENT of SYSTEM PERFORMANCE and AVAILIBILITY

1.0 OVERVIEW

This Section of the Report looks at the developments made in the modelling of the overall system performance and availability, and evaluates the likely effects of variations in device design, power chain characteristics and operational water depth.

The present mathematical model of the power absorption and conversion system for the proposed SEA Clam wave energy device has been shown to give good agreement with experimental, 1/15th scale model results. The mathematical model ('FoPcLam') has been applied to a range of variations of turbine damping, bag spring rate, water depth, sea spread, device diameter and immersion depth. The results identify areas of design improvement which will greatly increase the overall energy capture performance of the devices (up to 90% compared with the value assumed in Wave Energy Review Progress Report No 2) and thus, when combined with the improved estimate of availability (Advanced Mechanics and Engineering Ltd report), the optimised structural design (Coventry-Rendel, Palmer and Tritton report) and the expected improvement in overall performance of the Wells turbine (Section 3 of this Report), give strong indications that the predicted cost of electricity from a suitably sited array of SEA Clam devices will be in the range 3.5 to 6p/kWh.

1.1 INTRODUCTION

The base parameters used for comparison are those applicable to the 1986 SEA Clam design of a 60 m diameter, 12 bag device, with power absorption characteristics as defined by the Loch Ness, 1/15th scale model tests carried out with "serial mode" air turbine positioning.

The resource characteristics have been assumed to be those defined by the South Uist scatter diagram for a water depth of 42 m. The effects on resource level of water depth variations proposed in "Wave Energy Review Progress Report No 2", (June 1990), have been used. The general energy spread within a particular sea state has been assumed to be that defined by a Pierson-Moskowitz spectrum.

The likely yearly availability of a number of SEA Clam devices has been taken from work done by Advanced Mechanics and Engineering Ltd, in consultation with Coventry Polytechnic Energy Systems Group, on the presently proposed SEA Clam outline system design, as presented by Advanced Mechanics and Engineering Ltd to the Wave Energy Review. The design and development of the flexible bag, and its implications for likely Clam availability, are summarised in Section 2 of this Report.

The approach taken in the performance optimisation process has been to verify initially the satisfactory overall validity of the mathematical model by comparison with Loch Ness model test results and then, in the light of the excellent quantitative agreement, to use the mathematical model for all performance predictions.

1.2 MATHEMATICAL MODEL ('FoPcLam')

'FoPcLam' is a linear wave diffraction model of the SEA Clam device. The hydrodynamic calculations use the now familiar source distribution technique, which is a numerical boundary element method. The device is viewed as a freely floating body, free to move in heave, surge, pitch, sway and roll as well as a further 12 modes representing surging motion of the membrane panels. Air flow within the device is modelled as a set of air cells connected by linear dampers. The use of a linearized gas law incorporates compression of air in the cells and ducts and assumes maximum possible energy loss from heat conduction as air temperature rises. In this study only the serial configuration, in which a Wells turbine is placed between each pair of adjacent Clam cells, has been investigated. The latest Rendel, Palmer and Tritton design (steel hull version) has been used to represent section dimensions, buoyancy and inertia. Figure 1.1 shows a cross-section, with the discretization positions indicated. This section also closely represents the steel box section used in the Loch Ness model.

For each wave period the model calculates the response of the system to a plane monochromatic wave, of unit amplitude, incident normal to the torus at the point where membrane panels Nos. 1 and 12 meet. The principle of superposition for linear systems is then used to deduce mixed spectrum response and hence mean efficiency for sea states of any given energy period and amplitude. In this Report, the mixed spectrum is assumed to be of the Pierson-Moskowitz form. Overall yearly mean efficiencies have then been calculated by allocating weights to individual periods based on the proportion which they form of the annual energy contribution, as derived from a South Uist scatter diagram.

1.3 MODEL VERIFICATION

The model has been run at a range of turbine damping characteristics and bag spring rates, to produce energy absorption efficiencies for energy periods from 3 to 14 seconds, for both monochromatic waves and those with an assumed Pierson-Moskowitz spectral spread. Figure 1.2 shows a plot of efficiency against energy period for a 60 m diameter clam in 40 m of water depth for both monochromatic and Pierson-Moskowitz spectrums and for both "hard" damping and spring rate conditions relevant to the Loch Ness model and the "soft" conditions likely to be optimal in the expected South Uist conditions. These results are compared on the same graph with the upper bound line of the Loch Ness experimental results.

Owing to low power levels and experimental measurement accuracies, no reliable experimental results exist for energy periods less than about 5.5 seconds so comparisons will only be considered from 6 to 13 seconds.

It can be seen that the Loch Ness ("hard" damping) experimental results lie between the monochromatic and the Pierson-Moskowitz spectrum ("hard" damping) for the whole of the 6-13 second range, even though the predicted results cross over in relative position at about 9 seconds. This is entirely in keeping with previous spectral analysis of Loch Ness wave records which has shown the spectral spread for the short fetch, rapidly generated sea states usual at Loch Ness the spectral spread is rather less than that normally observed in the North Atlantic and characterised by the Pierson-Moskowitz spectrum. At the cross over point, (where spectral spread appears to have little effect on the absorption efficiency), the experimental results fit almost exactly.

In the light of the close general agreement between mathematical and physical model results and the inevitable conclusion that a better modelling of the actual Loch Ness spectral spread (to be tested at a later date) will bring even closer agreement, the absolute values of mean yearly efficiency, for a range of variations in design parameters, have been used to evaluate the likely power output from the SEA Clam.

1.4 PNEUMATIC TUNING

For the Loch Ness model tests, the bag spring rate was fixed (at a comparatively stiff rate (full scale equivalent approximately 800 pa/m² and a very limited amount of variation was possible in the turbine damping coefficient (general full scale equivalent approximately 0.016 -"Hard damping"). As can be seen from Figure 1.2 (for Mono-Hard, Pierson-Moskowitz Hard and Loch Ness Upper Bound), this gives high efficiency tuning in the energy period range 5-7 secs but a very rapid tailing off with low efficiencies for periods of >9 secs. This has a marked effect on mean yearly energy capture in sea areas such as South Uist, where much of the yearly energy is in sea states of energy periods 9-12 secs.

If spring rate and damping are changed to "softer" conditions (to 500 pa/m² and 0.036 respectively) then Figure 1.2 (for Mono-Soft and Pierson-Moskowitz Soft) shows lower efficiencies in periods of 5-7 secs but marked improvement for periods of >8.5 secs. The nett effect when applied to the South Uist scatter diagram for a water depth of 40 m is to increase the mean yearly energy capture from 0.34 to 0.41 of the total available; i.e. a productivity increase of 20%. When applied to the South Uist mean value of 47.8 kW/m, this gives a mean capture level of 19.6 kW/m.

There is some evidence that even softer damping improves the mean level in South Uist seas even further but because of the subsequent increased flow rates and cell volume changes, this effect may not be practically realisable at high power levels and hence the magnitude of any real further improvement would have to await a more detailed analysis of mixed sea response.

1.5 DEVICE DIAMETER

The original choice of 60 m diameter for the reference design of the Circular SEA Clam was based more on intuition than any mathematical justification so the result of a proper optimisation of diameter is of considerable interest, most particularly in the light of the outcome of the structural design and cost optimisation which has shown that in the proposed concrete design the cross-section is governed by buoyancy considerations, and not by strength. This means that the same design, possibly with some increase in prestressing, is quite capable of withstanding the wave loadings of a device up to 80 m in diameter; thus any cost implication in a larger diameter device is little more than linear in nature.

Thus the mathematical model has been applied to devices of 70 m and 80 m in diameter (and varying damping characteristics) to compare with the reference 60 m diameter device. The results are very promising and hold out great hope for considerable reductions in likely costs/kWh.

The following is a summary of results:- (Optimised damping and 47.8kW/m)

Diameter m.	60	70	80
Mean yearly capture	0.41	0.47	0.53
Mean power kW/m	19.6	22.5	25.3
Yearly output/device GWh	10.3	13.8	17.8
% improvement/device	9.5	46.6	89.2

(related to Review Progress Report No 2 value of 9.41 GWh)

This shows a possible 90% increase in energy capture for the 80 m diameter device with cost increases only in the region of 30 to 40%.

The energy capture results are obtained for a "ship's hull" design which is of a narrower section and has less inertia than the proposed concrete design. Thus it is expected that the energy capture figures will be better still when the model is applied to the wider, heavier concrete design.

1.6 <u>DEVICE DEPTH</u>

As with diameter, the chosen device depth was semi-intuitive though based on previous considerations of the 'straight' Clam device. Some limited analysis has now been carried out to look at the effect of reducing the active depth of the device. The results, summarised below, are based on a 60 m diameter device in 50 m water depth and with "soft" damping. The % changes are related to the reference section in Figure 1.1.

Submerged depth m.	7	6.125	5.25
% change in depth	0	-12.5	-25.0
Mean yearly capture	0.387	0.364	0.335
% change in capture	0	-6.0	-13.5

The results show that the loss in resource capture is less than the proportional change in depth but although structural cost would be less it is not clear that overall cost savings are likely to outweigh loss in output. However probably no cost effective improvement is likely with a depth increase.

1.7 <u>WATER DEPTH</u>

Wave Energy Review Progress Report No 2 suggested that advantage might be taken of the increased available power in water deeper than the reference 42 m. However because of the lack of energy capture efficiency information for depths other than approximately 40 m, it had to be assumed that the same performance would be achieved in other water depths.

To investigate the effect more thoroughly, the reference design model has been applied to a water depth range from 30 - 60 m and the results combined with the resource level as defined by Equation 1 in Progress Report No 2 to assess mean yearly capture power level. The results for the 60m diameter reference design with "soft" damping are summarised below:-

Water Depth m.	30	40	50	60
Mean yearly capture	0.454	0.410	0.387	0.376
Resource kW/m	40.9	47.8	51.4	53.5
Mean capture power kW/m	18.6	19.6	19.9	20.1

The results indicate that no real advantage would be gained by siting devices further offshore than is required for a water depth of approximately 40 m, as any resource increase is nearly balanced by the reduction in absorption efficiency. However, at least in initial instances of deployment, advantage could be taken of identified "hot spots" where available resource can be at least 10% greater than the general average for the area and depth.

1.8 <u>TURBINE YEARLY MEAN EFFICIENCY</u>

As well as the mathematical model of device energy capture performance, an analysis has also been carried out to assess the likely yearly mean efficiency of the Wells turbine operating in the duty cycle imposed by the South Uist sea state yearly scatter diagram. This analysis has shown that for the verified typical shape of a Wells turbine efficiency curve, the yearly mean efficiency for an optimised turbine design could be as high as 90% of turbine peak efficiency, depending on the spectral spread of the typical sea states.

Although reliable results for peak efficiencies have not been obtained for turbines as large as the 2m diameter proposed for the SEA Clam, work on smaller devices by Queens University, by SEA-Coventry and by the CEGB, (fully reported in Section 3 of this Report), has produced results which scale up to peak values of 70+% for turbines without guide vanes and 80% for the turbines with guide vanes as proposed for the SEA Clam. The resulting mean yearly values for these two cases are therefore 63+% and 72%, showing a very considerable increase over the value of 60% used in Progress Report No 2, and possibly yielding a 20% increase on yearly electrical output.

1.9 OVERALL EFFECTS ON DEVICE PRODUCTIVITY AND POWER COSTS OF RECENT WORK

In summary, considerable further investigation and design optimisation work has been carried out on the Circular SEA Clam since the Wave Energy Review Progress Report No 2. This work, by Advanced Mechanics and Engineering Ltd, Rendel, Palmer and Tritton and Coventry Polytechnic Energy Systems Group and funded by the Wave Energy Review has, in the areas of availability, structural cost and device productivity, provided evidence of substantial improvements over the figures used for the likely electricty cost assessment in Progress Report No 2.

The following tables summarise those improvements, set out current cost estimates and present an outline calculation of the cost/kWh of electricity which can probably be achieved by a suitably sited array of SEA Clam devices.

		As Progress Report No 2	RPT steel ref design	Proposed Concrete design
Diameter m.		60	60	80
Yearly Energy capture(GWh,air)		9.41	10.3	17.8
Turbine efficiency %		60	72	72
Generator efficiency %		91	91	91
Transmission efficiency %		96	96	96
Availability		85	93	93
Yearly Electrical output(GWh)		4.19	6.03	10.41
% increase over Prog Rep No 2		0	44	148
Structural Cost	£1000s	1750	1200	1700
Turbogenerators	"	360.6	400	450
M and E plant	"	192	200	200
Moorings (D=40m)	"	102	120	150
Installation	"	20	30	50
Transmission (2km)	"	230	230	250
Total	"	2654.6	2180	2800

Assuming a 25 year design life, O&M + insurance costs = 5.5% and discount rates of 10%, 8% and 5% respectively, (giving simple equivalents of 16.5, 14.9 and 12.6% /year), the yearly output and capital cost have been combined to give estimates of likely cost/kWh, as follows:-

Cost/kWh (16.5% overall) pence	10.5	5.97	4.44
Cost/kWh (14.9% overall) pence	9.44	5.39	4.01
Cost/kWh (12.6% overall) pence	7.98	4.56	3.39

1.10 CONCLUSION

The predicted cost of electrical output from optimised Circular SEA Clam wave energy devices ranges from 3.5 to 6 p/kWh.

SECTION 1

Figures

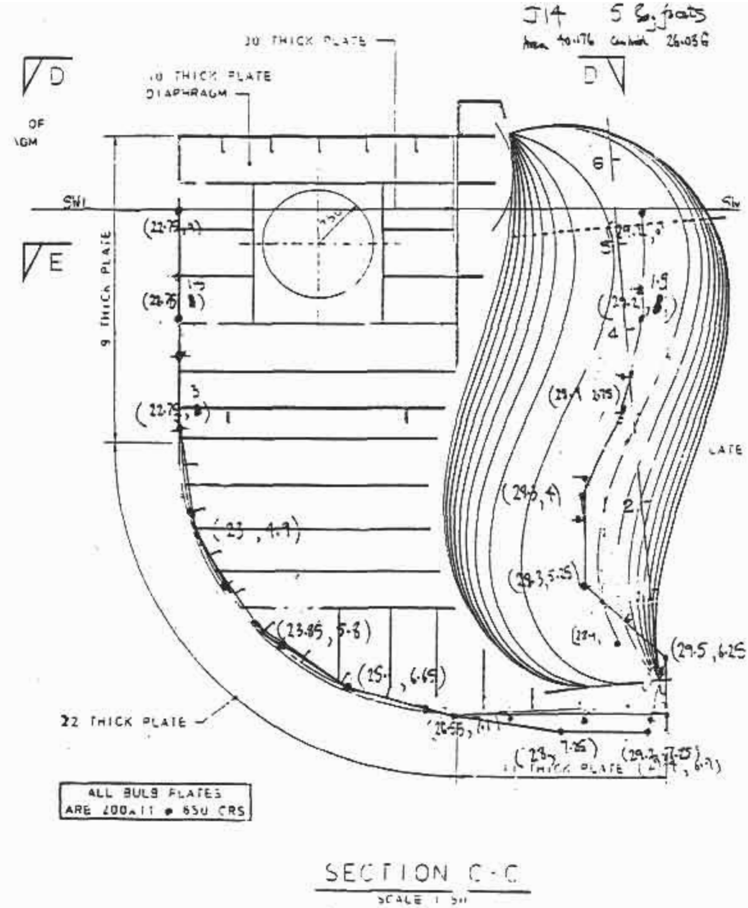

FIGURE 1.1: CLAM CELL CROSS-SECTION and
DISCRETIZATION POSITIONS for MATHEMATICAL MODELLING

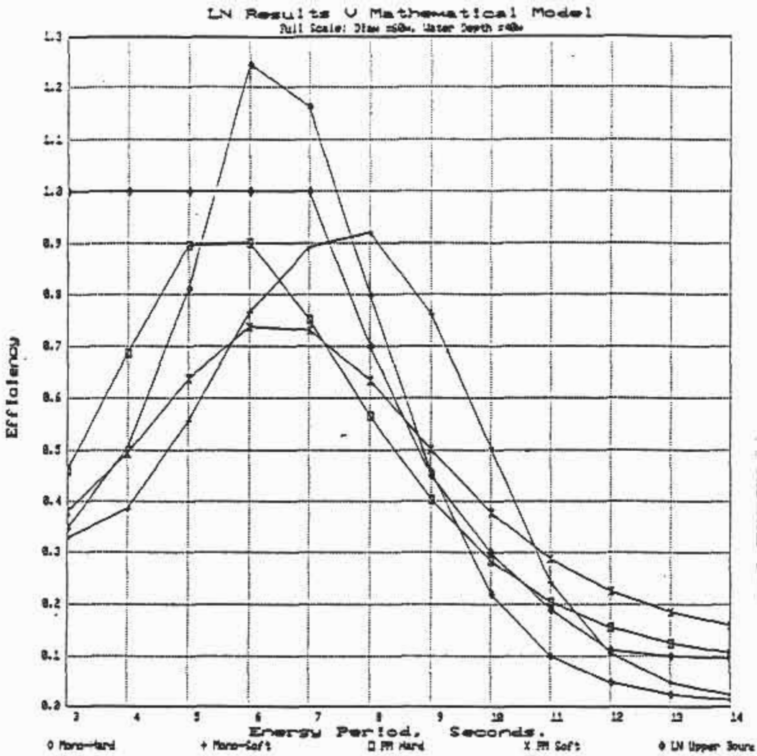

FIGURE 1.2: PREDICTIONS FROM MATHEMATICAL MODEL
COMPARED with LOCH NESS TEST RESULTS