A PROPOSAL FOR WAVE ENERGY CONVERSION NEAR CAPE TOWN

G de F Retief[1], GK Prestedge[2], FPJ Müller[3]

ABSTRACT

The South African wave energy program has been underway for several years and has included an analysis of the temporal and spatial distribution of wave energy along the full coast-line, determination of energy attenuation perpendicular to the coast-line at a site on the south western coast, and the development of a wave energy converter which is most suited to local conditions and requirements.

The resource analysis has shown that the inshore power levels occurring along the south western coast are as promising as any elsewhere in the world. A bottom mounted, V-shaped wave energy conversion device driving an air turbine has been found to be most suited to prevailing conditions.

The conversion characteristics of the device are presented, based on 1:100 scale three dimensional and 1:50 scale two dimensional model studies. Preliminary design studies of the proposed conversion system have underlined its potential viability as a cost effective supplementary source of power.

1. INTROOUCTION

Over 93% of the electricity consumed in the Republic of South Africa is provided through the centralised distribution network of the Electricity Supply Commission (ESCOM) which derives almost all its power from coal-fired stations. ESCOM's presently installed generating capacity of over 19 000 MW will have to be expanded to nearly 70 000 MW by the turn of the century. About 10% of this requirement will probably be met by nuclear power, most of the remainder will be centered around the large coal fields situated to the north east of the country. Although this coal is relatively cheap (providing South Africa with the fifth cheapest electricity in the world) the long transmission distances involved and an awareness of the long term value of non-renewable resources have led to an investigation into the potential utilisation of ocean energy, and more specifically wave energy as a supplementary source of power.

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1 Professor, Ocean Engineering, University of Stellenbosch
2 Principal Engineer, Watermeyer, Legge, Piesold and Uhlmann
3 Research Engineer, Ocean Engineering, University of Stellenbosch, South Africa

Wave energy has attracted interest throughout the world for many years. In a feasibility study of wave energy utilisation Leishman and Scobie (1975) listed some 340 United Kingdom patents, dating back to 1856, of devices which could apparently utilise ocean wave energy. The 1975 study showed that up until 1973 wave energy research had been a very low key activity, but that by 1974 a tremendous surge of interest was taking place, due mainly to the action of the OPEC countries, which had greatly affected the world's oil supplies. A great deal of work has since followed, mainly in the U.K. and Japan but with an increasing number of other countries also examining ways and means of utilising wave energy off their own shores.

Early assessments of the various ocean energy options in the coastal waters of South Africa identified the relative importance of wave energy for this region. Preliminary assessments of the resource were made by Van Wyk (1978) and Dutkiewicz and Nurick (1978), who identified relatively high energy levels to the south west of the country.

The present project which was initiated in 1979 included both a reassessment of the resource as well as the design of an energy conversion system. The resource analysis covered both a temporal and spatial distribution of wave energy using eight years of recorded wave data from a site near Cape Town (to determine long term variability), one year of synoptic wave data from representative sites for the coast-wise analyses and a three-gauge array off the Cape Peninsula to determine energy levels on a line perpendicular to the shore. Development of the wave power conversion system was based on the considerations listed in figure 1 and governed by the design philosophy which is presented in section 3.1.

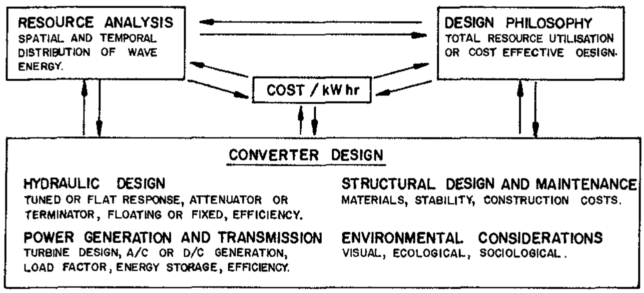

FIG I PROJECT COMPONENT DIAGRAM

2. WAVE POWER RESOURCE

2.1 Analysis procedures.

All the wave data used in this project were obtained by Datawell Waverider buoys recording digitally every six hours at a sample rate of 2 Hz for a record length of approximately 2048 data points. Records were then tested for quality control using the standard program of the National Research Institute for Oceanology (NRIO) which includes checks on successive equal values, wave steepness, low frequency energy, normality, stationarity and a number of other statistical improbabilities. After an FFT analysis the reduced data were stored in spectral density histogram form in a databank before further analysis.

Power computations were based on:

$$P = EnC \qquad (1)$$

using $$H = H_{rms} = 2\,(2M_0)^{\frac{1}{2}} \qquad (2)$$

and $$T = T_F = \Sigma\left(\frac{E_i}{F_i}\right) / \Sigma E_i \qquad (3)$$

All power figures were converted to representative "deep" water values except for the two shallow water stations in the wave gauge array off the Cape Peninsula.

2.2 Coast-wise distribution.

Waves formed in the major generating zone to the south west of Southern Africa undergo very little refraction before arriving at the tip of the sub-continent. A mean annual power level of approximately 45 kW per metre wave crest is typical off-shore of the Cape Peninsula. The remaining south western coastal belt (Danger Point to Saldanha Bay) has an annual average energy flux level of approximately 25 to 30 kW/m which diminishes northwards to levels of about 21 kW/m at Oranjemund and eastwards to constant levels of about 12 kW/m. Figure 2 shows the mean annual power levels at six coastal sites based on an analysis of one year's synoptic data for the period November 1978 to November 1979. The figures in brackets represent the wave power level in kW/m which is exceeded 90% of the year. A mean annual power level at a weather ship site 10°S 40°E is included merely for comparison purposes as the recording period did not coincide with that of the coastal analysis.

At an early stage of the project it was realised that in terms of power utilisation a wave power figure representing an average over a full year has very little value and can in fact be rather misleading. (Mean annual power levels are included in this paper for the sake of comparison with the many other wave energy studies which have limited their analyses to mean figures.)

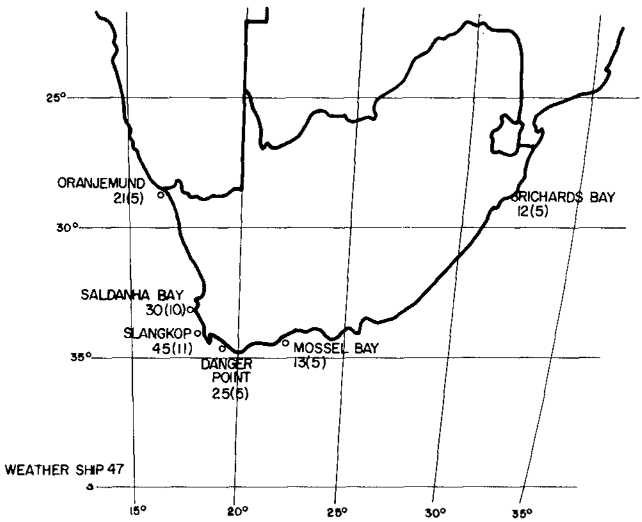

FIG 2 WAVE POWER DISTRIBUTION ALONG THE SOUTH AFRICAN COAST, POWER IN kW/m MEAN ANNUAL, (90% EXCEEDENCE)

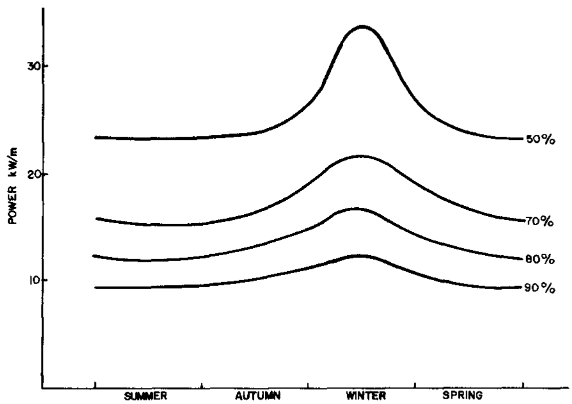

FIG 3 SEASONAL VARIATION OF POWER AT DIFFERENT EXCEEDENCE LEVELS : SALDANHA BAY

It will be noticed that 90% exceedence power levels of about 10 kW/m occur between Slangkop and Saldanha Bay, while the remainder of the coast-line displays a constant level of about 5 kW/m. These results can be very significant in terms of the level of optimum power conversion for which a wave power station is designed. For example, if a device were designed to produce an optimum cost benefit at a power level of 5 kW/m (which would provide power for 90% of the year) the potential application of this device along the coast would be totally different from some other device which was designed to convert all the wave energy it encountered at the highest hydraulic efficiency. Figure 3 shows the seasonal variation of power levels at 50%, 70%, 80% and 90% exceedence for Saldanha Bay.

The final analysis of the wave energy resource is thus of necessity dependent on the conversion characteristics of the proposed wave energy converter and the demand characteristics of the converted power. The interactions involved are shown in figure 1.

2.3 Wave power distribution at Slangkop.

In a joint project between the Universities of Stellenbosch and Cape Town, the Fisheries Development Corporation of SA Ltd and NRIO, three Waverider stations were maintained west of the Slangkop Light House on the Cape Peninsula for a period of over two years specifically to study shoaling effects on wave energy propagation. The dissipative mechanisms involved have been analysed by Shillington (1982).

The three stations were situated in 200 m, 24 m and 15 m water depths, and were backed up by a DOSO direction gauge (Retief and Vonk, 1974) at the 24 m station. A typical annual H-T scatter diagram with 10 kW isodynes for the 200 m station is shown in figure 4. Figure 5 shows the position of the three Slangkop stations with the mean annual and 90% exceedence wave power curves plotted against distance from shore. It can be seen that although there is a 30% reduction in mean annual power between off-shore and 0,8 km from shore (15 m deep station) the 90% exceedence curve displays a reduction of only 20%. The relatively high power levels occurring close inshore favour the use of fixed, shallow water energy converters which will avoid mooring problems and require minimum power transmission distances. Development of the energy converter was thus directed towards the inshore zone from the outset, as opposed to the initial deep-water approach of the United Kingdom researchers where the shallow-water power levels are relatively unfavourable (Crisp and Scott, 1981).

Although the Slangkop records displayed the highest mean levels of wave power measured around the coast this did not necessarily imply that Slangkop was most suited for wave power utilisation. In comparing the seasonal distribution of the 90% exceedence curves for Slangkop, Saldanha and Oranjemund (see figure 6) it was found that the more evenly distributed power at Saldanha suggested more favourable power generating characteristics than that at the higher energy Slangkop station.

Another form of analysis which assists in determining the design characteristics of the power converter is shown in figure 7 for Saldanha,

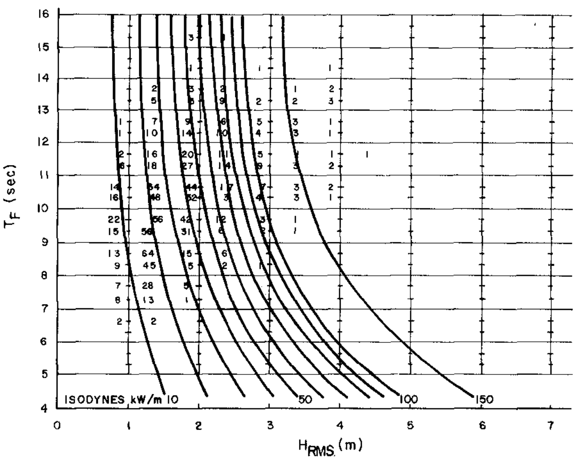

FIG 4 H-T SCATTER DIAGRAM FOR SLANGKOP (200m) VALUES IN PARTS PER THOUSAND

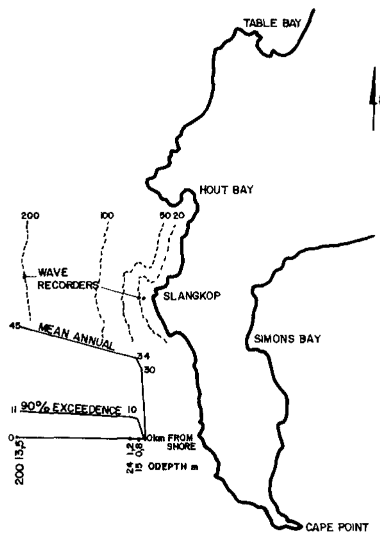

FIG 5 SLANGKOP WAVE POWER CHARACTERISTICS

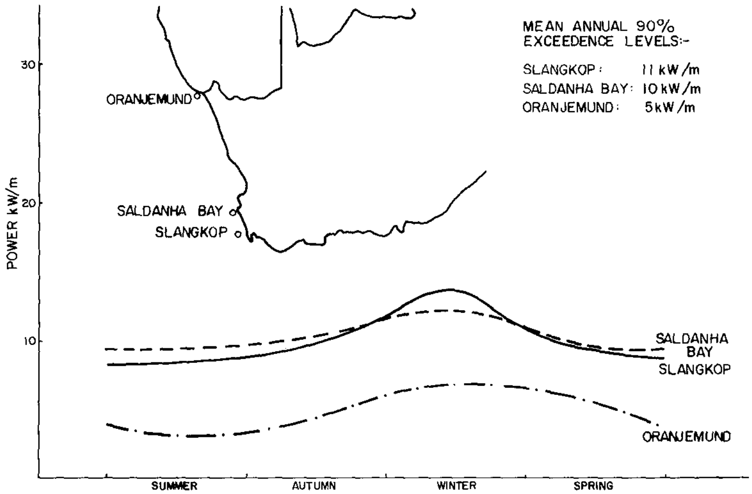

FIG 6 SEASONAL VARIATION OF POWER AT 90% EXCEEDENCE LEVEL FOR THREE STATIONS

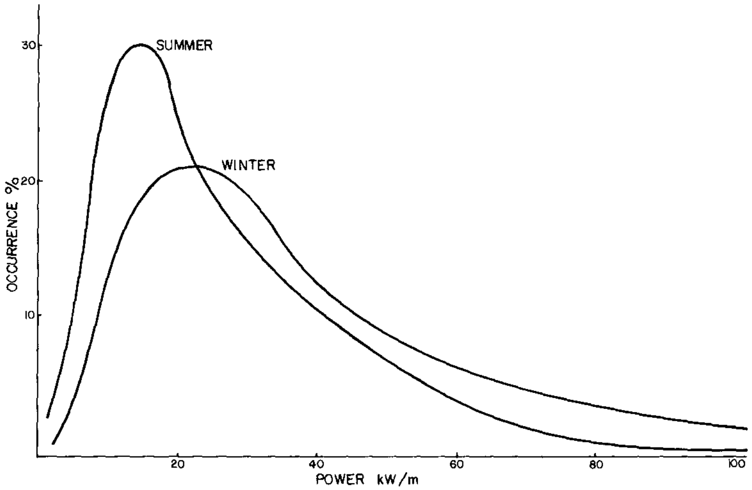

FIG 7 OCCURRENCE DISTRIBUTION OF POWER FOR TWO SEASONS AT SALDANHA BAY

where the occurrence distribution of power for various seasons or demand periods can prescribe optimum generating capability for the period under study.

In figure 7 the highest percentage of power in the summer occurs at about 14 kW/m while in the winter 22 kW/m appears to be most prevalent at this particular site.

Vimukta *et al* (1978) suggested that for a fairly large wave power program which is not combined with storage "there is little point in having a mechanical power cut-off greater than about 25 kW/m". For this project the larger converter described in section 3 was based on a 22 kW/m cut-off, the smaller on 13 kW/m.

3. ENERGY CONVERTER

3.1 Design philosophy.

In figure 1 the component interactions of the program are described and reference has subsequently been made to the concept of a design philosophy. In developing a new system in which a great number of variables interact it becomes essential to establish a well defined philosophy which will reduce the number of variables and qualify the project's stated objectives.

The following statements constituted this project's design philosophy:

- cost efficiency to be of prime importance (hydraulic conversion efficiency of secondary importance *per se*; total resource utilisation was not a specific objective if this should be in conflict with the cost objective).

- the system should not be dependent on energy storage (i.e. device to be optimised at a low power cut-off level).

- over design required for extreme storm events to be avoided.

- environmental impact and possible hazard to navigation to be minimised.

- design and construction of the device should fall within existing local technological capability.

- the apparent high levels of power occurring inshore along the south western coast of Southern Africa should be utilised if this could improve cost efficiency.

The decision to work independently of power storage was made mainly to reduce the number of variables and to produce a system which was more universal and versatile. (Where mountains occur close to the sea, wave power generators can naturally be employed to pump water to storage reservoirs. If sea-water is used and the reservoir is sited at least 600 m above sea-level the system can be used both as a pumped storage power scheme for the winter and a reversed osmosis fresh water supply scheme for the summer.) The greater majority of previously proposed wave energy converters have been aimed at high hydraulic efficiency, requiring storage of the extreme levels of power generated during storms, contrary to the proposal by Vimukta *et al* (1978) that "the emphasis of research should be switched away from efficient extraction of the large amounts of power available in strong seas and towards cheapness and reliability of supply under ordinary and calm conditions".

3.2 Proposed converter.

The considerations listed under 3.1 led to the following preliminary conclusions:

- the converter should be a fixed structure thus producing an efficient reference frame, simple technology (no mooring or flexible transmission problems) and limited maintenance.

- the device should be submerged to minimise environmental impact and reduce storm loading.

- installation should be close inshore to reduce transmission distance and provide a limited wave direction spectrum and depth limited design wave height.

- the device should be non-tuned and relatively insensitive with robust and simple control requirements.

The simple, yet elegant oscillating water column concept, first developed in Japan and later researched by a number of wave energy groups, was judged as most suitable to meet the above requirements. However, instead of directly extracting power from the oscillating air flow, a manifold system similar to that proposed by French (1979) for the Lancaster Flexible Bag Device was used to provide a rectified air flow. To enhance capture efficiency and improve structural stability the converter is angled to the wave orthogonal. To improve generating cost efficiency a pair of collectors is coupled in a V-formation to a single air turbine and power generator mounted above water level in a tower at the apex of the V. Figure 8 illustrates the principles involved. Figure 9 shows an artist's proposal of a V-converter constructed on ring foot pillars along a sandy shore line in 15 m to 20 m water depth.

3.3 Model studies.

Model studies used in the development of the Stellenbosch Wave Energy Converter (SWEC) covered a variety of cross-sectional shapes and internal proportions for variable collector length, orientation angle and submergence depth. Two dimensional flume tests were carried out at a scale of 1:50 (figure 10), while three dimensional wide tank tests were performed at 1:100 (figure 11) in the hydraulics laboratory of the University of Stellenbosch.

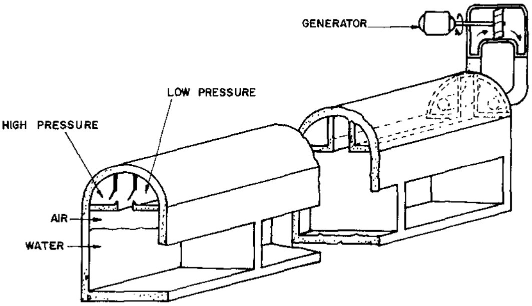

FIG 8 PRINCIPLES OF OPERATION OF THE SWEC

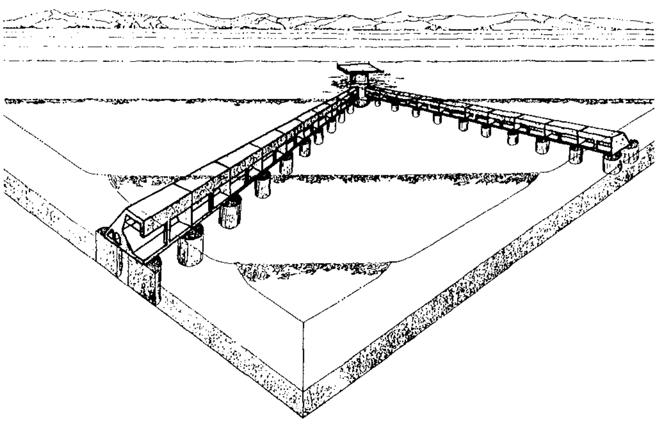

FIG 9 ARTISTS RENDERING OF THE SWEC

FIG 10 TWO DIMENSIONAL MODEL TESTS.

FIG 11 THREE DIMENSIONAL MODEL TESTS OF ONE COLLECTOR ARM.

The three dimensional models were built with the high and low pressure manifold ducts supported outside the model, above water level (see figure 11) so that Reynolds scale effects in the ducts could be minimised and observation and control facilitated. The compressibility of the air contained within the device cannot be scaled. To establish what effect this might have on the model studies a series of tests were carried out with compression chambers attached to the manifold ducts proportioned so that they would simulate the compressibility of air in the prototype. It was found that the compressibility of the contained air did not influence the device's power conversion capability but merely provided a damping effect on the higher frequency pressure fluctuations in the ducts.

Generated power in the model was measured by a sensitive volumetric gas flow gauge (fitted with a throttle control to simulate power loading) and pressure sensors monitoring the pressure gradient across the flow gauge. High frequency pressure fluctuations in the ducts (caused by valve slapping) were electronically filtered out to approximately simulate the prototype turbine response. Water level fluctuations inside the collector compartments were monitored by means of resistence probes. The two dimensional model was fitted with a constant head, variable volume air chamber to simulate the manifold system. Structural stability tests were carried out on a 20 m length of collector arm at a scale of 1:100 in a special test rig which measured horizontal shear and overturning forces simultaneously.

3.4 Converter characteristics.

Although the collector arms will normally be installed at an angle of about 30° to the coast-line it can be seen from figure 12 that precise orientation is not critical in terms of conversion efficiency and can vary by up to $\pm$ 15° of optimum.

Frequency response of the device (figure 13) displays a satisfactory band-width and allows a certain amount of freedom in fixing the length of the collector arm according to site conditions.

An important attribute of this device is that as long as the collector arm is maintained at some constant minimum length (sufficient to provide a smooth air flow through the turbine and dependent on the component of arm length normal to the wave crest) the cross-section of the collector arm can be scaled up or down and the cost efficiency of the system is maintained approximately constant. This implies that depending on the power cut-off level that is considered suitable for a specific site the device can be designed accordingly with no loss in cost efficiency.

The power cut-off is attained by throttling the air flow upstream of the turbine and the resulting conversion characteristics are shown in figure 14 for devices with cross-sectional height dimensions of 5,5 m and 9,0 m. Throttling of the air flow also limits vertical motion of the water surfaces within the collector arm and prevents slamming against the collector roof-slab.

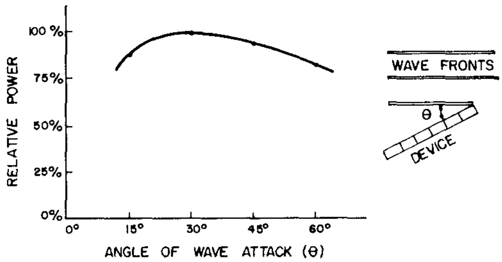

FIG 12 RELATIVE POWER GENERATED VS, ANGLE OF WAVE ATTACK FOR CONSTANT WAVE PERIOD (10 SEC.) AND ARM LENGTH (300 METERS)

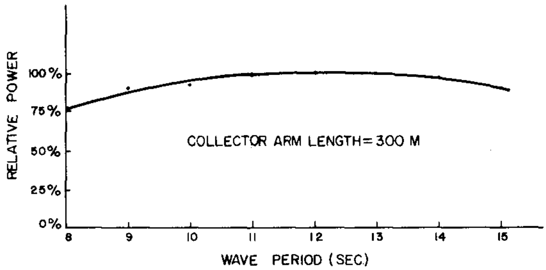

FIG 13 RELATIVE POWER GENERATED VS, WAVE PERIOD AT CONSTANT WAVE HEIGHT (2M)

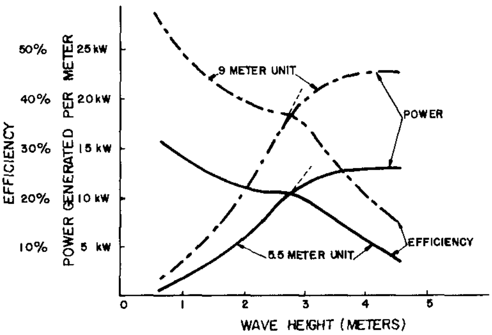

FIG 14 POWER GENERATED AND EFFICIENCY VS, WAVE HEIGHT FOR TWO CONVERTER SIZES

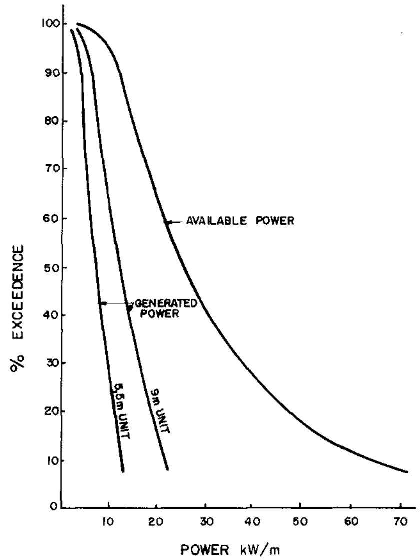

FIG 15 POWER EXCEEDENCE CURVES FOR SALDANHA: AVAILABLE AND GENERATED

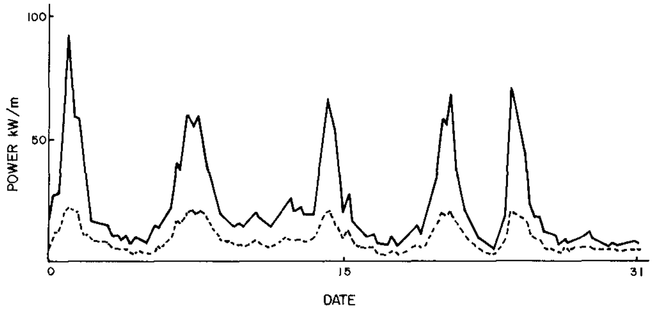

FIG 16 WAVE POWER AT SLANGKOP FOR JANUARY 1982

——— AVAILABLE

- - - - - GENERATED (9m UNIT)

Applying the curves shown in figure 14 to an actual site, the available and generated annual power exceedence curves for Saldanha Bay for the 9 m and 5,5 m units are shown in figure 15. The suppressed conversion characteristics of such a device can also be clearly seen in a time domain plot of available and generated power, as in figure 16 where the generation history of a 9 m unit installed at Slangkop is depicted for a period of one month in midsummer.

3.5 Prototype design.

For costing purposes engineering designs of a 9 m and a 5,5 m unit based on the format shown in figure 9 were drawn up. The design was based on a precast, 15 m long reinforced concrete module which is floated to site and cast into preplaced and ballasted ring foundations. Where installation is to take place on a rocky sea-bed the units will be laid on a prepared bed and fixed by means of rock anchors. The modules are intrinsicly very stable. In the flooded mode, used for placement, and before the units are anchored, they remain stable in waves of up to 3,5 m. This provides a useful weather window for fixing the units in place and coupling the air ducts (by means of flexible "subway" joints). The valves are durable, light-weight material offering low inertia and protected by buoyant "splash flaps". An airpump, housed in the access tower, will maintain the desired air volume in the system. The low pressure air turbine (Francis or axial flow) and coupled power generator will be housed above water level in the access tower so that flooding of the collector arms will not disturb the control and generating gear. Both A/C and D/C generating options have been considered and the rated output varies from 2,5 MW (mean annual) for a 5,5 m "V" collector to 4,4 MW for a 9 m unit. The final cost of A/C power delivered at the coast and based on a 100 MW grouping of "V" collectors along 9 km of coast, has been found to range from 4,5^{c} to 5^{c} per kWhr (RSA currency) which is considered competitive with existing power costs along large sections of the coast-line.

4. CONCLUSION

The Stellenbosch Wave Energy Converter has generally met all the original requirements described in section 3.1. The power produced appears to be cost competitive with existing power and the system relies solely on existing construction technology. Although further quantitative work is required on the potential disruption of littoral processes through the extraction of wave energy a preliminary assessment indicates that this should not be excessive. The device is robust and simple and will be virtually unaffected by marine growth with maintenance operations being largely limited to the access tower. At the end of its economic life the device can be flooded to become an artificial reef.

The primary aim of the above converter is to produce electricity at a viable present day cost. Consequently high hydraulic conversion efficiency was not a fundamental requirement. For an inshore device such as this, environmental considerations will in any case impose a limit on the extraction efficiency. The system is therefore not aimed at total resource utilisation but should offer a useful source of supplementary power for the future. Because of the ease with which the device can be scaled, the step required to move from laboratory to pilot installation will not require the same level of risk capital as is the case in many previously proposed devices.

ACKNOWLEDGEMENTS

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