# DETAILED DESIGN OF A WAVE ENERGY CONVERSION PLANT

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## ABSTRACT

A preliminary assessment of wave energy conversion by means of the Stellenbosch Wave Energy Converter (SWEC) has indicated the viability of this system as a supplementary source of electric power.

In order to refine the preliminary estimates of the cost of power delivered, detailed design of a 770 MW (rated output) installation at a site 60 km north of Cape Town has been undertaken.

This paper describes the power conversion characteristics of the SWEC at the proposed site, structural design of the collector arms and generating tower for both mass gravity or piled solutions, a construction scenario involving a casting harbour in nearby Saldanha Bay and the towing and placement of 53 m long precast modules, and finally an assessment of the environmental impact of the proposed 40 km array on the adjacent coastline.

The proposed system is found to be both technically and economically feasible and offers a useful contribution towards future electric power supply.

## 1. INTRODUCTION

The Stellenbosch Wave Energy Converter (SWEC) is a shallow water device developed over a number of years to meet the specific requirements for wave power utilisation along the south western coast of South Africa. An analysis of the wave power resource along this coast as well as a full description of the development of the SWEC are presented in Retief et al. (1982).

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The objective of the present project was to produce an in-depth analysis of a potential application of the SWEC with reliable projections of future costs and operation management. The site chosen had been identified in the previous study as one of the more favourable locations for wave power conversion and the overall design philosophy described in Retief et al. (1982) was adhered to throughout this investigation.

Although the general characteristics of the device had been determined in the previous study a further series of field and hydraulic model studies were required for the determination of design parameters and power conversion characteristics specific to the site. Model studies of the rectified airflow, generated by the SWEC, led to a detailed design of the air turbine/power generation system. A theoretical analysis of prevailing littoral processes provided input for an environmental impact assessment of the proposed array on the adjacent coastline. Sedimentation in the immediate vicinity of the converter was studied both theoretically and empirically. Final costing was based on a construction and management scenario developed in conjunction with a team of coastal engineering consultants and contractors.

## 2. CONVERTER CONCEPT

A typical converter unit, which would form part of the total power conversion array, is shown in Figure 1. For the site under consideration in this project the unit is to be installed in an average water depth of 14 m (i.e. 2 m submergence), approximately 1,5 km off-shore. The two collector arms forming the "V" are 160 m long orientated at $45^0$ to the predominant direction of energy flux at the site. Each arm comprises three precast concrete modules, each containing four chambers in which the water level oscillates. Each oscillation chamber is connected via rectification flap valves to the high and low pressure, closed-system air ducts which merge at the apex of the "V" to form the two legs of the generator tower. An axial flow air turbine mounted horizontally in the tower cabin converts the differential pressure between the two air ducts to mechanical power which in turn drives an alternating current electric generator. The module section shown in Figure 1 relates to the gravity design option - the alternative piled option is shown in Figure 14.

## 3. PROPOSED SITE

The proposed site for the converter array is shown in Figure 2. This 40 km long stretch of coastline, consisting of North and South Bays, is directly exposed to the almost unrefracted south westerly swells which are the cause of the peak levels of wave energy occurring along this section of the Southern African coast (Geustyn, 1983).

The study area has been well instrumented in the past and reliable wave height and direction data for the site are available. Mean annual wave power levels of about 30 kW/m are found in-shore at the generator site, which is conveniently situated, between the urban growth points of Saldanha and Cape Town, near to the national electric power network. The converter array will consist of 154 "V" units with a 770 MWe rating and mean winter capacity of 450 MWe.

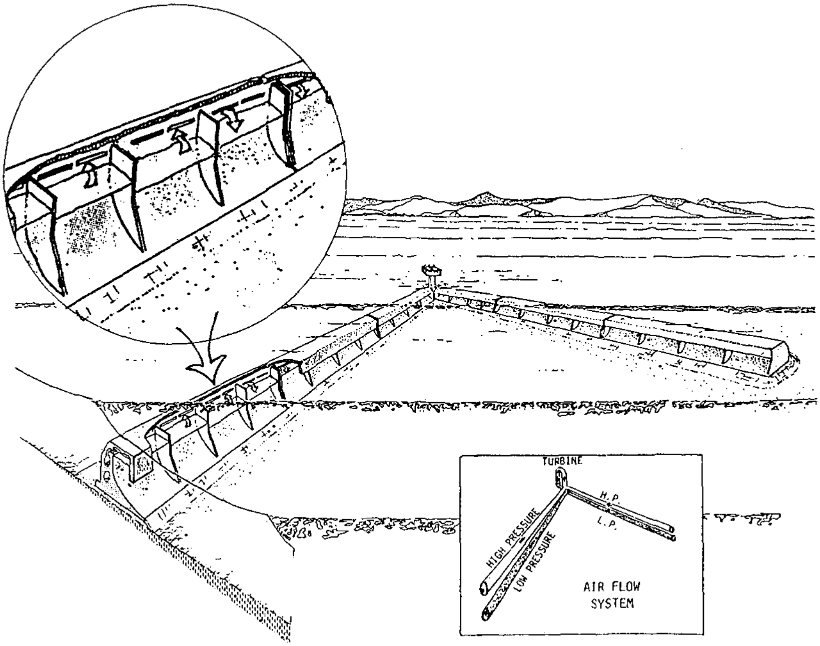

FIGURE 1: Typical Layout of Wave Energy Converter

The two bays comprise sandy beaches with an average off-shore slope of 1:100, bounded at each end by a rocky headland. Nett littoral drift is northwards. Off-shore currents are weak and variable and the mean tidal range is 1,0 m diurnal.

A variety of analyses were performed on the available wave data - typical seasonal distributions of wave power were presented in Retief et al. (1982), wave direction characteristics are shown in Figure 3 and long term fluctuations (measured over a five year period at a station at the southern end of the array in 23 m water depth) are shown in Figure 4. The long term analysis produced a maximum deviation from the five year mean of ± 5% for the mean annual power level and ± 20% to 30% for the mean seasonal power level. As with all forms of fluctuating alternative energy sources a feasibility study of wave power utilisation should include an analysis of the probable occurrence and duration of periods during which the power available falls below some prescribed demand level. Figure 5 shows a Weibull distribution, based on five year's data, of the return period and duration of "calm" events where "calm" is defined by the level of wave power not exceeded during that period.

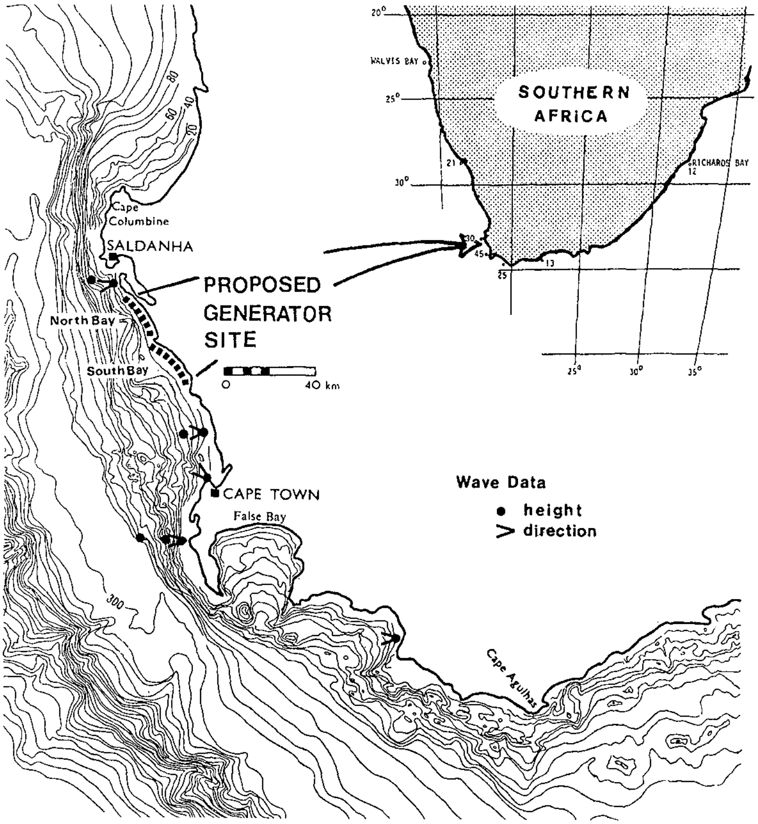

FIGURE 2: Proposed Generator Site

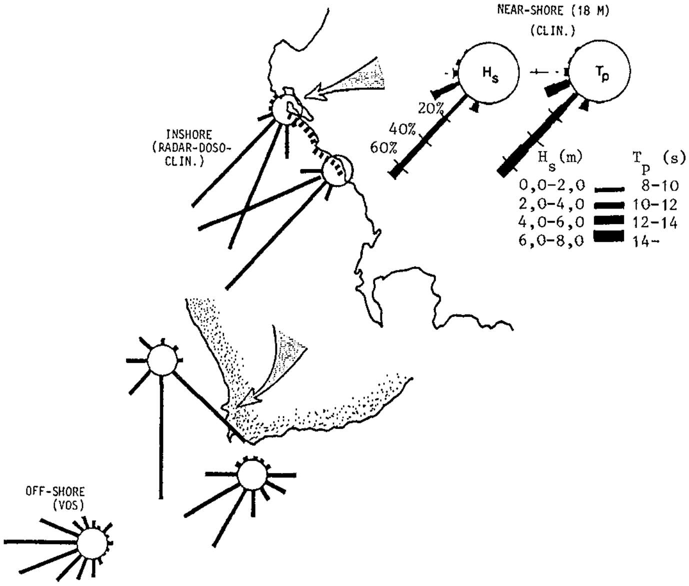

FIGURE 3: Wave Direction Analysis

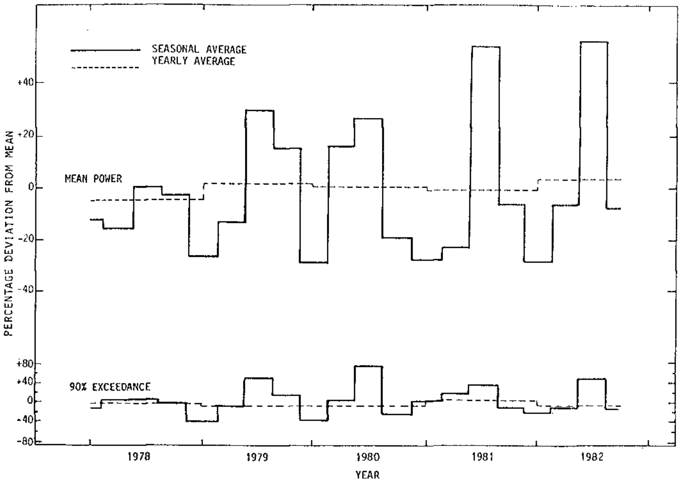

FIGURE 4: Seasonal and Yearly Variation in Wave Power

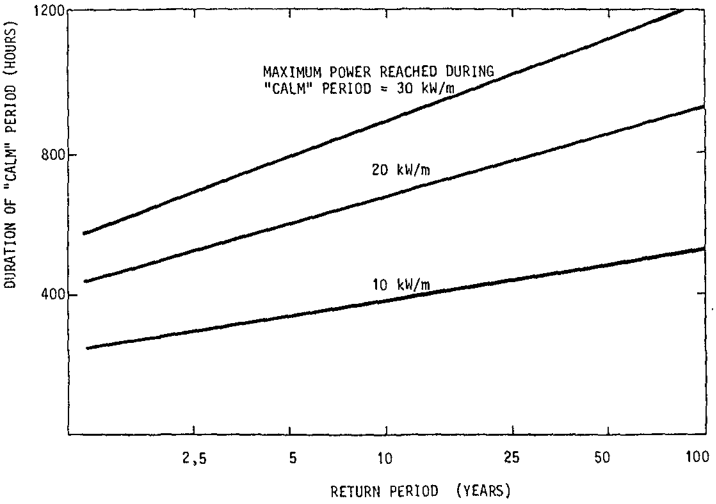

FIGURE 5: Duration of "Calm" Periods vs. Return Period

## 4. MODEL STUDIES

The physical and theoretical models which were used in the optimisation of the converter array design are summarised in Table 1.

| | | | | |
|---|---|---|---|---|
| Hydraulic Models | 1:60 | 3-D | Irregular Wave | Conversion Design<br>Sediment Studies |
| | 1:50 | 2-D | Regular Wave | Internal Geometry |
| | 1:100<br>1:60 | 2-D | Regular / Irregular | Structural Design |
| Theoretical Studies | LINREF Model (Crowley 1984) | | | Wave Refraction |
| | Regression Model (Swart 1976) | | | Extent of On-/Off-shore Transport |
| | Analysis based on Evans (1982) | | | Collector Arm Optimisation |

TABLE 1: Model Studies for Converter Design

### 4.1 Power Conversion

Figure 6 shows the 1:60 scale three-dimensional model of a "V" unit being tested in the irregular wave tank of the National Research Institute for Oceanology of the South African Council for Scientific and Industrial Research. A schematic section of the model in Figure 8 shows the submerged oscillation chamber scaled according to Froude and the airflow system constructed to Reynolds scaling above water level.

Parameters monitored continuously by computer included air pressure at various locations, airflow in both collector arms, and water level both inside and outside the collector arms. The airflow throttle was set at an optimum pressure/flow ratio of 30 pascals per $m^3$/sec. Although the air system was not a correct reproduction of the prototype unit, non-linear duct losses are greater at model scale than at full scale (especially for irregular wave spectra at higher energy periods) and the results were considered to be conservative.

An example of a typical Pierson Moskowitz test spectrum is shown in Figure 7. Variables considered in the test series included water depth/structure height, submergence depth, angle of wave attack, swept angle of "V", collector arm geometry, incident and transmitted wave characteristics.

FIGURE 6: Three-dimensional Irregular Wave Tests

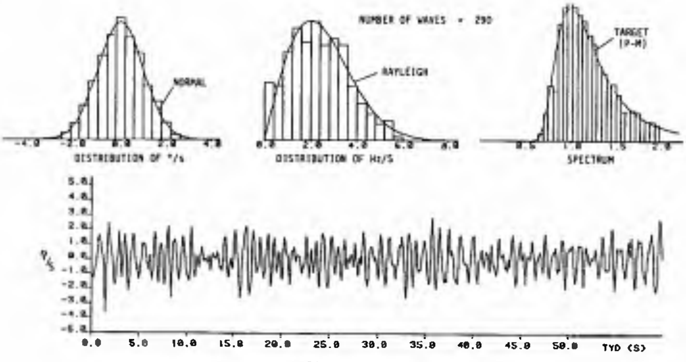

FIGURE 7: Analysis of Generated Irregular Waves

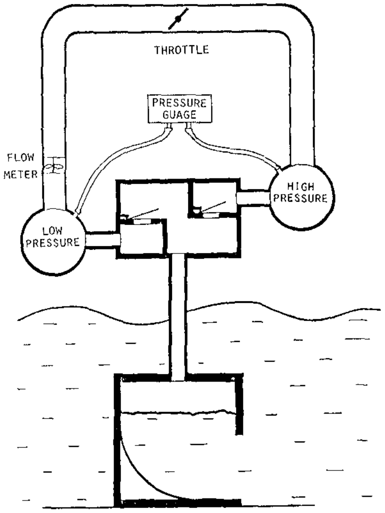

FIGURE 8: Schematic Diagram of Three-dimensional (1:60 scale) Model

The "V" shape of the collector arms not only enhances wave power conversion capability by reflecting "trapped" energy from one arm to the other, it also transmits the greater proportion of the unconverted energy shorewards. This relatively high transmission coefficient reduces the potential impact of the device on the shoreline, and is probably caused by non-linear effects along the collector arm which reduce the effective reflection angle of a wave slug.

In studying the frequency response of the "V" for different collector arm lengths it was found that the converter responds optimally to the zero crossing period, $T_Z$, of the spectrum and not the peak or energy periods as had been expected. As the SWEC is not a tuned resonator it can be theorised that optimum "coupling" with the incident wave profile would occur at a period which reflects average fluctuation of the water surface ($T_z$).

Directional sensitivity produced very favourable results when compared with the narrow direction spectrum measured at the proposed site. Figure 9 shows that 90% of the wave directions measured at the site fall within the 95% direction dependent conversion efficiency.

The percentage occurrence of power generated at discrete power intervals for one "V" converter is shown in Figure 10. This analysis was based on a 22 month wave record from the proposed site. The average rate of power conversion for the 22 month period is 2,2 MWe per "V", while the winter average was found to be 2,9 MWe per "V" (450 MWe winter average for the full array). The available and generated power in percentage exceedence form is given in Figure 11.

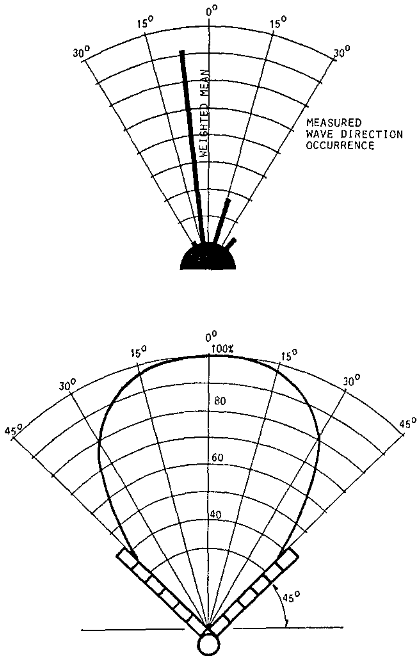

FIGURE 9: Relative Conversion Efficiency with Direction

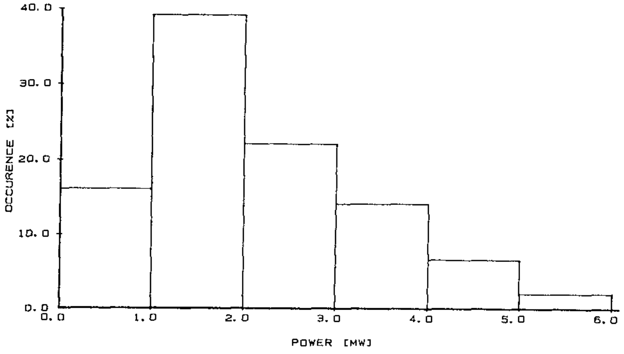

FIGURE 10: Occurrence of Power Generated for Period June '80-April '82

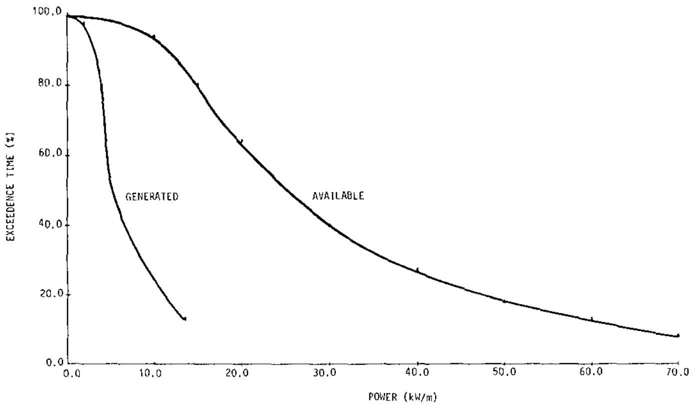

FIGURE 11: Cumulative Power Exceedence (Available and Generated)

## 4.2 Stability Design

The SWEC has a relatively complicated form compared with the cylinders or spheres for which wave force data have previously been published. As no data were available for structures with water depth to structure height ratios as low as 1,4 (an area where modelling of the free surface becomes significant) it was decided to revert to a two-dimensional model study as a first attempt at determining design forces. The tests were conducted at scales of 1:100 and 1:60 and are described in Morrison and Geustyn (1984). Figure 12 shows peak values of the normalised horizontal force ($f_x$) acting on the converter plotted against a dimensionless wave amplitude for various water depth/structure height ratios, where:

$f_x = F_{xmax}/\rho g a a_0$

and $a$ = structure height

$a_0$ = amplitude of incident linear wave ( $= H/2$)

$k$ = wave number

The measured curves are compared with those of previous similar studies and are found to display similar trends but with a more rapid reduction in force for higher ka values due probably to the complient nature of the front face caused by the opening.

By ignoring wave period and assuming a linear relationship between wave height and applied force Morrison et al. were able to compile a set of simple design curves for various water depths, which were used in the later structural design.

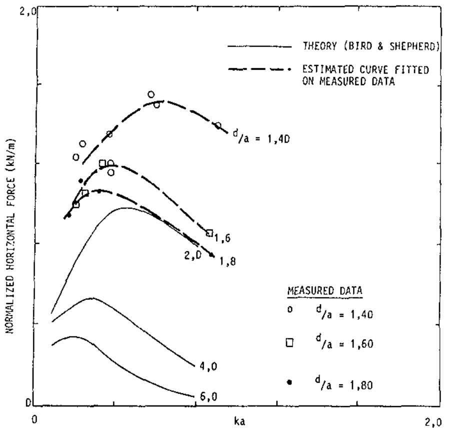

FIGURE 12: Horizontal Wave Force on Structure. Theoretical and Measured (Morrison & Geustyn 1984)

To resist forces acting on the structure two design options were persued. The one made use of a mass gravity solution which was model studied at a scale of 1:60 (Figure 13). The other solution entailed a theoretical analysis of a piled structure. Both were based on a maximum wave height/depth limited design condition . The design of the generator tower was handled in a similar manner. The force on the deck slab due to water column deceleration against the entrapped air cushion was determined by analytical modelling.

The finally selected sections are shown in Figure 14. Both would be placed by barge onto a prepared rubble bed. The gravity section is designed to be fully stable, immediately after placement, in the flooded mode. The mass surcharge introduced by the backfill, which is later placed by barge, is designed to accommodate the instability introduced by pumping air into the system when power generation commences. As the construction window on the piled option is more limited, driving of the 1,5 m diameter steel piles from a jack-up rig would commence immediately after placement. Both sections caused severe erosion of the seaward toe and a bitumen grouted apron of 2 t selected rubble was found to solve this problem. After the units have been secured on the bed the air ducts will be joined underwater by means of a flexible coupling specially designed for this purpose.

## 4.3 Sediment Studies

Sediment deposition and erosion in the immediate vicinity of the converter was studied in the three-dimensional 1:60 scale model, qualified by a theoretical prediction of seabed stability. It was found that under the predominant wave conditions the position off-shore is such

FIGURE 13: Two-dimensional (1:60 scale) Stability Tests

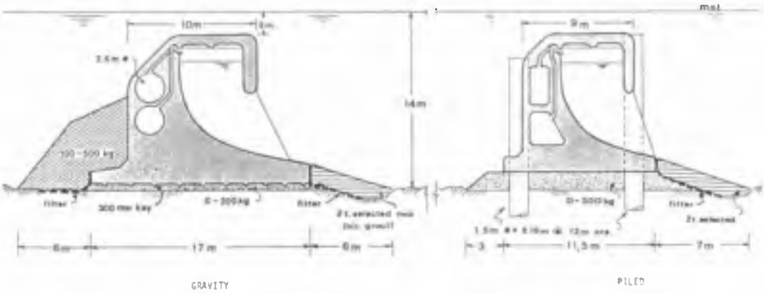

FIGURE 14: Alternative Installation Methods

as to be beyond the dynamic sediment swept prism. Under storm conditions a bar was found to occur in the apex of the "V". Further long term build-up or dissipation of this mound has yet to be determined in a more rigorous analysis of the processes involved. The possible need for a sand by-pass or maintenance pumping station has thus not yet been determined. From the data of wave transmission across the converter, determined in the 1:60 scale three-dimensional model, an estimate was made of the overall impact that the array would have on the prevailing on-shore/off-shore sediment processes in the bays. The anticipated seawards shift of the beach line is likely to be between 10 m and 20 m. An anomalous situation could occur at each end of the array due to a discontinuity in long-shore drift rates. To reduce this effect the array is planned to extend as far as the bordering headlands in each bay.

## 4.4 Airflow System Design

The rectification valves mounted in the plenum chamber above each oscillating water column will consist of 300 mm high plied rubber or neoprene flaps, with directional reinforcing, housed in a removable module. A buoyant splash flap will be installed at each valve opening immediately below the air cushion chamber. It is anticipated that an annual clean-up of the valves will be required to remove marine growth. This will probably entail removal of the complete valve module and its replacement with a serviced module while the converter is in a flooded mode.

Each collecter arm will have an airflow throttle control, housed in the generator tower, to damp vertical displacement of the water surface in the oscillation chamber and limit power conversion during storm events. A typical example of airflow surging through the turbine caused by wave-beat is shown in Figure 15.

## 4.5 Electro-Mechanical Power Conversion

Design parameters for the 3,5 m diameter, 8 m long axial flow variable pitch turbine are summarised in Figure 16. Airflow speeds of up to 100 m/sec will be experienced at the turbine. To counteract water drop erosion of the blades a nickel-aluminium-bronze or stainless-steel tipped G.R.P. construction is being considered. Anticipated maintenance includes an annual cleaning and inspection and 25 year replacement of the turbine. Conversion efficiency of the electro-mechanical system is estimated at 75%.

The variable pitch constant speed turbine will be directly coupled to a 5 MVA, 22 kV synchronous electric generator. The "V" units will be interconnected in groups of six, with each group connected directly to the national electricity supply grid by means of a 1,5 km long 22 kV, 35 MVA seabed cable.

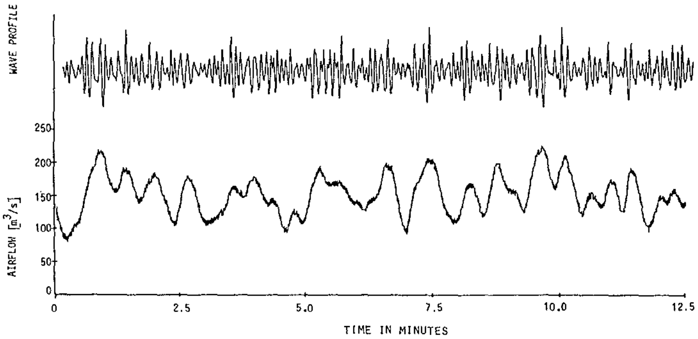

FIGURE 15: Typical Wave Train with Resulting Airflow through Turbine

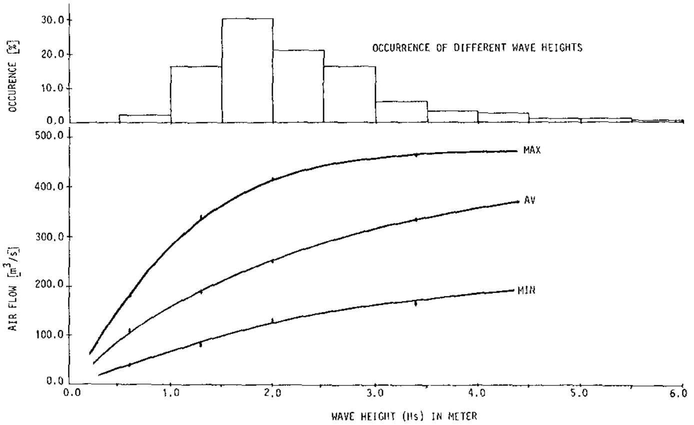

FIGURE 16: Airflow vs. Wave Height

## 5. LAYOUT AND CONSTRUCTION

A full set of wave refraction diagrams covering five deepsea directions (180°, 210°, 240°, 270°, 300°) and six periods (10,5; 12,3; 13,9; 15,2; 16,4; 17,5 secs) were compiled for the proposed site. This analysis identified the distribution of wave power along the shore, the long-shore energy flux along the 15 m contour and the optimum orientation for installation of the converter units. Figure 17 is an example of the most dominant south westerly swell (240°, 12,3 sec) approaching North Bay with a series of typical direction roses used for optimum converter orientation.

Figure 18 shows an artists rendering of the construction phases envisaged. Construction of the complete array has been planned to extend over a five year period after an initial preparation lead time of two years. The precast modules will be assembled in a specially constructed casting harbour within Saldanha Bay and towed to site suspended from a placement barge. The lowering of units onto the horizontal berm will commence at the apex of the "V". Each subsequent unit will be winched up to the previously placed unit to a tolerance of 500 mm and the flexible duct connectors will be installed, followed by the ballast rubble or piling by jack-up rig. The turbine/generator unit will be winched up directly into the tower cabin from a transport barge which will be temporarily moored between the tower legs.

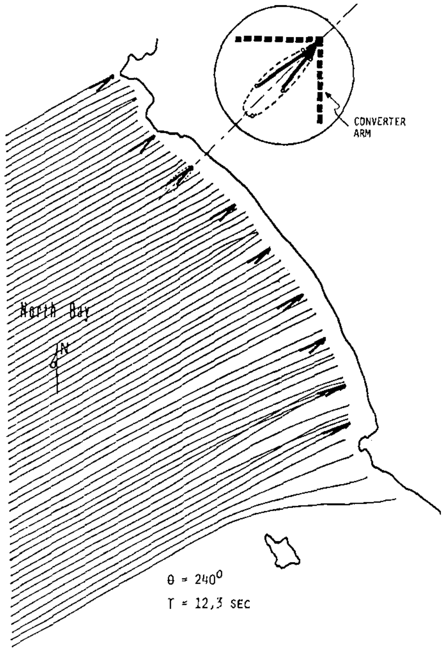

FIGURE 17: Converter Orientation Studies

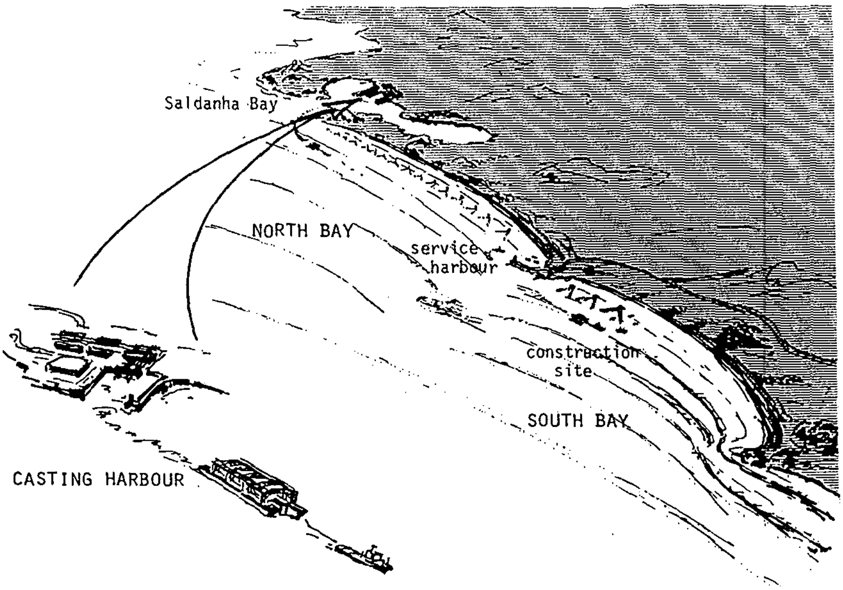

FIGURE 18: Construction Scenario

## 6. MAINTENANCE ANO COSTING

Apart from the annual servicing of the flap valves and generator unit, maintenance of the converter is expected to be relatively low and not to exceed an average present day cost of (RSA) 0,6 cents per kWh over the design lifetime of 50 years. Marine growth in the submerged section of the oscillating chamber is expected to stabilize at a thickness of 120 mm and has not been found to affect conversion efficiency. Water is expected to accumulate in the air ducts and turbine chamber and will be drained to collector points and automatically pumped out. An optimum air volume in the converter will be maintained by an electrically driven air pump housed in the generator tower. Navigation lights will be mounted at each end of the "V" and on the generator tower.

As the "elasticity" of the national electricity supply network can easily accommodate the expected variability in supply from this relatively minor source of power, costing has been based on total utilisation of the output from the converter array, which for an average year is 2,2 GWh of power delivered to the network (i.e. 14300 MWh per "V" per year).

The capital cost of a single "V".unit (based on the gravity option which was found to be less than the piled structure) is estimated at (RSA) R8,3 m. The projected cost of power delivered covers a range of values depending on the combination of financial parameters assumed. For an economic horizon of 30 years, an interest rate of 15% and an inflation rate of 12%, the present day cost of power delivered (discounted at 10%)

ranges from 2,6c/kWh (for a power tarif coupled to inflation) to 4,3c/kWh (for a tarif increase rate equal to 80% of inflation rate).

These figures compare very favourably with the present cost of nuclear power (RSA 5,6c/kWh) and coal fired power (RSA 4,7c/kWh) for the same area (SAICE, 1984).

## 7. CONCLUSION

The proposed 770 MW (rated output) wave power converter has been studied in sufficient detail to establish both a predictable means of implementation at what is considered to be a reliable estimate of the costs involved. An attempt has been made throughout the study to adapt a conservative approach to those areas which are as yet unproven. The system proposed is however well within the capability of present day technology and as there is scope for further reduction in the projected costs (by more rigorous optimisation of the civil engineering design vis-a-vis power conversion) the SWEC is considered to be a viable and attractive supplementary source of power.

## ACKNOWLEDGEMENTS

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