

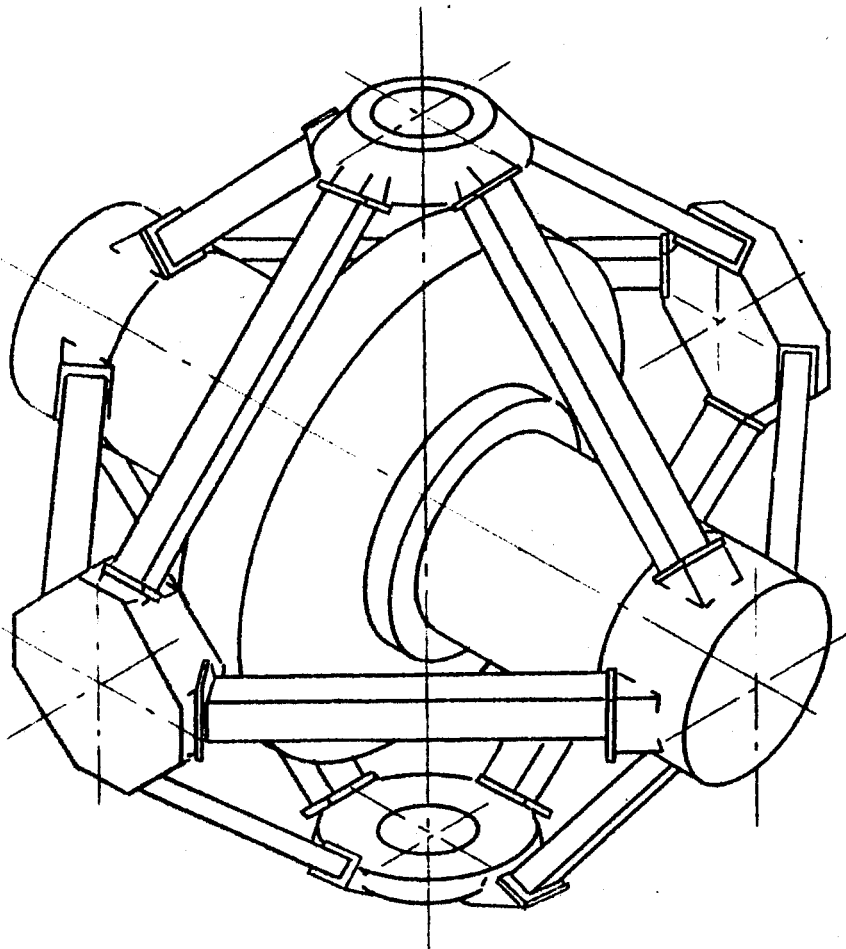
COMMERCIAL IN CONFIDENCE

Edinburgh-Scopa-Laing

# Wave Energy Group

Fifth Year Report

Volume 2 of 3



November 1979

Laing

EDINBURGH - SCOPA - LAING

WAVE ENERGY GROUP

FIFTH YEAR REPORT

on

SALTER DUCKS

November 1979

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WAVE ENERGY - SALTER DUCK

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EXECUTIVE COMMENTARY

Summary of Progress 1979

This year has seen our first attack on the problems of full scale design. The team has been strengthened by engineers from Merz and McLellan, the electrical consultants (whose report has been submitted separately), and from John Laing.

We concentrated our efforts on power conversion. The design selected uses gyro precession and high pressure oil hydraulics generating synchronous AC. The gyro method allows an efficient increase in angular velocity, avoids torsion of the backbone, isolates all the generating equipment from the sea and provides so much energy storage that we can claim a benefit from the transfer of off-peak electricity into the duck system and its return at times of high demand.

The gyro method requires the solution of engineering problems which are challenging but exactly defined. One such problem is the development of a high performance variable displacement axial piston hydraulic motor. After a thorough survey the unit designed by Clerk was selected. I am happy to report that Robert Clerk is now a Research Fellow at Edinburgh and that his design is to be taken up by industry.

Final decisions on the design of backbone section and joints need data from tests on the wide tank model. The present reference design is based on extrapolations from narrow tank results, agreed with the Department of Energy's consultants.

Progress on the working model free floating string of ducks has not been as rapid as we had hoped. We realised that if the benefits of compliant mountings were to be investigated it would

be necessary to control a very wide range of joint characteristics. We have designed an electronically controlled intelligent joint moved by an actuator inside each section of backbone. If the mooring forces are as low as predicted their measurements might be influenced by the stiffness of signal wires and so we have decided to build the computer multiplexing system into the individual ducks and backbone sections. While the production of the mechanical parts is nearly complete and their assembly begun the electronic side is still in the development stage. When complete it will include many of the features of the full scale system.

Tests in the narrow tank have been concerned with exploitation of the discovery of compliant mounting effects, and with the generation of energy from joint motion. The results allow the displacement of full scale equipment to be halved from last year's sizes without loss of output.

We have built an analogue network which models the properties of gyro power take-off and sends the correct torque signals to the model in the tank. No changes in efficiency have been observed between this and the previous arrangement. The drift of gyros can be controlled.

We have built apparatus for airborne wave height measurement using Machin's radar altimeter technique. The equipment has passed strict airforce specifications and one sortie has been flown. A report has been submitted and is referred to in Appendix II. The records have the statistical and spectral properties of sea waves and the RMS values are in good agreement with wave-rider output on the day of the flight. We were impressed by the efficiency shown by the air crew and are confident that the method will allow the collection of wave data over a wide area if WESC decide that this is desirable.

The wide tank has been used for a second year by other device groups. Its reliability has been satisfactory with outage time of one hour twenty minutes, a small improvement on the previous

year. Some of the visitors have used the multichannel data acquisition system and the analysis software written for the PDP11. An array of one hundred conductivity compensated gauges has been built and is undergoing calibration tests. We have helped with the design of the wave makers for the new wide tank at Wave Power Ltd.

Consideration has been given to the possibility of electricity transmission from wavefields further offshore. I believe that developments in sulphur hexafluoride insulation or superconducting cables would make it possible to build a spur projecting north west from Cape Wrath for much larger distances than at present planned for the inshore wave fields. I would like to draw the attention of WESC to a report by Babbie Shaw and Morton on the feasibility of long range tunnels.

Our accommodation problem has been reduced by the purchase of a temporary Portacabin type drawing office. Planning permission for a mezzanine floor in the wide tank has been granted and the parts have arrived. The shortage of accommodation will impose increasingly severe limits to progress in the future. Architect's plans for a heavy testing laboratory have been submitted.

The University members of the group are happy to be associated with the high levels of professional competence shown by their industrial colleagues, and their morale is excellent. The work of this year has produced a fall by a factor of eight in the expected cost of duck electricity and provided substantial evidence to support the cost calculations. While I am sure that further improvements will be made it may not be possible to achieve the same proportion.

S.H.Salter

Edinburgh Scopa Laing Wave Energy Group

November 1979

## 1.0 INTRODUCTION

In the late autumn of 1978, through a mutual arrangement made between S.H. Salter, University of Edinburgh and John Laing Ltd., a senior Civil Engineer from John Laing Ltd was attached to the Edinburgh Wave Energy Project team for a limited period. At about the same time a similar arrangement was made between S.H. Salter and Scottish Off-shore Partnership (SCOPA) whereby a design engineer from Babbie Shaw and Morton also joined the Edinburgh Device Team.

Resulting from these associations, John Laing Ltd were approached by ETSU in March 1979 and invited to become integrated members of the Edinburgh Project Team and to undertake a review of the civil, mechanical and structural aspects of the Project, and SCOPA were invited to carry out a similar review in respect of electrical generation and transmission.

In each case the review represented a double brief:

- 1) To assess the viability of the device at that date and consequent upon this assessment to discuss and develop, either in-house or with outside commercial interests, the future viability and credibility of the Edinburgh Device.

Resulting from this assessment, develop a provisional cost per kilowatt-hour of power generated on the basis of two Gigawatts (GW) installed capacity.

- 2) To establish and maintain close links with the Department's Consulting Engineers in order to try and obtain agreement between all parties in respect of design parameters, and details of device performance as a basis for the 1979 Report.

For the purposes of the overall exercise it was necessary to select a size from the range of possibilities and a 10 metre Duck of profile D0019 was chosen. The size of a duck is related to the diameter at the rear body over the spine and sizes range from 7.5m to 15m.

### 1.1 Design Work

Within the very short time that has been available for the assessment of the Edinburgh Device, and also taking into account the current state of device development, it has not been possible to produce more than outline schematic drawings and specifications upon which to assess viability and credibility. It would be foolhardy to say that all problems in respect of the device have been solved - this is certainly not so. However it is readily apparent that very significant progress has been made during the year towards providing credible solutions to many of the problems which were outstanding at the end of last year.

Before developing the work of the year in detail, it is felt right to comment upon certain aspects of the basic approach of the device team to Wave Energy:

### 1.2 Maintenance

From the outset, the approach of the device team has been to develop a device which requires minimum maintenance. The team discount the practicability of carrying out skilled maintenance at sea. No matter how well trained and technically capable an operative may be, it is felt that it is impractical to consider carrying out repairs and maintenance to the standard required when operating in a wet, dank, humid environment at comparatively low temperatures, within a structure that is constantly moving with an irregular motion.

The approach of the team has been therefore to instal the main mechanical and electrical equipment for power generation in a non-corrosive non-oxidizing environment isolated from the adverse conditions in the ocean.

Provision for interchangeability has been included and assemblies of spine units to permit complete replacement of failed units and subsequent repair under favourable conditions in a shore basin.

### 1.3 Viability

In carrying out the assessment of viability in respect of the civil, mechanical, structural and hydraulic aspects approaches were made to many specialist firms in respect of the device proposed. These approaches were based on schematic designs, albeit in many cases developed in considerable detail. In all cases, the companies approached confirmed that the proposals either incorporated their current practice, or, alternatively that the methods proposed were not their current practice but that they could foresee no reason why the proposed methods should not be developed.

In no case were the proposals considered to be outside current technology.

The technical viability of the device is supported to a considerable extent, by the interest shown - and the offer of willing future co-operation - by so many experienced companies in a variety of fields.

#### 1.4 Credibility

Credibility is essentially a subjective area of assessment and it is not easy to provide positive answers. Many of the proposals incorporate current practice and raise little or no doubt concerning credibility. Others, particularly those of the outstanding problem areas on which the main work of the team is currently centred, are areas where a technically acceptable answer has been devised but which it is felt requires refinement or improvement in order to provide operational reliability and hence credibility.

In many of these areas, it must be emphasised that considerably more research work is required in order to establish more clearly the true nature of the problem and within the concluding remarks these current problem areas will be developed in greater detail.

Bearing in mind the limited time of the current assessment, the device appears credible but a great deal of further detail work must be carried out both in research and development to reinforce the established confidence levels in the proposals.

## 2.0 DESCRIPTION OF SCHEME

### 2.1 Reference Design

This report has been compiled on a connected 2000 MW station.

Each Duck will have a peak output of 2.25 MW based on 75 kW/metre mechanical output x 30 m theoretical length. It is a hydrodynamic attribute that a duck 24m wide with a gap of 6m between ducks will act as though it is 30m wide. The mean annual average figure used is 20 kW/metre modified by a global conversion figure (allowing for the angle of approach of the wave). The conversion efficiency should be about 0.8 giving a landed electrical output of 14 kW/ metre assuming good equipment reliability.

A Duck is sized by the nominal diameter of the rear body at the spine. The reference size is 10 metres, suitable for the seas expected at the location selected (some 30 km offshore at South Uist, in a water depth of approximately 100 m). Ducks of from 7.5 m to 15 m might be selected for other sites if cost effectiveness were to become the prime consideration. The shape chosen is a medium beaked duck to section D0019 (see Edinburgh Fourth Year Report Page 3.1).

The ducks will be mounted in pairs on a 60 m spine length with freedom to rotate independently about the spine axis. Spine lengths will be connected with a universal joint of controllable stiffness. Each joint will embody a 'sea-mateable' section, the sections being alternately 'male' at both ends and 'female' at

both ends to ensure a uniform depth of flotation for both sections without recourse to ballast. The spine and duck body will include buoyancy tanks to allow the correct flotation attitude and degree of submergence.

Power take-off is based on the use of gyroscopes freely mounted in gimbals, the flywheels of which are used as power accumulators. The gyroscopic precession of the units is used to drive a series of ring cam reciprocating pumps mounted around the frame surrounding the flywheels. The rate of power extracted is initially controlled by selecting the number of pumping cylinders to be operating at any one time. Two ring cam pumps per gyro module feed at a constant pressure, probably 3200 psi (220.5 bar), into a common main, the output of which is fed to a 1500 HP 1500 RPM swashplate motor coupled to one end of an A.C generator and to the two motors driving each gyro. Two pairs of such gyro/motor systems are used per duck giving a total output of 2.25 megawatt (MW). The hydraulic motor attached to each end of the generator can become a pump, driven by the generator acting as an electric motor, for spinning up the flywheels and starting up the system. 'Fine tuning' of the system is achieved by motoring the flywheels to increase their nominal speed above 1500 RPM and thereby store surplus energy. Conversely energy can be extracted from the flywheels by angling the swashplate to cause the motor to pump, to maintain delivery into the common main to satisfy the constant generator requirement and to release the stored surplus energy. It should be noted that the cyclic variation in the flywheel speed necessary to absorb and release stored energy from a 10 second burst will be 2 RPM in 1500 RPM.

The spine joints will have a controlled compliance in the interest of efficiency, but it is also envisaged that in the future additional power will be obtained from the spine joint movement by means of a further pump/motor unit connected to the sets of hydraulic rams controlling the joint stiffness. The generators associated with the joint motors will be electrically in parallel with those in the duck body and can derive or send power to the gyros. This has an advantage in very rough weather when the gyros have reached their operational limit.

All generating machinery will be contained in sealed pressure vessels with a low pressure atmosphere of a suitable gas, thus reducing windage losses and at the same time reducing possible corrosion and contamination. As mentioned in the Introduction, no arrangements for internal maintenance are being made but by designed redundancy the design target life of 90% survival for 25 years is anticipated.

The duck-to-shore electrical power system is capable of handling 5 parallel 400 MW circuits and transmitting to the grid at 400 KV (notionally at Cruachan). This is described in detail under SCOPA Report Ref. N13.7/469 of November 1979.

## 2.2 The Sea

The data on which the design of the Ducks is based is presented in the Annual Reports (1 to 5 inclusive) of the Edinburgh Wave Power Project Team. This information stems from tests in the Narrow and Wide Tanks based on information from OWS India, and IOS, South

Uist. From these reports it will be seen that a mean annual average of 20 KW/m is available. The ducks have been sized for a peak output of 75 KW/m, and a torque limit of 0.75 MNm/m.

### 2.3 The Duck

The Duck is akin to a small section of ship designed specifically to roll. It is carried on a jointed spine to ensure optimum hydrodynamic efficiency in all sea conditions. A number of Ducks are mounted in a string.

The Duck comprises a Body and a Beak which are attached to the spine by means of retaining straps mounted around a bearing. The Body houses buoyancy chambers while the Beak contains a vessel in which is the main power generation equipment, termed the Power Module. The Duck normally rides with its Beak at sea level and lying with its centre line at an angle of some 37° to the horizontal. However, in extreme seas it may be submerged to about 30 metres, at which depth it will continue to generate (at 75 kW/metre). The use of reinforced and prestressed concrete is currently envisaged for its construction using well tried methods. Each duck will displace 2,800 tonnes, and will be about 25 m in length, the diameter of the rear body being 10m.

Alternative beaks in concrete, wood and steel fabrications have been studied, the results being included in Appendix 3.

Buoyancy chambers built into the structure are arranged to be flooded or 'blown' as required to give the correct degree of flotation. Details of the design appear in Appendix 2.

### 2.3.1 General Requirements for the Duck Body

- a) to support the detachable beak which contains the sealed pressure vessel containing the power module.
- b) to transmit wave forces as necessary to the power module.
- c) to maintain the correct freeboard and attitude in still water conditions for optimum power off-take in design wave conditions, by the use of a small element of ballasting for control purposes.
- d) to possess self-righting properties in the event of capsize.
- e) to be capable of resisting hydrostatic pressure due to submergence to 30 metres depth.
- f) to carry power cable reeling device.

### 2.3.2 General Description of the Duck

The duck consists of a boat shaped structure 25m long, having a beam of approximately 12m and located on the spine by two steel retaining straps of box girder construction. The ducks are ballasted using both concrete and sea water ballast to ensure that they float at the right attitude. Each duck consists of 2 distinct parts viz:

- a) Duck Beak - this will be of all steel construction and will contain the main pressure vessel consisting of a steel tube 4.8m O.D. (containing the gyroscopes, generators etc). It will also contain 3 smaller buoyancy pressure vessels. The envelope is of welded steel plate construction, the space between the various pressure vessels and the envelope being occupied by fresh water. The beak is attached to the body at four main attachment points which transmit the hydrodynamic forces between the two without excessive restraint which might cause distress to the pressure vessel. Lightly stressed attachments connect the edges of the envelope of the beak to the duck body. It is intended that all connections between beak and body can easily be severed for recovery of the beak from the sea bed in the event of the duck accidentally sinking.
  
- b) Duck Body - this may be of steel plate construction or of cellular lightweight concrete.
  - i) Steel Duck Body - this would be of steel plate construction having full diaphragms at approximately 800mm centres, and longitudinal plate stiffening ribs at 800mm centres. It would contain several cylindrical pressure vessels for buoyancy. The ducks attitude in the

water would be controlled by taking on sea water ballast into the buoyancy chambers. The space between the buoyancy vessels and the envelope would be occupied by fresh water.

- ii) Concrete Duck Body - this would be constructed from reinforced lightweight "Lyttag" concrete using natural sand fines and having a high cement content. The duck body would be of segmental construction, the segments being jointed using an epoxy resin and would be prestressed together longitudinally. Internal voids may be flooded with sea water to control the buoyancy and attitude of the duck. With both types of body, a main diaphragm occurs across the body at two points along the length at which the retaining straps around the spine are attached on the one hand and the pressure vessel on the other. In the case of the concrete body, these attachments will be prestressed together.

### 2.3.3 Design Parameters for the Duck

- a) The duck is to withstand a local point pressure of up to  $190 \text{ KN/m}^2$  due to dynamic wave action.
- b) The duck is to withstand a working hydrostatic pressure of  $300 \text{ KN/m}^2$  and an ultimate hydrostatic pressure of  $1000 \text{ KN/m}^2$  due to submergence to 30 and 100m respectively.

- c) The duck is to float in still water with the centre of the spine 5.5m below water level, and the centre line of the duck inclined at  $37^{\circ}$  to the horizontal.
- d) The centre of gravity of the duck is to be such that a line from it to the centre of the spine shall make an angle of  $2^{\circ} - 7.5^{\circ}$  with the centre line of the duck and hence render the duck self-righting.
- e) The free-board and the attitude of the duck is to be controlled by use of sea water ballast.
- f) The beak is to be bolted to the body to allow for recovery.
- g) The power cable connecting the duck to the spine is to be able to accommodate the duck motion without the use of moving contacts.

#### 2.3.4 Design Features

##### a) Buoyancy

The displacement of the duck when fully submerged is about 1220 tonnes, and when floating in the correct attitude (in still water) it is about 1150 tonnes. Hence it has an effective buoyancy margin of about 170 tonnes. Ballast/buoyancy tanks are provided to maintain attitude and depth, and may be used to sink the duck (and the neutrally buoyant spine) below wave action.

b) Structural Strength

i) Steelwork

The envelope would be designed to withstand the dynamic water forces only. The fresh water inside the duck would be separated from the sea water outside by a diaphragm incorporating a pressure equalising device, and only the internal pressure vessels would be designed to withstand the full hydrostatic forces.

ii) Concrete Structure

The concrete body would be designed to withstand the full hydrostatic forces acting on the envelope. It should also be able to withstand these hydrostatic pressures in any of the internal voids. Longitudinal prestressing, as well as serving to string together precast segments in the event of this mode of construction being used, is proposed to withstand the fatigue effects of as yet unquantified racking stresses caused by oblique wave fronts. Some transverse prestress is also envisaged through the narrow neck between spine and beak to cope with local stress concentration due to handling in the construction yard as well as at sea. Due to the complexity

of the necessary stress analyses which will probably require finite element methods, detailed structural calculations to verify the concrete sizes etc have not yet been finalised.

c) The Power cable connecting duck to Spine

The power cable connecting the duck to the spine passes down the length of the duck in a duct containing sea water. At one end of the duct it passes into the main pressure vessel containing the gyroscopes and generators, and at the other end it is wound on a concentric cable-reel of about 2.4m diameter. From the cable-reel it passes through the duck wall and round the outside of the spine, entering the spine on the opposite side to the duck. As the duck "nods" the cable is taken up or let out by the reel which is driven by a belt round the spine and reel drum.

d) Longitudinal Location of the Duck on the Spine

Rubber tyres on compliant mountings, located in sockets at each end of the duck and running on the external spine flanges serve to locate the ducks longitudinally on the spine.

## 2.4 The Spine

The spine comprises a number of sections each carrying a pair of Ducks. Currently joints between each length of spine have so been designed to provide flexibility

up to  $\pm 12^\circ$  per joint and hydraulic rams arranged to control the joint both horizontally (surge) and vertically (heave). This compliance of the spine (i.e. the control of these joints) is a particular feature of the concept, which allows maximum hydrodynamic efficiency, low mooring forces, and the possible opportunity (later) of a significant increase in the captured power.

It is envisaged that the spine will be of concrete construction and that it will be in sections 9.8 metres in diameter by 60 metres long. The joints will be a complete steel fabrication embodying a Hookes joint, about which all movements take place, and a fixed element. Each joint will contain 12 double acting rams arranged around a 7.5 m diameter pitch circle. But into the central 2m section which allows all electrical connections to be made at sea referred to as a "sea-mateable" joint. These rams will be cross connected in sets of 3. Thus the front end of a group of three surge rams on one side will be connected to the rear of the opposite set of 3 surge rams and vice versa so that one connecting pipe will be at high pressure while the other is at low pressure (see drawing No 1011). A swashplate motor (of the type used in the duck itself) complete with its own A.C generator will be connected between the high and low pressure sides. The swashplate can now be used to control the pressure in the rams and therefore the applied bending moment. Compliance of the joint will be controlled and the power thus generated could be absorbed into the transmission system.

The cylinders will be approximately 750 mm bore diameter with a rod of 250 mm diameter each giving some 800 tonnes thrust. The bending moment generated will be up to 20,000 tonne metres.

#### 2.4.1 General Requirements for the Spine

- a) To connect ducks into a string to provide the specific degree of rigidity which will optimise the duck performance.
- b) To provide a continuous duct for routing up to 100 MW of electrical power and a protected path for control cables.
- c) To have neutral buoyancy in the operating condition but with an internal reserve for trimming.
- d) To provide attachment locations for mooring cables.
- e) To provide a housing for step-up transformers at intervals at which the cable links to shore occur.

#### 2.4.2 General Description of the Spine

The spine will consist of concrete tubes, prestressed longitudinally and reinforced in the circumferential directions in lengths of approximately 60 metres, with two ducks mounted on each. These lengths will be connected by a mechanical universal joint controlled by a hydraulic ram system by means of which the compliance of the spine as a whole can be varied.

The mechanical and hydraulic parts of the joint are carried by a steel fabrication which is attached to the concrete tubes by prestressed bolts, and also serves as a closing bulkhead at the open end of each tube.

The concrete tube is provided with internal and external flanges in reinforced concrete which act as stiffening to the tubular walls against non-uniform pressures exerted, for instance, by the duck bearings. The external flanges also serve as a longitudinal location for the ducks and for the attachment of mooring cables. Bearing rings of Cupro-nickel plate are strapped and glued to the outer surface of the spine to provide a suitable surface for the duck bearing material ("slubber") to run on.

Buoyancy reserve is provided by means of a number of steel pipes acting as ballast tanks within the concrete tube so that stabilization of the spine can be achieved.

#### 2.4.3 Design Parameters for the Spine

a) The deflection of the mechanical/hydraulic joint will prevent the bending moment at the end of the concrete tube rising above 20,000 tonne-metres up to a maximum angle of  $\pm 12^\circ$  - the maximum angle which can be achieved with ram technology. Limit stops prevent joint deflection exceeding  $12^\circ$  leading to increased joint moments in extreme conditions. Data from future wide tank experiments will confirm the exact requirements here which could involve alternative joint designs with longer

angular capabilities. Our estimate of the probability of various angles is given in Appendix 9.

- b) A longitudinal tensile force of 1,000 tonnes due to chord shortening during wave deflection of the spine. This could be simultaneous with the design bending moment above, and is limited by zig-zagging the spine.
- c) A torsion of 10,000 tonne-metres due to the zig-zag.
- d) A transverse shear of 2,000 tonnes which is not simultaneous with the design bending moment.
- e) Account must be taken of the necessary fatigue life of the structural elements. In a 25 year life approximately  $8 \times 10^7$  waves will be encountered, of which it is anticipated  $1.1 \times 10^7$  will cause bending moments at the joints of 20,000 tonne-metres. A number of cases of moment exceeding this value may occur as indicated above; the number and extent of such exceedances cannot be estimated until further research has been done. Alternatively they may be limited in number by sinking the duck string in extreme conditions. (See 4th and 5th year reports of Edinburgh University Wave Energy Group).
- f) Due to wave action on the length of spine between the joints, a local bending moment at the centre of a 60m section of 28-30,000 tonne-metres may occur.

#### 2.4.4 Design Features

##### a) Buoyancy

The displacement of a 60 metre module length of the spine is about 4050 tonnes and the combined bare weight of the spine and mechanical/hydraulic joint is about 3400 tonnes giving a net buoyancy of 650 tonnes. Ballast tanks as described above are provided to maintain attitude and depth regardless of varying weights of structure, machinery, and marine growth.

##### b) Structural Strength

- (i) The bending strength of the spine has been calculated using normal weight concrete of 50 N/mm<sup>2</sup> cube strength prestressed either to 0.2 fcu or 0.25 fcu (ie 10 or 12.5 N/mm<sup>2</sup>) using prestressing tendons of 18mm diameter "Dyform" strand (exerting in the latter case, a total force of 16,500 tonnes). A graph illustrating the variation of extreme fibre strain with bending moment is attached (Drg. No L 2001) from which also the "failure" bending moment can be seen. It is then necessary to apply the concept of "fatigue life" to determine the number of bending moment reversals that can safely be sustained over the design life of the spine; to do this, it is necessary to have a histogram of occurrences of bending moments of different values and also to have S - N

curves (stress range versus number of repetitions to failure) for concrete and prestressing steel, appropriate to the circumstances; from these, by application of Miner's Rule, the adequacy of the structural strength can be determined. Currently, it is possible only to estimate the number of bending moment occurrences of a given value from the theoretical behaviour of a rigid spine in simplified wave conditions which yields, for instance, the figure quoted in 3e above. Also, there is little information on the fatigue behaviour of concrete, either plain or reinforced, in compression, or of the behaviour of prestressing strand.

From the bending moment/strain diagram, the strains for the various bending moments can be transferred onto the appropriate stress/strain diagrams for concrete and prestressing steel and the stress ranges obtained in each case; this has been shown on the diagrams (Drg Nos L 2002 and 2003) for bending moments of 20,000 and 30,000 tonne-metres. The diagrams on Drg Nos L 2004 and L 2005 are tentative S - N curves for plain concrete and prestressing steel. The curves for concrete are based on tests on plain concrete cubes reported in the Abeles Symposium "Fatigue of Concrete" - it will be seen that for a moment of 20,000 tonne-metres ( a stress range of 0.49 and a maximum of 0.76) we can

anticipate a life of perhaps  $3 \times 10^5$  repetitions and for 30,000 tonne-metres (a stress range of 0.76 with a maximum of 0.86) a life of 600 repetitions. The curves for prestressing steel (Drg L 2005) are based on a Goodman diagram for  $2 \times 10^6$  cycles supplied privately by Bridon Wire Limited, and indicate that the fatigue life for 20,000 tonne-metres moment is approximately  $1 \times 10^7$  repetitions and for 30,000 tonne-metres,  $5 \times 10^6$  repetitions. These figures, particularly for the concrete, tend to suggest that fatigue performance will be inadequate but there are a number of areas in which the calculations are very pessimistic:

Firstly, in deriving the bending moment /strain curves, the stress/strain diagram for concrete (Drg No L 2002) has been taken from CP110; this is based on the behaviour of rectangular beams in bending and gives an ultimate stress of 0.44 fcu. Regan and Hamadi in their paper on "Hollow Cylindrical Members in Combined Shear and Bending" in the Concrete in the Oceans research programme state that for such members it is more appropriate to consider the stress in the compression flange as an axial compression. They therefore use an ultimate stress of 0.72 fcu in their analysis, and find very good correlation with the experimental results. The adoption of a higher ultimate stress

figure such as this, would produce substantially lower concrete stress range values for the spine.

Secondly, the S - N curves for concrete are based on plain concrete cubes, since we have found that all experimental fatigue work on reinforced concrete has been on beams in bending where the fatigue strength has been limited by the tensile reinforcement. It is to be expected that the reinforcement in compression members (or compression flanges) would have a very helpful effect in extending fatigue life; also, it is likely that the smooth profile of a cylindrical tube as compared with the angular nature of a cube would lead to improved fatigue performance. Of the S - N curves presented a number have been estimated, but further curves at lower maximum stress values relevant to full estimation of fatigue life cannot be extrapolated.

Lastly, the S - N curves for prestressing steel are based on very limited information. The Goodman diagram supplied to us is largely conjecture; while ostensibly for  $2 \times 10^6$  cycles, 5 tests out of 9 were stopped without failure at that number, 2 were carried to  $10 \times 10^6$  cycles without failure, and 2 samples failed at less than  $2 \times 10^6$  cycles (1 probably due to grip damage). It is probable that if thorough and extensive

tests to failure were carried out, the fatigue performance would be found to be better than suggested by the S - N curve presented.

The discussion above is therefore intended to explain our approach to the fatigue problem and not to justify by itself the structural solution indicated, although we are confident that the solution will be found viable.

- (ii) The shear strength of the Section of the spine has been checked after reference to the "Concrete in the Oceans" research on prestressed concrete cylindrical tubes and found to be adequate to meet the required value.
- (iii) The direct tensile force will have the effect of reducing the total prestressing force from 16,500 tonnes to 15,500 tonnes thus momentarily reducing the bending resistance of the spine by, say, 6%. At the current stage of the design, this would not appear to be a significant problem.
- (iv) The torsion in the spine due to the zig-zag produces a shearing stress which is half that caused by the transverse shear, and is satisfactory.

(Note. It is presumed in items (ii) and (iv) that the fatigue behaviour does not differ significantly from that in bending and that it is only necessary to check the stress ranges in the same way as for bendings).

## 2.5 Spine Bearing

The bearings used between the duck and the spine require to have a low co-efficient of friction and to function when fully submerged for long periods without attention. Rubber is a suitable material, used in conjunction with a cupro-nickel sheet facing on the spine local to the bearing (see Drg No 1012). The loads expected are relatively small amounting to some 10 tonnes per metre. The loads are reversing every 10 seconds or so due to wave action and this fact is exploited by the use of a series of self-pumping circular pads mounted around the spine, each acting rather like a miniature hovercraft. Instead of air pressure the pad is fed with water from a second chamber with corrugated bellows for walls. By a suitable arrangement of automatic rubber valves this second chamber is recharged by each wave motion, causing the hovercraft to fly over the cupro-nickel with negligible friction and wear. With two such bearings, each a metre wide, loads of 150 tonnes per bearing (10 tonnes per metre) create pressures of a little over 20 lbs/in<sup>2</sup>

An alternative design using conventional rubber tyred wheels is regarded as a 'fall back' to the preferred water operated and lubricated bearing described. This may also be used, in conjunction with the preferred water lubricated bearings, specifically to handle the static load conditions.

## 2.6 Moorings

Strings of ducks will be moored either parallel to the predominant wave front or in a small-angled 'zig-zag' lying generally along the prevailing wave front. The individual moorings will comprise a system of Angels and Buoys designed to give near constant tension in the mooring ropes together with minimum bending at the end fittings. The system is being designed to allow the string to be submerged to about 30 metres under storm conditions, should this prove to be the preferred method, allowing full output to be maintained whilst ensuring the survival of the structures. With the mooring forces derived from tank tests and with the compliance of the system, it has been established that the duck string can be effectively moored using current materials and technology, and the rope manufacturers anticipate that an acceptable layout, fulfilling the required 25 year design life, can be devised.

## 2.7 Generation and Transmission

This is described in full by Merz and McLellan in the Scopa Report, Ref. N1307/469 of November 1979. Generation will be at 3.3 kV from a synchronous/induction wound machine, driven by a swashplate type hydraulic pump/motor unit. This motor derives power from a hydraulic main, fed by a series of ring cam pumping cylinders. These pumps are actuated by the precessional movement of four 17 ton gyro flywheels. The flywheels, 3.05m in diameter turning at 1500 rpm, are driven by a further pair of swashplate motors and the system is such that excess power is fed to the flywheel for storage whilst a shortage is made up by absorbing power from the flywheel. The control of this load cycle is by adjustment of the swashplate angle.

Total power generated by each duck is limited by the number of ring cam pump cylinders selected by the on-board power output controller. Power from the generator, mounted in the power module in the duck beak, is taken via a constant tension reeling drum to the spine and thence along the spine to a transformer. The output from 68 ducks (34 each side of the transformer) is then converted to 132 kV and sent via a flexible cable to a sea-bed junction box. The output from 3 of these junction boxes is sent ashore along a submarine cable of 400 MW capacity.

5 such units, giving 2000 MW total, are collected on shore and stepped up to 400 kV.

## 2.8 On-Board Control and Condition Monitoring

Each duck will be provided with electronic equipment to control the various electrical, hydraulic and mechanical functions. The control unit will receive data from an on-shore control station, from the ducks own sensors and from adjacent ducks. It will set the level of generation, submergence, spine compliance and other aspects of operation so as to optimise performance to the sea state. Embodied in the equipment will be a data logger (see 2.9) and facilities to handle and process the signals received from transducers monitoring such aspects as wear on the ring cam pump performance.

## 2.9 Operation

Overall control for a string of ducks will be from a land based operating desk. Each duck will carry a data logger (rather akin to the black box carried by aircraft) and this will be interrogated at regular

intervals from the shore. Normal operation of each duck will be automatic, under its own control system, but any special instructions needed to allow for wind direction, imminent storms or the like can be imposed from the shore station.

Start-up conditions, whereby the generator in a duck becomes a motor and the coupled hydraulic units become pumps, can be arranged from the shore station both for initial start-up of each duck and for subsequent starts after a prolonged absolute calm.

Similar procedures would be used whenever need arose, to exploit the considerable energy storage available to assist land-based power station operations.

## 2.10 Construction

For the concrete components of the duck and spine a 'green-field' site has been allowed. It is anticipated that the 60m reinforced concrete spine sections will be constructed from precast ring sections. These rings will be cast vertically, lifted and rotated through 90° and then located in a jig with 100mm joint between ring segments which will be cast insitu. The complete 60m spine section will be post tensioned. It is anticipated that the duck body will be cast in transverse sections the method being generally as followed in the spine manufacture.

The lengths of spine will be fitted with pre-fabricated steel joints at each end, these being imported to the site as a complete unit. A further production line will produce the duck bodies including casting in the power module containing the main generation machinery already sealed within the pressure vessel.

For the purposes of costing the Laing site at Graythorp has been used as a base for the manufacture and/or assembly of steel components. See Drg No 1013. Procurement from specialist manufacturers has been allowed in the case of generators, gyro assemblies, hydraulic equipment, (including swashplate pump/motor units), instrumentation, controllers, rams, pumps, compressors, special electrical plugs and the like. The duck beak, spine joints and similar equipment would be fabricated on site. All items are seen as being barge-loaded for onward transportation to the spine and body manufacturing site.

A completed spine length and two ducks will be floated in calm or sheltered water and assembled together. Strings of a minimum of 6 spine lengths (i.e. 12 ducks) comprising some 360m in length, will be taken to station at one time. Once on station the 'seamateable' section within the appropriate joints will be used to string the lengths together.

#### 2.11 Start-up

As each length of ducks is added to the string it will be brought into operation by connection to the 3.3 kV line and instructing the control system from the shore-station to operate the "start-up" sequence. The generator, in each duck in turn, will run on its induction winding driving the hydraulic unit at each end in the pumping mode, pressurising the hydraulic main to 3200 psi. This enables eductor pumps positioned in the sump to raise automatically the inlet pressure to 50 psi. The gyro hydraulic units will be in the motoring mode and will commence to spin the flywheels. Once the gyros have some rotation they will begin to respond to wave motion. The ring cam pumps are thus energised and

the change-over to the generating mode effected. Then the generator hydraulic units will become motors merely by angling their swashplates to the other side and the generator will revert to normal. The synchronisation of the generator is thereafter controlled by the swashplate angle. Power into and out of the flywheels is similarly controlled by the angle of the swashplates in their hydraulic units.

## 2.12 Maintenance and Replacement

A feature of the concept is that the generation machinery, including the gyros, is being designed to be maintenance free for 25 years. The whole of this equipment is being built into a large pressure vessel in a non-corrosive, non-oxidising atmosphere at low pressure. It is felt that under these conditions the long maintenance free period is achievable. Examples are cited under Appendix 7 "Reliability Considerations."

In the event of failure however, facilities are built into each joint to enable a spine/duck assembly to be removed and replaced by another. This can be done by temporarily shutting down one transformer group, a section of 133 MW output, of some 7% of the station. The faulty unit can then be towed to base, stripped down, refurbished as necessary, and retained as a spare.

### 3.0 THE MANUFACTURING AND CONSTRUCTION PROJECT

#### 3.1 Overall Project Concept

The establishment of a favourable environment for the gyroscopes and associated power generation equipment is a major feature of the concept. This will ensure low windage losses for the gyroscope discs.

It is anticipated that the entire power module will be built, fitted out, evacuated and tested mechanically and electrically before being delivered to the main civil construction site.

For the purposes of this report the mechanical construction site is taken as Graythorp on Teesside (See Drg No 1013) but this, of course, could be any coastal site with barge loading facilities. It is assumed that fully assembled gyroscopes are delivered to this site. Also allowed for is the basic manufacture of the spine joint units.

Towing facilities using barges and tugs are allowed for in the costings to the final assembly site somewhere on the west coast of Scotland. At this site production lines for casting of spine sections and duck bodies, handling facilities for these sections and means of post tensioning the units on a production basis are allowed; together with facilities for embodying the spine joints into the spine construction. Completed beaks, including the power module, are assembled to duck bodies. Completed bodies and spines are floated into a basin and assembled into one unit. A series of spine/duck units will then be towed to station and attached to pre-laid moorings.

## 3.2 Major Mechanical Components

### 3.2.1 Gyro Assembly

The gyro assembly comprises a laminated flywheel 3.050 m diameter clamped onto a 1 metre diameter hollow shaft. The laminated flywheel consists of two opposed stacks of pressformed cymbal shaped discs. The stacks are clamped to the shaft such that the centres are under compression, this compression then partially balances the tensile stresses induced at the operating speed of 1500 rpm. For details of the prestressed laminated flywheel see Appendix 7.1.

Driving torque is transmitted from the shaft to the flywheel by two light alloy drive plates which are clamped to the shaft and to the laminated discs by conical rings at the hub.

Inside the hollow flywheel shaft are two swash-plate motor/pump units which put energy into and take it from the flywheel. Also inside the shaft are the flywheel support bearings; loads are transmitted through these bearings to the gimbals. The gimbals are supported by, and precess within, the gimbal support bearings, which are located rigidly on the inner wall of the power module. Both the flywheel support bearings and gimbal support bearings operate on the hydrostatic principal and their selection has been the result of careful consideration of the many static and dynamic loads to which they could be subjected.

The use of the inside of the hollow shaft for housing the motor/pumps and the bearings result in a compact, torsionally rigid assembly, and with its operation in a controlled environment, is ideally suited for a maintenance free operation lasting 25 years.

### 3.2.2 Clerk Swashplate Motor/Pumps

The drive motors for the gyroscopes and for the generators are mechanically identical and consequently are both covered by this section of the report.

By making the two units identical we are able to reduce considerably the number of different components within the duck with the consequent improvement in reliability and reduction in cost. This has been achieved, without any loss in efficiency, by adjusting the gyroscope proportions such that energy exchange through the gyroscope motor/pumps is the same as that through the generator motor/pumps.

1. The function of the gyroscope motor/pump is to:
  - (a) initially run the gyroscope up to speed to make the duck operational
  - (b) increase the speed of the flywheel to store surplus energy whenever the energy in a wave exceeds the design limit.

- (c) take stored energy from the flywheel to supplement that from the ring cam pumps and so maintain a constant supply for power generation.
- (d) to make up gyro bearing and windage losses.

2. The function of the generator motor/pumps is to:

- (a) supply oil to the gyroscope motor/pumps in order that they may run the gyroscope up to speed as in 1(a) above
- (b) use power from the ring cam pumps, to run the generators at 1500 rpm to supply electrical energy to the grid.

From the above it was determined that the rating of the motor/pump unit would need to be 1.125 MW at 1500 rpm and 3200 psi hydraulic oil pressure; it must also be capable of operating at 2000 rpm; these requirements would have to be met both with the unit operating as a motor and as a pump, and be continuously variable between the two extremes. The other principal requirement is, of course, that the unit should be designed for 25 years maintenance free operation. We have available to us the design of the Clerk swashplate motor/pump which meets the above requirements and is partially developed and it is appropriate at this stage to consider some of the aspects of the Clerk motor/pump which make it eminently suitable for use in the duck.

1. The Clerk unit which is fully described in Appendix 10 is a dry sump unit with all bearing points hydrostatically floated; with the consequent lack of oil churning which is normally present in a swashplate pump operating with an oil filled casing. The swashplate is floated on hydropads which are, in turn, carried by a hydrostatic arc bearing.
2. High volumetric throughput at a high speed has been achieved by counterbalancing the portface which enables the sealing clearance to be automatically adjusted to suit operating conditions. Also, port faces are angled and shaped to prevent starvation of cylinders.
3. Fully floating cylinder sleeves have hydraulic pressure outside as well as inside the cylinder. Consequently the sleeves are subject to compressive stresses only and can thus be made of hard wearing ceramics and the absence of expansion under pressure reduces leakage.
4. As all the inter-related sub-assemblies are articulated, a totally rigid casing is not necessary, and a light construction can be used; also the top and bottom casings do not even have to be spigotted together, because perfect alignment is not necessary.

Bearing in mind the availability of the Clerk swashplate design there were two obvious courses to follow to obtain a suitable unit;

- (i) Contact a pump manufacturing company with a suitable smaller unit, who would be prepared to extend their range upward.
- (ii) Contact a suitable company who specialise in high quality production in the hydraulics field to develop the Clerk motor/pump.

Both possibilities were explored and a satisfactory solution was found when we contacted a well known hydraulic equipment manufacturer.

They had for some time been considering extending their existing range of swashplate pumps to cater for the increasing demand at the 'large' end of the market and had recently made the decision to develop a new pump, based on their excellent experience with their smaller units. Here was a company actually looking for a pump to develop and in talking to us, finding one already well beyond the prototype stage.

The firm were very impressed with the Clerk motor/pump and were readily able to appreciate the many features which make the unit more efficient, more reliable and more easily manufactured than any known variable swashplate pump.

Subsequent visits to their manufacturing facilities and discussions with their technical staff confirmed their suitability for the development and production of this pump in small quantities - say up to ten per week; extended manufacturing facilities being required before the full

production rate of 100 per week could be achieved.

### 3.2.3 Ring Cam Pumps

The ring cam pumps are the first stage in converting the precessional force of the gyroscope into electrical energy; they are positive displacement piston pumps.

If we consider the swept volume of precessing gyroscope as being our Planet then the pumps are located about the Tropics of Cancer and Capricorn; this frees the Equator for structure members, and allows smaller cam rings; the pumps are actuated by stationary ring cams located at the Tropics, the pumps themselves being carried on the gimbals. There are 24 pairs of pumping cylinders being actuated by 21 pairs of cam lobes for each of the two cam rings on a gyroscope. (See Drgs No 1006 and 1007). As the cam followers pass over the cam lobes, pairs of pumping cylinders are actuated simultaneously, consequently there is no nett force on the ring perpendicular to its motion.

The unequal numbers of pumps and lobes ensure a smooth power take off as each pair of cylinders will be on a different part of its stroke at any given moment.

The pumps themselves use externally pressurised liners which are identical to those used in the swashplate pump outlined in paragraph 3.2.2. The energy of precession is transmitted to the pumps through levered cam followers to the

pistons. All connections are all spherically mounted to avoid conflicts for minor misalignments. It is very important to load the rollers evenly over their contact line with the ring cam.

The inlet poppet valve is electromagnetically operated. Opposite pairs of units 'idle' if less throughput is required. The operation of the valving is controlled by a computing electronic circuit which is part of the duck's main system controller.

The poppet valves are chosen as the most reliable valve we can find. The Sirchaust valves of internal combustion engines can achieve lifetimes approaching our requirements in a much more hostile medium.

#### 3.2.4 Ring Cams

The two double faced ring cams per gyroscope are located as described in paragraph 3.2.3, at the Tropics of Cancer and Capricorn adjacent to the ring cam pumps. The ring cams themselves are stationary relative to the gyroscope and have 2 opposed pairs of lobes each of 63.5 mm rise. The nominal diameter of each ring is 4.0m.

The cam profile has been designed to ensure that there are no shock loads and this, combined with the suitable steel and surface hardening of the faces, will give the low wear characteristics essential for this application.

Wear characteristics, the necessary surface treatment and expected life factors are encountered in the manufacture of ball races and all fall within known technology in this field. Similar background exists in the manufacture of large pumps using ring cams and confident prediction is possible.

### 3.2.5 Joint Rams

The function of the joint rams is to control the relative motion between sections of spine, both in surge and in heave. At each joint there are twelve rams equally spaced within the perimeter of the spine. The rams operate in 4 sets of three to provide positive and negative thrust in surge and heave, respectively, about the Hooke's joint which connects the spine sections.

The rams are on a 7.5 metre pitch circle diameter and they each have a diameter of 750mm and a stroke of 1.5; operating pressure is up to 3200 psi and this will enable sets of three rams to produce the required thrusts of plus or minus 2750 tonnes. Each ram cylinder is of steel and mounted on gimbals to allow for the designed  $\pm 12^\circ$  relative angular movement of the spine sections. The piston rod is also universally mounted and all bearing points are hydrostatically floated. To ensure shock-free loading the pistons have been designed such that just before bottoming their movement is considerably dampened. The energy which is to be dissipated is utilised in driving a swashplate motor/pump which will drive a generator/motor and would produce additional power. Conversely

external power can be used to drive the rams and dictate the relative positions of the spine sections. The swashplate motor/pump is identical to that used to drive the generators and flywheels in the ducks themselves, and so keeps the number of different components to a minimum. The total distance moved by the rams during one year's operation will be of the order of 15 Km.

#### 3.2.6 Hydraulic Fluid Low Pressure Return Pump

The purpose of this pump is to return lubricating oil from the sump at the bottom of the power module to the low pressure circuit. A difficulty is that the pressure within the power module is only 10mm Hg. absolute. This means that very little suction head is available to prevent the scavenging pump from cavitating.

This problem is solved however by using kinetic energy type scavenging pumps mounted in such positions that whichever attitude the duck adopts there is a positive head of liquid to the pump which ensures satisfactory suction conditions. The pump used is an electric motor driven unit of approximately 20 KW.

#### 3.2.7 Start-up Hydraulic Fluid Pump and Driver

Before a duck can be put into operation all the hydraulic bearings will have to be floated using high pressure oil. As oil from the ring cam pumps will not be available for start-up, a pump is required to take oil from the reservoir and boost it to 3200 psi for use in the bearings and for driving the scavenging pump.

The pump to be used will be a swashplate pump driven by an electric motor. Once the duck is operational the pump will be stopped and bearing oil will then be taken from the main high pressure oil circuit fed by the ring cam pumps.

### 3.2.8 Duck Cable Reel

The purpose of the cable reel is to feed cable between the spine and the duck as they move relative to each other. The movement of the cable must be kept to a minimum such that strain in the flat stranded copper cable is low enough to ensure no failure in  $10^8$  cycles. The edges of the flat cable will be steel for protection of the copper. The drum on which the cable is stored will be rewound by an opposing, more elastic belt. This will keep the electrical cable under controlled tension despite variations in duck to backbone distance.

From the spine the cable is wound round the drum, the chamber passes through the drum centre and along the chamber axis before entering the module. This ensures adequate length in which the cable can absorb the necessary flexure without significant stress.

Relative angular movement between the spine and the duck will be less than  $300^\circ$  and the drum, which will be 2.5m diameter, will rotate through  $3\frac{1}{3}$  revolutions maximum.

### 3.2.9 Duck Ballast System

The duck incorporates a ballast system to regulate the level of flotation. This could be used for submergence during storm periods and resurfacing once weather conditions return to normal. The ballast system has been designed to allow the duck to move from normal surface operation to a submerged depth of 30m in one hour and to return to normal surface operation in a similar period.

The ballast system will comprise the following equipment:

Ballast chambers, of total capacity, 180m<sup>3</sup>, will be placed at strategic positions within the duck. These chambers will admit sea water to the duck to bring about the required changes in buoyancy. Each chamber is connected to the sea by a balancing valve which is used to control rate of descent/ascent, trimming etc. Each ballast chamber is fitted with a diaphragm to separate sea water from the air used to provide the motive power for discharging ballast.

Two diaphragm compressors withdraw motive air from the ballast chamber and transfer it to high pressure storage bottles. Provided that motive air remains free of contamination no serious problems are expected with diaphragm life. Heat from the compressor inter and after coolers is rejected into the ducks main hydraulic oil system.

High pressure storage bottles store the motive air received from the compression system whilst the duck is submerged in readiness for surfacing. These bottles operate at a maximum pressure of 200 bar. In addition a further set of storage bottles supplies make up air to the ballast system to ensure the charge remains adequate.

A control system regulates all variables in the ballast system and ensures the normal submergence operating cycle is completed smoothly, and also operates the compressors at regular intervals to prevent deterioration and ensure availability at all times.

#### 3.2.10 Pressure Vessel

This environmental container for the power generation equipment is a vessel 25m long x 4.8m diameter and weighs 108 tonnes empty. It will contain about 160 tonnes of machinery. It is of all welded, mild steel construction with stiffened flat plate ends, and circumferential stiffening rings. There are four strakes of thicker material in line with the four gyro assemblies, and the vessel embodies means of attachment to the duck beak. These two features ensure that the torque generated by the nodding of the duck is passed directly into the gyroscope assemblies. (See Appendix 1).

### 3.3 Manufacturing Facilities

Manufacture of the mechanical and electrical components will be placed with specialist companies throughout the country. It may well be that for certain components, a number of sources will be established. Full cognaisance will be taken of the quantities involved to keep the costs as low as possible. It may be necessary to establish new factories tailored to handle the required volume of products.

The pressure vessel and beak, together with the spine joints are allowed for as being manufactured at a specially set-up yard, at which assembly of the other mechanical components will take place.

### 3.4 Construction Facilities

Costs are based on the establishment of a green-field site somewhere on the West Coast of Scotland carrying out all the civil aspects.

Three lines of seven casting positions are envisaged for the duck bodies, producing one body every two working days.

A similar arrangement adjacent will poduce one spine unit every four days.

The breakdown of costs is given in Appendix 7.7.

### 3.5 Component Testing

The construction philosophy assumes that each component will be extensively tested and inspected (beyond normal acceptance standards) at its place of manufacture.

This work may well be carried out by a separate inspection organisation.

Each hydraulic motor will be run on a suitable dynamometer and its output checked.

Each flywheel assembly will be run up to its maximum speed of 2,000 rpm in a suitable enclosure.

Hydraulic and electrical components will be similarly tested to high standards.

All components will be suitably protected against the ingress of dirt during delivery to the assembly site.

### 3.6 Commissioning

#### 3.6.1 On Land

After final assembly of all equipment into the power module, the vessel will be sealed, evacuated, supplied with hydraulic fluid, furnished with its ultimate environment and put to work in a suitable rocking fixture simulating the motion of a duck and the electrical power output will be checked for voltage, current and frequency.

3.3 KV will be applied to the pod output terminals with the control centre set to the start-up mode. Generation mode will then be selected.

A series of diagnostic signals will be applied to the duck control centre and the responses checked.

### 3.6.2 At Sea

Once the assembly is positioned on station and attached to its moorings and its output cable, in suitable numbers, the start-up mode will be instituted from the Shore Control Station, the gyroscopes run up to full speed and the string set to "generate." Automatic control from the on-board control centre will then be established.

### 3.7 Placing Moorings

Allowance has been made for the placing of moorings by conventional use of barges and tugs. Each set of moorings, every 60m, will be provided with a central marker buoy at which point the ducks will be finally attached.

The rodes for each mooring will be continuous from anchor to anchor with a clamping system used at the ducks and each buoy and sinker. PVC Sheathed "Kevlar" or "Parafil" are thought to be suitable materials.

### 3.8 Tow-out and Hook-up

It is assumed that moorings will be pre-laid. Costs have been arrived at on the basis of conventional tugs and barges for positioning ducks on station.

It is in mind, however, that with a suitable power input, the spine joints could be enlivened such that a set of approximately eight ducks (on four spines) may be persuaded to swim in an eel-like fashion, thus dispensing with the tug. Helicopters could be used to supervise all movements.

It is anticipated that six pairs of ducks would be put on a station at one time with the fixed sea-matable joint between them already made. The joint between the sets of six would be made at sea in the manner designed.

### 3.9 Programme

Cost calculations have been done on the basis of one duck per two days and one spine per four days.

This summates to an overall ten year period for 1020 ducks (i.e. 2 GW output) allowing nine months within the period to set up the manufacturing facilities. There is, of course, scope to accelerate production beyond this cost basis. The programme anticipates that ducks will be put to work in sets of 68, with an output capability of some 150 MW. These are convenient sections for electrical connection and could be added to at approximately eight monthly intervals over nine years.

### 3.10 Estimating

Estimating has been carried out on the following unit prices where no firm quotation was available.

|                                    |           |
|------------------------------------|-----------|
| High precision machined components | £3000/ton |
| Medium quality machined components | £2000/ton |
| High grade steel fabrications      | £1200/ton |
| Low grade steel fabrications       | £ 600/ton |
| Concrete (placed)                  | £ 120/ton |

Full details of estimated mechanical, civil and construction costs are given in Appendix 7.

#### 4.0 OPERATION OF THE POWER STATION

##### 4.1 Introduction

The total connected capacity of the station is 2.25 MW x 1020 ducks giving 2295 MW - a little over 10% in excess of the nominal rating of 2 GW.

Details of the basic electrical control system will be found in Scopa Report N13.7/469. It will be noted that the use of large gyroscope flywheels provides a spinning energy store of about 1 MW per duck. Generation is synchronous a.c. and appropriate on-duck and shore station switching is provided to ensure maximum efficient use of the output.

##### 4.2 Output Levels over the Year

The maximum output that can be anticipated from the station is 75 KW per metre of wave-front, giving a total of 2295 MW. It is anticipated that such levels will be achieved for a large proportion of the time during the winter months of October to February. During the remainder of the year, output levels fall to as low as 6 KW per metre. It is thought that a total yearly output would be  $14 \times 30 \times 1020 \times 24 \times 365 = 3.753 \times 10^9$  KWH.

##### 4.3 Output Levels over 25 Years

It is not expected that full output from all the equipment will be possible over 25 years. 30% redundancy has been built into vulnerable items such as the ring cam pumps. The use of an individual on-board control system in each duck should ensure a figure of 80% availability over the 25 years when it is realised that pairs of ducks can be replaced in the event of serious

failure, and that a pair of ducks represents 0.1% of the installation.

#### 4.4 Shore Facilities

Overall supervision of the station will be from an electronic control console at an on-shore station. Normally all the ducks will be controlled each from its own on-board control, the on-shore station acting purely as a monitor. The on-shore unit, however, will be capable of starting up all the ducks; demanding output appropriate to the requirements of the grid; monitoring the performance of all the equipment within individual ducks; responding to emergency signals from ducks and shutting down malfunctioning ducks. The on-shore station will also monitor the complete transmission system from ducks to grid and be capable of remote operation of the switchgear.

#### 4.5 Manpower

Allowance has been made in the costings for a labour force of some 200 men as maintenance support plus eight Supervising Engineers at the on-shore control station giving 24 hour cover. Helicopters, tugs, barges and the support vessels are allowed for on a contract basis.

#### 4.6 Maintenance Facilities

The 200 men allowed for maintenance support are assumed to be housed in a 100,000 sq. ft. building with access to a deep water basin. No attempt at a maintenance at sea will be made but pairs of ducks will be brought to this basin. Complete beak power modules will be removed, refurbished and reinstated or replaced as appropriate.

Manufacturing facilities for duck bodies and spines will be retained.

#### 4.7 Operating Costs

For the purposes of calculating the operating cost, the following figures are used:

|  |                         |
|--|-------------------------|
| Capital involved in preliminaries setting up manufacture, development tooling etc.       | £145 x 10 <sup>6</sup>  |
| Electrical transmission installation complete lump sum                                   | £320 x 10 <sup>6</sup>  |
| Direct manufacturing cost of one duck + half of one spine (including contingency of 10%) | £1.66 x 10 <sup>6</sup> |
| Rate of manufacture (Including 51 spines per year)                                       | 102 duck/year           |
| Daily service charge   | £50,000/day             |
| Total project life   | 25 years                |

A Discounted Cash Flow Calculation at 10% interest gives 7.97 pence/KWH. A Discounted Cash Flow Calculation at 5% interest gives 5.5 pence/KWH.

Other methods of calculation can be used which will give lower costs/KWh, but the range would seem to be from 6p/KWh to 8p/KWh.

## 5.1 History

The concept of the duck as a wave energy device goes back some five years. Stephen Salter and his team at Edinburgh University have concentrated on small tank models of approximately 1/100 scale. Early in 1978 Scopa and Laing joined forces with Edinburgh and commenced investigation into the problems likely to be encountered in producing a full scale device. This report is concerned with that investigation. Further information into past activities can be obtained from Edinburgh Wave Power Reports 1st Year, 2nd Year, 3rd Year and 4th Year (1978). Reference may also be made to "Recent Progress on Ducks" - a paper presented to the Wave Energy Utilisation Symposium in Gottenburg, Sweden - October 1979 contained in Appendix 7.8.

## 5.2 Problem Areas

In the introduction it was noted that the device team was aware of areas where a technically acceptable solution had been incorporated in the reference design but where it was felt that refinements and improvements were necessary to provide greater reliability and increase credibility. The main areas in this category are:

- Spine joints and forces
- Moorings and mooring forces
- High voltage flexible cables
- Gyro equatorial bearings
- The duck/spine bearing
- The pressure vessel
- Hydraulic pumps/motors

### 5.2.1 Spine Joints and Forces

The spine joint is an area of considerable interest. The concept of providing restraint up to a certain limit, and a compliant system thereafter, appears to be technically the most favourable solution. However, the forces acting across the joint and the angular movement required at the joint need verification before a final design is possible.

Considerable testing of the long duck string in the wide tank at Edinburgh will be necessary before full design information is available.

It should also be emphasised that the basic design wave and any directional property it possesses has not been clearly defined.

### 5.2.2 Moorings and Mooring Forces

The device assessment has been based on measured forces for a duck model in the narrow tank at Edinburgh. Based on this experimental data, the mooring forces are very low, and it has been confirmed that subject to the elimination of bending fatigue the mooring system for the Edinburgh Device is within current technology.

The results of the wide tank tests on the long string of ducks will furnish confirmatory data and establish firmer design

parameters.

It is nevertheless clear that the mooring forces generated by the duck string are gratifyingly low.

### 5.2.3 High Voltage Flexible Cables

The transmission system from duck string to shore calls for a 132 KV submarine flexible cable (although the flexure can be quite easily limited in both its excursions and bend radius).

Also required is a submarine rigid cable of the same voltage.

Discussions with Messrs Pirelli at Eastleigh suggested that they could develop such a cable given time and money. Discussion with Messrs W.L. Gore, Dumfermline brought forth a design that would meet both requirements.

CEGB (CERL Leatherhead), in discussion with Dr H Whittington of Edinburgh University, stated that "132 KV cables were easy, 400KV was under development.." and "their SF<sub>6</sub>" cable could be marinised.." Messrs Pirelli are manufacturing test specimens of SF<sub>6</sub> cable at present.

It would further appear that a 765 KV flat configuration tower transmission would have advantages over the 400KV double construction circuit proposed and that 1050KV is virtually

becoming standard in the USSR. These developments might be of future use in wave energy. (Refer to SCOPA report No 13.7/469 [November 1979]).

#### 5.2.4 Gyro Equatorial Bearings

The main gyro bearings carry the entire torque exerted by a duck plus the perpendicular component of frame torque. These bearings must withstand a loading of some 160 tons each. Hydrostatic, hydrodynamic and a propriety type have been advanced by Messrs Glacier Metals Limited. Development is necessary before a 25 year life can be achieved for these components.

#### 5.2.5 The Duck/Spine Bearing

Effort is being directed at the water lubricated hovercraft type of pressure pad and Messrs Avon Rubber Company of Melksham have offered to undertake the development work involved. A fallback situation involving the use of conventional rubber tyres is under consideration but is thought to be somewhat cumbersome requiring a longer annular space between the duck and spine. Work will continue on this aspect.

#### 5.2.6 The Pressure Vessel

Whilst techniques for producing pressure vessels exist within industry, there has never been a requirement for a sealed vessel to hold a vacuum for 25 years. Bearing in

mind, however, containers for nuclear waste, steel vacuum vessels for mercury are rectifiers and similar vessels, it is felt that this is a metalurgical problem that is capable of solution. A certain amount of development work may be necessary, perhaps on the porosity of various steels together with methods of impregnation or coating of the finished vessel.

Details of the vessel envisaged appear in Appendix 1.

#### 5.2.7 Hydraulic Pump/Motors

This item of equipment is the key unit in the entire design and 12 are used in each duck. The prospect of a high efficiency, low maintenance power-unit offered by this design is extremely attractive. The dry casing, full hydrostatic bearings, ball-ended piston rods and various other features are worthy of full development, particularly since the design has already been largely-proved by prototype running. Messrs Towler Hydraulics Limited (a member of the Thorn Group) have already made an offer to continue the development and manufacture of the item as an addition to their range.

### 5.3 Further Development Work Required

#### 5.3.1 On the Spine

Estimates have been made of the various forces acting upon the spine based upon theo-

retical considerations and assumptions as to the character of the wave climate. Imminent tests in the wide wave tank will provide experimental results to give reliable figures in place of these estimates. In many respects these figures will be crucial to the satisfactory structural design of the spine. In order to correctly calculate the fatigue life of the spine, a diagram similar to Drg No L2006 (Appendix 2) is required, giving the number of occurrences of bending moments (and other forces) throughout the design life; the value of such a diagram depends not only on the tank tests but also on the accuracy of the wave climate information.

Further information is required upon the fatigue performance of both concrete and prestressing steel; some may be available from sources such as CIRIA.

### 5.3.2 On the Duck

The main problems with the ducks are related to cost and buoyancy. The correct buoyancy is relatively easy to achieve in an all steel duck but the cost may be prohibitive.

The present design for a 10m concrete duck does possess the correct buoyancy and self-righting properties, but with very little real margin for changes in detail. This margin could be improved by changing the rear profile of the duck slightly, and by increasing the breadth of the body of the duck. Alternatively reducing the overall buoyancy

of the duck from the present 170 tonnes to say 100 tonnes (i.e. reducing the free-board) would have a similar effect.

The use of a completely different material such as ferro-cement may provide a cheaper and potentially lighter structure and this should be considered during later stages of the project.

In the wave tank:

Further research is required to establish movements, shears, axial forces, angles, excursions of moorings, powers, efficiencies, etc. as a function of sea state, string angle, zig-zagging and backbone stiffness is required to determine whether the "Cut-back rear" of the duck envisaged in the present design adversely affects the efficiency of the duck. Further research would also indicate whether increasing the breadth of the duck (as suggested above) would be detrimental to efficiency.

### 5.3.3 The Beak

Research is needed to determine the permeability and absorptivity of lightweight 'Lytag' concrete in sea water, since this will affect the buoyancy of the duck, and the durability of the reinforcing and prestressing steel. A means of reducing surface

permeability of lightweight concrete by impregnation of the external faces with polymers may also be worth investigation as to methods and effectiveness.

The proposal for an all timber beak surrounding the pressure vessel should be pursued. Ekki is suggested as a suitable material by Messrs Mallinson & Co. and the initial costing is extremely favourable. (See Appendix 1).

#### 5.3.4 Mechanical Equipment

Tests scheduled for the near future in the wide tank will also produce much valuable information for areas of doubt in the mechanical field particularly in respect of spine joints (see 5.2.1). Refined efficiency curves will also be taken into account when optimising loads on gyro bearings (see 5.2.4) and duck/spine bearings (see 5.2.5). Essential development is foreseen in respect of these items in addition to the hydraulic pump/motors (see 5.2.7), ring cam pumps and gyroscope flywheels. A full size counter-rotating pair of gyros complete with pumps etc. should be mounted fully-piped and operational in the pressure vessel in the designed atmosphere and rocked simulating the sea. They should then be fully loaded, whereby the proposed generator can be tested at the same time.

## 6.0 CONCLUSIONS

It is an attractive prospect to be able to produce energy without depletion of natural fuel resources, which can be put into commercial service within a decade. The promise of intelligent ducks hardly stretches the imagination when one considers recent advances in the microprocessor.

The mechanical and hydraulic system maintenance problems are largely solved by enclosing the equipment in a non-corrosive, non-oxidising, low-pressure environment.

The swashplate pump/motor unit requires proving but confidence is lent here by the fact that this unit has been taken up by a large commercial firm operating in this field.

The operating costs quoted cover a range which is largely affected by the interest rate obtaining. Attention is drawn to the Discounted Cash Flow Calculations in Appendix 7.7. An agreed basis should be established for such assessment.

It is felt that immediate development work should be carried out on the following:

- a) Experimental operation of a full size gyro disc.
- b) Experimental verification of all the proposed bearings.
- c) A full size pair of gyros in a pressure vessel to establish the best atmospheric environment.
- d) Experimental work on civil materials to optimise final structural design.

- e) Research into the suitability of concrete to be used for spine construction.
- f) Work to prove the bearing on the spine joint.
- g) Marine testing of materials, cables and components.

This report has concentrated on the technical and economic aspects of the Device. It is obvious that there are political financial and environmental aspects of Wave Energy, of both national and international significance, which are outside the scope of this report. No allowance has been made for spin-off advantages in allied fields.

When these factors are set beside the attractiveness of the prospect and the confidence in the cost estimates obtained, the Device has an overwhelming appeal.