

Wave Powered Desalination.

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ABSTRACT

The electrical energy needed to drive desalination plant can be produced from renewable energy sources if their erratic outputs can be made to match the strict specifications of an electrical network. However energy from sea waves can also be used directly, using the vapour-compression desalination process. This inherently provides the correct impedance match to wave inputs and does not suffer from wild swings of power level. This paper extends one given to the 2005 World Renewable Energy Conference, (Salter, 2005) by the inclusion of numerical predictions and proposals for a mooring design.

Keywords: Duck, desalination, vapour-compression, reverse-osmosis, wave energy, high purity sterile water. PVDF. Strut-mooring.

INTRODUCTION

One of the wave energy devices studied in the 1970s and 80s was the Edinburgh duck. Figure 1, taken by Jamie Taylor in 1976, shows a duck under test in a narrow tank.

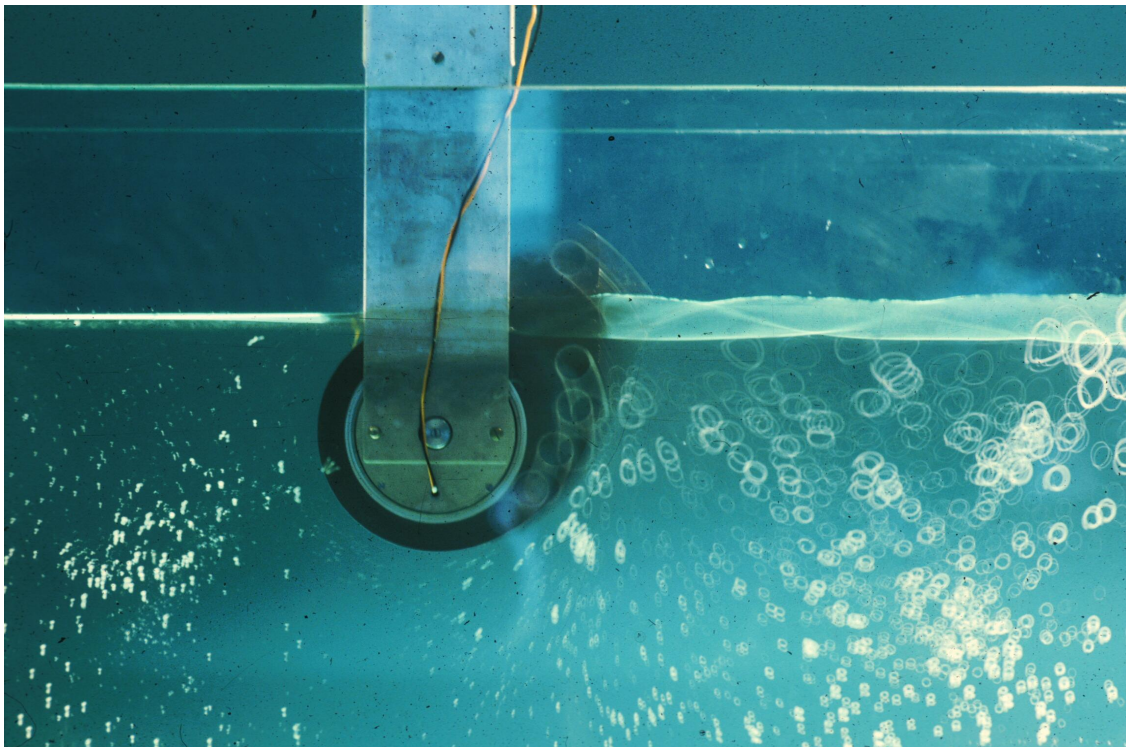


Figure 1. A time exposure of a small-scale duck model with tracing fluid

This photograph is a one-second exposure of a 1/100 scale model on a fixed mounting. The wires are coming from of an electromagnetic dynamometer, which is absorbing power. Waves are approaching from the right. Drops of a neutrally buoyant tracer-fluid consisting of a mixture of carbon tetrachloride and xylene with titanium oxide pigment have been injected to show the decaying orbits of wave motion.

The amplitude of the incoming waves can be measured from the thickness of the bright band. Nodes and anti-nodes due to the small amount of reflection are evident. However the thickness of the bright band to the left of the model is largely due to the meniscus, as is confirmed by the very small orbits of tracer fluid in this region. As the energy in a wave is proportional to the square of wave amplitude we can use the photograph to do energy accounting. If reflected and transmitted waves are one-fifth of the amplitude of the input they would have one twenty-fifth, or 4%, of its energy. This means that 96% has gone into the movement of the test model. The dynamometer showed that just over 90% of the power in the full width of the tank had been absorbed by the power take-off, leaving 6% loss through viscous skin friction.

A later model-mounting with controlled stiffness and damping in heave and surge allowed us to replicate the behaviour of models on a long, compliant, yielding spine and to make the circular stern of the model behave like the highly efficient Evans cylinder, Evan (1979). The movement generated waves that cancelled the longer ones that were escaping below the model and so widened the bandwidth of efficient operation. For very large scale electrical generation we proposed mounting many ducks – at the very least ten – on a long spine which could flex to provide the correct mounting compliance and yield to avoid extreme bending moments. While this would have given very large output from a limited sea front, the need for a minimum installation of about 60 MW made it unattractive for initial investments before confidence was established. It was therefore interesting to study a solo duck.

It was shown (Budal and Falnes 1975) and others that in a wide tank solo devices could extract *more* energy from the sea than was contained in their own geometrical width and so appear to have an efficiency of more than 100%, just as the power from a radio antenna is not set by the diameter of the wire. This led to the new terms of ‘capture-width’ and ‘capture width ratio’.

An asymmetric device able to move in the right combination of vertical and horizontal directions should be able to get energy from a width of wave of $3/\pi$ times the wavelength. Unfortunately very wide capture widths from small devices would require very large excursions, which soon make things non-linear. Nevertheless David Skyner (1987) tested a tank model on a mounting which could simulate intelligent fore and aft mooring legs and was able to achieve capture width ratios of 1.8 over nearly all the useful Atlantic spectrum.

Sadly, we found that Ducks on tension leg moorings suffer from severe snatch loads if the moorings go slack and then retighten. This would occur quite often in small but steep waves. A possible solution to the mooring problem will be described later.

Desalination basics

Of the several techniques for desalination, reverse osmosis is the present well known favourite. A high and preferably fairly steady pressure (3 to 6.5 MPa) is used to pass some fraction of seawater through a semi-permeable membrane while retaining most of the salt. The pressure gradient is from the source to the product and so there is a possible route by which the product can be polluted. Desalination membranes for general use are designed to meet, but only just meet, the World Health Organization guideline for total dissolved solids below 1000 parts per million, (Bartram, 2006). Reverse osmosis needs careful filtration and chemical pre-treatment to give the membranes an economical life.

There is an alternative but less used technique known as vapour compression (Darwish and Dessouky, 1996). Figure 2 shows a block diagram. Seawater at a temperature close to boiling point is trickled down one side of a hot heat-transfer surface. Pressure is reduced by a pump so that some water is converted to vapour, drawing the necessary latent heat from the heat transfer surface. The pump increases the pressure of the vapour by about 20 kPa, thereby increasing its temperature by a few degrees, and delivers it to the other side of the heat-transfer surface, which will have just been cooled by the loss of latent heat. The pure vapour condenses and releases its latent heat, which is used again and again for evaporation of more sea water.

While the volumes of vapour are very large, the pressure drop is much smaller than for reverse osmosis. But more importantly the pressure drop is *from* the product *to* the feed so that any leaks will lose small amounts of product rather than contaminating it. With an

efficient demister to remove the small drops of water which are thrown from the boiling surfaces it is possible to produce an extremely pure output, better than 0.5 parts per million. As the output will have been taken to a high temperature for several minutes there is a further means for sterilisation. Pharmaceutically pure water has been produced from hospital sewage and the method has been used to dry the mash residues from whisky manufacture. The only intractable source of polluted output will be volatiles in sea water, which have boiling points close to the operating temperature.

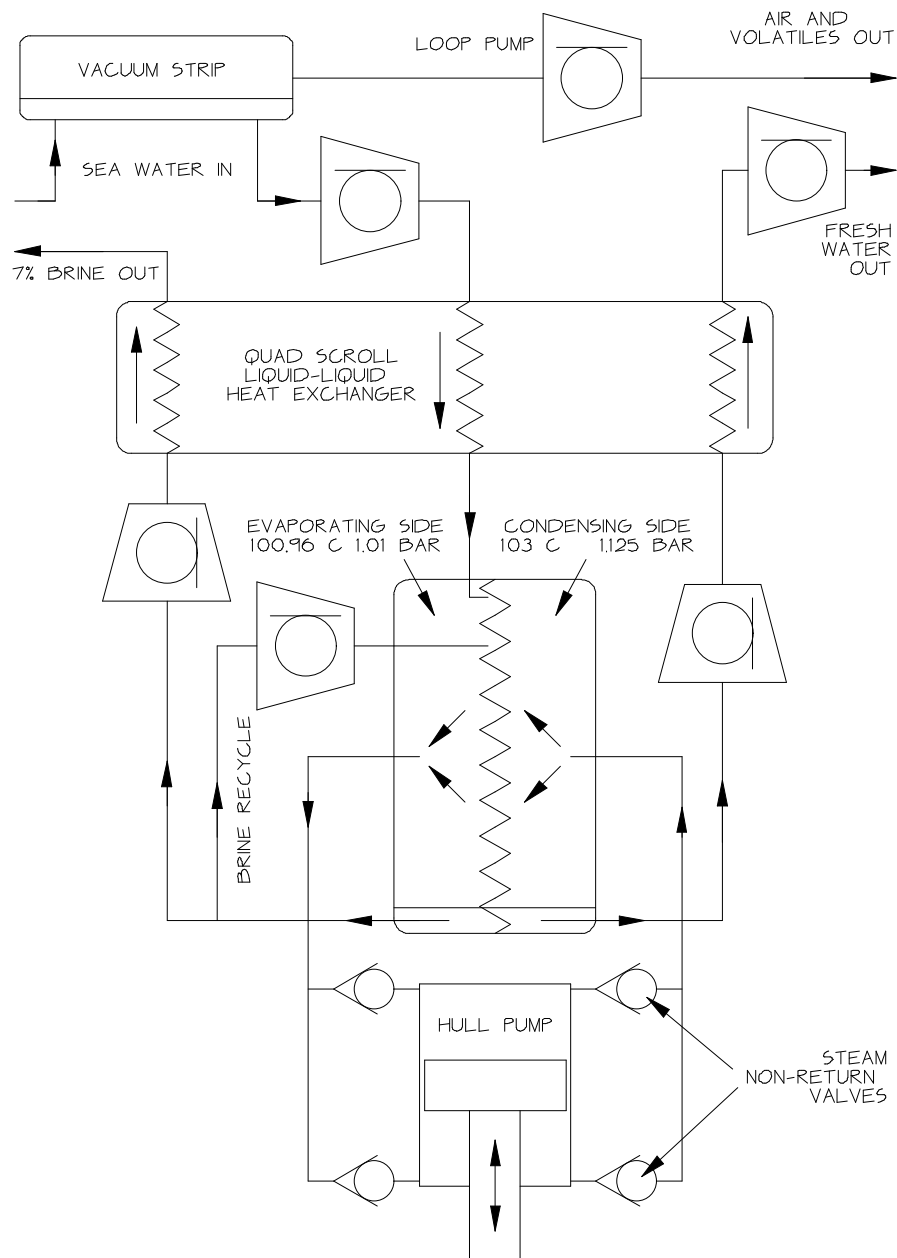


Figure 2. The block diagram of the vapour compression process. Most of the work done by the mechanical pump goes into raising the temperature difference across the steam heat exchanger. Latent heat is recycled.

The continuous recycling of the latent heat can make the process very efficient. The energy needed depends on the heat exchanger area and heat-transfer coefficients. The value is given by the product of the latent heat of steam (2.256 MJ/kg at 100 C) times the temperature difference across the heat exchanger divided by the absolute temperature of operation. A part of the temperature difference is the result of the boiling point of salty water being above the condensing temperature of pure water. For 3.5% NaCl sea water the elevation is 0.46 C but as soon as some has evaporated the strength of the remainder will rise, perhaps by a factor of two. The remainder of the temperature drop depends on the heat exchanger and, for economic reasons, is likely to be larger. With a perfect heat exchanger and 3.5% NaCl feed operating at 373.3 K the energy requirement would be only 2.78 kJ/kg or 0.77 kWh/m³. For a more realistic brine strength the requirement would perhaps double to 1.55 kWh/m³ for a very large heat transfer surface working at a very low rate. For practical throughputs the energy requirement would range from 2.5 kWh to 10 kWh or more per cubic metre and so would straddle the energy requirement of reverse osmosis plant. The hot fresh water and the hot double-strength brine contain heat which is far too precious to be discarded. Much of it can be recovered by transfer to the incoming sea water flow. We might have two volumes of 3.5% salt water being converted to one volume of fresh water and one volume of double strength brine. The energy loss will depend on the temperature difference between incoming and outgoing streams.

Fouling of heat transfer surfaces

All desalination methods are bedevilled by the problem that some of the many materials dissolved in seawater are close to their limit of solubility. An increase in solution strength or a rise in temperature can make them come out of solution and form a hard scale on any suitable substrate. This will grow in thickness and will rapidly reduce the heat transfer coefficients, halving them in a few days of operation. This problem has been tackled by Maxwell Davidson who has, over the years, produced a series of heat transfer materials with steadily improving transfer coefficients resistance to fouling and very long operating life even in contact with ammonium sulphate and flue gases. The present choice is a metal mesh which has been sprayed with a continuous layer of polyvinylidene fluoride, usually known as PVDF or Kynar, filled with flakes of carbon to improve heat transfer. The PVDF layer has excellent high temperature properties and resists fouling in the same way as a non-stick Teflon-coated frying pan. It is also used for the fibres of some reverse osmosis modules.

Pumping with waves

In conventional vapour compression systems, energy for driving the very large volumes of vapour is provided through turbo-compressors which have to rotate very fast. But it would also be possible to use a slow, positive-displacement pump formed by the body of a Duck, half-filled with water. It would have a central partition dividing a pair of steam compartments as shown in figure 3. While the Duck undergoes its wave-driven alternating rotations, the 'water pendulum' tends to stay fixed and so the system forms an enormous, positive-displacement pump with no sliding seals or accurate machined parts and very low internal losses.

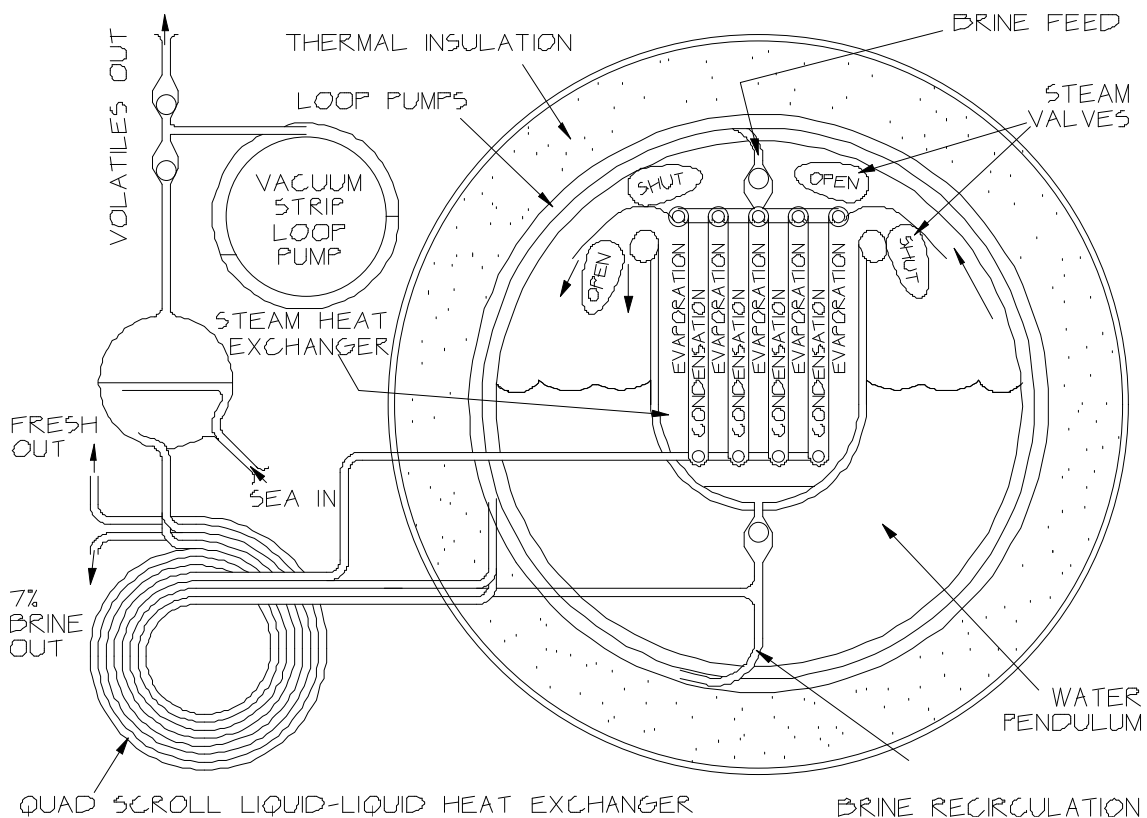


Figure 3. A simplified layout of the hull pump.

The torque opposing the wave motion of the Duck comes from the pressure-difference across the partition. This will be set by the temperature-difference across the heat-exchanger, which will be determined by throughput and so proportional to the angular-velocity of the Duck body. With the direct relationship between the pressure across the partition and the angular velocity of the Duck body we are close to the ideal damping of a wave energy device with none of the misery that this normally involves (Salter, Taylor Caldwell, 2003).

There is also a need to pump all the working fluids round the Duck and to pump the product ashore. It would be nice to avoid the use of any electrical items in the hot, wet conditions. This can be done with a mechanism known as a loop pump. We all know that a column of liquid in a vertical tube induces a pressure at the bottom with a value of fluid-density times gravitational-acceleration times column-height. We are used to situations where gravity is constant. But exactly the same thing happens in a coiled pipe which is subjected to alternating *angular* accelerations. Rectifying valves can prevent return flow. There will be room for many loops to be wrapped round the pumping chamber. Each 360 degree loop can easily produce a pressure of 30 kPa. With several loops in series we can pull a vacuum to remove dissolved gases, lift water from bottom to top of the steam heat exchanger, pump fresh water ashore, and even up to a respectable height of reservoir.

An updated layout of the system is shown in figure 4. Here the previous front shape of the duck has been replaced by offsetting the rotation axis of a circular cylinder. Numerical modelling (Cruz, 2006) gives hydrodynamic coefficients and capture widths.

Heat exchanger design

The Maxwell Davidson heat exchanger (Davidson 1974) consists of sheets of the heat transfer material into which have been pressed corrugations that lie at 45 degrees to the sheet edge as in figure 4. The press tool is used twice to make two rectangles of corrugations separated by an area of plain sheet. Other holes can be punched out for pipe work and clamping rods. When a sheet is folded into a U shape the corrugations will contact one another and make the form of an X. A large number of U-folds are clamped together with short spacing tubes which can form feed sprayers and condensate collectors. The open ends are sealed by the inflation of an elastomeric bag to a pressure higher than the one chosen for the process. Sea water will be fed to the gaps *outside* the U-folds. It then moves as a falling film down the sheets and drips from the bottom of the U from where it will be collected for recirculation. Vapour will be drawn off and pumped through a demister stack to the *inner* surfaces of the U-folds where it will condense and collect at the bottom and be drained. The falling film is ideal for heat transfer and there will be lots of demisting taking place in the heat-exchanger itself. This design allows the construction of heat exchangers with very large areas, many thousands of square metres, at a cost not much greater than that of the raw material.

Valve design

Very large volumes of steam have to be pumped and we need valve areas with hydrodynamically fair passage shapes so as to reduce the pressure drop through the valve. The valves have to operate at a high temperature for every pumping cycle, about 5 million operations a year. There will sometimes be impacts from water. They will be expensive to service and so must not fatigue.

The practical layout is shown in figure 4 top right. The valves are made from sheets of an elastomer reinforced with a wire mesh to give a controlled stiffness. The sheet will be rolled into the form of a long cylindrical tube with its long edges clamped to a cruciform section running the length of the pumping chamber. Inflating the tube will make its section nearly circular, with a diameter that just fills the valve passage and will close it. But a reduced pressure will force it to an elliptical section and open the valve. The end-plates on the cruciform section inside the valve tube will limit the range of movement of the tube in both its circular and elliptical states. This means that a closed valve will be able to withstand quite large water impacts without buckling.

The internal stiffness of the textile will tend to make it adopt a circular shape and close the passage. Preforming the reinforcement can increase the effect. For the two valves controlling the outlet from the evaporating side, closure can be assisted by gravity. The force to open valves can be increased if the insides of the valves from the evaporation side are connected to their own pumping chamber while the two valves controlling the flow back to the condensing side are cross-coupled to the opposite chamber. We do not want any water in the valves and so air-filled bags in the two compartments will generate the actuation pressures.

A Mathcad simulation of the desalination process has been written to predict temperatures, pressures, weights and productivity as a function of Duck dimensions and wave conditions. Graphs of results for 0.7 metres root mean square wave height at 7 second energy period are shown in figure 5 and the theoretical productivity as a function of wave amplitude and period is shown in figure 6.

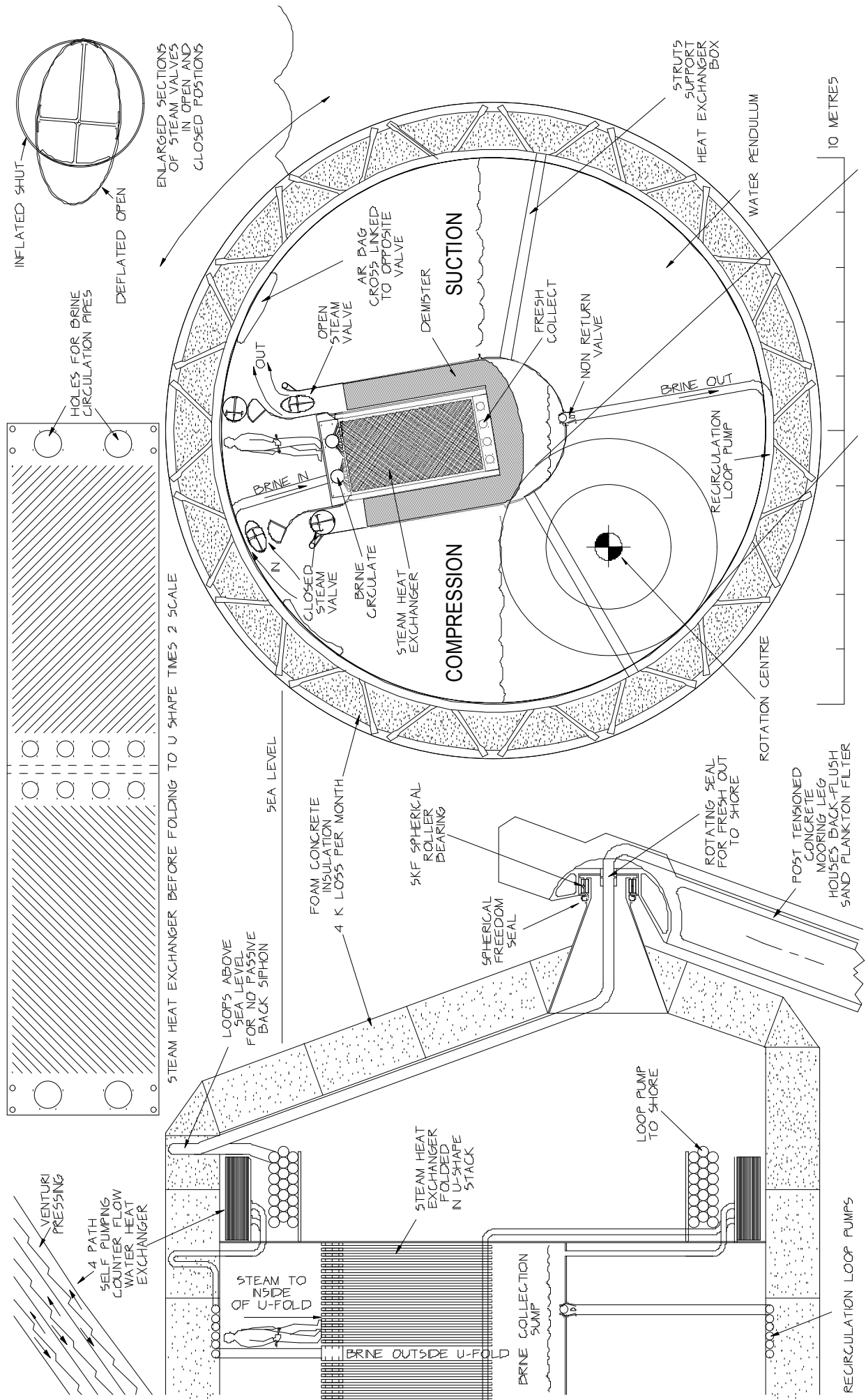


Figure 4. Sections through the desalinating duck. People would not be present during operation!

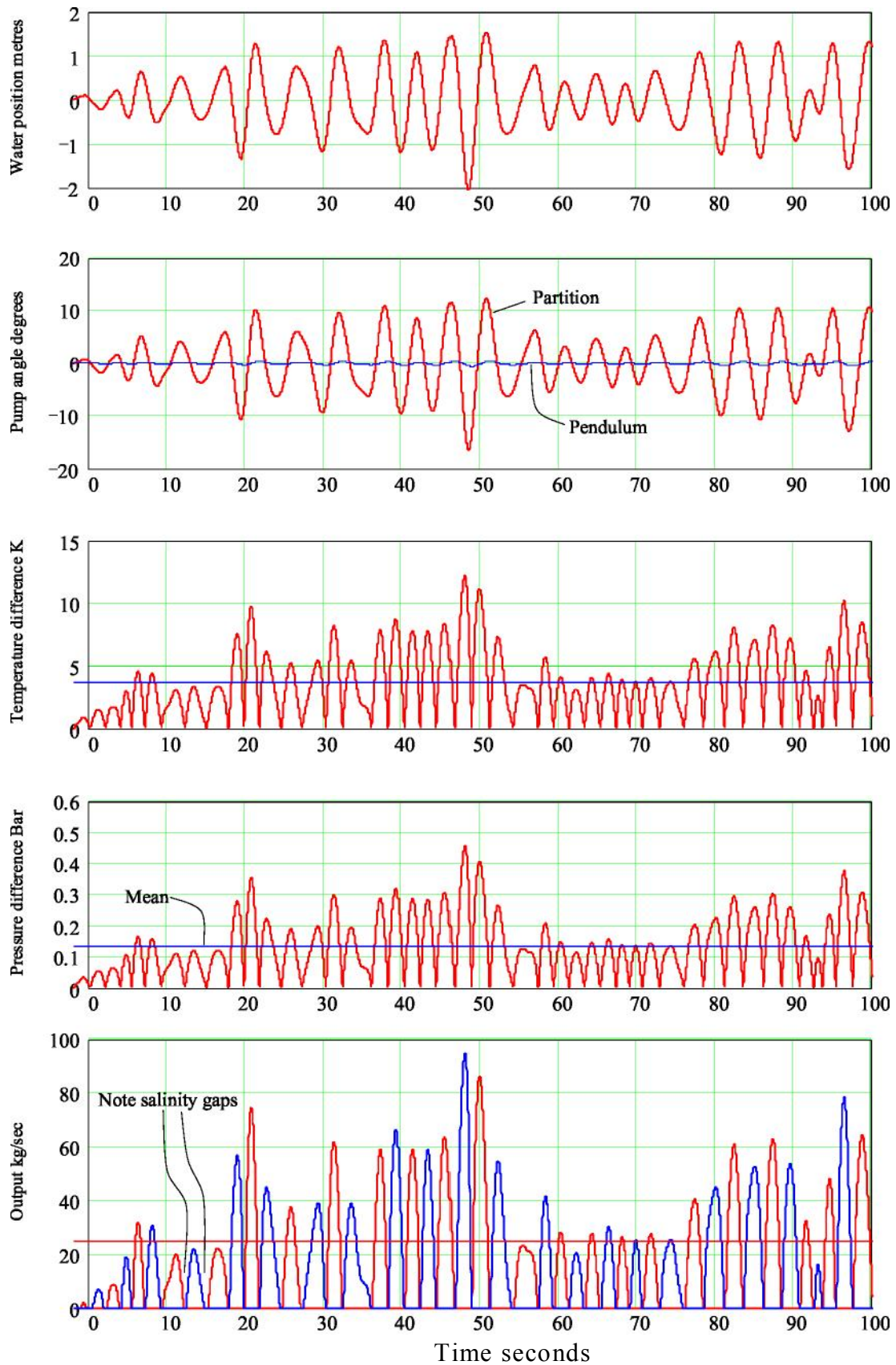


Figure 5. Mathcad output of water position, angles of the hub pump, temperature and pressure differences and the instantaneous output of fresh water for a 0.7 metre root mean square wave height and a Pierson-Moskowitz spectrum with an energy period of seven seconds. This would produce about 2000 cubic metres of fresh water a day from a 12 metre diameter duck. Note that significant wave height is now, by definition, four times the root mean square height but that other, less satisfactory, definitions exist.

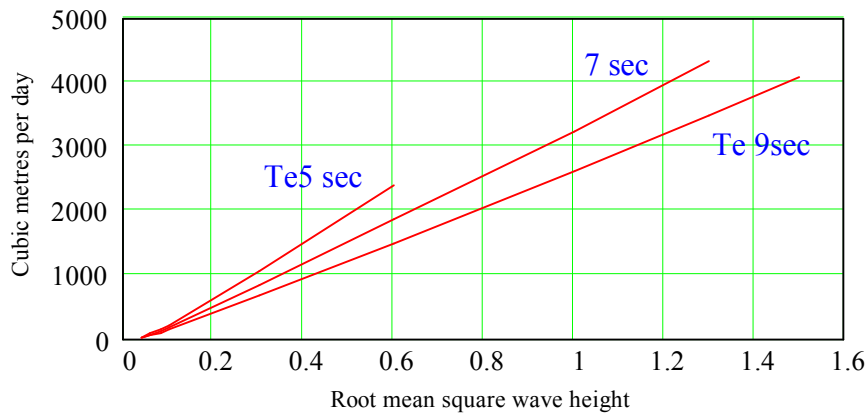


Figure 6. Theoretical estimates of productivity for the reference design as a function of wave amplitude and energy periods of 5, 7 and 9 seconds. Note the nearly linear relationship at larger wave amplitudes and the small offset due to the elevation of the boiling point of sea water. This is also evident in the bottom graph of figure 2 for waves around 10 seconds into the sequence. Careful tank testing will be needed to confirm this prediction.

Heat recovery

Other energies calculated by the Mathcad simulation software are the pressure drops of vapour through the demister, round the pipes and bends and through the valves. Next it calculates energy for moving liquids through the system, the viscous losses of the pump and heat lost through the container walls. All except the last of these losses will rise with throughput. There is a need for a liquid-to-liquid heat exchanger to warm incoming sea water from the outgoing product. Again the angular motion of the duck can be turned to advantage. We can make a cheap heat exchanger by wrapping four sheets of PVDF-clad mesh in a four-start spiral. This forms four passages. The sequence of layers will be used for half the incoming sea water, the outgoing fresh water, the second half of the incoming sea water and the outgoing, high-strength brine.

The four sheets can be pressed into an asymmetric sawtooth form with the angles equivalent to those of a Venturi tube. This means that the flow resistance in one direction will be less than that in the other. The alternating movements of the duck will induce a flow with a small direct component superimposed on a larger alternating one. This distributed pumping avoids the large pressure that would be needed to force water through long passages by a pump at one end. It is difficult to think of a more satisfactory heat transfer mechanism. Warmth and a regular supply of nutrients will encourage rich biological growth in the inlet passages. However this can be prevented by the daily discharge of a small quantity of boiling water.

Heat will be lost through the casing and through the difference in temperature between the in-going stream of seawater and the out-going streams of fresh water and extra strength brine. Heat will also be lost through the difference in chemical energies of fresh and salt water. Heat will be generated by all the internal flow losses and the work done in compressing steam. It is absolutely necessary to understand each of these mechanisms if we are to regulate the temperature swings to the chosen narrow range. Overheating and the consequent overpressure are a real possibility.

The likely dimensions of the duck mean that heat loss through the casing is surprisingly small. If we provide a metre thickness of foam concrete with conductivity about 0.1W/mK round a 10 metre diameter 20 metre long pumping compartment we will lose just under 5 kW through a temperature difference of 75K. The large water mass inside the duck means that the temperature would fall by less than 4 K a month if all flows were stopped. It would be quite possible for ducks to be filled with hot water at the factory, towed long distances to installation sites and still be at working temperature on arrival. At most places with water problems, solar inputs would be enough to maintain temperature in prolonged calms.

There are two ways to regulate temperature. The dominant heat losses are in the output streams. We can provide slightly more area than is necessary to maintain temperature but split this between two heat exchangers. By cutting the flow through one for a variable fraction of the time we can adjust their effectiveness. The second method is to gain heat by increasing the number of times that water is dropped through the steam heat exchanger before being pumped ashore.

Duck body bearings

The bearing requirements for many renewable energy applications are often beyond those of off-the-shelf components. At the start of this project it was expected that desalinating ducks would need special hydrostatic bearings which would use filtered sea water pressurised by wave forces. It was a surprise to find that, for the tropical wave climates where desalinating ducks are like to be used, we can use a bearing from the standard SKF large-bearing product range. Bearing ratings are essentially three numbers moderated by a series of application factors. There is a load that will do damage with a single application. There is another load that will start damage 10% of a large population of bearings following the application of a million rotations. An equation allows the calculation of the fraction of a population that would be damaged for other loads and other numbers of rotations. The third figure is the load that is low enough never to cause failure no matter how many rotations occur.

If we have a scatter diagram for a chosen wave climate and know how to use the Rayleigh distribution to get the total number of waves in each small range of amplitudes, we can combine loading data with the second of the above bearing ratings to get the fraction of bearing life that each wave will use up. It turns out that for a moderate wave climate such as Lanzarote in the Canaries, a pair of SKF spherical roller bearings which can take the single highest wave in ten years will also have 90% survival probability over that period. Most of the life will be used up by the very large number of medium sized waves. SKF advise that far more bearings fail because of seal problems than from loading.

Moorings

A crucial problem for all marine energy sources is developing a reaction against which the device can do work. Wave powered desalination raises the following requirements.

- For a solo duck in the North Atlantic 100-year wave the forces will be about 40 MN.
- The mooring may have to rotate 360 degrees about a vertical axis and follow movements of waves and tides in the elevation axis.
- We may have to make an attachment to a sea bed of soft sand.
- We may need to remove and replace equipment especially in the early days of the project.
- We may not be allowed to leave permanent hardware in the sea bed.
- We should try to avoid the need for heavy weights and large anchor-handling vessels.

Because of the snatching problem of ropes the system will use post-tensioned concrete tubes as rigid struts, with bearings to give spherical freedom at both ends. Fatigue happens as a result of tensile stresses and so will not occur in the compressed concrete. The wires which provide the compression will be under constant tension and so will not fatigue either. The values of mooring loads are now being measured in a test tank. Until full results are available we are using a specification appropriate to Atlantic conditions, much higher than in likely drought-stricken countries. The 40 MN force will be applied at an angle of about 45 degrees. When this reaches the universal joint it will be split into vertical and horizontal components of about 28 MN.

The sea-bed attachment will be split into two parts with a quick disconnect between them. The permanent part shown, in figure 7, will be in the form of a tripod with legs made from post-tensioned concrete. The wall thickness will be about 0.9 of the diameter - thin enough for the tubes to be buoyant for easy towing when full of air but able to sink if filled with water. The top of the tripod will be a hollow cast-steel shell large enough for people to work inside applying tension to the post-tension strands.

The tripod will be towed to site and lowered to the sea bed. Water jets at the bottom and underside of each leg will eject sand and allow the tripod to sink in the sand. By adjustment of flow rates between legs the correct attitude can be maintained. When the tripod has reached the chosen depth, the direction of water flow will be reversed and water will be removed from the body of sand round the leg. As we remove water from around the legs the weight of the surrounding sand, increased by the pressure of the head of sea water above it, will produce a large radial force on the outer surface of each leg. The friction caused by this force will prevent the leg from sliding out of the sand. A friction coefficient of 0.3, a water depth of 50 metres, a dry sand density of 1600 kg/m³ and a buried length of 30 metres will give a friction force of 45 MN so a single leg could resist the 100-year Atlantic wave load.

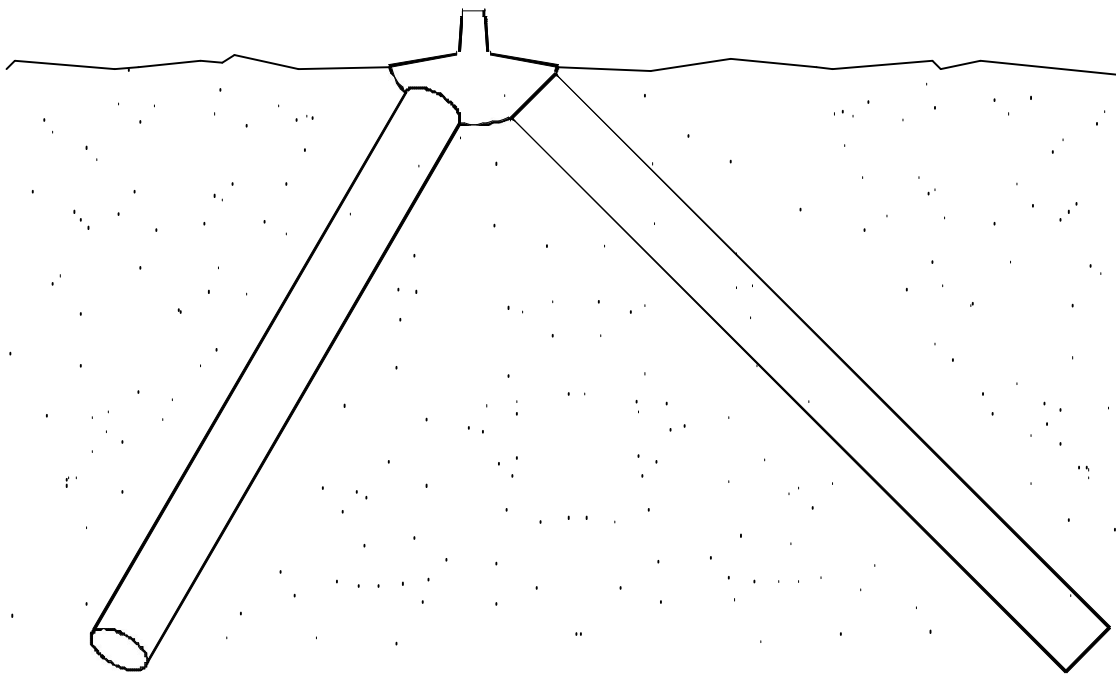


Figure 7. Part of the mooring is a tripod anchor made from three, slip-formed post-tensioned concrete legs. It is sunk in the sand by controlled water-jetting and retained by suction.

The flow rate needed to remove water in contact with the leg will depend on the grain size of the sand. With coarse sand this may initially be quite high but as pumping proceeds the passages between sand grains will be progressively blocked by smaller grains and the flow rate will fall. With a non-return valve at the top of each leg, the inner volume can serve as a vacuum store to maintain suction. Initial pumping can be provided from a surface vessel but, later, this function can be performed by loop pumps in the desalination system. These are required anyway to strip dissolved air from the water feed.

If ever it is necessary to remove the tripod, the vacuum can be released and air pumped into the inner leg volume to give positive buoyancy. Water jets on the outside of each leg can then fluidise the sand above the tripod, which will rise through the sand and then to the surface. This design means that all installation and removal can be done with very light vessels fitted with water, air and vacuum pumping systems.

The universal joint at the sea bed is shown in figure 8. While the large angular movements of the displacer body are suitable for rolling element bearings they are less attractive for cases where there are many movements through angles much smaller than the gaps between rollers. The SKF catalogue shows that the GEC 1250 PSA plain bearing has a static load rating of 64 MN and a dynamic rating of 36.5 MN. This can take the horizontal loads and can provide the freedom to yaw about the vertical axis so that the system can align itself to waves from any direction. However these values apply at zero velocity and allowable loads fall at very low velocities, even a few millimetres a second. Ten millimetres per second is equivalent to a rotation period of 7 minutes – so the bearing can rotate fast enough about the vertical rotation axis to follow a change of weather patterns.

The velocity of the SKF GEP 480 P4S bearings for the elevation movement in a 1.5 metre amplitude 8 - second wave in 50 metre water depth will be 7 mm/sec and so the velocity restriction will often be more serious. We propose that the velocity limit can be increased by fitting one (or two) hydraulic rams at the lower end of the mooring struts. These will give oil pressures proportional to the applied load. This oil can be fed to the loaded side of each bearing to offset a large part of the applied load as in a hydrostatic bearing, but with a pressure ratio not quite sufficient to provide complete separation. The vertical component of the strut load will be taken by pads of flat disks made from Glycodur F, mounted on spherical seatings which can tilt to give evenly-spread loading against a thrust face.

Installation

The first experiences of installing pioneer wave energy devices have not been happy, with long delays and expensive day-rates for installation vessels. We must also expect that early devices will have to be installed and removed quite frequently. The challenges are that good wave sites will have few calm days and that items weighing thousands of tonnes will often be moved by waves randomly through distances of metres but must be positioned to millimetre accuracy.

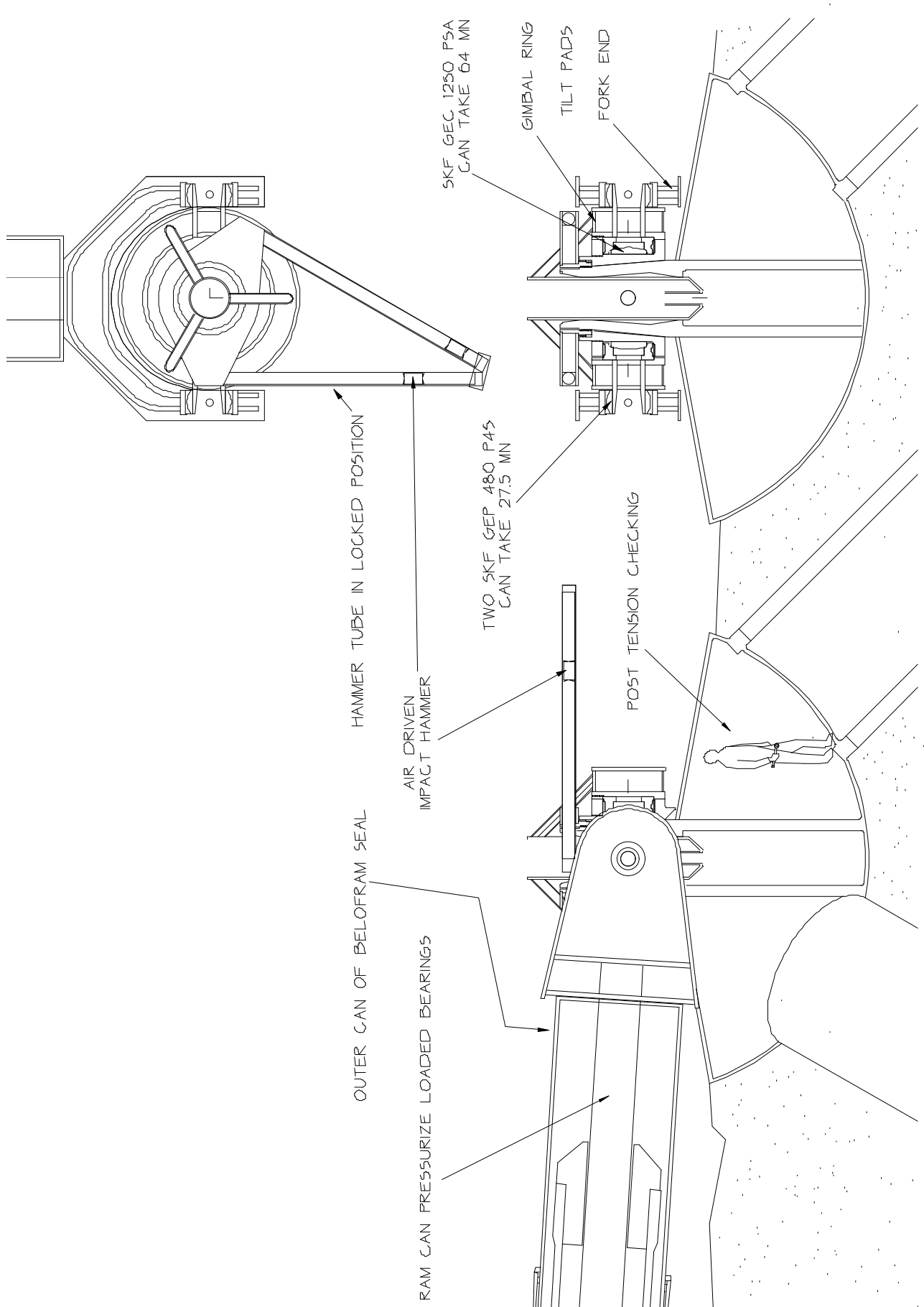


Figure 8. The universal joint at the bottom of the mooring legs can be disconnected from the tripod head by a hammer-driven breech screw.

The design approach is to use modern electronic navigation methods to control the *forces* exerted by a number of very light, agile vessels in a tightly coordinated way as opposed to the traditional method of using a slow, heavy vessel with *position* control. The vessels would have a strong central box surrounded by very large air-filled tubes, much larger than those of conventional inflatables. Some of the control can be done with direct pushing. But in addition, strips of magnetic beads consisting of neodymium tiles energising steel pole pieces lying parallel to the air tubes can be attached to any ferrous plating and provide both pulling and shear forces quite large enough for moving wave devices and even large ships. They can be quickly released by the inflation of a pair of flattened fire hoses. The vessels can also carry low inertia, *torque-controlled* winches to apply force with a vertical component up to their safe change of freeboard. Each vessel would be driven by a pair of Voith-Schneider propellers driven by compact and lightweight ring-cam Diesel engines with a power rating of 600 kW. The Voith-Schneider propeller uses vertical-axis blades with cyclical pitch-variation to give rapid changes in the magnitude of thrust and direction. Together these can produce a bollard pull of the order of 1 MN from each inflatable.

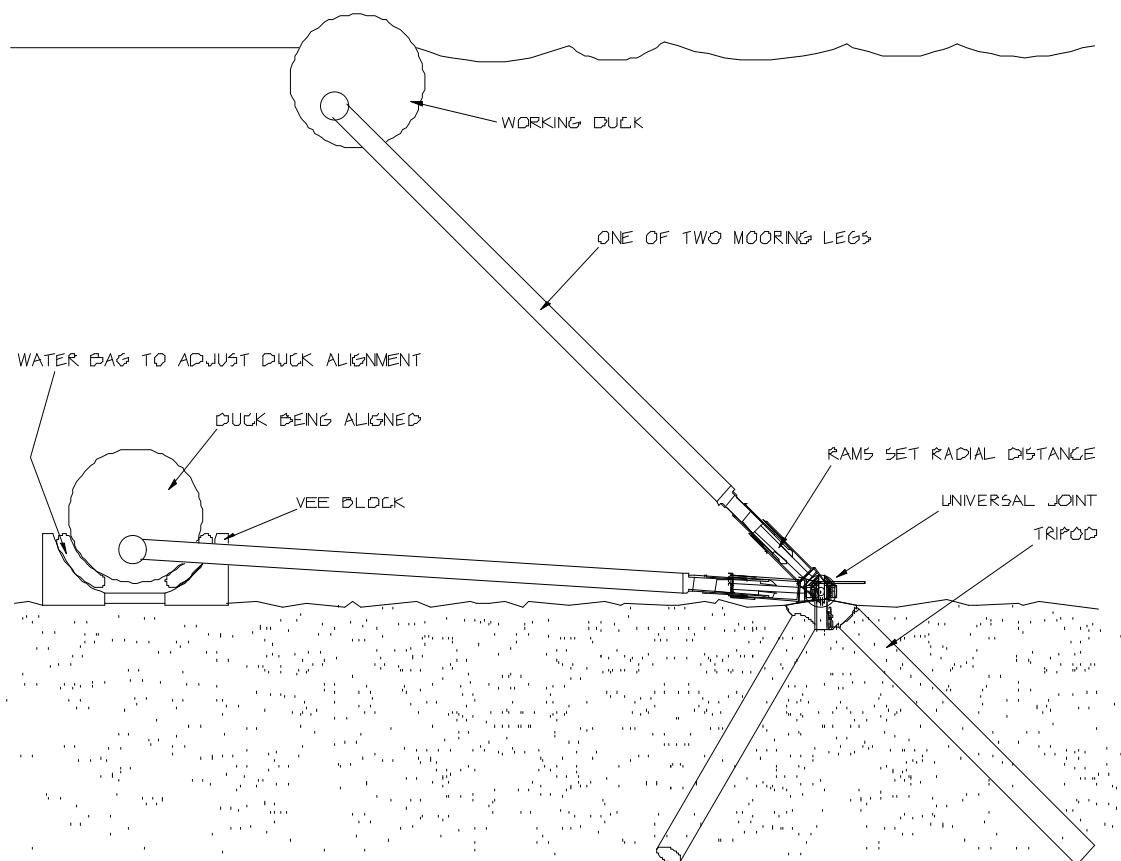


Figure 9. A composite view showing the fully flooded duck in the alignment position on its Vee-block and water bags and raised to the working position with half the water removed.

These vessels would be aligned by a mobile structure in the form of a Vee-block with four water-filled bags on its sloped faces as shown in figure 8. The Vee-block can be towed on the surface. Water would be pumped into it to give slightly negative buoyancy so that it can be lowered to the sea bed and then sunk at the correct distance from the tripod. Wave forces and buoyancy would be used in an intelligent way to avoid all heavy lifts. At a water depth of 50 metres the amplitude of wave motions is much lower than at the surface. For an 8-second wave period, the horizontal movement at the sea bed is only 8.5% of the surface one and only 11% at the top of a Duck lying on the bed. By choosing the amount of negative buoyancy and applying judicious pulls by the installation vessels, we can make fine adjustments, say 300mm, to the position and angle of the Vee-block relative to the tripod. More water can then be added to hold the Vee-block in place.

The Duck will be filled with fresh water so that the top of its body is nearly awash but the mooring legs will be filled with air to give attachment points above the surface. It will be moved to position over the Vee-block and lowered to make contact with the water-filled bags on the slope surfaces. The bags will be flexible but have an inelastic textile reinforcement so that when the weight of the cylinder is applied they will provide an accurate and rigid support. The bag pressure will follow the pattern of wave loadings. A shoreward acceleration of a wave will increase the shoreward bag pressure and reduce that in the seaward one. By opening and shutting a valve between the bags at times chosen to suit the phase of the wave loading, we can make micro adjustments to the bag volumes to as to move the cylinder to the correct angular direction relative to the tripod. The mooring legs can be lowered with acoustic distance measurements to a datum marker on the tripod. The cylinder at the end of the mooring legs can be used to make radial adjustments. The final contact will be between a female cone on the universal joint and a male cone at the top of the tripod.

Locking of the universal joint to the tripod will be done with a mechanism known as a breech screw. These were originally used for opening and closing the chambers of large breech-loading guns. The normal threads of screw and nut are partially cut away in, say, six grooves, leaving just less than half the thread on each. The cut-aways allow the screw to be fully inserted into the nut with an axial movement. All the remaining threads can then be mated with a partial turn of the screw.

A breech-screw big enough to retain a universal joint loaded with 40 MN can be turned by an inertial impact hammer. This will consist of two tubes 4 metres long with a 170 mm bore. They will contain free-sliding 'pistons' of solid hardened steel running on Teflon seals. A piston will be moved to the outer end of the cylinder by air pressure. This will be abruptly reversed with vacuum on the inboard side and 10 bar air pressure on the outboard side. By the time the piston reaches the

hardened plug at the far end of the cylinder, its velocity will be over 65 metres per second and its momentum over 2600 kg m/sec. The magnitude of the resulting force will depend on the time over which momentum is converted. With a short stiff connection to the screw threads this is likely to be fast but if necessary it can be extended by force transfer through a stack of Bellville washers. If it extended to one millisecond, the impact force would be over 2.6 MN.

Water will then be removed from the cylinder hull so that it rises to its working position at the surface. The final locking of the breech screw can be done when wave forces are pushing the system downwards and forwards. The Vee-blocks can be removed to install other systems.

Conclusions

Wave energy can be used directly for the production of very high purity, sterile fresh water even from polluted sources, provided that non-scaling heat transfer materials such as PVDF are available.

The energy requirement is set by the area of heat transfer surface. Several thousand square metres will be required for each unit but the Maxwell Davidson design gives heat exchanger costs which are little more than that of the sheet material. Energy requirement can be below 2 kWh per cubic metre at low power levels but rises at higher ones to straddle the requirement of reverse osmosis.

Output volume is almost linear with wave amplitude, except for a small offset due to the elevation of the boiling point of salt water, and is higher at shorter wave periods. For 12-metre diameter by 24-metre wide Ducks, output will be of the order of one or two thousand cubic metres a day in a tropical wave climate exposed to a large ocean.

The low thermal conductivity of foam concrete means that heat losses for objects of the likely dimensions are not a problem. Heat gain is quite possible and needs careful temperature regulation. It may be possible to build fluidised bed technology followed by suction to install the heavily loaded moorings in sandy sea beds without heavy lifting vessels.

Attachment and removal can be performed by means of a set of several light, agile, inflatable vessels with torque-controlled winches, magnet contact strips and tightly coordinated vector thrust propulsion.

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REFERENCES

Anon. SKF bearing catalogue. 2006.

From <http://www.skf.com/portal/skf/home/products?maincatalogue=1&newlink=1&lang=en>

Bartram J Callan P. Guidelines for Drinking Water Quality 3rd edition. WHO Geneva 2006.

From http://www.who.int/water_sanitation_health/dwq/gdwq0506.pdf

Budal K, Falnes J. A resonant point absorber of ocean-wave power.

Nature, Vol.256, pp.478-479 1975.

Cruz JMBP and Salter SH. Numerical and experimental modelling of a modified version of the Edinburgh Duck wave energy device. I. Mech.E. Journal of Power and Energy, Special Vol 220 pp 129-147, 2006.

Darwish MA, El Dessouky H. The heat recovery thermal vapour compression desalting system: a comparison with other thermal desalination processes. Applied Thermal Engineering vol 16 pp 523-537 Elsevier 1996 .

Davidson MW. Multistage Evaporator US Patent 3808104 vol 921 p 2042 1974.

Evans DV, et al. Submerged Cylinder Wave Energy Device: Theory and Experiment.

Applied Ocean Research, vol.1, pp 3-12 1979.

Salter SH Wave-powered desalination. Proceedings of Conference on Energy for Rural and Island Communities, Inverness, September 1985, pp 235-241. J. Twidell (Ed.), Oxford: Pergamon.

Salter SH. High Purity Desalination Using Wave-driven Vapour Compression.

World Renewable Energy Conference Aberdeen 2005.

Salter SH, Taylor JRM Caldwell N. Power Conversion Mechanisms for Wave Energy. Proc. Inst. Mech. Eng. Journal of Engineering in the Maritime Environment. vol, 216. pp 1-27 July 2003.

Skyner D. Solo Duck linear Analysis. Report to UK Wave Energy Steering Committee 1987.