Research Requirements for 4th Generation Wave Energy Devices

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Primary and secondary objectives

The only present objective of wave energy research should be to ensure the survival of the first sea-going plant. Once that has been achieved we can reduce the costs by cautiously cutting factors of safety, changing designs to suit new materials or production methods and by increasing the sophistication of control strategies. This paper discusses the steps in the research to these objectives. The emphasis is on the needs for the next generation of wave plant but the borderline between generations is not distinct and investigations suggest that some topics may not have been covered completely for all devices in previous generations.

SURVIVAL

Statistical distributions

Engineering artefacts can suffer failures dramatically where something suddenly breaks or progressively through corrosion, fatigue or wear. To achieve an acceptably low failure rate it is necessary to understand both the stresses that the sea is inducing in the equipment and also how good the equipment is at enduring these stresses. As so often in engineering, both stress and resistance have a complicated statistical pattern. It is helpful to think of them as two probability distributions with the asymptotic upper skirt of the stress distribution approaching and overlapping the lower skirt of the endurance limit by hopefully only the very slightest amount. In many cases the statistical distributions will be close to the mathematically convenient Gaussian distribution but we can not always be certain of this. For a mature technology, the small amount of overlap is in effect set by accountants, insurance brokers and public opinion.

There are four ways to reduce the overlap of the two distribution skirts. The first is to bodily move the mean value of the endurance distribution to some higher value by applying a ‘factor of safety’. In the early days of wave energy the experts on mooring would say that they usually applied factors of 5 or 6. There was some uncertainty as to whether this factor was the ratio of mean endurance to mean stress or whether it was the ratio of the weakest item on the lower skirt of endurance divided by the highest point on the upper skirt of the input stress. Clearly humans are not good at thinking about asymptotes and low probabilities. Factors of safety are really factors of ignorance and lead directly to factors of waste.

The second way to achieve survival is to reduce the standard deviations of the two distributions. This can be done by research on either or both stress and endurance. Understanding stresses requires very detailed tank testing to seek out the most unfavourable combinations of wave conditions. Understanding the endurance of new types of components requires testing of parts and subassemblies either on the bench for internal parts or in realistic sea conditions for external ones. However provided loads are accurate it is not necessary that actual power be transmitted ashore.

The third way, better still, is to design mechanisms which chop off the upper skirt of the stress distribution at a chosen value, even if these mechanisms have to be complicated. We can then work at the higher value for a large fraction of the time getting a better value for the capital investment. This chopping can be done by methods such as yielding as in the duck spine, by pressure relief valves in hydraulics, by over-topping of wave-concentrating walls, by submergence or by opening the diameter of the water cylinder of the IPS buoy. A large part of the capital cost of wave energy plant is associated with the strength of the primary structure. If this fraction of the cost is proportional to strength, limiting the stress to that at the economic limit should reduce the cost of Atlantic plant by a factor between 6 and 10 so that there is plenty of money to pay for some complexity.

The best way of all to minimise the distribution overlap is to have the stress-skirt chopping-point externally adjustable so that, if there are unpleasant surprises in the shape of the endurance distribution, we can still back away from disaster. This also gives the commercial option to sacrifice plant life for electrical output at times of unusually high electricity values which are a feature of recently introduced electricity trading arrangements. Such external controls will also allow us to do useful things like switching off the input power during installation, inspection and maintenance, a requirement often forgotten in the excitement of early invention. There is therefore a need to understand possible stress-limiting mechanisms and the effects of stress limitation of power production and increased range of movement.

Tank tests for survival.

Computer simulation is very useful now at predicting the forces and movements of several kinds of objects in waves provided that they are small enough to be linear. It may eventually be able to predict the loads in the non-linear regime of extreme waves but at present the only way for estimating loads on anything but the very simplest shapes is by tank testing.

The model should be tested in a representative series of irregular seas over and beyond the complete scatter diagram for a time equivalent to about 20 minutes at full scale. The force signals should be used to calculate one force coefficient based on the ratio of root-mean-square force to root-mean-square wave amplitude with terms involving water-density, gravity and model size to give a non-dimensional coefficient. We also calculate a second coefficient based on the ratio of the peak values regardless of whether they were close in time.

For a 20 minute full-scale test period the peak-derived coefficients of a linear system should be about 3.5 times the root-mean-square derived ones if the behaviour corresponds to Gaussian statistics. Low freeboard devices may show a smaller ratio at higher wave amplitudes but anything more than 3.5 should be investigated in closer detail. Both coefficients should be plotted against wave amplitude for a series of energy period up to values which are well above (say 25%) the limiting steepness observed in the scatter diagram. This allows the entire fluid loading behaviour of a model to be displayed on one diagram. Figure 1 shows the results for the surge forces on a duck in a narrow tank. The curves of peak-derived coefficients against the root-mean square amplitude at which they were measured can reveal if there are dangerous upward trends or reassuring downward ones.

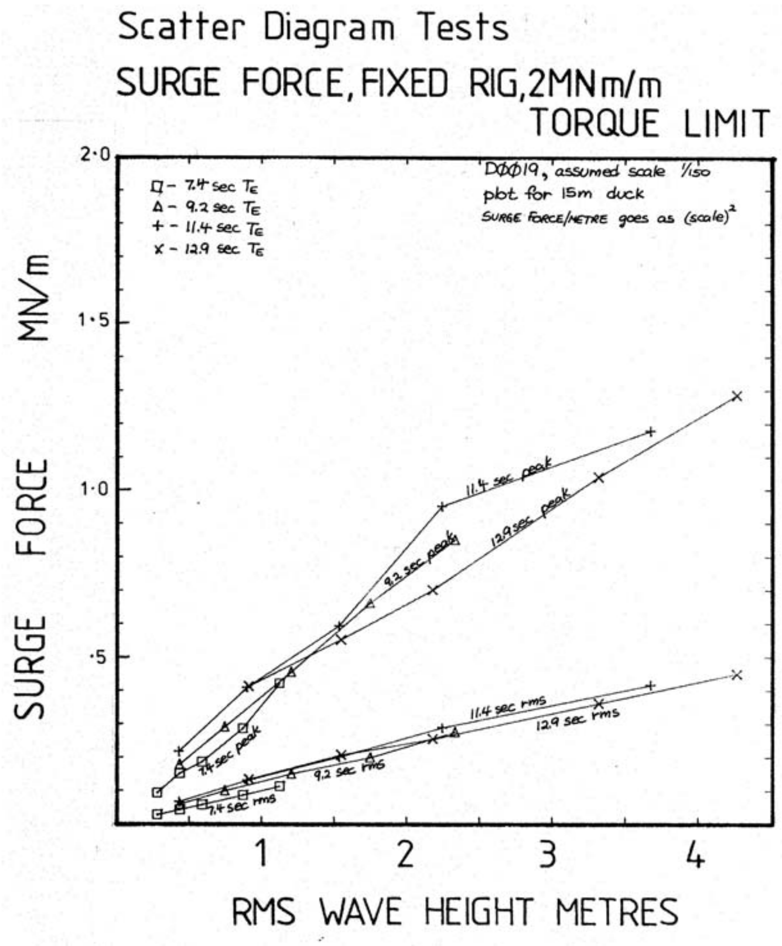

Figure 1. Root mean square and peak surge forces against wave amplitude measured by Glen Keller for a range of periods. There are no dangerous increases at higher levels.

For behaviour in extreme conditions it is necessary to generate an exactly repeatable, extreme-amplitude wave group. The ratio of peak to root-mean-square can be as high at 12. In a narrow tank the most dramatic event is achieved by choosing the phases of the components of a spectrum so that they coincide at a particular point. Because the velocity of propagation is affected by wave amplitude it may be necessary to use manual adjustments to correct the phase values which were calculated with linear theory for low amplitude velocities.

In a wide tank a regular train of very steep waves can be created by focussing wave fronts from many directions towards a single point. It used to be thought that waves could not be generated with height-to-length ratios more than 1 in 7. This is not true. Either of the above techniques can achieve a height to central wavelength ratio of 1 to 4.5. Together they can produce an astonishing but unlikely event from apparently calm water.

The model should be moved to a series of test positions around the nominal breaking point. Force records for each of the possible operating modes should be time-linked to a series of photographs or video frames. Figure 2 shows a sequence of photographs of a narrow tank duck in a freak wave spaced at one second intervals full scale. Figure 3 shows the superimposed force results for a series of positions. Interestingly there was a very strong down ward and *seaward* tendency and the largest forces did not occur at the steepest part of the wave but often at the trough after next.

We can then explore more closely for the wave event which shows abnormally high force coefficients by using a computer hill-climbing method. We make random changes to the phase of one component of a multi-tooth spectrum and see if this produces an increase in the peak force. If there is an increase then that phase value is retained another tried for another tooth. This can lead to ‘sneak’ waves which could cause severe damage even if they appear relatively harmless. There might for example be an extremely low trough rather than an extreme crest. Finding them may be a lengthy process and many device teams have not reported that they have completed it. We should also remember that our language, eyes, instruments and video equipment make us concentrate on the vertical rather than the horizontal excursions of the water but that some wave devices have larger force coefficients in the horizontal than in the vertical direction.

When all these tests have been completed we should have a clear picture of what the sea is going to do to our structure. By knowing the wave statistics of a site we can draw a probability distribution of the whole-life stress and so understand what must be done to avoid prompt overload failure and delayed fatigue failure. We will also be able to reduce costs but avoiding unnecessary strength. Although doing this thoroughly sounds tedious it will provide more accurate information than is available to engineers working on applications such as vehicle suspensions.

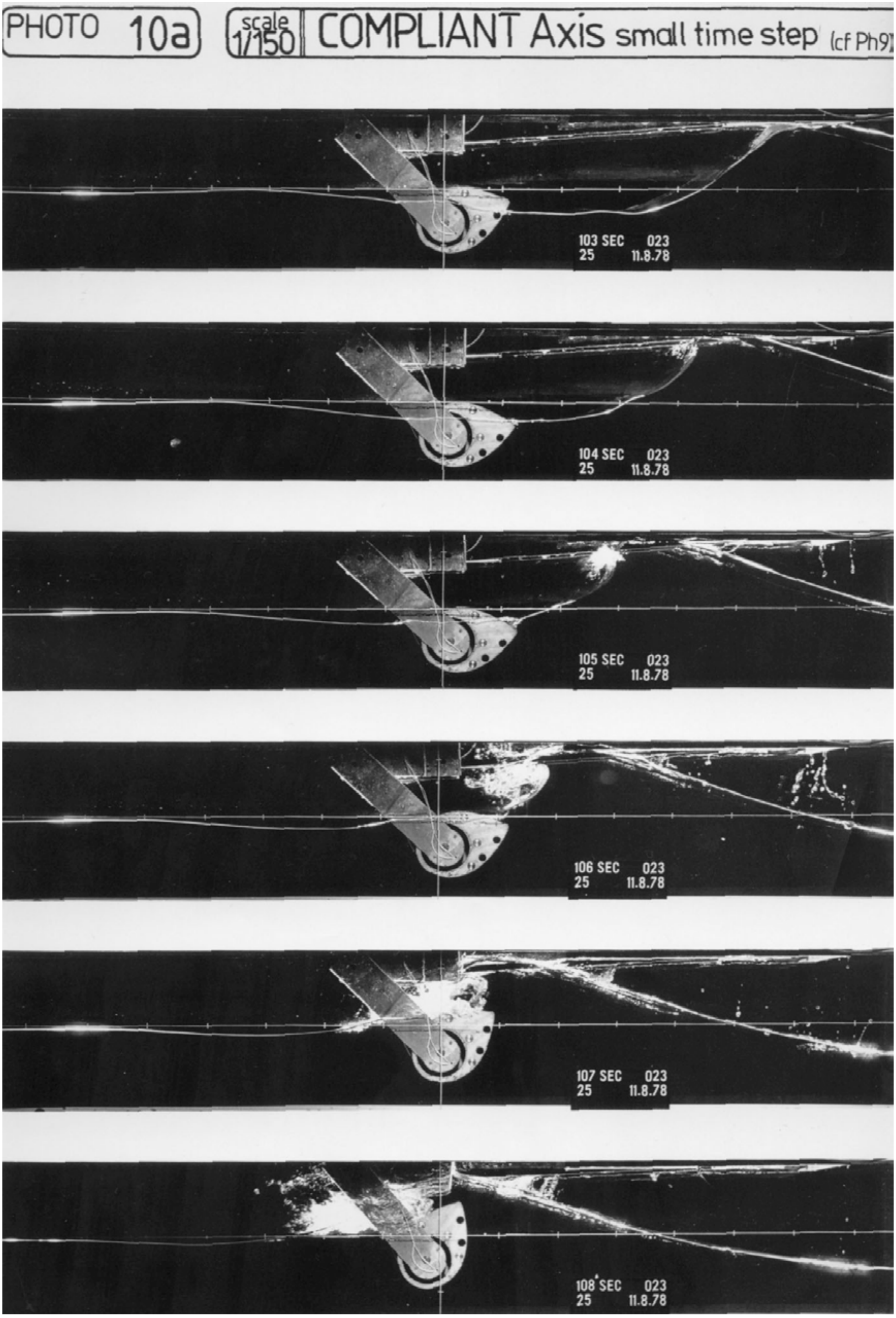

Figure 2. A sequence of photographs by Jamie Taylor from the 1978 Edinburgh report showing a freak wave hitting a narrow tank duck. Intervals are 1 second full scale.

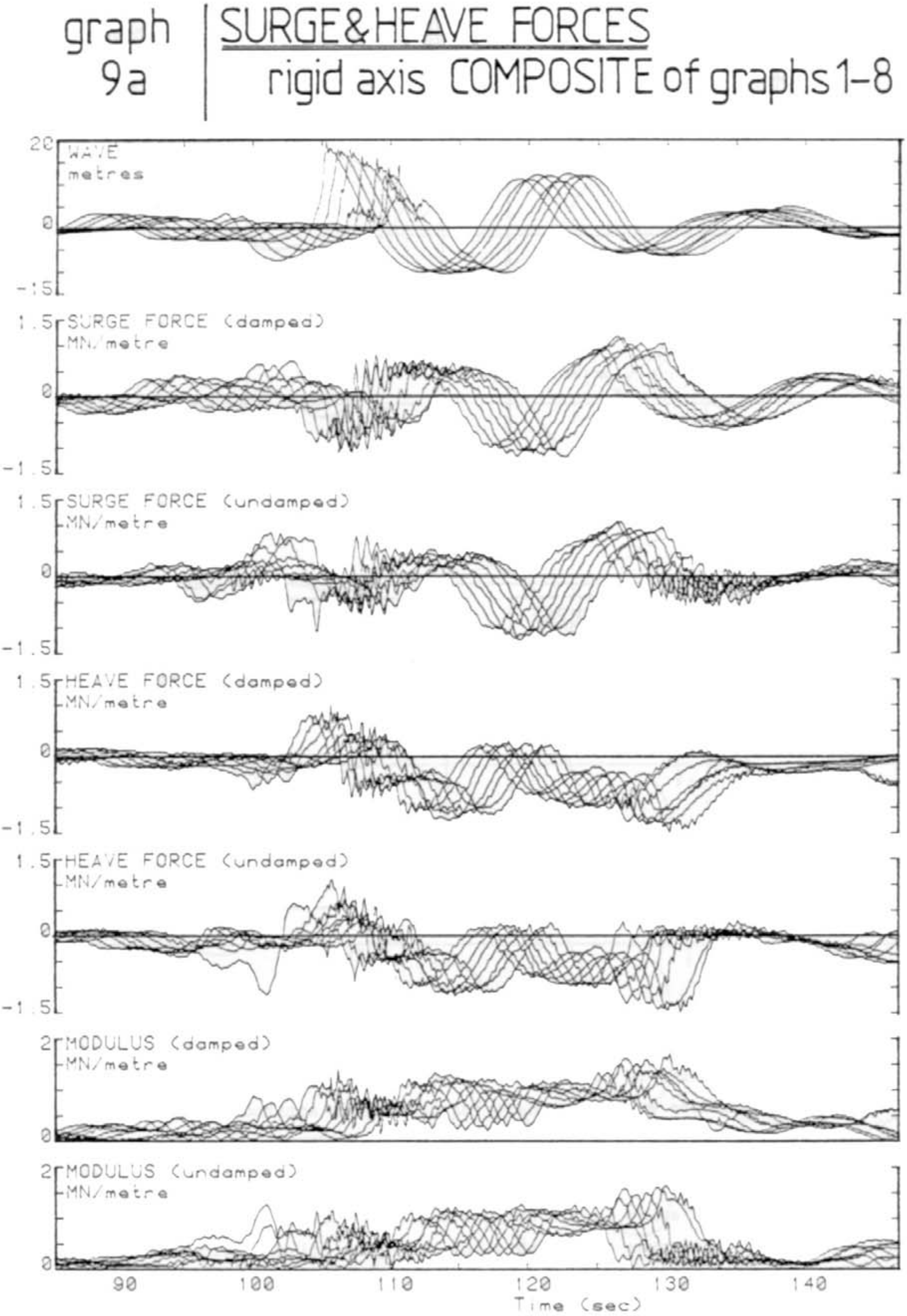

Figure 3. Superimposed forces records for various positions round the nominal break point. Note the strong downward and seaward effect and the lack of coincidence between extreme wave crest and extreme force.

Achieving reliability of components

The cheapest and quickest way to achieve reliability for internal parts of a wave energy system is to use laboratory test rigs to develop and prove new sub-assemblies under conditions where controlled loads can be progressively increased under careful observation with comprehensive instrumentation. However this is not sufficient for items exposed to the external influences of the chemistry and biology of sea-water.

Calculation of the sea water fatigue endurance is particularly difficult for welds to the point where the Edinburgh group will go to any lengths to avoid them. Fatigue research requires large samples of test specimens. The experiments are very boring and incompatible with investor deadlines and the demand for rapid publication rates now needed in universities. Minor changes in surface preparation or design detail like small holes can have large effects so there is a wide range of conclusions and wide variations in allowable stress limits between different classification societies. Some industrial groups refuse to release the values they have painfully and expensively discovered to be safe perhaps in the hope that their competitors will lose money by repeating them. This action is questionable if they have received any public money. There is a research requirement to assess the vast amount of experimental data and filter out a subset for the conditions which will apply to wave energy.

The biological problems are significant because layers of fouling can produce changes in chemistry with substances like hydrogen sulphide which in turn change corrosion rates. Fouling does not reduce performance of wave devices to the extent we should to expect for tidal stream plant but waves will induce more reversing stresses and so will have more serious fatigue.

An outline design for a component test platform is given in the section on tidal stream energy and is reproduced here. It would consist of a floating platform with which could expose multiple sets of components such as cable entries and fasteners and exercise subassemblies such as seals and bearings. A sketch of the design is given in figure 4. The platform would be moored close enough to be able to draw electrical power from land to drive the three-phase induction motors through variable-frequency inverters mounted on the platform. These can drive shaft seals and ram exercisers. Such an experiment would also confront many of the mooring, and electric-cabling problems of wave and tidal-stream.

The key design problem seems to be the safe location of fairly heavy test rigs by a coupling which also allows easy inspection and replacement. This is not easy on a moving platform where a shift of the position of the centre of gravity is undesirable. We must recall the expression ‘loose cannon’. A solution is to mount experiments on a pair of clamp plates joined by rectangular section tubes which carry plastic bearing pads. The combination would act like a saddle and be tied to a large (42 inch) mild-steel tube with a girth strap. The equipment would be designed so that its centre of gravity was close to the centre of the tube. To examine submerged parts the girth would be loosened a little and the saddle rotated by pulling with a Tirfor winch at a suitable connection point. The contact between plastic bearing pads and mounting tube would be nicer if it could be clad with a thin shim, say 0.5 mm of cupro-nickel or stainless steel, with junction to the mild-steel protected by epoxy paint.

I have argued previously that renewable energy research is are an expensive way to relearn the basic and painful lessons of marine engineering. A series of mishaps to items on the platform would be much less of an embarrassment than any to a complete power-generating device. The longer that the test platform is operated the higher will be the value of the results and so it should begin as soon as possible.

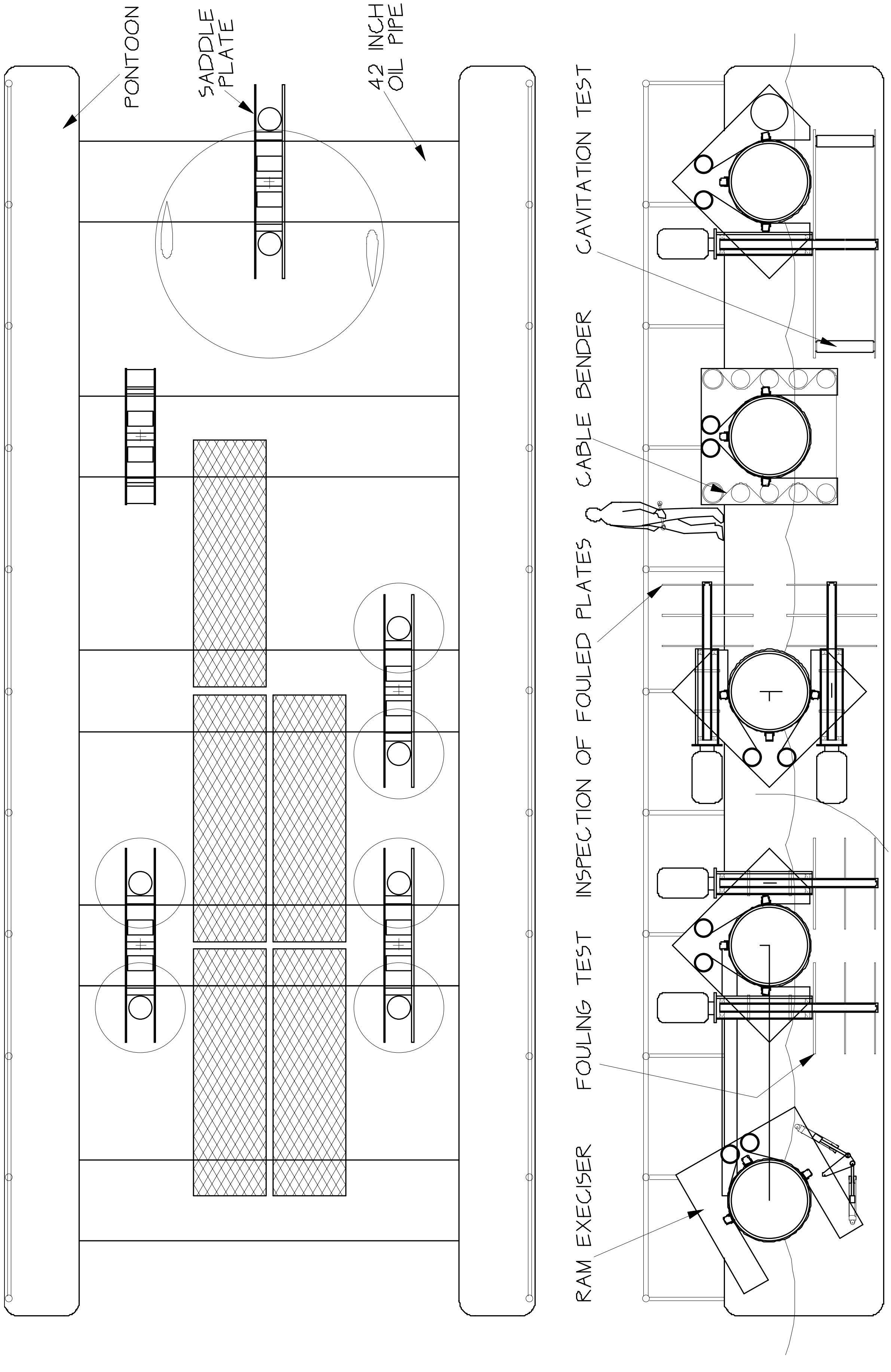

Figure 4. A ladder raft for testing components and sub assemblies.

COST REDUCTION

Control strategy

As well as getting parts to the right strength we can reduce the cost of wave-generated electricity by improvements to the sophistication of the control strategy. Here the investment is mainly into research because the resulting software can be replicated over many devices at almost no extra cost. This path requires both the hydrodynamic knowledge and also the outline design of a power conversion mechanism which would allow it to be applied. The need for improvement can be seen from a comparison between graphs of the efficiency against period of a device in regular waves compared with graphs for random or pseudo-random spectra. A useful task will be to account for this difference.

The concepts of phase and impedance apply to all wave energy devices even to the ducts and ramps of overtopping ones where the impedance changes drastically through the wave cycle in a different way for each amplitude. We need to know how to chose shapes with the impedances we want or know the impedances of the shapes we have chosen for other reasons. This implies that we can calculate or measure the mass and damping coefficients. The best way to measure them is to oscillate a model in calm water and measure the amplitude and phase of force needed for a given amplitude over the range of frequencies. The ratio of force to velocity gives the damping coefficient at each frequency. The ratio of force to excursion at low frequency gives hydrostatic spring. The ratio of force to acceleration gives total inertia. The frequency at which force is exactly in phase with velocity is the point of resonance. The rate of growth of the spring and inertia at frequencies on either side will be a pointer to bandwidth.

Making apparatus to shake models or pump water columns in just one direction is easy. The problem is that reflections from the tank walls will effect the measurements and the results will show a fuzz for each half wavelength of the round trip to the reflector. The fuzz should be exactly consistent from test to test. Provided that it is are not too large we can eyeball through it but it would be much more satisfactory to reduce the reflections.

Several ways are possible. The first is to avoid parallel opposing side-walls which can become the hydrodynamic equivalent of a laser. Almost all tanks have quite a large fraction of parallel wall with no absorption.

The second is to improve the quality of beaches. Most beaches work badly at low steepness. We could improve them by having active absorbers round the full tank perimeter which can operate at sub-millimetre waves. The design would have to be very cheap. For a shorter length it could take the form of a corral of active absorbers in a circle round the shaker rig or a super absorber at one focus of a reflecting ellipse with the shaken model at the other.

The third is to mount the test rig on a slowly moving carriage so that we sweep though the range of reflection distances.

While a one-dimensional shaker is quite easy to make there are several wave devices in which two or more degrees of freedom are of interest. Richard Yemm has designed an extremely versatile force stick which has a low inertia motor with a zero backlash drive to a carbon fibre tube with a stiff load cell. A set of these, perhaps a total as six, can be used to drive any object in any combination of any degrees of freedom.

Options

Once we know about impedances the stages of power take-off sophistication are as follows:

- A true damping coefficient with force proportional to velocity at the value that is correct for the most useful part of the input spectrum.

- A design in which the spring and inertia, including added inertia, is low but giving a resonance at the most useful part of the spectrum. This implies that we can calculate or measure values of the reactive impedance. Some designs can show multiple resonances.

- The addition of reactive terms to the power take-off force so that some part of the undesirable spring or inertia is cancelled. With ducks we found that negative spring was most useful. This technique involves the double passage of reactive energy which should be kept small relative to the real part and demands very low transfer losses.

- The next step is to change the damping coefficient for different parts of the spectrum. This apparently needs an electronic filter which can change the amplitude of a signal without changing its phase. Experts in the field say that it can be rigorously proved that this is not possible. However it is possible to make a filter which changes phase without changing amplitude. It may be possible to beat the prohibition by using advance warning of waves to come using a wave sensor to seaward of a wave device.

- The ultimate control would have the right damping at all parts of the spectrum and simultaneously cancel all the reactive terms. This is called complex conjugate control because the correcting force is the mathematical complex-conjugate of the force used to drive the reactance.

A close approximation to complex conjugate control was achieved by Paul Nebel for his PhD in 1994. He used duck models in a narrow tank with irregular waves of very small amplitude so that their interactions were negligible. He recorded a wave train in the absence of the model and calculated what the ideal forces and torques should be. He then played these commands back for an exactly repeat of the wave train. This method requires exact fore-knowledge of the wave. The system was entirely open loop and so the unpleasant problems of closed loop instability were avoided.

Computer simulation

In the early days of wave energy it was possible to cut a model shape in balsa wood, sand it, varnish it and get the first narrow-tank measurements more quickly than the our computer could predict its behaviour. That has now changed. Computing power is no longer a bottleneck. There are several commercial packages which can calculate the forces on and movements of objects in waves as a function of frequency and direction. One produced at MIT known as WAMIT is being used at Edinburgh and University College Cork. The Aquadyne package is being used by IST Lisbon for research into oscillating water columns. The main applications are for the post-design confirmation of the behaviour of marine structures.

The WAMIT software requires a description of the model in terms of the 3-D co-ordinates of the corners of triangular or quadrilateral surface patches. A companion package, MULTISURF, which was intended for yacht design, has a utility which will produce lists of co-ordinates in a suitable file form. WAMIT will then return the model response as a second file table. The results can then be transferred to MATLAB and plotted. The main difficulties that we have found were that MULTISURF does not always produce the low aspect-ratio meshes which WAMIT likes and does not allow manual adjustments. Predictions of damping and added mass agree with tank measurements at short and medium wave lengths but not quite so well at longer ones.

The need to link together four pieces of software means that the complete process is still tedious. There is a need to improve the links before we can use the full power of WAMIT as a tool for improving model shapes rather than for checking a given shape. Computer modelling of this kind can still not handle non-linear conditions. Nevertheless the potential for testing a given model over wide range of conditions is impressive. Figure 5 is a MATLAB contour plot of efficiency against wave period for a range of slope angles of the sloped IPS buoy carried out for the UK Department of Trade and Industry.

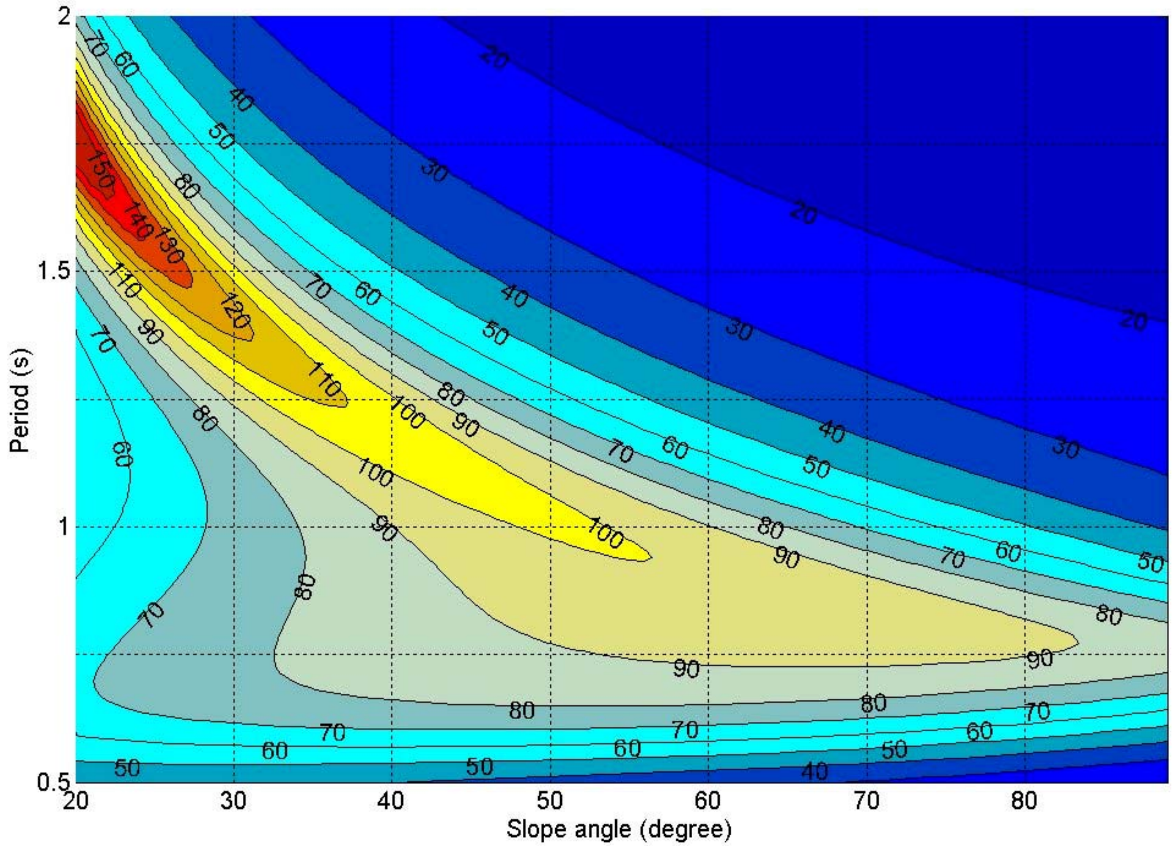

Figure 5. Computer predictions by Gregory Payne of contours of efficiency for a 300 mm buoy on a fixed guide as a function of slope and wave period. The point absorber effect is evident.

Future research requirements are better automatic meshing, investigation of the range of conditions for which computer results can be trusted, means for sweeping through a series of model shapes and perhaps eventually the extension to the non-linear regime.

Computers can also be used to model the various stages of the power conversion, energy storage and electrical transmission of a wet model driven by tank waves if they can be described by mathematical functions. The crucial question is whether the simulation can operate fast enough for real-time feedback to transmit the effects of power limiting when, say, an energy store is full or there is an electrical disturbance to the land network.

Several packages are available. HP-VEE, MODEL MAKER, VIS-SIM, SOFTWIRE and SIMULINK are being considered. SIMULINK is our current favourite because of its affinity with MATLAB and its claim to be able to analyse data flow in real time. An installation is planned for work on the sloped IPS buoy.

Tank Testing Versus Full Scale Trials

Wave energy researchers are fortunate that the Froude scaling rules for force, velocity acceleration and power etc. work very well down to the point where surface tension takes over from gravity as the restoring force allowing insects to walk on the water surface. Gravity and surface tension become equal at a wave length of 17 mm, four orders of magnitude down on a full scale ocean. At scales down to 150 the only worries are the cross forces on cables, the steady drag forces from currents and the relatively higher viscous forces which will reduce measured efficiency by a few percent. Work in the MAST programme showed that scaling rules for forces work well over this range even for objects as non-linear as breakwaters in shallow water. Results will appear in Pearson, J., Bruce, T., Allsop, N.W.H. & Gironella, X. (2002), "Violent wave overtopping - measurements at large and small scale" . Proc. 28th Int. Conf. Coastal Engineering (ASCE), Cardiff.

Specific advantages of tank testing are

- Computer generated tank waves can be deliberately orchestrated to investigate a particular problem and repeated exactly even if the probability of natural occurrence of a malevolently chosen wave group is very low. In the tank you can stage an event with an average return period of 100 years every 20 seconds so that a short series of trials can give information equivalent to millions of years.

- You can vary the model position, attitude, power conversion status and subject it to the same wave sequence so as to be sure you have explored the entire danger area.

- It is easy to test in waves which exceed those which occur in nature by a controlled amount.

- It is easy to stop the waves to recover a capsized model, repair instrumentation or check a calibration.

- It is easy to photograph the waves, the movements of the model and tracing particles in the fluid.

- We can test with models that are cheap, easy and safe to handle.

- Mistakes made at small scale in private do not damage the credibility of the entire technology. Indeed they can be very informative.

- A final advantage of tank tests is that, in some mystical way, they seem to transmit to mathematicians the keys to the solutions of hydrodynamic problems hitherto thought to be intractable.

The importance of sophisticated tank tests has been shown very recently in the March 2000 issue of Offshore Research. This contains a report on tests on a floating production storage and offloading vessel carried out by HRWallingford. The tests compared the roll response in the long-crested seas (the sort you can make in a towing tank) with the response in short-crested seas which need multi-bank wave-makers in a wide tank. The report states:

"*Roll was found to be the most significantly different with increases in the extreme roll of up to 150% in short crested waves when compared with long crested".*

It is astonishing that after all the marine industry experience of ship-like forms there can be an uncertainty by a factor of 2.5 in a parameter as important as extreme roll. One reason given was "*the limited availability of facilities which can generate short crested waves or multidirectional waves"*. Further information will shortly be released from

www.hse.gov.uk/research/frameset/offshore.htm

Tank tests do not yet reproduce the effects of currents and current-wave combinations which can be very complicated especially when waves are propagating against the current direction. Fortunately there are many attractive wave sites which do not have high current velocities. The currents at most open-sea wave sites will have moderate velocities parallel to the coast with even lower velocities at greater distances from shore. Even so, the problem is of some concern to wave devices with compliant moorings which present a large area to the current direction, especially if the current uses up the slack in a slack mooring or if there are vortices which act differentially along the length of a long device caused by combinations of two currents.

The similarity problem may be more serious for tidal-stream plant where some designs are vulnerable to wave action. The Edinburgh group has initial designs for a round tank which could reproduce any combination of waves and currents independently round 360 degrees. Figure 6 is taken from a paper given to the Marec 2001 conference at Newcastle and shows the design. It is not unreasonable to expect that the combination of waves and currents will reveal hydrodynamic effects as important as the observations of extreme roll mentioned above. The Edinburgh group is building a 2-metre diameter flow table to test the 48-blade variable-pitch vertical-axis rotor technique needed for complex, multi-directional current control.

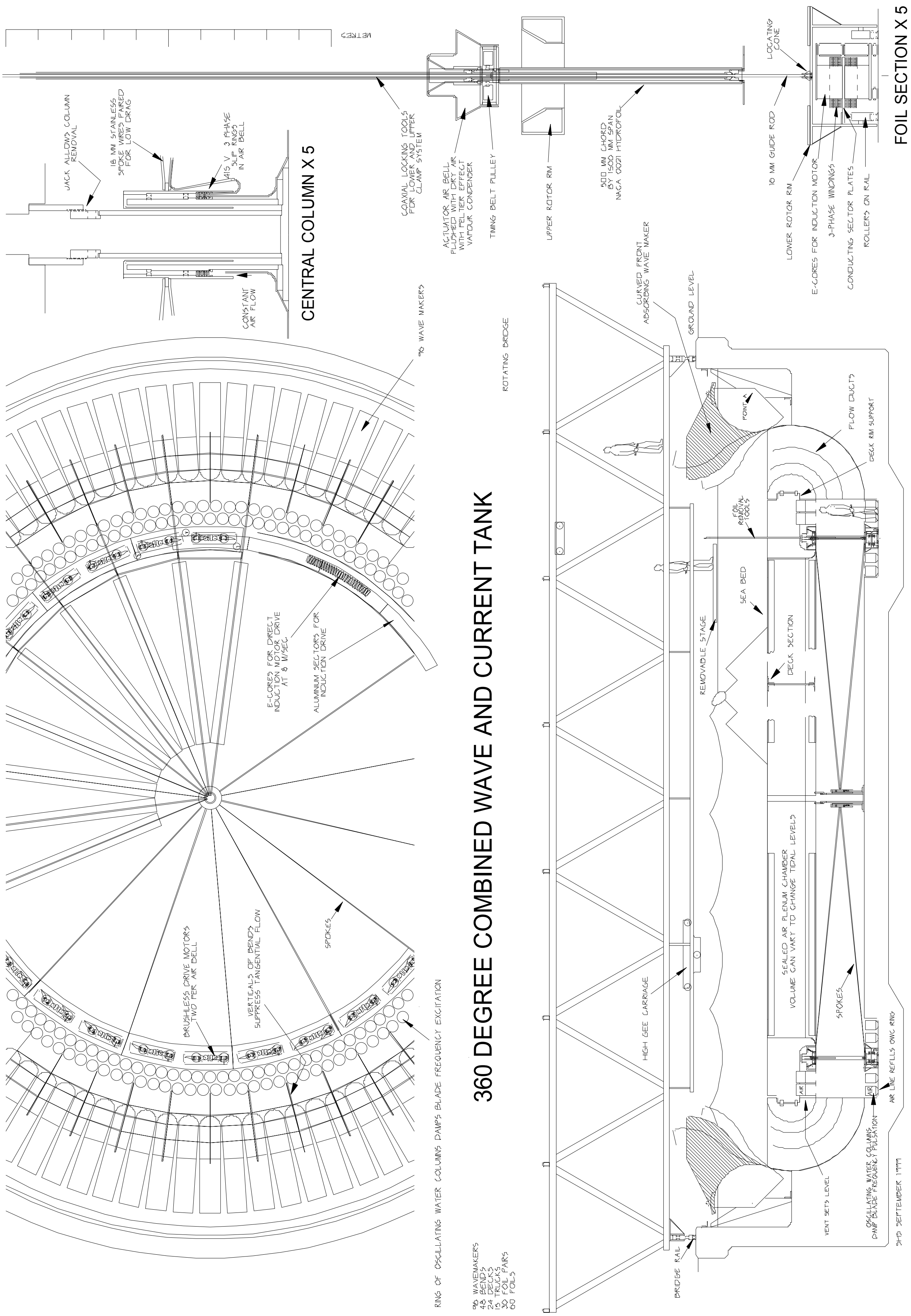

Figure 6. Views of a 360-degree tank with complex combinations of wave and current patterns from any direction.

There are only three negative features of tank tests.

- They do not reproduce the biology and chemistry of sea water or their slow effects over long periods. For example in the early '70s it was found from the gas platforms in the southern North Sea that the fatigue rate of steel welds in sea water was frequency dependent with the highest fatigue rate at wave frequency. This was however not known until nearly all the platforms had lost their cross bracing.

- They do not give the photo opportunities demanded by public relations advisors.

- The interpretation of tank tests require a degree of technical intelligence which, while moderate, exceeds that of many politicians and investors.

The problems with full scale testing of complete devices are that

- You cannot be sure of getting waves when you want them and not having them when you need a calm for installation inspection and repair. Indeed it almost seems that you can be sure of not getting waves when you do want them and of getting them when you do not.

- Even if you accept what the weather dictates it is hard to measure the wave input accurately.

- It is quite impossible to reproduce particular events and

- It is quite impossible to use absurd extremes which can be very informative.

- It is difficult to vary model parameters.

- Minor problems to small components likes seals, bearings, cable terminations or shackles, which may be quite unrelated to the essentials of the device, can cause expensive damage and waste a great deal of even more expensive time. The general public are quite unable to distinguish such problems from those which are inherent in the technology.

- Full-scale devices will be testing relatively small numbers of critical components, sometimes only one, rather than the large numbers that are needed to provide meaningful statistical reliability data.

- Out door work on an entire power generating system is so expensive that iterative problem-solving is ruled out.

- Problems are likely to involve the loss of the data links needed to deduce their cause.

A Reciprocating Flow Wind Tunnel

In the early stages of wave energy, low-pressure air was by far the most favoured power conversion technique and the unidirectional Wells turbine was the favoured machine design. The reasons for this were:

- Air turbines offered a painless way to increase the slow velocities of waves to the high velocities needed for electrical generators.

- The Wells design had the lowest idling losses of any turbine and a linear pressure-to-flow relationship which could be tailored to suit the damping coefficient of a water column.

- Advocates argued that air turbines were simple with only one moving part.

The problems were that the only experimental data then available on turbine conversion efficiency in wave-like flows showed a rather narrow curve of efficiency against flow rate with a maximum of 40% in a reversing sinusoidal flow and 35% in a statistically realistic flow. This was far below the theoretical 82% peak efficiency in the best steady air-flow and would give an unacceptably poor return for all the upstream civil investment. However these alternating measurements were made with small turbines at low Reynolds numbers and it was hoped that large machine would perform better. Under the Joule programme we carried out a rather crude theoretical analysis of the Gaussian efficiency of air turbines with fixed and variable pitch using open-field lift and drag coefficients for sections along the blade span. We concluded that the peak efficiency for full size fixed pitch machines at correct Reynolds numbers would be about 55% falling quite sharply either side of the best flow rate.

In February 1992, at one of early European Joule wave energy meetings and despite my lack of enthusiasm for low-pressure air power-conversion, I put forward an outline design for a facility to test air turbines at full size values of pressure and flow. The design, shown in figure 7 involved a cylindrical hole cut into chalk and lined with a concrete-plaster-polyurethane surface. Inside the cylinder would be a piston made from part of a geodesic dome driven by a double acting high-pressure oil ram. The cap of the cylinder would be a second geodesic dome with removable panels to allow the modelling of any pattern of ducting leading to any attitude of turbine and also the insertion of guide vanes, stop valves, by-pass valves, pressure sensors, flow-direction indicators, video cameras, anemometers, smoke-generators and spray injectors. A tunnel from the underside of the cylinder would lead to a vertical shaft feeding air through flow straighteners to a vertical axis machine which would enjoy ideal but perhaps less attainable straight-line flow.

The piston would be driven by a high-pressure oil hydraulic ram with oil from an electrically driven, multi-bank, double-ended wedding-cake hydraulic machine with some banks going to a pressure accumulator for energy storage. The system is shown in figure 8. Electrical energy from turbines under test would pass through all the conditioning electronics and then drive an induction motor on the other end of the wedding cake unit allowing most of it to be recovered. The power drawn from the grid would therefore be only the mean losses round the loop. The pump could provide any statistical pattern of airflow include realistic sea inputs and perversely chosen alternatives. Measurements of ram position and pressure differences would give direct, absolute measurements of the conversion efficiency of ducts, guide vanes, turbine and diffusers with quick, safe access for repairs and instantaneous emergency stops. It would suffer none of the problems of flow measurements in oscillating water columns with internal sloshing. It would allow realistic development of stop valves and bypass valves. It would allow a burn-in period long enough to correct infant mortality before equipment was shipped to isolated wave sites.

I was given advice that turbine ratings for oscillating water columns would be up to 4 Megawatts and so the test facility was sized at 10 metre bore, 10 metre stroke, 1 bar pressure capability with a peak power rating of 10 Megawatts. The cost estimate in 1992 was 2 million ecu. Clearly this would be too much for an individual device team but a moderate expense if it was run by a pan-European or international consortium. It would also give a splendid chance to demonstrate the performance of digitally-controlled, high-pressure oil, poppet valve machines at high power levels.

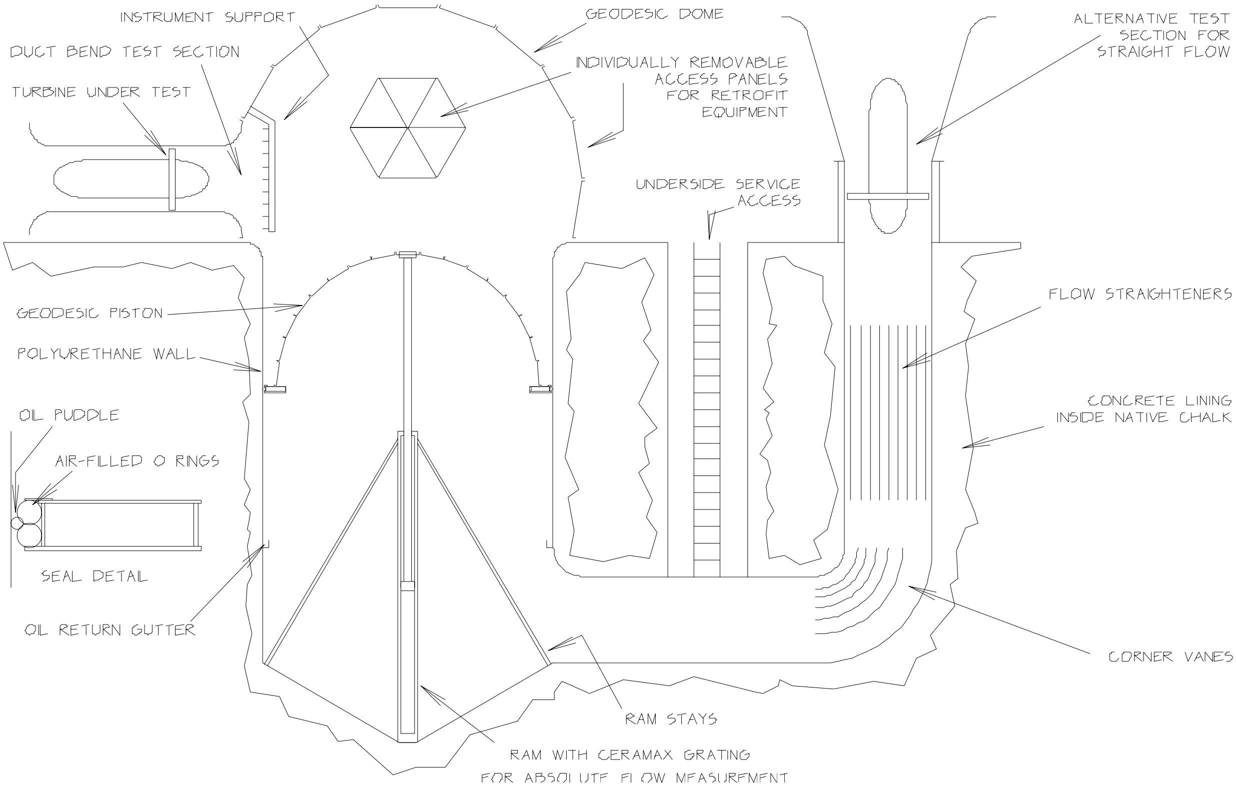

Figure 7. The reciprocating flow wind tunnel can test all the mechanics and electronics for low-pressure air power take off and recirculate all the energy produced by the turbine.

The proposal was emphatically rejected by the air turbine advocates as being unnecessary, too expensive and a waste of time.

Ten years on we have a fixed-pitch turbine in the Azores which suffered from a 2-winter interruption in civil construction, has loose guide vanes, a repaired sluice valve, a balance problem and a severe oil leak. We have had a second fixed-pitch machine in the Limpet which has been operating for over a year but with reports of excess noise and total secrecy about its conversion efficiency. We have a bladeless, variable-pitch machine sitting in Lisbon with a satisfactory demonstration of the strength of its root attachments but no money to build a complete set of blades. The general air turbine community is no nearer knowing the operating efficiency of the most essential part of their technology. The silence of Wavegen about Limpet performance is not encouraging.

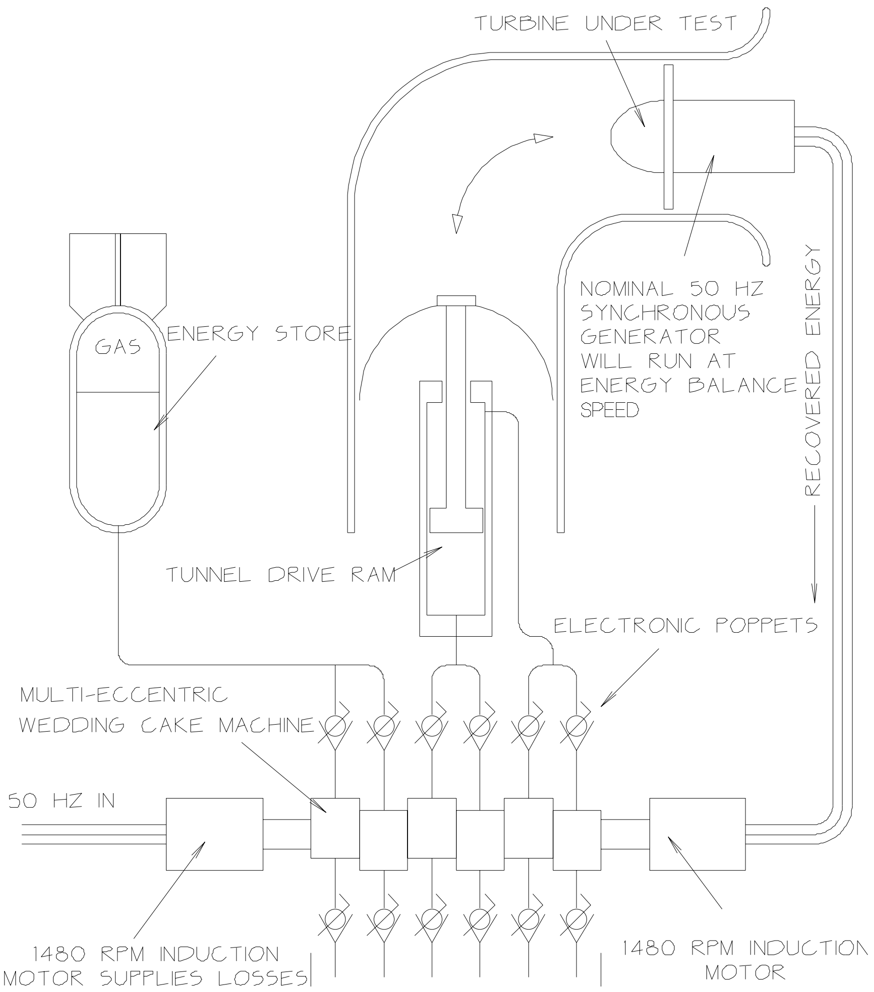

Figure 8. A multi-eccentric poppet valve machine driving the turbine test tunnel.

Work on air turbine designs has since convinced me that the 4 megawatt rating was far to high. The combination of droplet erosion, Mach number effects, idling losses and convenient generator speeds points to turbine ratings around 500 kilowatts so that a smaller reciprocating flow tunnel with a peak rating of about 1 megawatt would be adequate. All the other arguments appear even stronger today. It is my duty to urge the air turbine community to reconsider their 1992 decision if they want to avoid a wasting a second ten years. At the same time my dislike of low-pressure air leads me to hope that they will ignore this advice!

High-pressure Oil Research

Most conventional hydraulic components have evolved from the times when energy was a very small fraction of total operating costs. Many applications use machines at a range of power levels which is narrow compared with the requirements of wave energy and so there was no incentive to reduce part load losses. Consequently the overall productivity predictions in a Gaussian range of pressure and velocities are every bit as bad as that of air turbines.

The use of hydraulic rams as the link from the displacer of a wave energy device is obvious and there is no problem about achieving the thrusts needed. There may be some difficulty about getting the long range of stroke needed by well-designed devices because the strokes could be at least twice the wave movement. However this problem has been effectively solved for the Swedish IPS buoy with its change of passage diameter. If sufficient stroke is not provided there is a need for work into end-stops which might have to handle instantaneous power levels much higher than the rating of the wave energy device.

There is also a possible question about rams in wave plant having to move at a higher velocity than conventional hydraulic rams. Most of these have been designed for the lowest possible oil leakage even at the expense of seal friction losses. The velocity problem can be solved by a modification to the ram seals involving the cutting of a fine-pitched helical thread through the ram seal so as to deliberately increase the leakage loss and also reduce the shear loss to the point where they are roughly equal. This in turn requires the development of a technique to recover the leaking oil. This could be a large Belofram rolling seal or a secondary scavenging stage.

The development of the Ceramax rod coating by Hydraudyne may now allow rams to operate directly into sea water. Sub-assemblies of rams, seals and coatings with re-circulating energy flow are good candidates for tests on the platform described in the tidal section.

The end-stop problem does not arise for rotary plant like the duck. During the first UK wave programme the Edinburgh group designed low speed hydraulic pumps using multi-lobe ring-cam pumps with torque sufficient for the duck system and with variable delivery achieved by selective disabling of poppet valves using the newly available microprocessors. It was expected that these pumps would feed oil to Clerk tri-link motors which had a mechanical variation of displacement but which had been designed with particular emphasis on low losses. We built a 600 kilowatt tri-link machine and showed that the low power losses were as predicted. However the industrial partner who had promised to carry out full power tests withdrew.

As part of the first Joule programme the Edinburgh group extended the digital poppet valve technology to fast machines. All fast machines had hitherto used axial pistons. Our new geometry uses radial pistons driven by an eccentric but the displacement is controlled by electronically-operated poppet valves on the outer surface rather than port face valves close to the axis. This change allows the use of multiple banks, perhaps as many as ten, on a common shaft. There was now only one fast high-pressure interface rather than two and it was at a much smaller radius than in an axial piston unit. Unlike all previous variable-displacement designs oil would never be pressurised unless the energy was going to be used. The machines could simultaneously take oil from or deliver oil to many independent sources or sinks of hydraulic energy such as the ram set of a duck spine joint. The change from pumping to idling to motoring could occur in half a shaft rotation time and be different for different banks. This makes them highly suitable for interfacing to gas accumulator storage. In a renewable energy application the rotation speed would be set by a grid locked synchronous generator while the torque into or out of the generator would be set by the product of oil pressure and the number of poppet valves enabled to pump, idle or motor. The multi-bank configuration also allows two stages of a machine to work against one another so that the problems of finding large test rigs are reduced. This idea can be extended to allow parts of an entire wave energy device to be exercised for test purposes in calm water.

To get operation fast enough to run at synchronous speeds required the use of lightweight plastics for the poppet valves and one of the Joule tasks was to demonstrate that the chosen material had sufficient fatigue life. A group of 12 sample valves were tested to 1.5 x 10^9 cycles at 50% over stress.

The technology is being developed by a spin-off company Artemis Intelligent Power. They have built a series of units at the small sizes for which applications could be found. These have included pumps and motors for commercial customers using hydraulic oil water and petrol. Applications have been in laboratory hydraulic supplies, digital position control of a mine-clearing vehicle with 5 mm advance per computer bit and a small vehicle transmission with regenerative braking. However all the machines built so far have been at power levels far below those needed for wave energy with typically 18 kilowatts per bank rather than the megawatt per bank of the original concept and not yet large enough to show the benefits of the new annular poppet valves.

The next step in the evolution of fast poppet-valve machines should be to progressively increase power rating in stages chosen to suit land-based applications which can share the cost. The reciprocating flow wind tunnel is one such. Regenerative transmissions for taxis, buses and commuter-railway locomotives are others.

Direct electrical generation

The leading academic expert on electrical machines of the 1970's was emphatic that the velocities associated with waves were far too slow for direct electrical generation. We were told that nobody wanted electricity of random voltage, frequency and phase. Unless we could achieve heroic advances in iron permeability or the coercivity of permanent magnets or room-temperature super-conductivity, the weights of iron and copper would be sure to sink any floating device.

Since then there has been the development of neodymium boron magnets and also a remarkable reduction in the costs of electronic frequency-changing equipment. The land-based electronics of the Archimedes Wave Swing was completed in 2001 and the sea plant which uses direct generation is to be launched in 2002.

Markus Mueller at Durham is working on directly-driven transverse-flux machines and their conversion electronics. He reports as follows:

The transverse-flux machine is capable of an air-gap shear stress of 200 kN/m^2, orders of making it a suitable candidate for direct drive wave energy. However, the machine structure is far from conventional, there are large magnetic forces, and the machine suffers from a very low power factor, less than 0.5. With any direct drive power conversion system, a power electronic interface is required to convert the variable output from the wave energy device to a constant voltage and frequency for grid connection. For machines with low power factor the converter will be overrated compared to a conventional permanent magnet synchronous machine. The mechanical structure holding the machine together, the bearing arrangements and sealing the electrical generator are major issues for all generator topologies in a direct drive wave energy converter.

The work taking place on direct drive wave energy converters has shown the potential for this method of power conversion, but the optimum integrated solution is not yet clear.

Research on fourth generation wave energy devices should include full mechanical and electrical designs for wave energy devices considered suitable for direct drive wave energy conversion. A full costing study should be included to enable comparison with other wave energy power conversion technologies. The major issues to be addressed are:

- Bearing arrangements : could the sea water be used to provide a fluid bearing, and how would this reflect on the topology of electrical generator adopted.

- Sealing arrangements : could the machine be operated fully flooded so that no seals are required, and what effects would this have on the choice of generator topology; and if not what is the status of sealing technology.

- Corrosion : what is the status of marine friendly coatings for protection in both sealed and flooded systems.

- Electrical generator topology and associated power converter : it is not sufficient just to optimise the force density of the electrical machine, the power converter requirements have to be included in the design optimisation. The generation of smooth power into the grid is an important issue. A full investigation of all the possible combinations needs to be addressed, taking into account mechanical structure issues as well as the issues outlined above.

In summary an integrated approach is required in any further research into direct drive wave energy converters, to determine optimised electrical and mechanical designs for particular wave energy devices.

Storage and the grid interface.

The square of a Gaussian distribution has a most unattractive ratio of peak to mean values. We pay for the peak but get paid only for the mean. We also have to use components with constant losses which may be a small fraction of a steady high output but which are a much larger fraction of a low mean output. The distribution boards can impose strict rules on voltage and phase deviations and will insist on automatic disconnection if the delivered energy is out of limits. The earlier we can store energy the cheaper and more efficient will be the plant downstream of the store and the less likely we are to be forcibly disconnected.

The gyro flywheels needed for hermetically sealed power conversion in 1981 ducks provided plenty of storage, more than the 100 seconds needed to give a flat output, but needed extremely low-loss bearings which still imposed an undesirably low torque limit. The present preference is for gas accumulators. Pressure accumulators cost the same per unit weight as machine tools and have extremely high factors of safety which could perhaps be reduced by improved enclosures or by techniques used for explosion suppression. There is a research requirement to reduce the cost of gas accumulators by a factor of at least five. A good start would be to persuade the manufacturers to stop stamping their names on the accumulator casings and thereby inducing unpleasant and completely needless stress raisers.

Compression leg moorings.

Very long tension-leg moorings are in use with deep-water positively buoyant offshore platforms. Tank tests show that they appear to be less satisfactory for shorter lengths needed for wave power and tidal stream devices because of the high snatch loads which occurs when tension is reapplied after any slackening. The problem is the very large amount of kinetic energy of the high inertia wave device which has to be absorbed or dissipated in the mooring leg. Snatch loads will arise in the steeper waves of quite moderate seas. Solutions involving a shock absorber would have to have an instantaneous power rating at least an order of magnitude above the mean power of the wave device.

An alternative might be a compression leg made out of a single concrete tube (nice for slip forming) post-tensioned to about 40% yield or a dual base-to-base tetrahedral truss of tubes. Hollow construction could make the leg neutrally buoyant for easy installation. Its design would be strongly driven by buckling in compression but calculations show that compression legs could be used in water depths up to 50 metres and perhaps more. Buckling resistance is improved by an increase of diameter at the centre of the leg. Wave loading is reduced by a smaller diameter near the surface.

Post-tensioned concrete members arranged as pair of delta-frames could be used for a pair of contra-rotating vertical axis tidal stream generators.

There is a research need for a study of post-tensioned concrete tubes with particular emphasis on elastic stability.

Short term wave prediction

The partial coherence of waves allows extrapolation of future waves for phase angles large enough to be considered for improved power take off strategies based only on the velocity or force on a wave device. A longer forecast of a minute or so could be used to smooth output variations for devices with energy storage by pre-emptively reducing output if a lull is foreseen.

Warning of extreme wave groups could give time for survival measures to be taken

Michael Belmont at Exeter is working on forward-looking laser techniques. It would also be possible to use wave sensors to give advance notice. This is already in use in test tanks to control absorbing wave-makers as an alternative to force-based absorption.

The initial research requirement is to establish the extent to which forecasts can improve power conversion. The work of Paul Nebel suggests that it could be very useful.

Reverse power flow in slender grids

The present design of electricity distribution networks assumes that centralised generators feed energy to peripheral consumers. Everybody wants to use appliances designed for the same nominal voltage and so the resistive drop along the direction of propagation is corrected by multi-tapped transformers which can increase the secondary voltage by up to 10% in steps of 2.5% to make up for the resistive voltage drops. Although tappings can be changed to suit various load patterns, work by Whittington and Wallace at Edinburgh has shown that the range of adjustment is not going to be enough for the reversal of flow direction involved with wave energy coming from the coast to central consumers. Replacing a large number of transformers will be possible but the distribution boards will certainly want to be paid to do this and have already demonstrated their willingness to exploit their strong bargaining position when it comes to grid reinforcement and connection costs. Distribution transformers last for a very long time unless they are destroyed by lightning strikes and so it will many years to replace the present ones through natural wastage.

One possible option is the addition of a specially-designed correction transformer as shown in figure 9. It would have a one winding in parallel with the present seaward winding but with copper diameter chosen for, say, only 10% of the rated current. It would have the same turns but a separate set of tappings with their own switch. This is necessary because the supply authority will not want to open existing casings.

The landward winding of the correction transformer would have turns for only 10% of the voltage but copper for the full secondary current. It would be in series with the present landward winding.

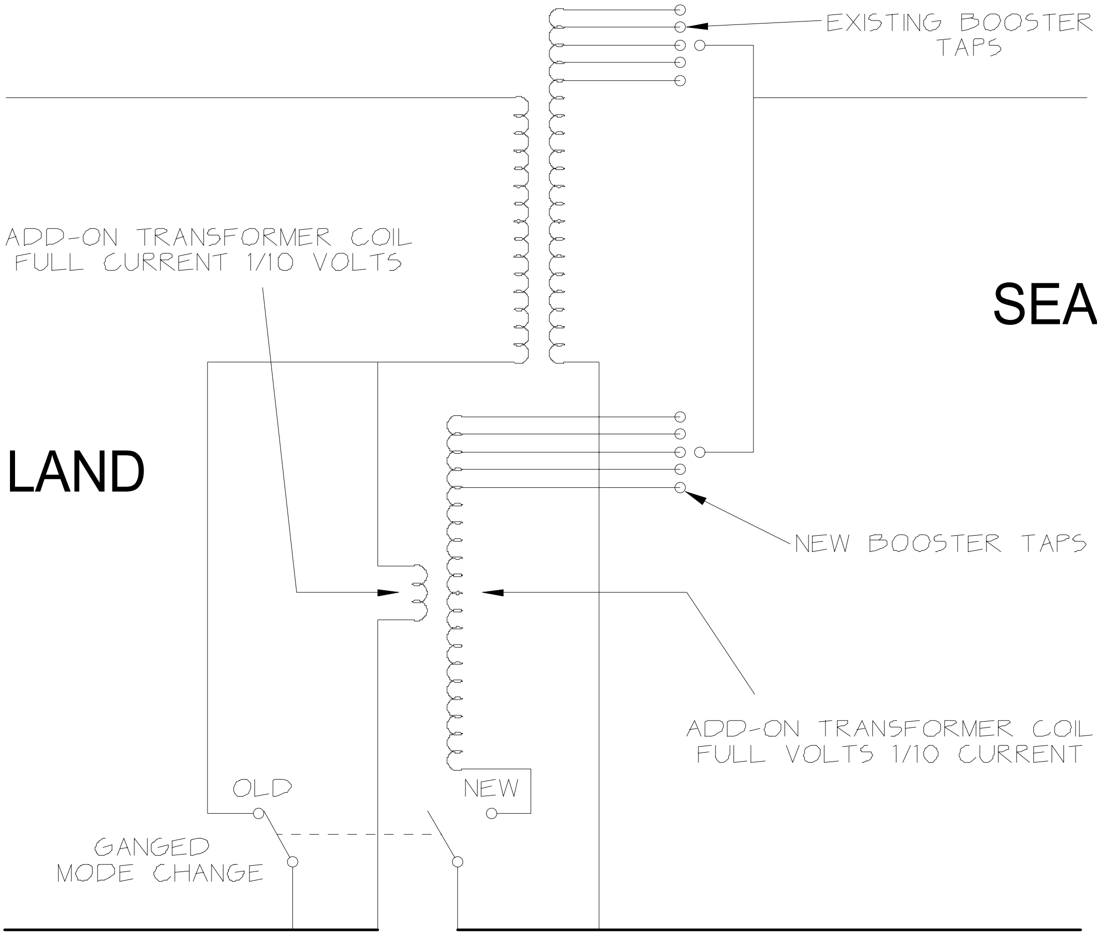

Figure 9. The booster transformer allows power to be fed from the coast to the centre without exceeding voltage margins on either side of the transformers.

During land-to-sea transmission the low voltage winding of the correction transformer would be shorted by part of a double-pole single-throw switch and the untapped end of the high voltage correction winding would be left floating by opening the second pole of the same switch. This would mean that conditions would be exactly as they are now. The change of direction would require the simultaneous operation of both poles of the switch to bring the low voltage coil of the correction transformer into action just as the floating end of the high voltage coil is connected to the seaward neutral.

Other things being equal its cost of the correction transformer should not be much more than 10% of the cost of a complete new transformer but it might be prudent to spend a bit more on long-life tappings because they will be used much more that at present. The feasibility of this idea is being discussed with transmission experts and it is already clear that the problem is serious for all remote renewable sources and several other factors are involved. The most interesting areas of research are the matching of tap ratios from old to new units and the switching of transformer taps. At present tap changing is done with mechanical switches but it might be possible to persuade the rather conservative distribution boards to try thyristor switches.

Bearings

Many machines can be described as interesting bearings joined together by boring solid lumps.

If the turbine problems of low-pressure air devices prove insoluble there may arise a need for geometrically tolerant bearings which can take high loads at low speeds. The favoured way to get geometrical tolerance is to use spherical bearings which can give 360 degree movement about one axis and as much as 15 degrees about the other. The SKF Plain Bearings catalogue shows that there are many off-the-shelf parts with very high load capability under grease lubrication but rather low velocity capability. There are also marine versions of the Glacier Vandervell DU material. A higher velocity without life restrictions could be achieved with hydrostatic technology but this raises the problems of the working fluid being lost to the sea. For restricted degrees of movement we can use flexing elastomeric enclosures as seals.

For large rotations two solutions may be possible. One involves the development of a magnetic liquid known as a ferro-fluid which is strongly attracted into magnetic gaps. These are used very successfully as seals for vacuum equipment. Unfortunately all existing ferro-fluids seem to have some degree of miscibility with water and would soon be lost. Discussions with makers have suggested that a solution will be very difficult. The second involves the use of sea water itself as the hydrostatic fluid. Its viscosity is rather low but not impossibly so. It would have to be filtered to remove abrasive and biological materials but much of the exit flow can be recycled if it is impeded by a less than perfect seal. There would have to be high-pressure, salt-water pumps with much longer lives than at present. A bearing with floating pads able to take about 2 degrees of misalignment is described in the tidal-stream section.

Magnetic squeeze films

The specification for the radial bearing between duck and spine was a long way off the edge of the map of any known bearing technology. The bearing load at joint yield was 30 MN. The spine would be bent out of straight and round by 50 mm and could not be made to any initial accuracy. We wanted zero friction, zero wear, infinite life and no lubricants lost to the sea.

The solution was the subject of a PhD thesis by Colin Anderson and is shown in figure 10. It uses a mattress of water-filled ‘concertinas’ over the entire contact area of the duck to spine interface. One side of the concertinas was in contact with the concave inner surface of the duck body. The other side is in contact with a sheet of material having the elastic properties of a stiff carpet. The rubber of each concertina has a gentle spring rate which tries to open it. In calm water the 3 mm clearance between the carpet and the spine is maintained by rings of ferrite magnets. Rings on the spine are embedded in a bituminous layer like road tarmac. Rings on the duck are moulded between the layer of carpet supporting the concertinas and a second layer. The layers of carpet have exit holes which allow water to be squirted out to a thin gap between the inner carpet and the convex surface of the duck spine. Refilling should be made faster than emptying.

When the large forces of big waves on the duck are divided by the large area between duck and spine the pressures are quite moderate, around 50 kiloPascals. This pressure is sensed by water in the concertinas and water in the gap between carpet and duck spine. Water will flow under this pressure towards an unloaded part of the bearing but has to flow a long way round the duck spine through the relatively thin gap. It will take several minutes to exhaust the water in the concertinas and we can be quite sure that the wave load will have reversed long before the inner carpet contacts the spine. The faces of the bearing never touch and so do not wear. At duck velocities in moderate wave conditions, the viscous losses across the 3-mm gap are acceptably low. To reduce internal fouling by hard-shelled organisms, the water in the bearing would be chlorinated to about 2 parts per million. An acceptably small amount of this water, would be lost through the ends of the bearing and so chlorine replenishment in quantities suitable for swimming pool systems is necessary. Anderson's thesis contained information on the optimisation of the magnets and a method to maintain their alignment despite the elastic strain of the spine.

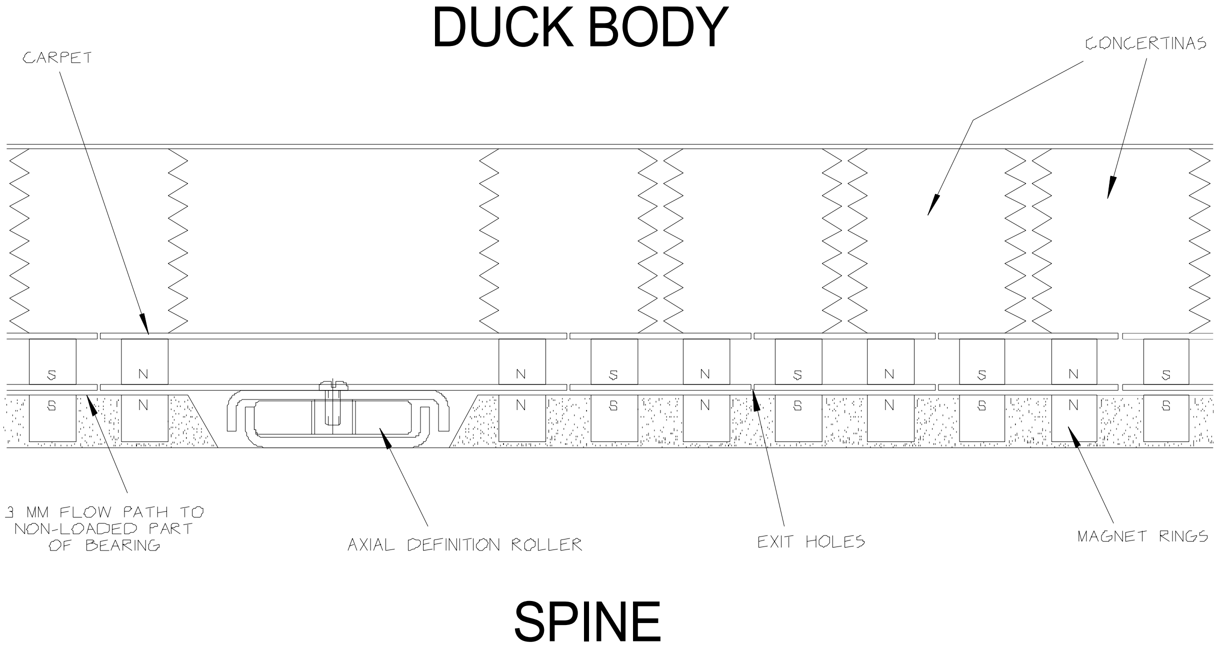

Figure 10. A section through the magnetic squeeze film bearing developed by Colin Anderson. By using the full area between duck and spine the pressures are kept very low.

To test the idea a vertical thrust bearing using magnetic squeeze film technology was built with a diameter of 1.2 metres. It worked first time with no modifications and could support the weight of a man for 60 seconds. It could be applied to any wave device with a suitably large bearing area. Anderson did a more detailed design for the slide bearing of the Budal and Falnes buoy. The main research requirements are the methods of assembling the carpet belts and magnet rings.

Elastomeric seals

The rams of the Pelamis joints have to be able to rotate about the rods ends but are small enough to be sealed with off-the-shelf air springs made by Firestone and others. They are used in the arduous conditions of the suspensions of heavy goods vehicles and railways coaches. They should perform very well in the less hazardous conditions under water.

The task of designing an equivalent seal for a partial rotation about an axis through the seal seems daunting and reveals an interesting difference between two classes of rotation. We have sketched designs which look like part of a Scottish kilt but do not look convincing.

Rolling seals known commercially as Beloframs which act like a stocking rolling back over itself can be used as zero-leakage, translating seals to protect the rods of hydraulic rams from the sea and also the sea from oil leakage from hydraulic rams. The sizes which are commercially available use a fabric reinforcement clad with isoprene but are far below those needed for most wave energy applications. The stop valve for the Azores used a pair of 1.2 metre diameter beloframs and the Edinburgh team had to build a large, computer-controlled lathe to spray cores of polystyrene with a layer of two part elastomeric polyurethane known as Irethane. The solvents contained methyl-ethyl-ketone which is highly toxic. The creep rate of the resin was higher than we expected but still just acceptable for the 1 bar pressure requirement. After two years the material seemed to have become a little more brittle. If there is a need for more large beloframs there will be a research requirement to find the best combination of elastomer and perhaps textile reinforcement.

Big face seals

In the early days of wave energy it was thought that 10 metre diameter seals would be quite impossible. This conclusion may have been changed because of the development of the Ceramax coating by the Dutch company Hydraudyne. They exhibited an hydraulic ram which was thickly encrusted with limpets and which had been in sea water for 10 years. However the rod was a glossy in apparently perfect condition. Examples are shown at

http://www.hydraudyne.nl/engels/hydraudyne/ceramax_cims.html

The coating is applied by flame spraying followed by grinding and could be applied to the flat faces of large steel rings. A non-contacting seal could be made by pulling a sheet of rubber against the Ceramax with magnets embedded in the rubber but separated from it by a flow of pressurised seawater to the pockets of hydrostatic bearings. There would be some flow to the inside of the seal but this could be isolated with a labyrinth and scavenged. The technology could be tested using a pair of back to back seals with a diameter of, say, one metre to run in sea water.

Sea water pumps and filters.

High pressure sea water is already used to drive power tools for divers where the risks of electrical tools are considered unacceptable. Water can safely be discharged to the sea. Because pumps have to work with such a poor lubricity fluid they have to be made with exotic materials such as ceramics and stainless steels. The present design life of around 1000 hours is quite unacceptable for energy generation. There is therefore a requirement for an infinite-life, sea water pump with a pressure capability of 200 bar or more to feed hydrostatic bearings. This is a much higher pressure but a lower flow rate than needed for reverse osmosis.

This difficult problem could be made a little easier if most of the exit flow from a bearing was recycled and small losses made up with carefully filtered seawater. This leads to the requirement for a filter which can operate for very long or infinite periods with a filter performance suitable for the fine clearances imposed by low viscosity. Poppet valves seem to be more appropriate for pumping sea water than any port face design.

Recovering the flow from bearings and driving sea water through filters will require a second design of pump which can have a much lower output pressure, only a few bar, but be able to operate with large abrasive debris.

Materials research

Materials will always determine the ultimate performance of any engineering product and the most successful technologies are those for which the right materials have evolved. However there has not been time for this to happen with wave energy. The only cases known to me are the development of mooring ropes and the design of poppet valves for computer-controlled pumps which use the remarkable resistance to Hertzian stress of carbon filled poly-ether-ether-ketone known as PEEK.

Except during times of extreme steel shortage large ships are made of steel. This will, be true for early wave power devices. Steel has low tooling costs with the opportunity for self-jigging of complex shapes. It is versatile, has consistent properties, is easily modified and can take retrofitted holes or welded-on lugs. Although its fatigue and corrosion are not very good they are, at least, well understood except for regions round welds. We know how to calculate stress distributions unless the shapes are very complex. We know how to use cathodic protection to reduce corrosion rate, but not quite to zero.

The negative features are the relatively high energy content which could lead to higher costs in future and the expense of painting (which can double the cost) and need for frequent repainting which requires return to a dry dock. A dream development would be an especially tough super-paint which could be applied to welds to give them the fatigue endurance in sea water of the parent metal in dry or oily conditions.

For wave devices in multiple production there are many attractions in concrete. It needs no painting. It gives an ideal alkaline environment for internal steel. With the correct quality control and a slight excess of cement, cracks can repair themselves. The fatigue problems are much reduced particularly if it can be put into an initial compressive stress by tension members which are at a constant stress. Structures can be made with double curvature which gives excellent strength in thin-walled panels and shells. Samples taken from the Mulberry harbours built for the 1944 Normandy invasion and from the tower of the recently demolished 60-metre 3 MW wind turbine on Orkney show that internal steel is in excellent condition. While most ships are scrapped after 25 to 30 years the hull of a concrete ship from the first world war is still in excellent condition.

The negative features are that normal manufacture requires shuttering which can cost more than the delivered material and is usually thrown away after the production of each single item. The shuttering structure may have to be strong enough take the entire weight of the structure. Shuttering is particularly expensive if the structure has to use internal compartments to achieve buoyancy. Wave power plant does not need many large internal compartments and foamed concrete can be made with a density low enough for solid items to float. Unfortunately the foamed material slowly absorbs water.

Developing countries in the far east make much greater use of concrete in the from of ferrocement which uses finely divided reinforcement and a fine aggregate with a consistency which can be applied by a hand trowel avoiding the need for shuttering. Provided that the manual labour is cheap, very large structures can be produced with low capital investment. It is even possible to make canoes. The nearest equivalent in the west is slip-forming in which concrete is continuously poured into a short length of shuttering ring which is slowly advanced at the rate at which the concrete sets. This is very economical for right circular cylinders but has also been used to make tapered legs for oil platforms.

The research requirements for concrete are for

- Impermeable foam concrete with density sufficient to be buoyant or foam with an impermeable skin.
- Reusable shuttering panels moved under computer-controlled hydraulic rams which define the shape of the structure only where the concrete is still liquid.
- Techniques for pouring concrete in water so that it is never necessary to support any weight.
- New materials for reinforcement which can be sprayed along with a liquid mix so that there is no need for hand placement. It is possible that the cost of carbon fibre may reduce enough to allow this.
- Non-destructive inspection techniques which could prove that contractors had used the specified quantities of cement, reinforcement and post-tensioning.

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Companion reports from the network are available from
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Conclusions

Borders between generations are blurred. This report has described and argued the case for work which will have to be done for future generations of wave power device and some of which should have been done for existing ones.

Much more device optimisation could be done with the greater power of present computers, provided that the conclusions for higher wave amplitudes can be confirmed with tank experiments.

The most expensive items discussed are the 360 degree combined wave and current tank and the 500 kWatt reciprocating flow wind tunnel for air turbine development. Both would have to be shared European facilities. Both would find use in many other fields of research. The cost of both would be less than a single ship or oil platform.

Integrating remote sources of intermittent energy into a network with strict limits on supply quality will be a serious problem even if it comes from sources with adequate storage.

Summary of proposed research items.

Understanding stress statistics and stress-limiting mechanisms.
Extreme wave tests for all devices.
Search for wave groups with high force coefficients.
A raft for testing components and subassemblies in seawater.
Measurement of hydrodynamic impedance in N degrees of freedom.
Beaches or absorbers working at sub millimetre amplitudes.
Frequency-dependent damping.
Understanding the difference between regular and random wave efficiency.
Complex conjugate control.
Short-term wave prediction.
Better automatic meshing for computer modelling.
Investigation of the range of conditions for which computer results can be trusted.
Means for sweeping through a series of model shapes.
Extending computer modelling to the non-linear regime.
Combining tank models with computer models of their power train.
Combined 360-degree wave and current tank.
Reciprocating flow wind tunnel.
Larger poppet valve motors for 1500 rpm generator drive.
Bearing sealing structural design and electronics for direct electrical generation.
Much cheaper gas accumulators for storage.
Add-on booster transformers for reversed power flow.
Geometrically tolerant hydrostatic bearings.
Long-life high-pressure seawater pumps and filters for hydrostatic bearings.
Magnetic squeeze-film bearings.
Large Ceramax face seals
Bigger rolling seals.
Super paints for complete isolation of welds.
Impermeable, buoyant foam concrete.
Reusable shuttering for ferrocement.
In-water construction methods to avoid gravity stress.
Chopped carbon strand reinforcement of sprayed concrete.
Post-cure inspection of concrete.