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A Personal View of Renewable Marine Energy

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Wave Energy is emerging from a long period in the wilderness which began in the early eighties. Marine current technology is still in the first honeymoon stage. But enthusiasm can easily turn into over-enthusiasm and this can easily end in tears. I would like to suggest ways in which tears can be avoided.

We must initially design devices which will survive and be reliable but eventually we will have to make them economical. Their initial productivity does not have to be maximised but it must be what was predicted by their designers.

Survival

Survival of anything subject to waves depends on the mathematics of the asymptotic skirts at each side of the Gaussian distribution - the beautiful bell-shaped curve which applies to so many branches of technology. Our estimates of the highest wave that will ever occur in a very long period have to be based on the extrapolation of observations of waves over a much shorter period coupled with advanced statistical arguments. Engineers ought to be uncomfortable with asymptotic phenomena because they have no sharply defined limits and there is always a nagging uncertainty. There is further uncertainty in estimating loads from information on wave height alone because the very highest loads do not necessarily occur with the very highest waves. On top of all this we may not be totally certain about the precise strength of even the simplest parts, let alone the more complicated ones. Their strength variations will also have a Gaussian distribution. We have to expect that parts will grow weaker with fatigue and corrosion but we may not be sure about how fast the strength distribution drifts down. Finally the rare but extreme loads are associated with power levels far above any economical limit and so they do not earn any return on the investment needed to resist them. If we make wave devices with the brute strength to stand up to the very worst loads they will be heavy and expensive because infinity is such a big number. Factors of safety are really factors of ignorance and lead directly to factors of waste.

If asymptotic skirts are killers, the inevitable solution must be to design devices which can either hide from extremes or yield in a controlled way to loads greater than those associated with the economic power limit. The latter trades high stress for range of movement. If the movement is a rotation, a large one need be no more expensive than a small one. One of the attractive things about waves (but sadly not currents) is that the direction of loading reverses in eight seconds or less. The mechanisms which allow hiding well below the wave surface or yielding over a range large enough to avoid a peak load may at first look complicated to simpletons but they can reduce the cost of load-sensitive items by an order of magnitude. Such a large cost reduction can buy lots of research and development. My preference is for a well-defined, if complex, solution over a vague and simple one. Apparent simplicity will often turn out to be the extent to which the difficulties are hidden. Statements about means and standard deviations are stronger than wishful claims that something is ‘simple and robust’.

The ideal would be a stress-limiting mechanism which can have the limiting values retrospectively down-loaded from the owner’s computer so that we can approach, but not exceed, safe values through the entire life of the plant. I believe that this will much easier to achieve with digital control of high-pressure oil mechanisms than with any other energy-processing technology.

Some wave energy teams have put an enormous effort into understanding the fluid loading on their devices in a wide range of wave conditions, including some of very low, but non-zero, probability. The Froude scaling rules work very well for wave effects on things with the shapes of typical wave devices and even for things as non-linear as breakwaters. Reynolds scaling for lift and drag is less satisfactory but there are ways for corrections to be made. The great advantage of tanks is that you are in control of the test conditions and can command a calm to recover your model or zero a force sensor and then, a minute later, generate exact repeats of the wildest event of the wildest storm in a thousand years. What is missing so far is the combination of currents and waves that characterises many potential locations. The interactions between them are complex and, in the case of currents coming into waves, potentially very dangerous. The industry needs a new type of tank with complete control of both.

Design calculations and general assembly drawings of such a full-size tank are available. A cross-sectional view is shown in figure 1. The tank will have three layers. The top layer is the test region. Below this will be air space intended to reduce source inertia seen by the rotor. Below the airspace will be the return path intended to retain as much as possible of the kinetic energy left in the flow from the test region. The wave-maker shape will create no stern waves and will continue the curve of the 180-degree return bends. This shape has previously been used for wave-making and energy generation.

The rotor will have a rim drive in the form of a linear induction generator wrapped round into a circle. Three sets of E-cores in an air-bell at the bottom rim of the rotor will pass flux through aluminium sector plates and will drive it at a near constant speed set by mains frequency and the pitch of the cores. Water velocity in or out of the test region then be determined largely by blade pitch. This design allows the retro-fitting of extra coils for increased drive torque and higher current velocity.

Pairs of blades will be mounted on bogies which run on rails. It must be possible to remove and quickly replace any bogie without draining the tank. Blade pitch will be set by brushless servo-motors in air-bells on each bogie. Command signals for the pitch-change motors will come through an induction loop running once around the outer rim and once back around the inner rim of the rotor. Servo power will be fed through cables running along the spokes of the rotor from a central slip ring in yet another air-bell. All air-bells will be continuously fed with dry air so there need be no seals in the entire design. Humidity will be controlled by Peltier effect chillers in each air-bell compartment. Evaporation rates will be reduced by a layer of cetyl alcohol on the water surface in each compartment. Vertical velocity profiles can be varied by adjusting flow impedance round the bends. Even though it would be cheaper than the loss of a single prototype, such a tank would be too expensive for a single developer and would have to be run as a national asset.

Availability

My second point concerns achieving high availability. Systems can fail for reasons other than the exceedance of a strength limit. They can leak, jam, come loose and corrode, be vandalised and covered with bio-fouling and bird droppings and fail in many hundreds of other ways which are hard to foretell until it is too late.

During the first UK wave programme the Department of Energy engaged consultants who claimed to tell you the availability of a bilge pump to six places of decimals - a greater precision than our knowledge of fundamental physical constants. Despite the exactitude with regard to bilge pumps there was some uncertainty about the marine cables used to bring power ashore. In 1980 a second set of consultants issued a working paper which said that the figure for power cables should be 330 kilometre years per fault. In 1982 they issued a second paper reducing the figure to 125 kilometre years per fault. In their 1983 report, which led to the closure of the programme, they issued a third figure of 10 kilometre years per fault. This failure rate was very severe for the duck, which was the furthest offshore of the devices under study.

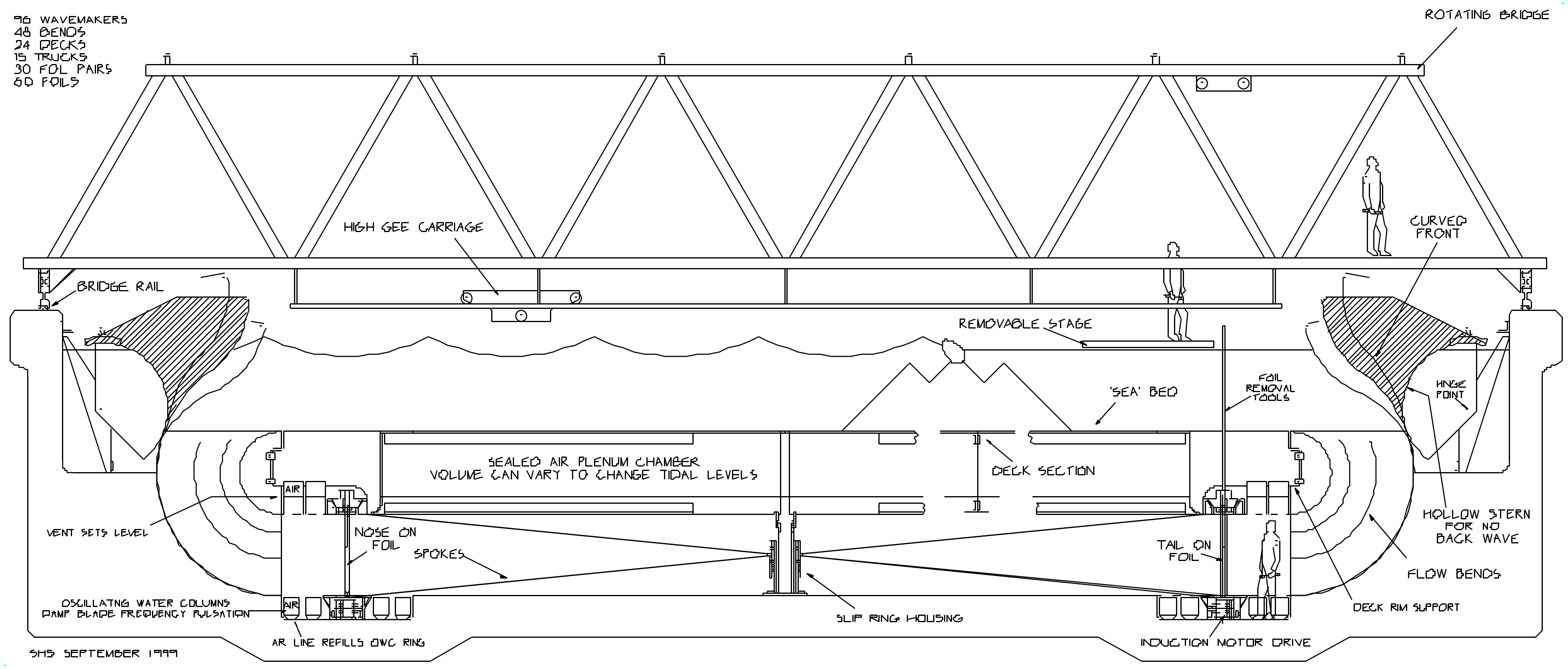

Figure 1. A cross section of a wave/current tank which can generate any combination round 360 degrees.

Meanwhile in Norway, the true figure for the many power cables to islands was 625 kilometre years per fault. In 1982 the North of Scotland Hydro Board laid a 43 kilometre-long cable across the approaches to the Pentland Firth. This has waves nearly as high as and currents higher than the Atlantic wave fields. Now, in 2005, this cable has operated without fault for 989 kilometre years. Having two orders of magnitude error in the estimate for the reliability of items in series is not acceptable.

In contrast a very bad reliability figure was achieved by the first submarine cables which were laid to the Scottish island of Gigha without a route survey. The problem was that layers of alternating hard and soft rock strata had at some distant time been rotated through 90 degrees. The soft layers had been eroded away and cables were laid across the remaining hard edges where they swung like a hammock on razor blades. The source of the problem became obvious when a camera was sent down. This showed the pattern of rock strata and allowed a better route to be planned. Now the Gigha connection is as good as all the others.

The lesson should be that component reliability is not a fixed number like density or yield strength of a material but the result of a market-led dialogue between designers, users and insurers. Salter's first law of reliability says that the value will lie between 0 and 100%. It will be proportional to the investment in research and development and to level of our understanding of the working environment in which the equipment will be used. The reliability of wind turbines, which rose from about 5% for first large-scale American installations to well over 98% today, is a good example. Wave engineers can do, and they will have to do, as well. Salter's second law predicts that the failures will occur at the junctions either of components or design responsibilities, and reliability is inversely proportional to the number of separate organizations involved.

A complete power-generating system can suffer a catastrophe from the failure of a minor component, something as trivial as a cable gland. Premature deployment of unreliable plant is a slow (months and years to rebuild) and expensive (millions of pounds per event) way to relearn the painful lessons of marine engineering. Failures can destroy an entire industry as in the case of the Hindenberg airship. But we learn a great deal from them. It may be necessary to suffer hundreds of failures before the final economic systems go to sea. Instead of testing complete prototype plant, which might test only one item at a time, we need to test large batches of components - large enough to be statistically significant - of many rival types of seal, bearing, washer, split-pin, circlip, cable, termination, surface coating, pump, hose, filter, plug, socket, weld protection, electronic enclosure, material combination and every working sub-assembly. We must test them in the laboratory ashore and also in the real chemistry and biology of the sea.

This could be done on a raft in the form of a ladder with round rungs - something like the sketch drawing of figure 2. Test-rigs would be held on saddles which can rotate round the rungs to allow inspection without fear of anything getting loose. Power to drive them can come from the land and much of it can be recycled. With many candidate parts tested in parallel we will be able to pick the cheapest of the reliable ones and understand the failure modes of the cheaper ones.

Unfortunately a component test raft offers no ministerial photo opportunities. The public relations value of a *really* reliable grommet is nearly zero. The investment in a raft will seem expensive to the backers of a single developer at the early stages. But if it is not done there may be no later stages. The industry must apply united pressure on governments to provide a component test raft, must share the results produced and must circulate details of *all* mistakes in a way similar to the aircraft industry and the wind energy pioneers.

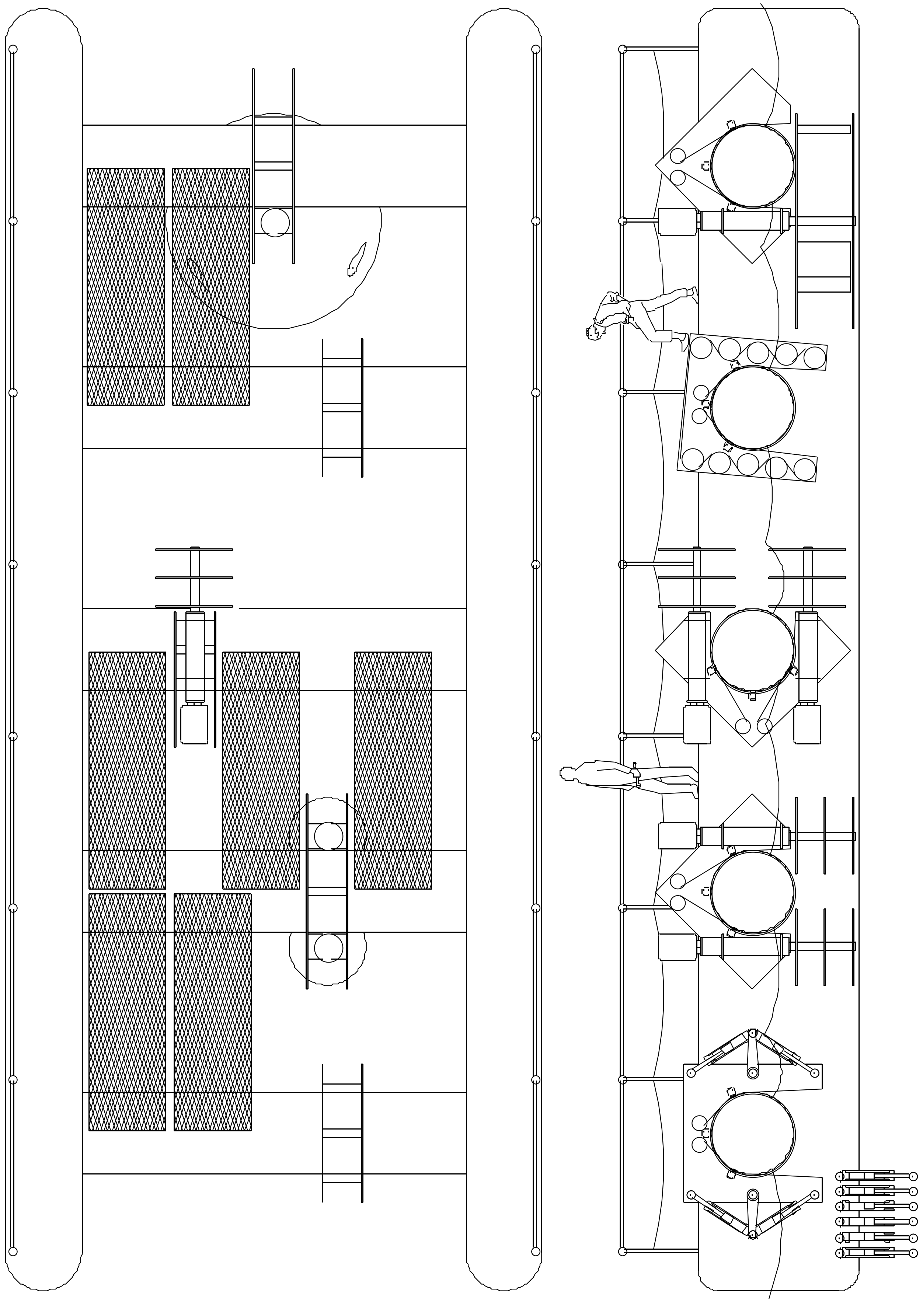

Figure 2. Plan and elevation sketches of the test platform.

Installation

While we must take all the useful information we can from the marine engineering industry there may be flows of information in the reverse direction. One such has been the development of wave tanks and wave-maker technology. A second might involve the way offshore objects are towed. We have to find a means of installing and removing equipment at short notice that is cheap enough to be used frequently, perhaps in the early stages, every day.

The present conventional technology uses tugs and cables. An inelastic cable connecting two objects which are far enough apart to be in waves of opposite phase can experience a tension which is the relative separating acceleration (possibly twice the acceleration of the water in a wave) times the mass of the lighter object. Even higher tensions can result if a cable is allowed to go slack and then retighten after the build-up of kinetic energy. An elastic cable can store energy which will be one half the square of this tension times the spring rate of the rope. If the cable should ever part it will release this stored energy in a frighteningly short space of time. To connect or disconnect heavy cables at sea requires the intelligent communication and control of large forces at both ends. Cables can apply only tension and in only one direction at a time and are slow to make changes in direction. The only attractive thing about a cable is that it can be coiled for compact stowage. Everything else is very bad.

Conventional tugs must able to make trans-ocean crossings lasting many days in any weather and must provide acceptable living conditions for quite large crews. This makes hire expensive, typically tens of thousands of pounds a day. The vessels have to be paid for as they move between jobs and when they have no work. It seems that the universal method of moving objects at sea has many undesirable features. So much for making use of existing marine technology.

A better system would place the two objects close enough to be in the same wave phase and arrange that their phase and amplitude responses to wave spectra were similar. The driver vessel would be able to apply force of either polarity in any direction with a mechanism of zero length with rapid (less than one second) changes between directions. It would allow instant connection and disconnection of the driven vessel with intelligence at only one point and no need for large handling forces. For the installation of renewable energy plant it need have an endurance of only a few hours and those in daylight and selected weather. It need not have more than three people aboard. It should be cheap enough to be owned by the operators of the devices.

Calculation of the forces between magnetic poles shows that they can develop friction force of about 200 kN (or 20 tons in nautical usage) per square metre of pole area. One square metre would be 8 rows of 12.5 mm poles 10 metres long and could pass the full thrust of a pair of 300 kW (or 400 HP) outboard motors at 3 metres per second, nearly six knots. Magnet friction can tow the largest ships let alone wave energy plant. An inflated vessel like an oversize version of the Avon inflatable range can have its heave response tuned to the response of the object to be towed by the addition of gravel ballast in sets of bags along the underside. This reduces relative motion. A pair of additional oversize side-tubes with hinged connections to the inflatable can allow some mismatch in pitch, heave and roll and damage-free nudging contacts with the object being towed. A line of magnets on the edge of the side tubes will attach themselves to the target but can be released by the inflation of small tubes on either side. Pressure in these release tubes can be used to set an automatic self-disconnection at any chosen level. The maximum tow force will be set by the need to keep a positive surface tension in all directions in the skin of the side tube. The vessel will be driven by a pair of outboard motors, one fore and one aft with rather fine pitch propellers and 360 degree vectoring mountings so that they can turn about their own centre and apply force in any direction. Two such vessels, one at each end or on each side of the device being installed, could move it any in any direction. Figure 3 shows what one might look like.

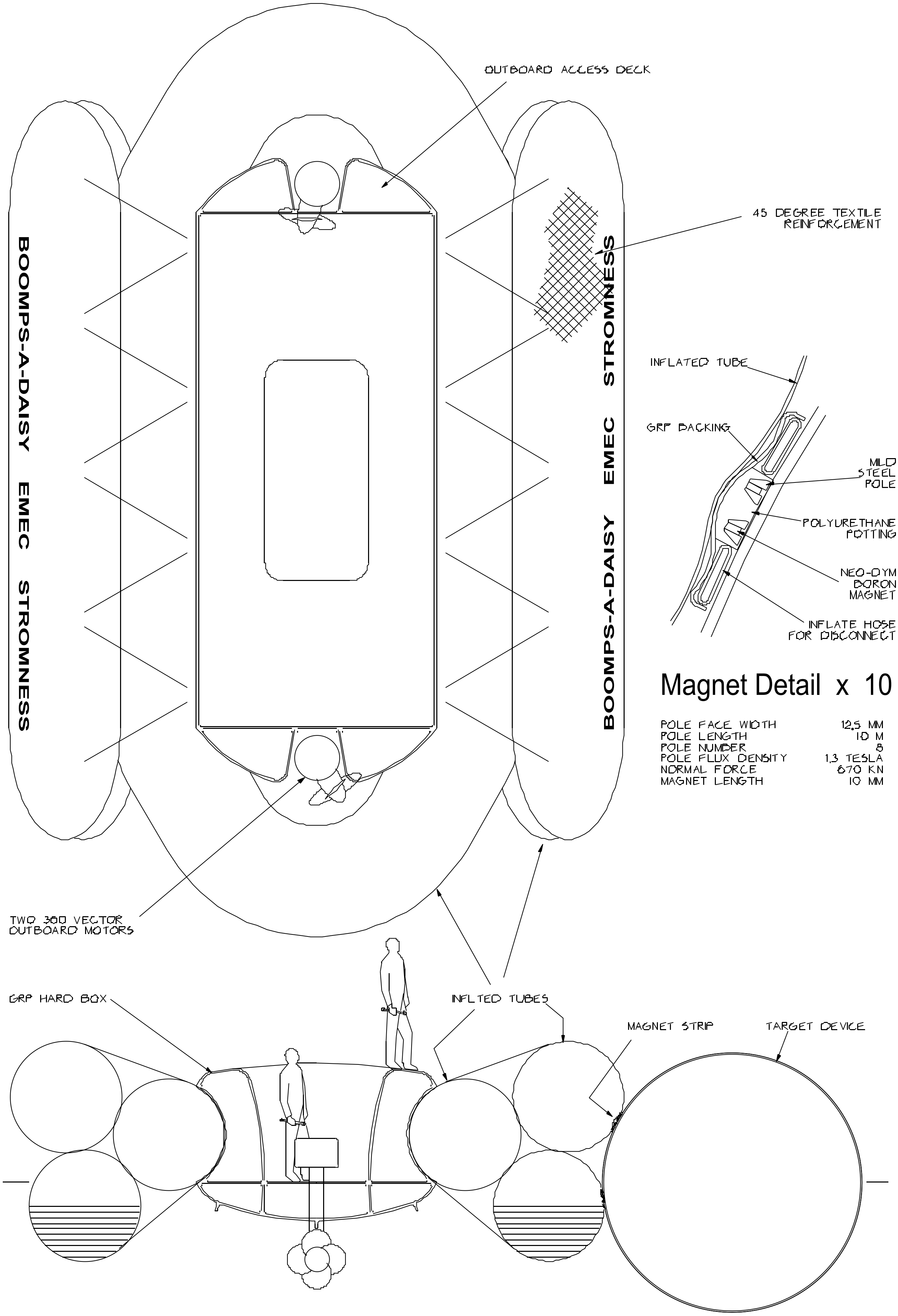

Figure 3. A vessel designed to install marine energy plant.

Some thoughts on the hazards of the sea

With all this talk of failures and safety factors it is easy to drift into the common belief that the marine environment is hostile. When people are asked to list the hazards of the sea the obvious one is the size of the waves. But to complain of the dangerously high waves at a good wave site is like complaining of the high temperatures in the flame of a thermal plant. For low-freeboard devices the stresses in large waves rise at slightly less than the first power of wave height while the available power rises with the square. The analogy in thermodynamics would be of higher temperatures giving higher Carnot efficiency. This means that the economic viability should *rise* in higher waves. This should not be regarded as a hostile feature. Marine currents might also be regarded as a hazard but the same arguments of power rising with the cube of velocity while stresses rise with only the square applies. Marine current designers would dearly love higher velocities.

After wave height and current velocity, there is salt. But salt is found at 28 times greater concentration on land and is thrown at high speed, mixed with abrasive gravel, at the underside of every vehicle in an attempt to overcome the serious hazard of icy roads. After salt there are poisonous jellyfish, great white sharks, drifting icebergs, none of these common in European waters. At this point the list usually terminates. I hope that delegates to this conference will help me extend it.

The list of hostile features for land is longer and much more diverse. There is a wider range of temperatures with rapid changes between extremes combined with very poor heat transfer to still air. Air offers very little damping to resonating objects and the wind can induce much higher frequencies of oscillation. There is gravity unopposed by buoyancy with point loading rather than distributed loading. There are cliffs, gullies, crevasses, and steep gradients. There are rockfalls, mudslides, landslides, subsidence, collapsing tunnels and avalanches, volcanic explosions, lava flow and earthquakes, none of which are anywhere nearly as predictable as bad weather at sea. Trees grow very tall but all eventually have to fall. Being under the two hundred year tree when it comes down can be dangerous. When trees are not falling they can be catching fire and spreading it to others. Some have thorns with poisoned spikes. There are snakes, tsetse flies, mosquitoes, river-born bacteria and scorpions. There are corrosive chemicals, asbestos, dioxins, mercury, heavy-metals, NOX, SOX, carbon monoxide and Diesel particulates.

There is abrasive gravel and sand driven at high speeds in storms. There are higher water velocities with rocks driven by flash floods. Tornadoes on land move sheets of corrugated iron, bricks and even camper vans at much higher velocities than the spray in typhoons and hurricanes at sea. Tornadoes occur more frequently and with less warning. Tidal waves and rising sea levels are a danger to any coastal structure but of no concern to deep water floating ones. Narrow gaps, traffic congestion, barbed-wire, low bridges, quicksand and marsh make it harder to move large structures on land while there is almost no size limit in the deep sea. Electric cables on the seabed are safe from lightning, vandalism, kites and model aircraft. Properly routed marines cables are more reliable than those on land. Planning objections, which are crippling onshore wind, should be fewer for distant offshore installations.

You can dive from greater heights into water than on to earth, and buckets of water hurt less than buckets of stones. It is more comfortable to be under 50 metres of water than 50 metres of rock. Corrosion of steel in clean sea water, which is free from acidic exhaust fumes, occurs at a rate one-fifth of that in the air of a damp industrial city. This can be shown by examination of the steel hulls of 19th century sailing ships abandoned in the Falklands after damage in the passage round Cape Horn and of the remains of riveted hull wreckage (built before World War II) on a beach on Islay.

There can be no doubt that our wave fields are thermally, gravitationally, flammably, structurally, meteorologically, chemically, zoologically, botanically, seismologically, tribologically, logistically and administratively more attractive than many places on land. It was the benign marine environment that allowed life on earth to begin. The creatures that survived species extinctions were those that lived in water. The reason that some made hesitant steps to life on land was that the sea was getting too crowded. They managed to survive on land only by learning all about the dangers.

Getting economical power from sea waves will be difficult and will need the very best engineering skills. I accept that conditions at sea are very *different* from those ashore and that every aspect must be carefully considered. However the difficulties arise not so much from hazards at sea as from our practice of applying land-based technology to marine conditions without sufficient thought.