Engineering Ideas for Brighter Clouds

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ABSTRACT

It may be possible to reduce global warming by increasing the reflectivity of marine stratocumulus clouds thereby reducing the amount of solar energy that is absorbed. Quite a small change to the reflectivity could stop further temperature rise or even produce a reversion towards pre-industrial values. This paper gives a brief account of the physics behind the Twomey effect and its application for marine cloud brightening by the release of sub-micron drops of sea water into the marine boundary layer using a fleet of mobile spray vessels. We argue that the mobility of spray vessels and the short life of spray are advantageous by allowing rapid tactical control in response to local conditions. We identify the main engineering problem as spray production, which in turn requires ultra-filtration of plankton-rich seawater. The proposed engineering solutions involving Rayleigh nozzles etched in silicon and piezo-electric excitation are illustrated with drawings. The results of a COMSOL Multiphysics simulation of drop generation are given, with nozzle diameter, drive pressure, excitation frequency and power requirement as functions of drop diameter. The predicted power requirement is higher than initially hoped for and this has led to a modified vessel design with active hydrofoils giving much lower drag than displacement hulls and turbines. The active control of hydrofoil pitch angle can be used for power generation, roll stabilizing and may also reduce hull loading similarly to the suspension systems of road vehicles. The need to identify unwanted side effects of marine

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cloud brightening has led to a method for using climate models to give an everywhere-to-everywhere transfer function of the effects of spray in each region on weather records at all observing stations. The technique uses individual coded modulation of the concentration of cloud-condensation nuclei separately in each of many spray regions and is based on methods used for small-signal detection in electronic systems. The first use in a climate model shows very accurate measurement of changes to a temperature record and that that marine cloud brightening can affect precipitation in *both* directions. Replication with other climate models will be necessary. The paper ends with tentative estimates for the cost of mass production spray vessels based on actual quotations for parts of the spray generation hardware and on the cost of Flower-class corvettes used by the Royal Navy in World War II which were built in similar numbers.

1 Introduction

Any reader of this paper will already know about increases in atmospheric CO_2, Arctic ice loss, methane release, carbon embedded in imports and the progress to date of our world leaders in finding solutions to these problems. This paper describes some of the engineering ideas needed to implement a proposal by John Latham to increase the reflectivity of marine stratocumulus clouds by an amount necessary to offset the thermal effects of increased greenhouse gases.[1]

2 A Reminder of the Physics

The power density of the solar input at the top of the atmosphere, not quite constant, is about 1360 W m^{-2}. At mid-latitudes the input over 24 hours is about 340 W m^{-2}. Changes since preindustrial times have retained about 1.6 W m^{-2} more than before. If CO_2 concentrations are to double, the extra power density is expected to be about 3.7 W m^{-2}, which is less than 1.1% of the input. Quite a small change to the reflectivity of the earth or its clouds could stop further temperature rises or even produce a reversion to pre-industrial values.

The most commonly mentioned method to increase the reflectivity of the earth is the injection of aerosol particles such as SO_2 into the stratosphere as discussed by Robock in Chapter 7. In this chapter we discuss the engineering design for a proposal for the use of sub-micron drops of filtered sea water. Drops released from near the surface would be spread by turbulence through the marine boundary layer. We can make an engineering estimate of turbulence by taking about 15 minutes of video of marine cloud formations and speeding it up with a viewer which allows continuous scrolling back and forth through the sequence.[2]

The speeding up lets us see that clouds behave like floppy rollers with diameters reaching from sea level to cloud top of which only the top part of the roller becomes visible as increasing height produces cooling to the point of condensation. We can see that 180° of roller rotation takes about 10 min indicating velocities up and down of the order of 1 m s^{-1}. Nature does not like uneven concentrations and uses turbulence to spread nuclei fairly evenly through the boundary layer.

After release near sea level the drops will evaporate to leave crystals of dry salt. The ratio of drop diameter from 3.5% salinity sea water to a dry salt sphere is 3.92. The ratio to the side of a dry salt cube is 4.86. Dry salt has a high reflectivity and some solar energy will be reflected back to space. This initial gain in reflection from the dry crystals is called the 'direct Twomey effect'. However, there is also a second mechanism known as the 'indirect Twomey effect' which occurs if the salt crystal reaches the cloud.[3] Even if the relative humidity in air is above 100% a drop cannot form without a nucleus to start its growth. In air over typical land there are 1000 to 5000 nuclei cm^{-3} and so drops form very close to the spout of a boiling kettle. In the clean air of the mid ocean, however, there may be only 10 to 100 nuclei cm^{-3} and so the water that cannot be in vapour form has to be in relatively large drops, with diameters of the order of 25 μm.[4]

Hydrophilic materials like sea salt of the right size are excellent cloud condensation nuclei. If an extra nucleus approaches a 25 μm drop, water can evaporate from the larger nucleus and condense on the smaller to produce the same liquid volume in two drops each 19.84 μm in diameter. The ratio of projected areas rises by 26%. In some conditions, particles in ship exhaust gases can increase the reflectivity of marine stratocumulus clouds enough to be detected by eye, around 20%. Twomey used cloud reflectivity observations from satellites and nuclei concentration from aircraft to investigate the effect. Schwarz and Slingo derived an analytical equation for reflectivity change based on cloud depth, liquid water content and the initial concentration of cloud condensation nuclei.[5] For thin clouds and common ranges of other parameters, the change in reflectivity is 0.075 of the natural log of the fractional change in the concentration of condensation nuclei. If $N1$ is the initial drop concentration and $N2$ the drop concentration after spray the change in cloud reflectivity is

$$\Delta R = 0.075 \ln\left(\frac{N2}{N1}\right)$$

This means that a doubling of the number of nuclei will increase cloud reflectivity by 0.058 from a typical value of 0.5. Latham showed that the volumes of water which would have to be sprayed to reverse the thermal effects of anthropogenic damage since pre-industrial times were surprisingly small, of the order of 10 m^3 s^{-1} for 0.8 μm drops.[1]

The calculation depends on assumptions on nucleus life and initial nuclei concentration. The life of the nuclei is shortened by rain and drizzle. Smith

Park and Conserdine give a graph as a function of drop size suggesting a typical half-life of 60 h for our size.[6] The assumed initial nuclei concentrations are the ones suggested by Bennartz for clean mid ocean air.[7] The short life means that the spraying process must be continuous but offers the option of rapid, tactical control which can be varied to suit satellite observations of raised sea surface temperatures, the phase of monsoons and the state of the El Niño oscillation. Control engineers will appreciate the low phase lag. A short life also allows us to avoid getting any aerosol over the Arctic in winter where it would act as a blanket to reflect back long wave radiation going out to space as studied by Kristjanssen.[8]

Cloud reflectivity and the resulting energy changes can also be predicted by global climate models. However, the best modellers are quick to point out that agreement between different climate models is not good. Some of the differences can be explained by the differences in assumed values of drop life, initial nuclei concentration and the spread of spray diameters which not always specified by modellers. The changes in cloud reflectivity needed to reverse global warming are well below what can be detected by eye. However, it may be possible to superimpose large numbers of satellite images to enhance the contrast between a single spray wake and the surrounding clouds so as to measure effects in a wide range of climate conditions and geographical regions.

3 The Main Engineering Problems

We need an energy-efficient mechanism to produce a mono-disperse, submicron spray despite the plankton, oil and silt found in sea water. We need mobile platforms which can generate energy, be moved round the world to suit tactical spray plans and have acceptable, if not total chance, of surviving extreme conditions. We need fairly long and well-matched service intervals, at least as long as the intervals for antifouling treatment of ship hulls. We should avoid the need for any appreciable volume of consumable materials which cannot be made at sea. However, we could make at least chlorine, hydrochloric and nitric acid, ammonia, sodium hydroxide, sodium carbonate, ozone and hydrogen peroxide.

3.1 Spray Generation

The most challenging problem in the entire project is the production of spray. After consideration of spinning disks, electrostatic bagatelle, the high velocity collision of opposed jets saturated with high pressure air and Taylor cones produced by high voltage fields, we settled on the well-known technique studied by Rayleigh of pumping water through small nozzles but with high-frequency ultrasonic excitation. Neukermans describes work on the expansion of supercritical salt water through much larger nozzles.[9]

The nearest present technology for the spray generation is inkjet printing. Several eminent pioneers in the ink jet industry were consulted. Their opinions were unanimous and emphatic that the nozzle clogging problem was totally insoluble. It is therefore useful to identify differences between the two requirements. The drop diameter of the very best graphic arts ink jet printers of 2013 is 15 μm and the suggested diameter for this project is 0.8 μm, so the ratio of drop masses is 6600.

However, while a single blocked inkjet nozzle will spoil the look of text, a billion blocked nozzles will reduce the output of a spray vessel by only 2%. Despite having sticky pigments, an inkjet nozzle must operate first time after months on the shelf and weeks of inaction but the ink on the paper must be dry enough to be handled in few seconds. Spray nozzles work with no solid content, and can have an elaborate start-up and shut-down procedure. They can be back-flushed with fresh water every few minutes and dried with ultra clean air. Inkjet parts must sell for a few pounds, weigh a few tens of grams and manage with no filtration after leaving the factory. The filters for a spray vessel can weigh more than a tonne, operate continuously and form an essential and critical part of a £2 million vessel.

The COMSOL simulation shows that mono-disperse drops of the right size can be produced. Drop regularity is aided by a small amount of ultrasonic excitation. For 800 nm drops we need a 370 nm nozzle, a pressure of 80 bar and an excitation frequency of 27 MHz as shown in Figure 1.

The predictions for the pressure needed to make drops are in reasonable agreement with an equation given by van Hoeve *et al.*, who write that the lowest critical velocity can be expressed in terms of a Weber number.[10] The Weber number is the ratio of kinetic to surface energy of drops in a jet. If ρ is fluid density, d is jet diameter, U is jet velocity and γ is the surface tension the Weber number is

$$\mathrm{We} = \frac{\rho d U^2}{\gamma}$$

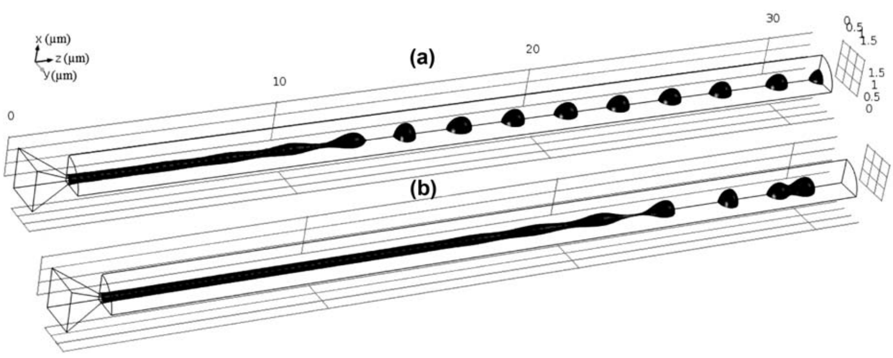

Figure 1 A COMSOL Multiphysics simulation showing that a small amount of pressure modulation at the frequency predicted by Rayleigh will enhance drop breakup and narrow the spread of drop diameters.

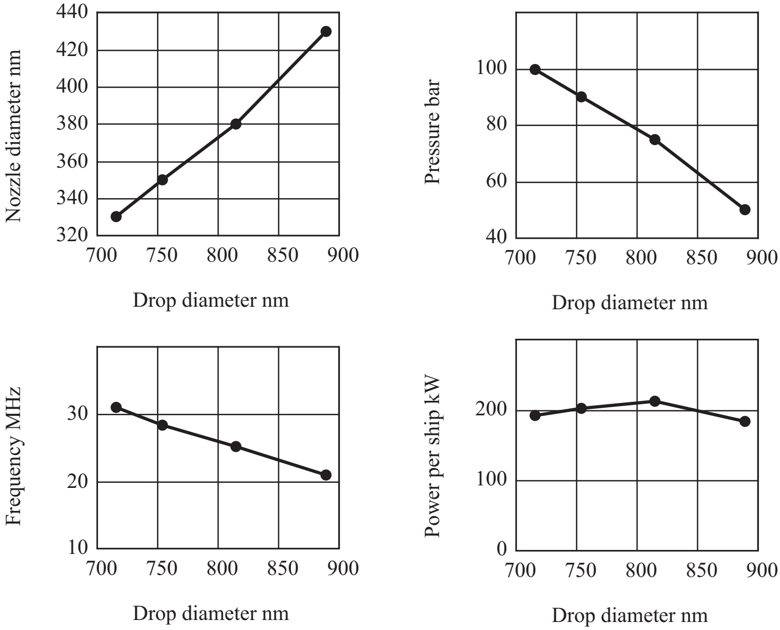

Figure 2 COMSOL results for 'nice' drop breakup showing the values for nozzle diameter, pressure and excitation frequency which are suitable for a range of drop diameters. The power is based on the pumping to produce 10^{17} drops s^{-1} per ship, not including the drive for piezo-electrics. It is the drop number of the best size that drives the Twomey effect, not spray volume. This leads to the flatness of the power *vs.* diameter curve.

This must be >8 for good drop breakup. We can replace the square of velocity with 2 times pressure over liquid density, giving an absolute minimum pressure of 4 times surface tension over nozzle diameter and then add more pressure for the pressure drop in the approach to the nozzle. COMSOL predicts that, with a small pressure pulsation at the best frequency, drops show some ellipsoidal wobbles and then settle to a spherical shape. The COMSOL Multiphysics software has been used to show in Figure 2 how the choice of drop diameter affects the values for pressure, nozzle size and excitation frequency.

The popular choice of piezo materials for high power and high frequency is PZT4. Piezo electric materials have a very high dielectric constant and so an element with a fundamental resonance at 27 MHz would have a very large capacitance needing enormous currents. We can reduce the problem by using thicker ceramics and driving them at a high harmonic, we hope the tenth, of the fundamental. At these frequencies the magnetic fields around a conductor force the current away from the centre and all the low frequency rules for resistance are wrong. We mount two nozzle wafers back-to-back as close as possible, as shown in Figure 3, and send current back and forth

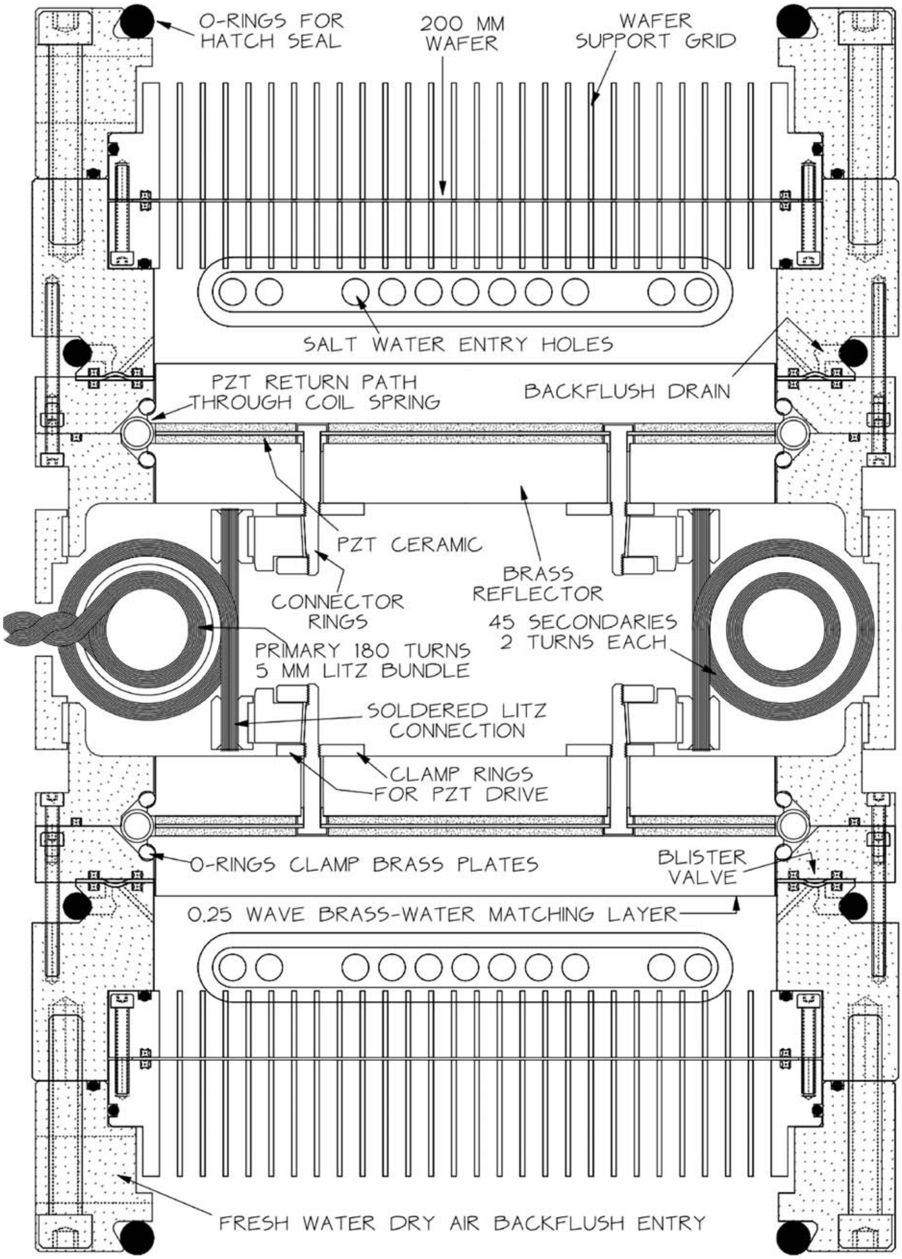

Figure 3 A cross-section through a pair of spray modules placed close back-to-back and separated by a toroidal air-cored transformer. Charge to provide the pressure pulsation flows back and forth between the two modules through the transformer's 45 secondary windings, with losses made up by the primary winding. The modules can be sealed by hatches to allow desalinated water to be pumped backwards through the wafers which are clamped between a pair of stainless steel grids. The PZT4 piezo-electric elements are exactly what would be used at frequencies of about 45 kHz in ultrasonic cleaning baths and will assist back-flushing of any clogged nozzles resulting from imperfect primary filtration.

from one to the other, through 45 bundles of Litz wire each of which forms two turns of secondary winding of an air-cored toroidal transformer. The primary of the transformer has two layers of 90 turns. With a turns ratio of 90 and with 45 secondary windings in parallel, the current cycling back and forth between the PZT ceramics is over 4500 times greater than the current in the primary winding.

4 The Wafer

Microfabrication technology allows enormous numbers of very small features to be produced by successive stages of deposition of a wide range of materials, application of photo resists and etching. The only limitation is that everything must exist in a world of only 2 dimensions. The favourite base material is silicon crystal. This is extremely strong but also extremely notch sensitive. Careless handling of what seems a robust component but which has an undetectable scratch can leave the user holding a large number of exactly rectangular and extremely sharp razor blades which cost £1000. Notch sensitivity is not a feature of silicon nitride which can be deposited on both sides of a silicon wafer. The deposition temperature is quite high and the contraction on cooling puts the silicon into a most desirable compression.

The main requirement is to produce an array of billions of holes that are as near as possible identical in both outlet diameter and cross section, where the outlet diameter is likely to be in the order of hundreds of nm. Achieving these small dimensions repeatedly and uniformly across 200 mm diameter silicon wafers poses a major challenge to both the photolithography and etching processes.

The viscous pressure drop through a nozzle depends on the inverse fourth power of the passage diameter. An interesting feature of the cubic lattice of a silicon crystal it that it can be etched to form a pyramid shape with a half angle of 35.26°. This means that we can have a low viscous pressure drop most of the way to a small exit orifice as shown in Figure 4.

The use of silicon on insulator material (SOI) reduces the variability of the process and simplifies the fabrication sequence. SOI wafers consist of a three layer sandwich: the top 'device layer' of single crystal silicon is relatively thin; then there is a buried layer of silicon dioxide; then the bulk silicon or 'handle' wafer. The small diameter nozzles will be created in the thin device layer using an etch process that terminates at the buried oxide layer. Similarly, the other side of the wafer (the 'handle' side) will be etched to create larger diameter holes with the etch process terminating at the oxide layer. Finally, the oxide layer will be removed by etching from the handle side, thus leaving an array of spray nozzles that are open all the way through the sandwich.

The detailed process sequence to achieve these features will require optimisation but, in outline, it will be as follows.

The SOI wafer will first be thermally oxidised and then a layer of silicon nitride will be deposited on both sides using a low pressure chemical vapour deposition system (LPCVD) at about 850 °C. The resultant nitride film will be

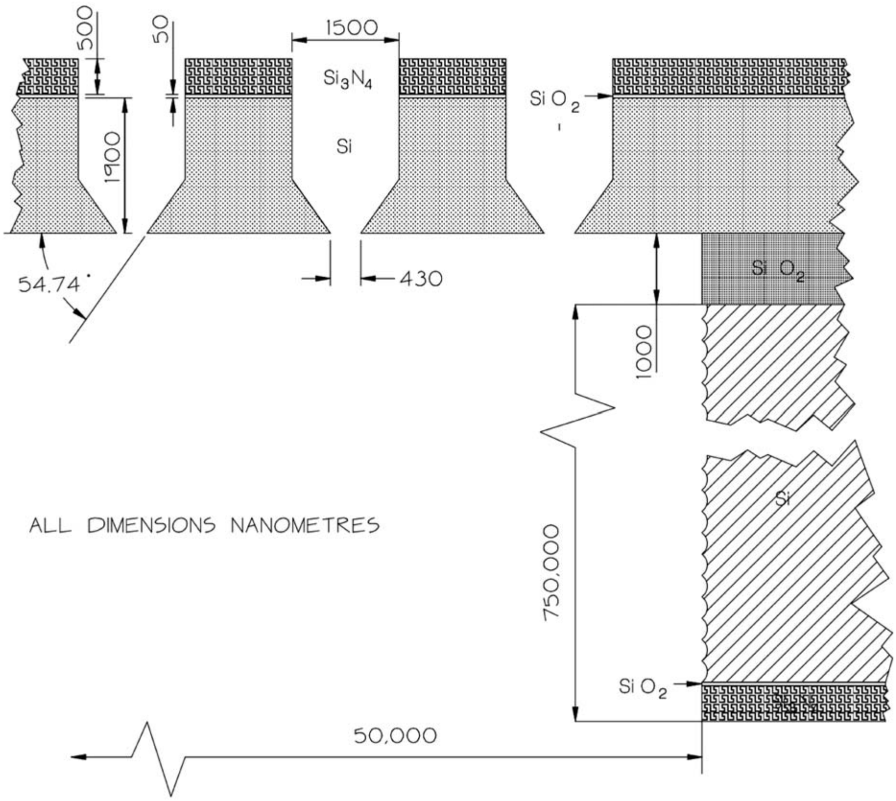

Figure 4 The proposed dimensions of nozzles in nm. A large number of 430 nm nozzles with tapered entries meeting in a 50 μm hole through the 750 μm dimension of each 200 mm wafer. The 'tide marks' in the thick silicon show successive layers of etching of the Bosch process.

in tension, thus improving the mechanical strength of the wafer, and silicon nitride is a very good masking material for the etch processes which will be used.

The outer nitride–oxide film on the device side will be patterned using photolithography and etched to create windows of the appropriate dimension. Then, a wet etch process using TMAH or KOH giving an etch rate that is sensitive to the crystal orientation will form pits in the thin silicon device layer with sidewalls at 54.74° to the surface. The etching will stop when the oxide layer is reached.

Variations of etch rate across the 200 mm diameter wafer have to be taken into account as these can result it variations in nozzle diameter. It is proposed to form the cylindrical part of the nozzles in a relatively thick layer of silicon nitride using reactive ion etching (RIE) and then form the tapered section in the silicon of the thin device layer using wet etch. The use of a thin device layer combined with an etching where the sidewall angles are defined by the crystal planes helps to reduce variability. An indicative arrangement is shown in Figure 4 with some tentative dimensions – these are likely to change as a result of process optimisation.

Again, on the handle side of the wafer, the outer nitride–oxide film will be patterned to form windows of the appropriate size, around 50 μm. The handle wafer will be around 730 μm thick so a deep silicon reactive ion etch (DRIE) based on the Bosch process will be used to form holes with almost vertical sidewalls, all the way through the wafer, stopping at the oxide layer. These deep silicon etch processes typically use SF_6 as the source of etchant (F) and C_4F_8 as the source of passivation (polymer) material to protect the sidewalls.

After inspection to confirm that all the silicon has been etched from both the small nozzles and the larger holes, the oxide layer will be removed by reactive ion etching from the handle side.

The attenuation of ultrasound at tens of MHz is very high. The ideal solution would be to include the piezo-electric excitation in the body of the wafer or its support grid. At present this looks very difficult but microfabrication engineers have a long track record of achieving the apparently impossible in a few Moore's law cycles.

5 Filtration

If spray generation was the most challenging part of the project, the second is filtration to the level needed to prevent nozzle clogging. Before the use of the Salk vaccine, polio caused many deaths and many more cases of permanent paralysis. Ultra-filtration technology was developed to remove the 29 nm diameter polio virus from drinking water. This technology is now used in very large quantities for pre-filtration of sea water going to reverse osmosis membranes.[11] Filters clean up feed water taken from quite near the coast which will be a more severe requirement than with our mid-ocean water. The suppliers of Seaguard X-flow filters, the Dutch company Pentair, will guarantee operation for 5 years and expect most to last for 10. The present installed capacity is 6 000 000 m^3 day^{-1} and plant with a capacity of a further 3 000 000 m^3 day^{-1} is under construction. These volumes are considerably larger than inkjet printer consumption. While filter engineers are confident about filtration to the level required they may have been doubtful about the feasibility of inkjet printing!

The plan is to run a set of eight filters in parallel with some of the water from seven filters going to back flush number eight and to change the back flushed one every few minutes. The block diagram of the system the filtration system is shown in Figure 5.

Each filter module needs two valves working in sea water and the output from each bank of filters must be sent either to a spray head or to the other filters. Valves must control the flow of salt water and, after the filtration stage, must not produce any wear debris which could easily be produced by the sliding motion of a spool valve. The proposal is to use blister valves. These are the watery equivalent of the field effect transistor. Large numbers can be formed by a single sheet of rubber clamped between two plates of ABS plastic. Figure 6 shows a section of a blister valve.

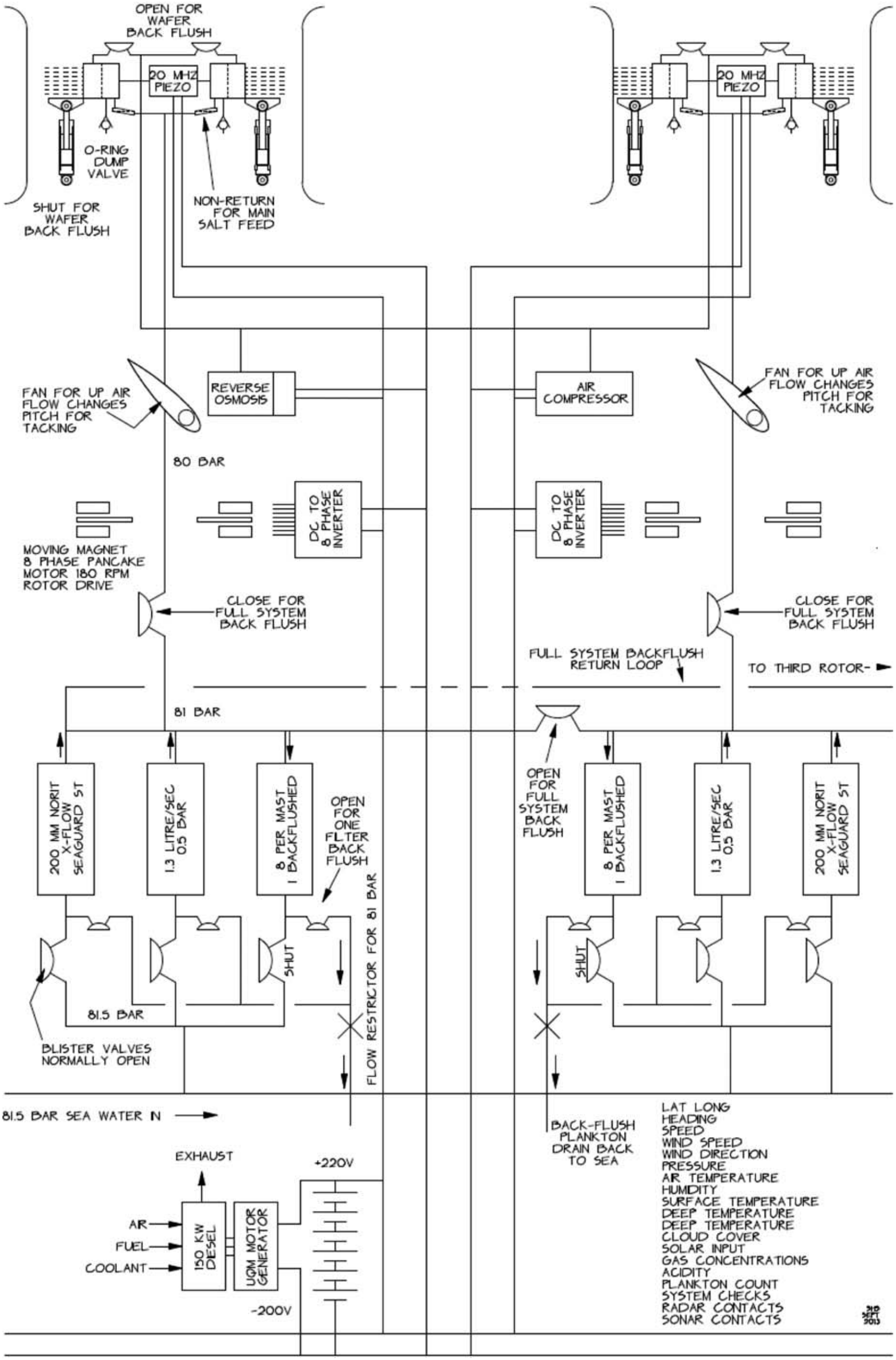

Figure 5 Plankton are removed by banks of 8 filters (3 shown) with sequential back flushing.

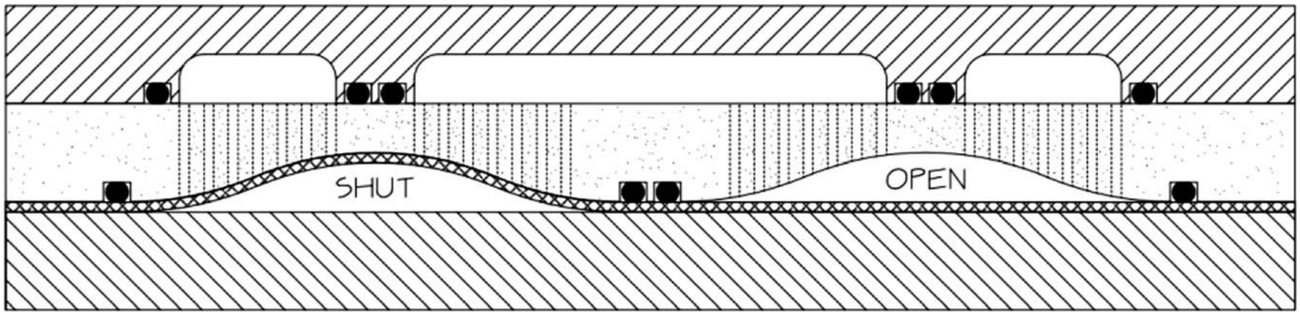

Figure 6 A sectional view through a blister valve. Oil pressure on one side of an elastomeric membrane can block a grid of passages on the other side with the minimum creation of wear debris. The similarity to a field effect transistor is not accidental. Two valves for each of eight filter modules plus two more for back-flush connections between filter sets can be formed by a single rubber sheet. It was frustrating to learn that the idea and even the name 'blister' had been anticipated by Perkin Elmer in 1996.

Flow into the valve comes through a large number of small holes in the upper block, through a smooth-edged cavity and out through a second set of small holes. If hydraulic oil at a pressure slightly greater than the pressure in the salt water is pumped into the space below the cavity, the rubber will rise to the ceiling of the cavity and stop the flow. The oil flow for each blister valve will be controlled by an electromagnetically operated poppet valve.

In order to perfect the operation of the Pentair Seaguard filters, however, we have to expect more contamination from the pipe work connecting the filters to the spray heads. We have to transfer the cleanliness standards of a micro-fabrication clean room to a ship yard. It is a sobering thought that a spherical blob of tar in cigarette smoke is perfectly sized to clog a spray nozzle. Furthermore we must not allow salt water to dry out or fresh water to freeze in the nozzles. It will therefore be necessary to back flush the silicon wafers, with fresh water followed by super-filtered dry air.

The wafer back-flushing needs the provision of a hatch to close the exit of the wafer housing. The hatch will be closed, the salt feed cut off and fresh water pumped backwards through the wafer nozzles. We can now use the high frequency ultrasonic system at much lower frequencies as an ultrasonic cleaner which it so closely resembles. Figure 7 shows a plan view of the spray head.

Most of the dirt in hydraulic systems is built in from the start. The first step in the clean-up will be to make all fittings leak proof and pump the system to a high pressure, 50 to 100 bar, with super filtered air. This will be released abruptly through a large steel ball retained in a cone by a magnet flux. The sudden release of pressure will cause sonic pressure pulses along the pipes to remove debris. The process will continue until the air coming out is deemed sufficiently clean.

The system will be resealed and pulled down to a hard vacuum. Then a heater will be turned on in a basket of a material known as Parylene. This converts it into a vapour which instantly spreads to the entire inner surface area of the system. Gas molecules get everywhere and condense to form a uniform layer over the remaining dirt on pipe walls.

6 Vessel Design

The places where marine cloud brightening will be most effective are in clean air far from land, but these locations vary with the seasons and so hardware should be mobile. Supplying conventional fuel, food, water and medical attention to mid oceans is expensive. This suggests that spray should be produced by unmanned, wind-driven vessels perpetually cruising the oceans and dragging some form of generating plant through the water to provide energy for the spray equipment. Initial ideas for engineering hardware are given in a paper by Salter *et al.*[12] Instead of textile sails the driving force would come from Flettner rotors. These are vertical spinning cylinders which can produce much higher force per unit area than sails.[13] The speed of rotation acts in a way similar to the angle of incidence of an aerofoil but is

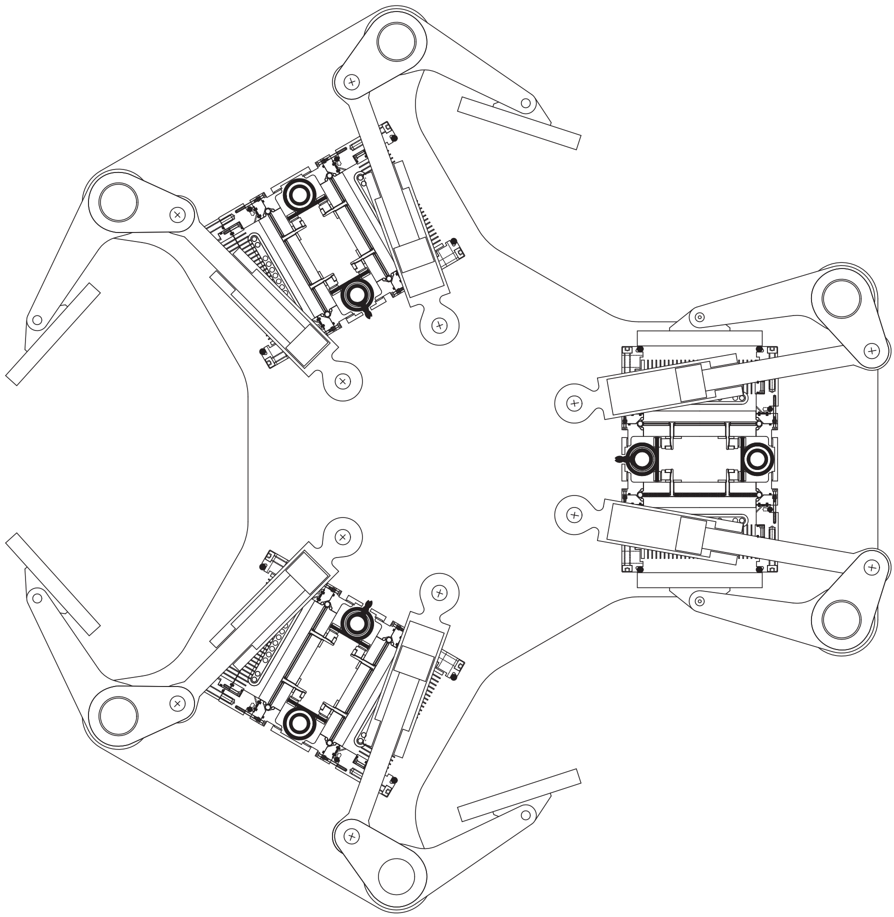

Figure 7 The spray head seen from above, showing open and shut wafer hatches. Shutting the hatch allows the wafer nozzles to be back flushed with desalinated water and dried with ultra-filtered air. Putting wafers back-to-back shortens the distance over which the large charge which actuates the piezo-electric elements has to travel. The exit passages are horizontal so that any water can be cleared by pitch and roll motions. A fan below the spray head will move a vertical air stream at 9 m s^{-1} towards the reader.

much easier to control by computer. The high agility of Flettner rotors relative to textile sails is a particular attraction. Rotor-driven vessels can stop, go directly astern and rotate 180° in either direction about their own centre or any other point.

Spray will be blown up through the rotor by an air flow of 9 m s^{-1}, just less than the Weber coalescence velocity and will emerge at a height of 25 m.[14] It will be entrained with surrounding air and the mixture will rise to a height of about 5 rotor diameters above the rotor top. The relative humidity very close to the water surface will be nearly 100%. This falls to typically 60% at a few metres and then rises slowly to 100% at the cloud base. The very large surface area of the spray means that evaporation of the spray plume up to 100% relative humidity will be fast, leaving large numbers of liquid drops. The upward velocity will fall rapidly above 35 m. For drop sizes of 800 nm, we have to increase the Stokes prediction for the still air falling velocity from 19.8 to 23.8 μm s^{-1}.[15] However, this is very small compared with the turbulent velocities in the marine boundary layer which is an appreciable fraction of the local wind speed but with a vertical component clipped at the surface.

Latent heat for the first stage of evaporation will come from the surrounding air of the expanding plume. We can use psychrometric charts (a graphic representation of the physical and thermodynamic properties of air-water mixtures) to get the temperature drop. For an input humidity of 60% and a dry bulb temperature of 15 °C, the temperature drop in the wake will be about 3 K. The resulting density increase will mean that the cooled plume will fall rapidly and spread out over the sea surface taking heat from the water below for any further evaporation. The air above the plume will cool at night but the water below will stay at almost the same temperature causing most of the subsequent rise.

The tops of the original Flettner rotors were fitted with a flat disk to reduce air flow from the high to the low pressure side of the rotor. Alexander Thom argued that the addition of extra disks would increase the lift coefficients and reduce drag coefficients.[16] This was supported in practical tests by Norwood.[17] More recent computational work by Craft *et al.* has shown that the lift coefficients of 10 and above predicted by Mittal and Kumar at low Reynolds numbers,[18] also applied to ones at 10^6.[19] They also found that drag coefficients fell with increasing spin ratios down even as far as the negative ones suggested by Mittal and Kumar at low Reynolds numbers. They found that the increased lift coefficients at high spin ratios due to extra fences were not as high as Thom had hoped and that fences needed higher drive torque. However, most importantly, they found that drive torque coefficients of 0.0025 were encouragingly lower than those predicted by Glauert.[20] Unfortunately the drive torque coefficients of the 10 500 tonne Enercon Flettner ship have not been published.

Mittal and Kumar showed that there were critical rotation speeds which produced large oscillatory forces from vortex shedding. At a spin ratio of 4.5, with a predicted a lift coefficient oscillating between 21 and 23, the instantaneous drag coefficient ranged from +0.7 down to −1.5. Forces were stable between spin ratios between 2 and 4.3 and again above 4.8. However, these oscillations were not reported for either of the Flettner ships and were not observed in the trials of Cloudier, a 37-foot sea runner converted to rotor propulsion by Marples for a television production company. It may be because the computer modellers use the numerical equivalent of rigid mountings for their rotors. A partly flexible rotor on a more flexible mast on a ship which is free to roll to make waves will provide damping tending attenuate any oscillatory forces.

The first rotors used by Flettner for his 1926 Atlantic crossing were made of steel but, even so, weighed only one quarter of the rigging they replaced. With modern composites they can be made even lighter than a conventional mast because a thin-walled tube has such a high structural efficiency. Indeed the wall thickness needed to resist the rotor bending stress in a Category 4 hurricane is so low (0.7 mm) that the failure mode would be buckling. The rotors will therefore have a double skin separated with corrugations. With foam filling they can provide buoyancy to prevent total capsize. The structural design is driven not by stress but by the need to keep deflections within the angular range allowed by a pair of SKF spherical thrust bearings. The high lift coefficients mean that a given thrust can be achieved with a lower centre of pressure so that heeling moments on the hull and bending stress at the mast foot are reduced. Indeed when the wind is from the quarter a rotor vessel heels *into* it.

We require the spray generation system to be above the spherical bearings which support the weight of the rotor and transmit its wind loads. This means, however, that salt water, fresh water, dry air, electrical power for piezo-excitation, high pressure oil for hatch operation, medium pressure oil for blister valve operation and oil return line have to pass through the 150 mm bores of a pair of SKF 29330 bearings. The SKF data shows that we could lift the entire vessel out of the water and spin it on one bearing.[21]

7 Justification of the Trimaran Configuration

Let us recall the evolution of ship forms. The original mono-hull form remains the favourite for heavy cargoes and large numbers of passengers. Internal spaces are large and have convenient shapes. Most of the hull surfaces are easily formed from single curvature plate. Roll may be high but recovery from roll is usually certain. The wave-making resistance rises very sharply at speeds approaching a value (in m s^{-1}) of 1.34 times the square root of the water line length (in m) and many mono-hulls never exceed this. There is therefore a strong incentive to build long vessels.

The wave-making resistance of a catamaran is lower than that of a mono-hull and shows smaller humps in the wave-making drag curve, especially if the demi-hulls are staggered so that the waves of one hull interfere with those of the other. Surface shapes are more complicated. Internal space is less convenient. Roll is less than that of a mono-hull but, if capsize does occur, recovery can be problematic. Capsize stern over bow, known as ‘pitchpoling’, can sometimes occur when vessels are driven too hard. Waves give catamarans more uncomfortable, or perhaps a more exciting, ride with appeal being a factor depending on the age and courage of the skippers.

Trimaran enthusiasts honour the Polynesian inventors by retaining their words. The central ‘vaka’ (the main hull) is joined by one or more ‘akas’ (the supports) to two ‘amas’ (the outriggers). The trimaran configuration is now the preferred configuration for very high performance vessels needing both speed and survival in rough, round-the-world conditions. The vaka can have adequate internal space for spray equipment. Roll resistance and problems of recovery from capsize are similar to those of the catamaran but comfort in oblique seas is better. The correct staggering of the amas can produce a very high degree of wave cancellation for particular chosen speeds but for cancellation at the very highest speed, the amas have to be placed so far forward, or so far aft of the vaka, that structural integrity is questionable.

Trimarans (and also other vessels) can be capsized by very steep waves which can occur by rare phase combinations of the components of the wave spectrum, from refraction over shallow water such as the Labadie bank between the Scillies and Fastnet or when waves meet an opposing current such as the Aghulas off the east coast of South Africa. The probability of a capsize can be reduced by careful course planning and spray vessels are more likely to operate in the summer hemisphere. The use of unmanned vessels changes the safety argument. If the propulsion force for a vessel is a strong driver of its cost, we should calculate how the extra cost multiplier of monohull drag compares with the fraction of trimarans which might be lost in extreme conditions.

The design of a trimaran geoengineering spray vessel has been inspired by record breaking yachts such as Banque Populaire V and Hydroptere.[22] However, it differs by the need for a heavier payload due to spray generating plant and the need to generate quite large amounts of power – perhaps 300 kW – for spray production. Banque Populaire displaces 23 tonnes and Hydroptere only 7.5 tonnes with only 0.9 m^2 of living space per crew member. A spray vessel will have the same 40 m waterline length as Banque Populaire V but, with the additional spray equipment, may displace as much as 90 tonnes. It would of course be quite improper for decisions about vessel design to be influenced in the slightest way by the prospect of making a contribution to record-breaking yacht design.

The 2008 spray vessel design had two ducted turbines, very much larger than any propeller for that size of vessel. The ducts round the turbine rotors would reduce tip vortex losses and could provide the function of a keel to resist beam forces. Generation could be done with rotating permanent magnets in a rim generator with flux cutting speed limited by cavitation. Alternatively, a more conventional generator could be driven at higher speeds through epicyclic gearing. The blade pitch and chord taper are chosen to give an equal pressure drop along the span.

One unfortunate feature of these arrangements is that cavitation problems are unevenly shared, being much worse at the blade tips. Another issue could be the possible requirement for higher speed during the non-spray mode, to move fleets of spray vessels for tactical spraying at sites in the opposite hemisphere. It also turns out that, even with good hull designs, the force needed to drive the hull is much larger than the force needed for the turbine. Operating a turbine over a wide range of speeds seems to require variable-pitch blades without much room for the pitch change mechanism. These thoughts have led to a new proposal for four, separately flapping akas hinged at the junction of the hull with high pressure oil hydraulics to control the amas for roll stabilisation. The concept draws heavily on ideas for vehicle suspension, first used by Citroën in 1952 and later adopted by several other motor manufacturers,[23] and combines them with the hydrofoils of Hydroptere.

In calm or very low wind speeds the vessel would be supported by the buoyancy of the vaka and amas. However, hanging down below each ama will be a submerged hydrofoil with variable pitch as shown in Figures 8 and 9. When the wind increases enough for the forward speed to reach a critical value for take-off, probably 4 m s^{-1}, the pitch of the hydrofoils would

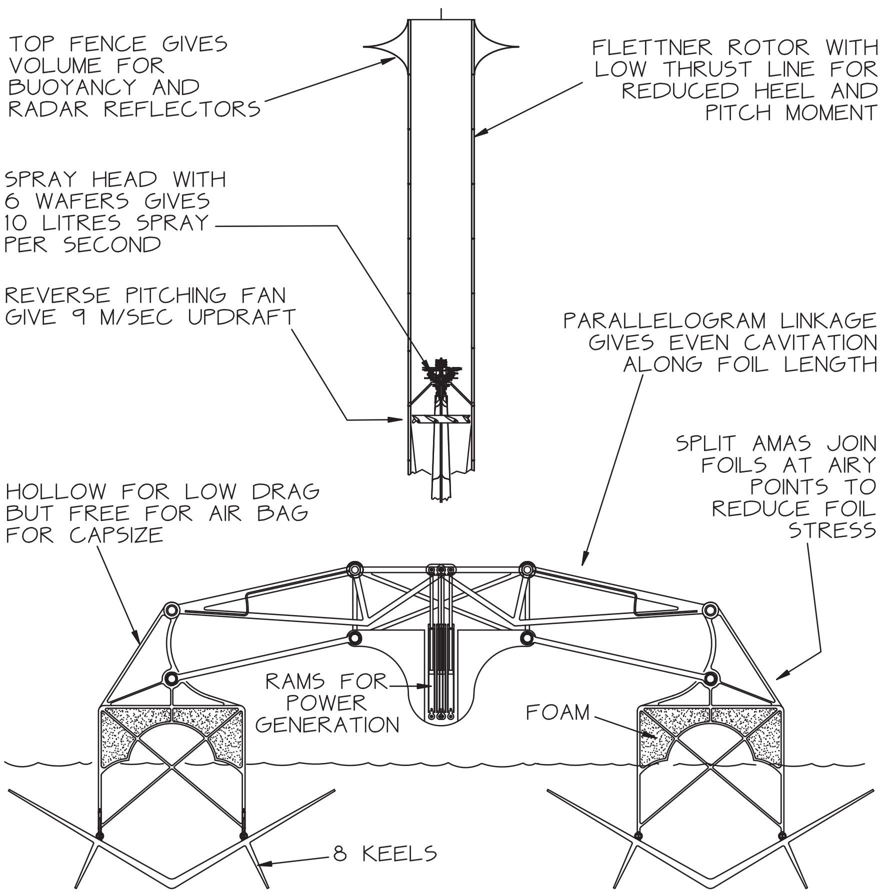

Figure 8 A front view of the trimaran spray vessel with hydrofoils below four amas. The mean load on each foil will be one quarter of the vessel weight. However, alternating variations of the hydrofoil pitch angle can be used to control roll, pitch, heel and trim and will generate large amounts of power on board the vaka to generate spray and spin the rotors. The dihedral angle of the hydrofoils means that at high speed the wetted area can be very low but the transfer from ama buoyancy to foil lift can happen at low velocities. Most of the energy taken from the wind will go into spray production rather than overcoming vessel drag. Movement of the amas by swell in windless conditions can provide energy for communications and controls. Hydrofoils can also be used for propulsion.

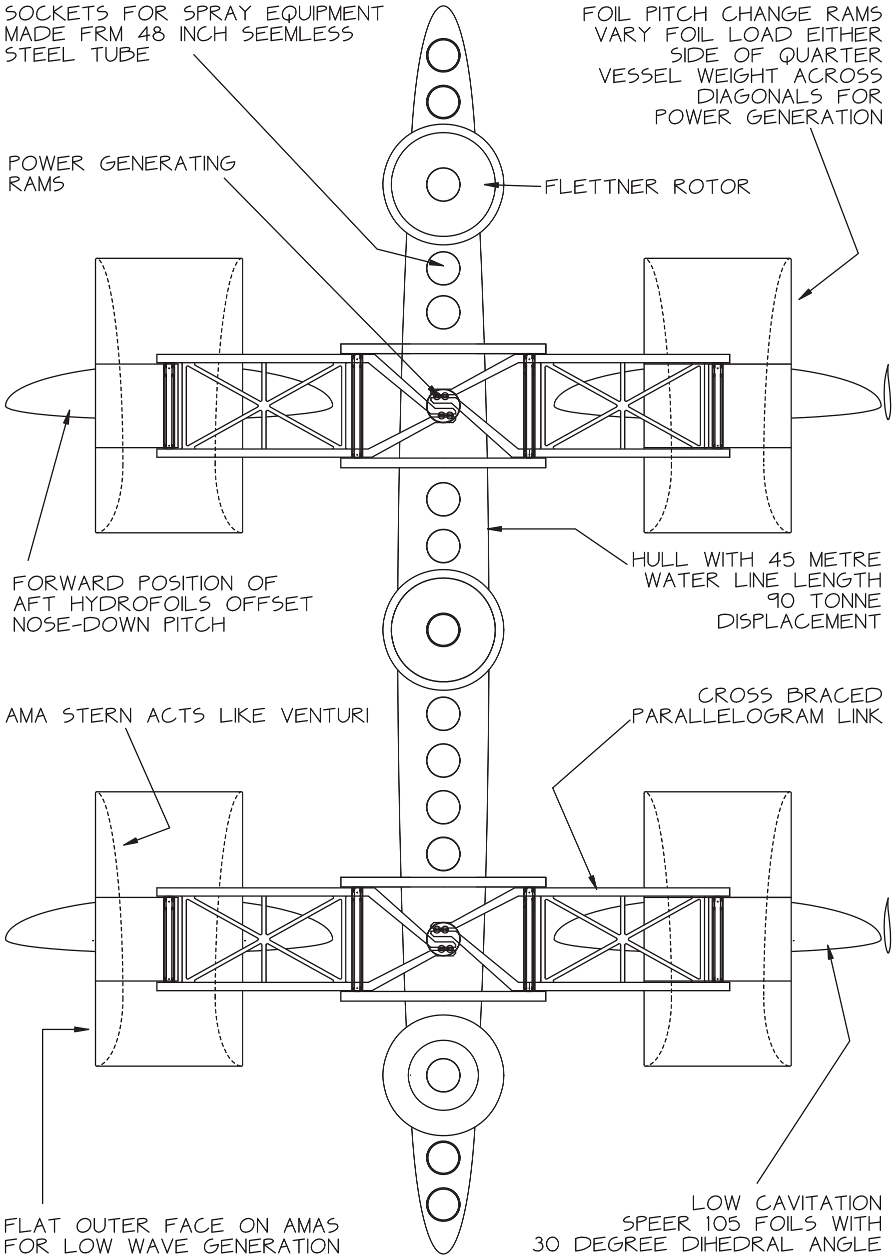

Figure 9 A plan view of the spray vessel. The four amas have been split into two sections so that hydrofoils can be mounted at their Airy points (the points used for precision measurement that support a bar horizontally to ensure minimal bending). This reduces foil stress by a factor of 5 relative to support at two ends and by a factor of 20 relative to a cantilever support. The flat outer faces of the amas will give a low wave-making drag. The gradual expansion of the inner section will act like the exit passage of a Venturi (a short piece of narrow tube between wider sections for measuring flow rate or exerting suction).

be increased so that each could support a quarter of the vessel weight. With fast control of the hydrofoil pitch angle we have the ability to control roll, pitch and heave motions. The foils are supported by a pair of vertical struts with a separation chosen to equalise the hogging (curving upwards) and sagging (curving downwards) stresses analogous to Airy points. Buckling of the struts will be critical and so we will use carbon fibre. Many hydrofoil craft use quite large dihedral angles. At higher speeds the vessel rises in the water thereby reducing the wetted area of the foils and there is an automatic control of roll and pitch. The transition to foil-born mode can take place at low speeds. However, large dihedral angles make the problem of pitch variation more difficult because the pitching moment on the foil will vary with depth of immersion. If we have confidence in the control loop for foil pitch it would be possible to have fully immersed foils with no dihedral angle. This would remove some of the anxiety about droplet erosion from spray at the surface but would lead to an increase in wetted area which, at the moment, seems more important.

Rigidly connected amas and hydrofoils will suffer severe wave loading at high speed in rough seas. Accelerations for a given bump amplitude rise with the square of encounter velocity, and this sets an upper limit to operating speed. Allowing controlled movement of the amas is like fitting independent suspension and shock absorbers to an unsprung cart, and can push the operating envelope to higher speeds and rougher seas. Furthermore, the damping of a shock absorber can be replaced by a mechanism which can generate energy.

Suppose that instead of equal sharing of the vessel weight between four hydrofoils we momentarily increase the pitch angle of the fore port foil by one third and decrease it for the fore starboard. This would produce a roll torque on the fore section which can be exactly balanced by a reduction in foil pitch on the port aft and an increase at the starboard aft.

When the akas approach the end of the allowable travel we reverse all four pitch angles. This would induce large alternating torsional stresses in the mid-section of the vessel but would not affect pitch or roll. The resulting movements of the two upward moving foils with the large forces would do work on hydraulic rams. The movement of the akas would resemble that of some water walking insects and might appear to be an ungainly waddle but the vaka will advance smoothly and steadily. Four akas moving through 1 m against a third of the weight force of 90 tonnes will produce $>$1 MJ per stroke. While conventional turbines are designed to maximise energy production per unit of swept area with less consideration of the thrust, the opposite is the case for this application. We can afford to sweep a large area but want to minimise drag.

Foil angle adjustment is done by tilting the foil support struts about an axis through the ama with a pair of hydraulic rams either side of the ama above water level. The SKF company offer spherical plain bearings with amazingly low friction coefficients of 0.025. However, the entire weight of the vessels plus a factor for power generation must be taken by just eight bearings. Their life prediction equations indicate 4 years of operation. The angular motions are only a few degrees and so are uncomfortably small for rolling bearings. The proposal is to buy SKF parts and use spark erosion to cut the pockets for hydrostatic bearing pads fed by oil pressure from the power take off rams. The small angular deflections mean that we can seal everything with corrugated rubber gaiters and recycle the oil flowing out of the bearings. The obvious new design problems are extra moving parts, the conversion of irregular reciprocating forces to electricity or steady pressure oil flows, stress reversal leading to fatigue, multiplication of the weight force of the vessel by the leverage ratio, passing these forces through bearings, cavitation and the need for rapid pitch control.

If these problems can be solved there may be a number of advantages:

- Transient loads from wave impact can be reduced.
- Roll, heave and pitch motions on the vaka can be controlled.
- Heel and trim can be controlled to suit wind direction.
- Most of the power generation mechanisms can be placed inboard above the surface.
- Flotsam can be avoided.
- Amas can be lifted out of the water for inspection and maintenance.
- Cavitation pressures can be made the same along the span of the hydrofoils.
- The sweep velocity can be set according to power requirements and vessel speed.
- Driving the amas as wave makers can produce a side thrust.
- Driving the hydrofoils with the right foil pitch variation can produce propulsion.
- The pressure in hydraulic rams can be used to feed oil to hydrostatic bearings.
- It may be possible for ama movements and air bags to aid recovery from capsize.
- Moderate amounts of power, enough to preserve communications and essential control functions, can be generated from wave motion with no local wind.

Several of these requirements can be made easier by the use of newly developed digital hydraulics technology which originated in the needs of wave energy.

8 Digital Hydraulics

Work on power conversion for wave energy has showed that conventional hydraulic machines did not have suitable power ratings, flexibility of control and part-load efficiency for the demanding requirements of waves, especially the wide range of amplitudes. Conventional fast machines use an axial configuration for the chambers about the rotating shaft and the variation of the angle of a swash plate or axis of a cylinder bank to change the volumes of oil delivered per rotation. This can take seconds on a large machine so the bandwidth and loop gain of feedback loops are low. There is one inlet and one outlet port for each shaft and so it is difficult to control oil flows to and from different sources and sinks. Quite large surface areas have to move at high speed very close to one another so that there is an awkward compromise between shear and leakage losses. Pressure and the resulting leakage are present all the time even if no work is being done. The fine moving clearances must not be affected by the large forces.

The new fast digital hydraulic machines use a radial configuration so that one crank shaft can drive or be driven by pistons in many banks.[24,25] The geometrical changes of swash plate angle are replaced with decisions about the state of two electromagnetically controlled poppet valves at each chamber, one going to an oil tank at a low boost pressure and one going to a high pressure gallery. Poppet valves have a higher dirt tolerance than the sliding surfaces at a conventional port face. With clean oil they have virtually zero leakage. Unlike port faces and spool valves they can continue to function despite seat wear.

The shaft will usually run at a steady speed, often 1500 or 1800 rpm. Decisions about the valve state are taken by a micro-computer at times close to top or bottom dead centre for that chamber. This allows each chamber to idle, to pump or to motor for the next half rotation of the shaft but never requires a valve coil to oppose the force of high pressure oil. With six chambers in four banks there will be 24 decisions made for each shaft rotation so response can begin in 2 ms and get to its full magnitude in half a rotation *i.e.* 20 ms. Variable-rate pumping is achieved by the decision whether or not to hold open a low pressure valve at bottom dead centre. If the valve is held open, oil will flow back to the tank. No work will be done. The energy in flow losses will be about 1/500 of the work that would have been done if the valve had been allowed to close and oil delivered through the high pressure valve. If motoring action is required the high pressure valve will be held open at top dead centre so that oil can flow in to the chamber and do work on the crank. Just before the shaft reaches bottom dead centre, however, the high pressure valve is closed and the very last part of the stroke is done with energy stored in the finite bulk modulus of oil and elasticity of the mechanical parts. The timing is chosen so that chamber pressure is the same as the low pressure tank at bottom dead centre so that the low pressure valve can open to allow the oil to exit. The high pressure valve will now be very firmly closed against its seating by the high pressure. The piston will rise, delivering oil to the tank, but just before it reaches top dead centre the low pressure valve will close and oil in the chamber will be compressed up to the high pressure needed to open the high pressure valve, so that the cycle can begin again. Valve operation always takes place when there is a low pressure difference across a valve and so the machines are quiet, making less noise than the induction machine which drives them.

Nearly all the forces inside a digital hydraulic machine are due to an oil pressure. This means that the pressure can be fed to the far side of a part under load to form a hydrostatic bearing with either very low or zero contact force. If, a rather big if, oil can be kept clean, then the life of hydrostatic bearings can be made indefinitely long.

A further application of digital hydraulics in a spray vessel is the generation of the pressure for required for spraying. We first thought that the pressure needed would be suitable for down hole pumps such as the Grundfos SP series. These combine a long stack of hydrokinetic impellers with a three-phase ac motor in a package which will fit in a drilled well-shaft. Stainless versions can operate in salt water. Efficiencies of 80% at the lower pressures are possible but these efficiencies are reduced at the higher values of pressure which have been shown to be necessary by the COMSOL Multiphysics analysis, which showed that 80 bar would be needed for monodisperse spray at 800 nm.

Digital hydraulics favours high pressures but low flow rates. While there has been a steady increase in pressures used for hydraulic machines, there is a present upper limit of 400 bar set by the availability of commercial seals and fittings. However, it is possible to design pressure exchangers in which a cylinder is fitted with two linked pistons of differing diameter. These will enable the step down from 350 bar to the 80 bar suitable for nozzles, with a corresponding increase in flow volume. The 80 bar oil must be separated from water. The rubber separating membranes used for gas accumulators are notoriously unreliable, perhaps because there is no accurate control or limitation of strain. It may be possible to achieve a satisfactory fatigue life with the design shown in cross-section in Figure 10.

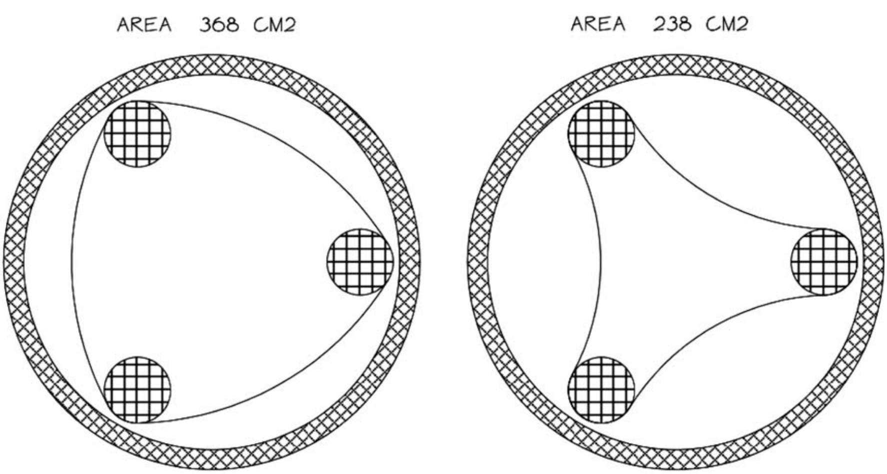

Figure 10 A sectional view of the oil to water pressure exchanger. The design is based on Cadwell's work on the fatigue life of rubber.[25] Reversal is bad. The strain in the rubber tube is only 10%.

The fatigue life of the design depends on the rubber fatigue life measurements made by Cadwell in 1940.[26] During an elaborate series of tests he showed that it was the *reversal* of strain which shortens life. If the strain goes from 100 to 125% of the unstressed dimensions his specimens were lasting nearly 10^9 cycles, while going from zero strain to 25% would give a life of only 10^7 cycles.

The body of the pressure exchanger is an open-ended tube with end caps retained by three stainless steel rods. Around the rods is wrapped an open length of rubber tubing. The rods are pushed apart by a series of increasingly larger trefoil-shaped section so that they can be forced into holes in the end caps. A final parallel set of expanders can be left in place to reduce bending stresses in the rods. Each end of the volume is closed by a fairing resembling the trousers of a fat, three-legged person. With the proportions drawn, the strain variation in the rubber is only 3%, a tenth of the strain which would fail at 10^9 cycles.

Salt water goes into the centre of the rod group through a silicon nitride non-return valve and is pumped out through another non-return valve at the other end. Oil can be put in and taken out through ports at the centre.

Figure 11 shows the block diagram of power generation for the moving akas and the pumping system from oil to water.

9 The Mathematics

So far, people modelling geoengineering have applied fixed concentrations of aerosol to selected parts of the atmosphere regardless of its state or the season of the year. For the very long lifetime of stratospheric sulfur this is a reasonable simplification. However, for tropospheric sea salt this would be similar to buying a car with all the movements ever needed for its steering wheel stored in a read-only memory. It would be odd if the phase of the El Niño oscillation or the timing of a monsoon had no effect.

One of the earliest predictions of the effects of marine cloud brightening was by Jones *et al.*[27] They tested the effects of continuous spray at three small areas, one off California, one off Peru and one off Namibia. The area totalled 3.3% of the oceans but produced a cooling of nearly 1 W m^{-2}, about two thirds of the anthropogenic thermal change since pre-industrial times. Their results predicted that spray would increase precipitation by useful amounts in several dry regions of the world but would reduce it by 0.8 to 1 mm day^{-1} in the Amazon. This is small compared with present precipitation values of 6.5 mm a day and was not shown in modelling by Rasch over a wider area.[28] However, interference with precipitation anywhere must be a cause for anxiety.

The main effect of spray is to reduce sea surface temperatures by amounts which are small compared with the change from cloud to clear sky, and even smaller compared with day to night. Lower sea surface temperatures mean less evaporation but also higher temperature gradients to produce higher wind speeds and faster water transport in monsoon winds. Rain needs large

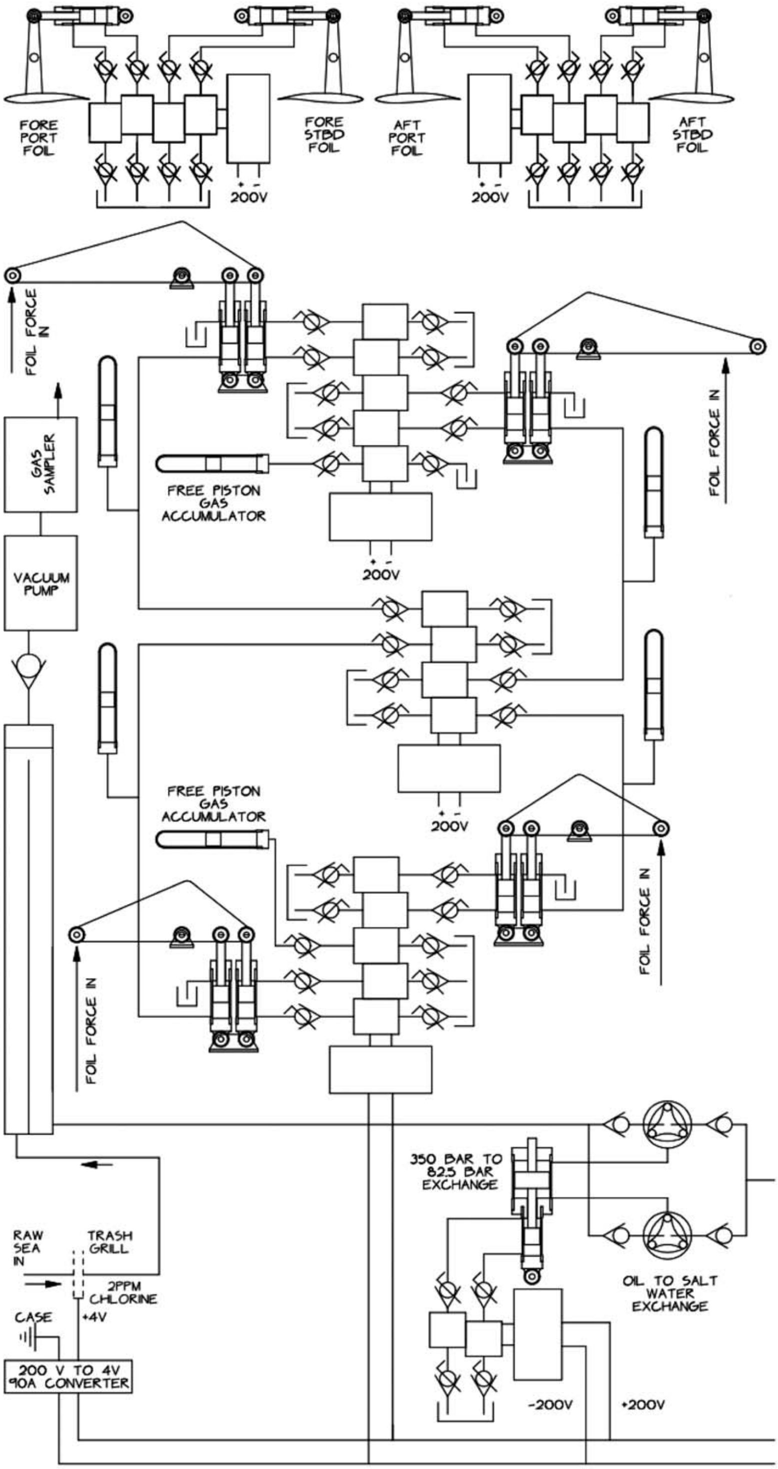

Figure 11 Multi-bank digital hydraulics are used for power generation from the moving akas and the pressure conversion from oil to water.

drops and so reducing the drop size in clouds will reduce the probability of rain but this effect will be stronger over the sea than the land and so there will be more rainfall further inland. There are at least six other conflicting climate mechanisms involved. Bala and Caldeira showed that widespread marine cloud brightening led to a small *increase* in river run-off over the Indian sub-continent.[29]

We may be able to employ a technique from electronic signal processing to use climate models to produce an everywhere-to-everywhere seasonal transfer function of all the side effects of cloud brightening. The first experiment on the idea started with a real day-by-day temperature record over 20 years. The annual variation and a smaller component with a six month period were subtracted by eyeball adjustment of amplitude and phase, which was found to be quicker than an approach based on Fourier transforms. The mean value was then subtracted to give a convincing spread of observations similar to a Gaussian distribution. This was then perturbed by additions and subtractions of temperatures of ± 0.2 K to 1.2 K in steps of 0.2 K together with a further four 'changes' of zero amplitude. The choice of a random change was made every 21 days. This was done with nine separate independently random sequences. The resulting perturbed temperature signals, which looked very like normal records, were passed to an independent analysis programme which had information only about each of the sequences on which to base a detection of each of the amplitudes. The scatter of the correlation results, mean errors and the standard deviation of the scatter are shown in Figure 12.

The next experiment of the technique was with a real climate model, the HadGAM2, carried by Parkes.[30] He divided the world's oceans into 89 regions of similar area, and multiplied or divided the initial settings for the concentration of cloud condensation nuclei in each region according to separate independently random sequences. Figure 13 shows the scatter of his predictions for changes in precipitation made by each of the different spray sources around the world at a middle-eastern observation station in the Middle East. Clearly precipitation can be varied both up and down and the scatter is acceptably small.

The results show a drying of the Amazon due to spray off Namibia, in line with those predicted by the Hadley Centre work,[27] but also showed the opposite effect from many other regions with a strong effect from the Aleutian islands in the opposite hemisphere.

The full set of the Parkes results is available online.[30] Confirmation of the data with other climate models would be highly desirable but have not yet been published.

10 Costs

Politicians and investors want firm cost estimates at an early stage of the project, even though their opinions about the cost of NOT preventing

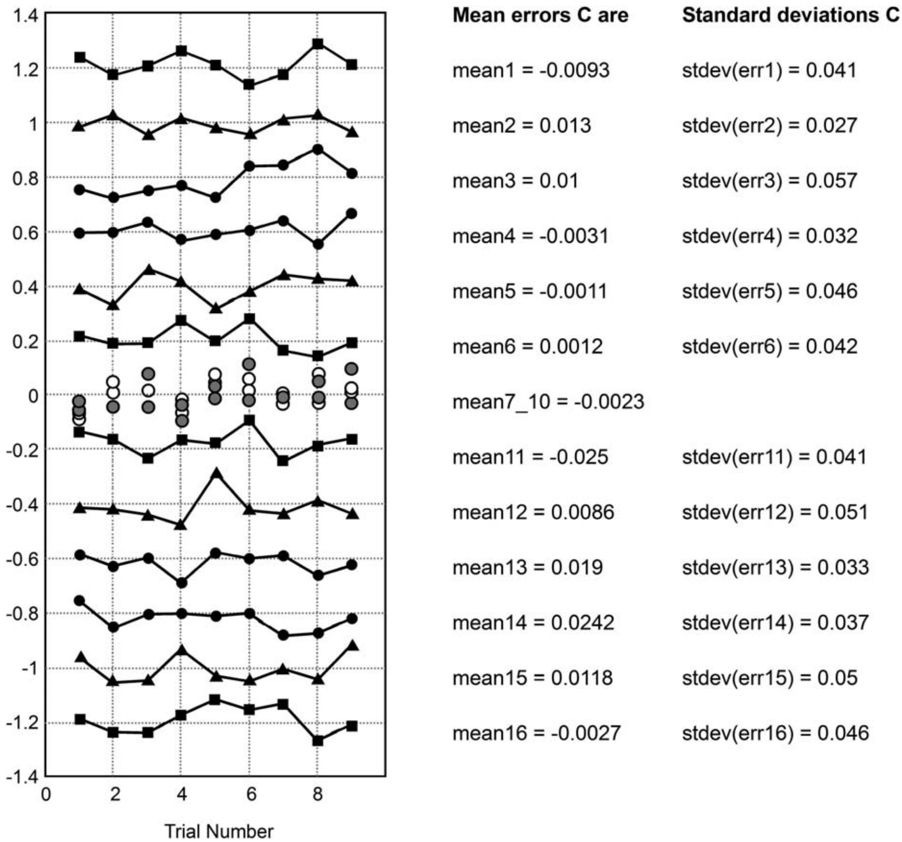

Figure 12 A very expensive thermometer would be needed to detect the difference between the original perturbation and the detected result.

climate change are uncertain. The site at [31] gives a useful list of official estimates. Even when a product is being made and sold, its true cost is likely to be a commercial secret. However, it may be possible to use parametric costing using rules based on the nearest similar products made in similar quantities and adjusted by weight, power rating and inflation.

Most ships are made in quite small numbers. Large private yachts are usually status symbols of wealth. One possible 'nearest similar product' is the Flower class corvette built hurriedly for the Royal Navy in World War II. It was based on the design of a whale catcher by Smiths Dock. In 1940 the cost was £60 000, very little of which went for the comfort of the ship's company.[32]

Corrections for the changed value of money are available from several websites.[33] The mean of four estimates for a corvette built today with UK inflation is £2 613 151 with the highest being £2 844 356.

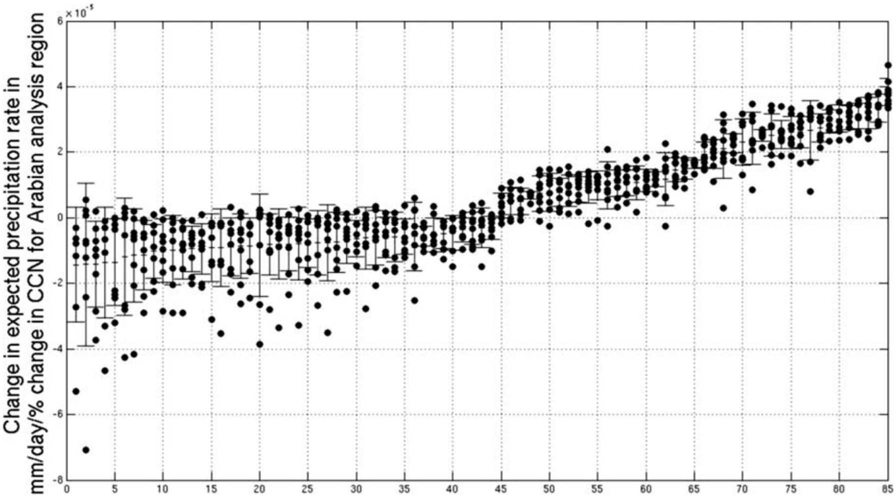

Figure 13 The results from a PhD Thesis by Ben Parkes showing the scatter of precipitation results from eight runs with different coded sequences of the variation of the concentration of condensation nuclei at 89 ocean regions. Precipitation can be changed in both directions.

Table 1 A comparison of corvettes and spray vessels.

	Flower Corvette	*Spray vessel*	*Ratio*
Displacement	925 to 1015 tonnes	90 tonnes	10.2
Water line	62.5 m	40 m	1.56
Power	2050 kW	300 kW	6.8
Crew	85	0	
Number built	225	$\sim$300 for 1 W m^{-2}	0.75
Speed	16 knots = 8.23 m s^{-1}	23 knots = 12 m s^{-1}	1.45
Range	3500 miles	unlimited	

The costs of displacement and power will have scaling rules which are a little less than linear. The cost of spray-related components is expected to be about £150 000 per vessel. Even though spray equipment will be novel, writing off the development costs over three spray systems per vessel will give a helpful reduction. Since inventors should never be trusted to publish the costs of their own inventions, readers are invited to pick their own scaling rules, interest rates, write-off fraction and the annual cost of ownership of vessels. Most ships last for about 25 years: the cost estimate of £200 million per year for a cooling of 1 W m^{-2} for marine cloud brightening made by Shepherd *et al.* appears to have written off entire spray vessel fleets rather more frequently.[34] See Table 1 for a comparison of the features of corvettes and spray vessels.

11 Conclusions

Although the engineering problems of marine cloud brightening are formidable there are a number of feasible engineering solutions that have been explored:

- Microfabrication technology can produce billions of orifices per wafer in silicon wafers clad with silicon nitride.
- Piezo excitation of a Rayleigh jet can give a very narrow spread of submicron drop sizes but the capacitance of the piezo-electric elements is large.
- Back-flushing ultrafiltration membranes, used originally to remove 30 nm polio viruses from drinking water and now for pre-filtration in reverse osmosis, can prevent nozzle clogging but nozzles can also be back-flushed.
- The improvement in lift and drag of Flettner rotors hoped for by the addition of Thom fences is not supported by computer modelling.
- It may be possible to use hydrofoil technology with controlled pitch variation of four foils to produce very large reductions in hull drag and several hundred kilowatts of on-board power generation.
- The complexity of parallelogram linkages for moving amas is offset by reductions in stresses in the akas and vaka due to shock loading as in vehicle suspensions.
- Comparisons with inflation corrected cost of WWII corvettes suggest that spray vessels built in similar quantities might cost about £2 million each.
- If the Schwarz and Slingo interpretation of Twomey's work is correct, then a few hundred vessels will be able to correct the thermal effects from pre-industrial times at an annual cost below that of world climate conferences.
- The short lifetime of condensation nuclei allows the use of tactical marine cloud brightening, with times and places for spraying chosen with regard to the phase of monsoons, observations of sea surface temperatures, Arctic ice and jet stream positions. Intelligent control will be much better than steady spray.
- It may be possible to borrow a technique used in signal processing with random sequence variation of the concentration of condensation nuclei, followed by the correlation of each sequence with model results, to get an everywhere-to-everywhere transfer function of spray. This could let us make wet places drier and dry places wetter.

Acknowledgements

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