Marine Cloud Brightening Spray Development

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A useful way to plan a program in a new and unfamiliar field of technology is to make a list of potential show-stoppers and then rank them in their orders of severity, cost of reaching a solution and time to reach that solution. While it is useful to reduce the interdependence between each part of the system and every other part, it is important to understand every interface between the parts. This cannot be done without some initial work for the each stage of the entire system. Decisions about tackling problems in series or parallel will depend on the money available and the urgency of finding a solution. For each potential show-stopper there may be an alternative with its own numbers for cost and time. If urgency is extreme then alternatives should be explored in parallel. At present marine cloud brightening has zero official funding but predictions of the rate of Arctic ice loss show that there could be a high degree of urgency.

The show-stoppers for marine cloud brightening can be set out in logical dependence order as follows:

- The design and testing of an energy-efficient technique for producing mono-disperse, submicron spray.
- The generation of enough energy for spray production and vessel operation.
- The design of a sea going vessel to carry equipment for the above.

Although we should work on the show-stoppers in rank order we should do enough work on the entire project to make sure that we are not relying on the impossible. Some cheap but slow items associated with component life testing would benefit from an early start. A spread sheet with cost estimates and a time line is given overleaf. The rest of this document is short descriptions of problems and the proposed solutions. Longer versions are available.

Vessel command and control functions will be important but have a low dependence on other parts of the system. There is existing technology already far ahead of what is needed so this is not a show-stopper. The later we leave its development the cheaper and more reliable it will be.

Overall system design

Outline design of complete spray vessels has been going from the start of the project in 2004 with modifications and updates as problems have been revealed. Work is described in a paper for the Royal Society of Chemistry, in press, May 2014. While work is by no means complete to the point of dimensioned detail drawings there is good information about available packing space for equipment, its likely weight and energy requirement. A block diagram of the energy paths is attached.

For spray vessels propulsion is by Flettner rotors. Power generation is done by moving hydrofoils driving high-pressure oil in hydraulic rams. Versatility has been achieved by having sockets in the hull made from 48-inch seamless steel pipes into which tubular equipment can be placed, protected by O-ring seals at just one interface and quickly removed.

Month		3	6	9	12	15	18	21	24	27	30	33	36		
Work package														**Total**	**$K**
Filtration check with 1.2 micron super-scale nozzles		40													40
Erosion test to check maximum velocity			30	5											35
Pipe cleaning tests				20	1	1	1	1							24
PVDF piezo film experiments				40											40
Super scale drop production with 10 mm chip				30	20										50
Tests of oil to rubber to salt water idea.				40	1	1	1	1							44
Confidence in COMSOL simulation achieved				:=) ?											
Major break point	:= (													**233**	**$K so far**
Order accommodation Malvern Spraytec ULPA bits				140											140
Recruit staff, update electonics and software				140											140
Manufacture pyramid entry 360 nanometre nozzle wafer					40	40	100								180
Spray generation of 800 nm drops from 10 mm chip							40	40	40						120
Know pressure and frequency of piezo chopping							:=)								
Design of full size piezo excitation and drive circuitry							60	60	60						180
Coagulation tests									50	50					100
Design and build double Pentair filters with backflushing									80	80	80	80			320
Design and build single 200 mm wafer cell									80	120	160	80			440
Design 6 wafer mast head unit									80	80	160	80			400
Consumable materials		10	10	10	10	10	10	10	10	10	10	10	10		120
Consultancy, travel, casual labour		10	10	10	10	10	10	10	10	10	10	10	10		120
Quarterly spend		60	50	435	82	62	222	122	410	350	420	260	20		
Cumulative spend			110	545	627	689	911	1033	1443	1793	2213	2473	2493	**$K**	**2493**

This spreadsheet 10 May 2014. Email S.Salter@ed.ac.uk

Blue indicates main staff activity

Overheads are based on $160 k per graduate engineer a year as required by Edinburgh University.

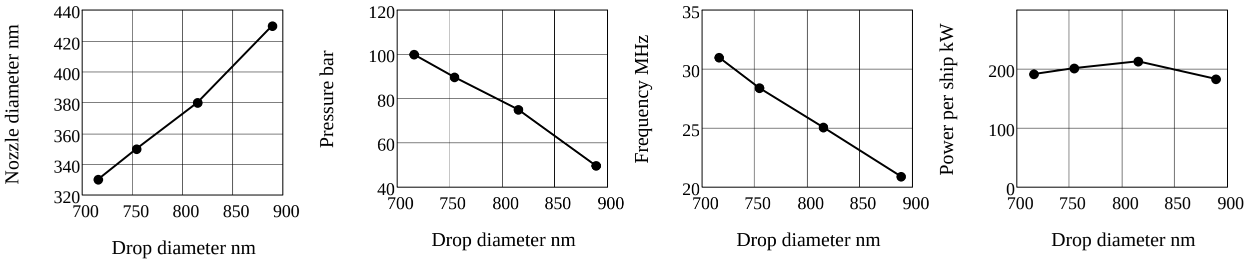
Every line is a potential show stopper. In that event staff salaries will continue until a new job is found and unspent money will be returned.

No plan has ever survived the first contact with reality.

The present vessel design has several spare equipment sockets. It could take a crew in just tolerable comfort. All the connections for pipes and power will be made from the top surface of each module like the back-plane for printed-circuit cards of old mainframe computers. Maintenance will be done by module exchange rather than by work in a dockyard. The project can use several generations of modules in the same hull. Perhaps when the technology is mature we can incorporate all the equipment in one compartment.

Spray production

A large number of different spray generation methods have been studied and taken to the point of general assembly drawings. Advice from atmospheric physicists is that mono-disperse spray is desirable. This points to the use of Rayleigh breakdown of jets, which can be helped with a small pressure pulsation at the frequency of largest varicose growth. Tom Stevenson devised a method which allows a large number of submicron nozzles etched through an 8-micron thickness of silicon to meet 50-micron holes through the rest of the wafer so as to give a very short passage and low viscous loss. Andreas Tsiamis has done COMSOL simulations for pressure, nozzle diameter and pulsation frequency as a function of drop diameter. With a 1 bar piezo excitation the results are shown below.



The major uncertainty is whether raw sea water can be filtered well enough to prevent clogging of the very small nozzles (370 nanometres) needed for the Rayleigh jets. The Dutch company Pentair (formerly Norit) are confident that the filters they supply for pre-filtration to extend the life of reverse osmosis membranes will be suitable. They will need back-flushing several times an hour. However the Pentair optimism is disputed by widely-respected pioneers from the inkjet industry. A comforting thought is that while just one blocked nozzle in an inkjet printer will be annoying, even unacceptable, a full scale wafer running at 27 MHz will have 230 million nozzles. We can afford to have several million of them clogged.

Filtration

The first show-stopper is nozzle clogging.   Pentair filters give flow rates that are an inconveniently large for initial laboratory work. We have some much smaller and cheaper Chinese domestic water filters made by Litree which use cross-flow rather than back-flow for flushing. We have a set of 10 mm square chips with etched holes of various diameters either side of one micron in a 5 mm diameter array. These were made by Camelia Dunare using contact printing which has a lower resolution than mask projection methods and the smallest holes did not etch through.   We will begin with 1 and 1.2 micron diameters.

The Malvern Spraytec is excellent for sensing particles in air. But commercial equipment for detecting particles in water, especially biological organisms which have a refractive index close to that of water, is not available. However we can get the necessary information by passing filtered water through a nozzle chip and measuring either the rate of increase of pressure difference across it from a high impedance flow source or the reduction in flow rate from a source of constant head. Measuring pressure is easier than measuring flow but a possible method is described later. At the start the low rate of an unclogged filter will be of the order of 1 mL per second.

Clogging will be followed by a back-flushing process with piezo-electric excitation at the frequency used for ultrasonic cleaners. We can also measure the chip breaking pressures for a number of outlet diameters to get a feel for the strength and notch sensitivity of silicon.

The degree of clogging of a badly clogged filter can be assessed by measurement of the pressure drop due to flow of ULPA air. We may also be able to do chemical analysis of the blocking material.

High velocity water erosion test

We have had silicon wafers with various type of surface protection and one with no protection sitting in sea water since June 2009. All appear to be in their original state but the water was not moving. It is known that stainless steel is not stainless for water velocities above about 5 metres per second because the protective surface film is removed, allowing corrosion to begin. In very well-filtered water stainless steels can take a higher velocity, perhaps 10 metres a second.   We need to move salt water through silicon nozzles at velocities above the 70 m/second predicted for the highest velocity through a wafer. Erosion can be detected using the increase of flow through an eroded nozzle – the inverse of the method used to detect clogging.

Pipe cleaning

The project has to solve the problem of getting the conditions of a micro-fabrication clean room transferred to a ship yard. While all the modules for the 48 inch tubes can be factory sealed we have to make pipe connections on deck and we must be confident that we can clean the pipes .The usual approach of having bright red plastic plugs on all ports and hose ends which are removed at the last moment will not be adequate.

The first step of the cleaning process is to pump a filtered solvent cleaner through the pipes and drive ultrasonic waves through the liquid, circulating it until its comes out clean.

Then we seal the entire system and pump in a drying flow of air fed through ULPA air filters (see http://en.wikipedia.org/wiki/ULPA) to a pressure of 10 bar . We can excite the pipe walls with sound waves to agitate any material still on them.   The feed pipes will have a bore of 50 mm. At some part in the pipe system, remote from the wafers, will be a valve in the form of a cone flared to 70 mm. In contact with the cone will be a plug with a spherical section held shut with a 110 mm iron disk attracted to a magnetic gap with a flux density of 1.4 Tesla. The valve will unseat when the force on exceeds the magnetic force. This will induce a super-sonic shock wave along the pipe. The air coming out can be sampled by a Malvern Spraytec system and the process repeated until no more debris comes out. It might be a good idea to fit the seal with a linkage and shock absorber.

There may still be some material clinging to the pipe walls and at junctions. This can be sealed in with Parylene. The system will be pulled down to a low vacuum. Somewhere in the piping will be a pocket with an electric heating coil containing Parylene.   When this is heated its vapour will move through the entire pipe system except for the wafer section and the Pentair filters. Both can be isolated by the non-return valves needed for back-flushing. Parylene gas will penetrate every crevice and condense on the cold walls to form a sealing layer outside all the remaining dirt particles. This will also prevent future corrosion. The main uncertainty is the size of any particles subsequently shed by the Parylene layer.

We can test results by feeding well-filtered salt water directly to a nozzle chip and then to a chip through a treated pipe and comparing the two clogging times. This technology must be tested early in the programme because we will fail without it.

Parylene insulation for PVDF sheet

Most high-power ultrasonic generation is done with PZT-4, a brittle ceramic with a high electrical permittivity. This was chosen for existing designs.   Disks that would be resonant at the required frequency would have an enormous capacitance and need very large currents. Their acoustic matching to water is bad and would need a quarter-wave layer of material with intermediate acoustic properties. The disks of the right thickness would be very fragile and are not available as standard sizes.

A possible alternative is the use of a thin flexible film of PVDF plastic with cupro-nickel cladding. PVDF has a better acoustic matching to water, much lower permittivity, a natural frequency closer to the required one and availability in widths of 200 mm. We can cut it with scissor and drill holes for water feed through it so we have it almost in contact with the wafer nozzles and avoid the high losses of salt water at 27 Mhz. If we have 1 mm diameter holes through the piezo material and its backing plate and use a 14 micron ‘stud’ length of one quarter of a wavelength of a 27 MHz excitation the pressure drop is about 1.4 bar.

PVDF film will still need extremely high currents and lots of heat will be generated but the flow of water should make this possible. At 1.6 litres a second a 10 C rise will remove 68 kW!

The two main problems are whether or not we can get complete filling of all the gaps for the transmission of ultrasound and complete electrical insulation of all the cut surfaces from the salt water going through them. It may be possible to fill all the gaps and insulate all the water surface surfaces using parylene. We have tested this with 240 volts AC applied across adjacent tracks of an immersed printed circuit.

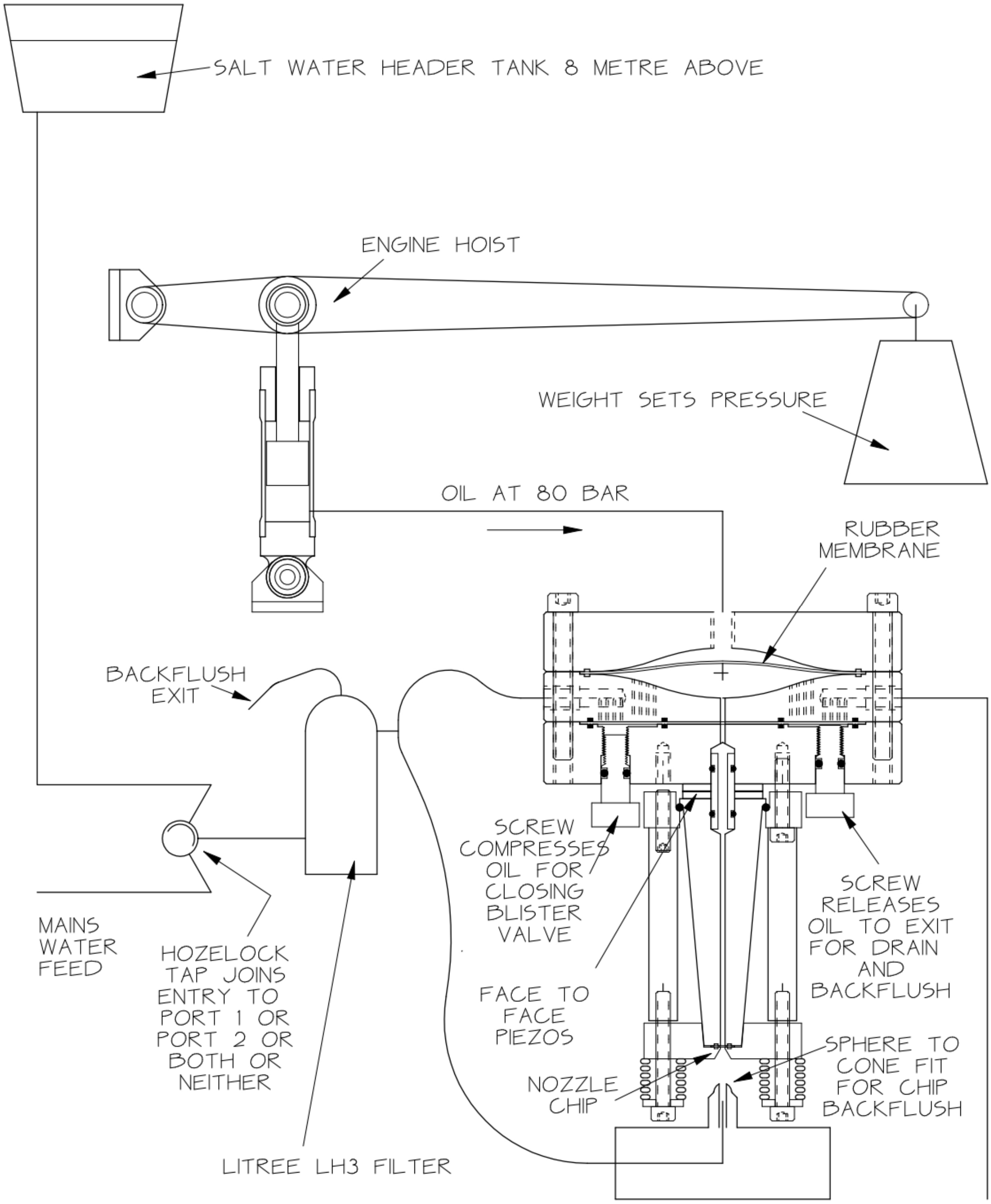
Super-scale chip tests.

We can learn a great deal from comparing drops from super-scale nozzles with COMSOL predictions for the larger 1 micron and 1.2 micron diameters in existing chips. The figure below shows the test rig for drop generation. To start the process the weight is removed from the engine hoist to relieve oil pressure. The blister valve on the exit path is shut. Salt water flows from the header tank, through a Hozelock valve, through the Litree filter, past an unpressured blister valve and fills the underside of the membrane chamber. The entry blister valve is closed and the weight is placed on the engine hoist to pressurise oil, and thus salt water, and feed it through a passage in the ultrasonic horn to the nozzle chip.

The Hozelock valve can select fresh water to flush the Litree filter or the membrane chamber. The chip can be backflushed with filtered water coming through the sphere-to-cone contact below the chip. It may be possible to measure the flow rate with a displacement transducer on the hydraulic ram of the engine hoist.

The two major problems are that piezo-electric ceramics have very high electrical permeability and so high capacitance and also that the transmission losses of salt water at high frequencies are large. The approach is to transmit the sound through a tapered brass horn in contact with the chip and to drive charge back and forth between two capacitances.

Tests on super-scale nozzles will increase confidence in the COMSOL predictions and justify the manufacture of the correct nozzle sizes with optical projection from a mask. We should do this in consultation with potential manufacturers. Large numbers of 10 mm square chips will be tested to establish safe pressures.


SALT WATER HEADER TANK 8 METRE ABOVE
ENGINE HOIST
WEIGHT SETS PRESSURE
OIL AT 80 BAR
RUBBER MEMBRANE
BACKFLUSH EXIT
SCREW COMPRESSES OIL FOR CLOSING BLISTER VALVE
SCREW RELEASES OIL TO EXIT FOR DRAIN AND BACKFLUSH
MAINS WATER FEED
HOZELOCK TAP JOINS ENTRY TO PORT 1 OR PORT 2 OR BOTH OR NEITHER
FACE TO FACE PIEZOS
SPHERE TO CONE FIT FOR CHIP BACKFLUSH
NOZZLE CHIP
LITREE LH3 FILTER

Oil to rubber to water tube test.

The typical pressure of reverse osmosis pumps is somewhat lower than is needed for marine cloud brightening and the flow rates are much lower. Many have rather short life times. But Clyde Union (now SPX) make long life units, the HPRO and CUP-BB3, which can deliver pressures and flow rates that might be suitable. I am in contact with engineers from SPX about this approach. My contact at the Glasgow office is Scott Cruickshanks.

We will examine existing pump designs for life, weight and dimensions and compare electrical drive with the alternative option of rubber tubes squeezed by hydraulic oil from an Artemis digital hydraulic machine. The key problem will be the fatigue life of rubber with salt water on one side and hydraulic oil on the other. We must find out if Cadwell's fatigue results apply in these fluids but could discover this with a bank of quite small specimens. Even with a higher cycle rate a long time is desirable.

Equipment ordering

When (if) solutions have been found for the more obvious show-stoppers we can justify purchase of expensive instrumentation. We need a Malvern Spraytec for drop size statistics and data logging for mass flow, charge transfer and pressure differences.

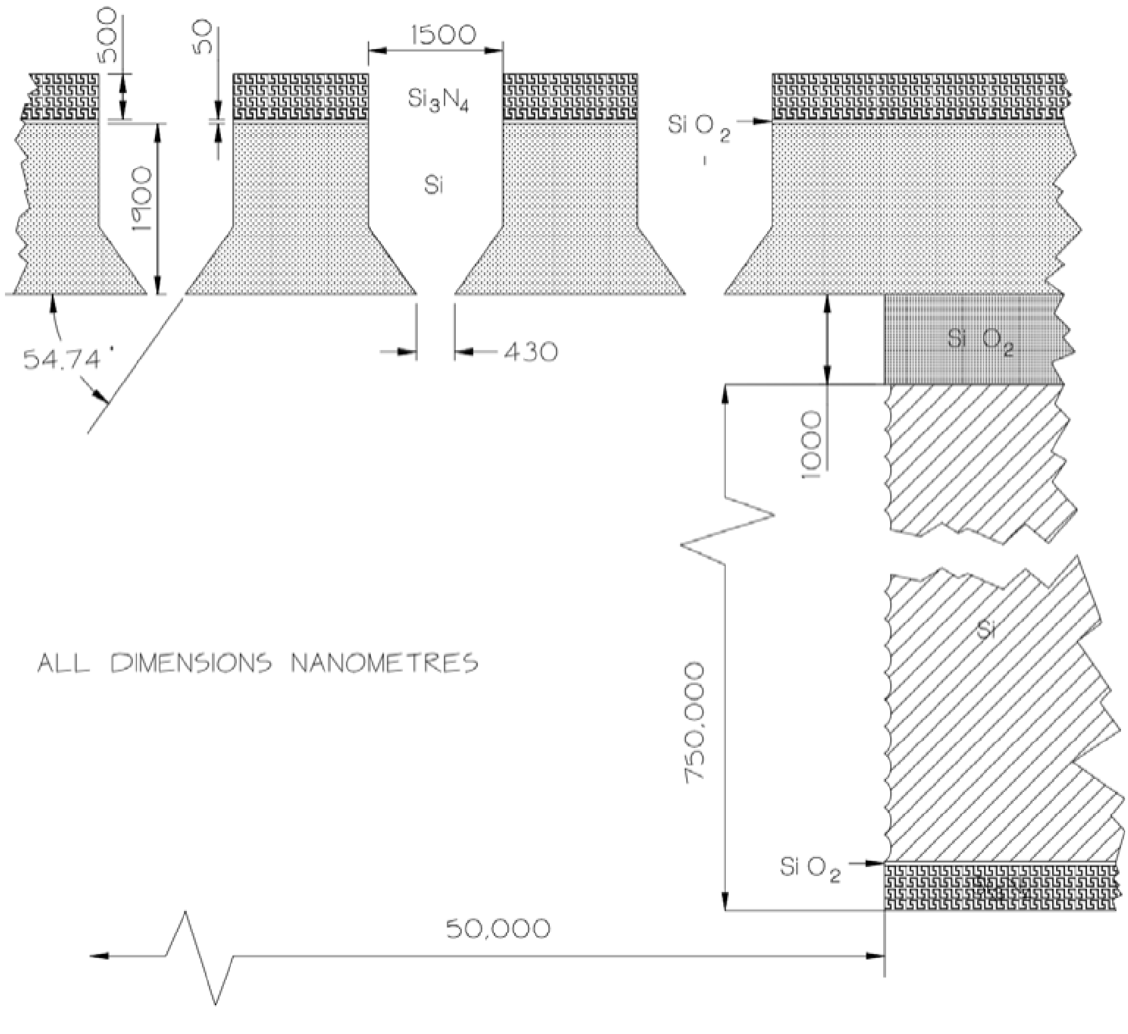
Previous experience has taught me that easy and rapid communications within a team are essential and this is best achieved if they are housed in the same corridor of a building close to the machine shops and test laboratories where they work. I bought such a temporary building which was very efficient but not beautiful and which Edinburgh University has had demolished. Replacing it will cost about $80k. I am arguing with the University that the 100% overhead does imply suitable accommodation and that, if this has to be supplied for the project, some overhead adjustment is indicated.

We had a very well equipped machine shop and electronics equipment for the wave energy programme but much of the electronics is now very old and some replacements will be necessary.

I would like to pass all information to a group of younger graduate engineers doing mechanical, electronic and computer simulation. I would also like to offer short term employment to gap-year and vacation students as well as specialist consultants.

Manufacture of pyramid entry wafers.

Viscous losses go with the inverse fourth power of passage diameter. But crystalline materials with a cubic lattice can be etched with sloped entry holes. Production of the nozzle wafers will be quite unlike normal wafer production for electronic applications. While some work can be done at the Scottish Microfabrication Centre, based at Edinburgh University, we must work alongside a commercial group who would be suitable for later mass production. We are in contact with local companies Semifab and Ratheon both based at Glenrothes, about an hour from Edinburgh. We can test pyramidal nozzles of the right size in 10 mm chips cut from small wafers but we must build relationships with at least two companies that can make them on 200 mm wafers. The present nozzle dimensions in nanometres are given below.



Spray generation of 800 nanometre drops.

When wafers with pyramid entry nozzles if the right size are available we will cut 10 mm square chips and measure drop diameter spread as a function of pressure and piezo excitation with a Malvern Spraytec. We will build instrumentation to log flow rates, pressure drops and charge transfer. With smaller nozzles the filtration problem will be more severe.

Full size piezo excitation.

Ultrasonic pressures ought to narrow the spread of drop diameters in Rayleigh jet break up but very high frequencies are needed. Piezo electric materials have high permittivity so large quantities of charge have to be transferred. The proposal is to connect two capacitances via a large number of secondary windings of an air-cored toroidal transformer with a high voltage drive to the primary winding. At 27 MHz the transformer must be wound from Litz wire.

Coagulation tests

It has been suggested by Stuart et al. in dio:10.5194/acp-13-10385-2013 that it will be impossible to make mono-disperse spray because the high drop concentration will lead to coagulation. However if drops can be given similar electrostatic charges then they should repel one another. Because of the triboelectric effect it may be quite hard NOT to charge them. It is easy to measure the charge generated from spray. No electrostatic effects were considered by Stuart et al.

We can also inject dry nuclei and warm, humidified ULPA filtered air into a collecting bag, allow the air to cool so that drops can form, leave it for various times and remove samples for size analysis with a Malvern Spraytec.   If the original spray was mono-disperse the presence of drops with double, triple etc. mass will indicate the degree of coagulation.

The University of Manchester operates a cloud chamber and instrumentation which would be very suitable. Control of pressure allows rapid adiabatic cooling. Hire costs are $1600 a day. My contact there is Paul Connolly.

Design and build Double Pentair filter

The full scale design will use eight Pentair filters for each of three spray heads. One of the eight will always be back-flushing with some of the water from the other seven. The necessary valving for switching between filters must work in salt water and not have any sliding parts that could generate wear debris. The design uses blister valves built into a stack of four layers of ABS plastic with a complex set of passage ways. The blister valves will need high-pressure oil actuation. The full block is 1200 mm in diameter and uncomfortably large for available space. However we can test all the key ideas with just two Pentair filters which can be switched with blister valves in exactly the same way as in the full size block. The filtered water will be fed to a single 200 mm wafer.

Single 200 mm wafer test.

The next level of the project will be building and testing a single full-size wafer. It will need 1.7 litres a second of ultra-filtered salt water at pressures up to 100 bar and a versatile system for piezo excitation. The flow rate is uncomfortably large for indoor use and we must devise a way to collect and recycle the spray. Filtration will need two Pentair modules with casings to take the full pressure and blister-valves to give back-flushing. There are several machines to pump salt water to 100 bar, some with rather short life, but we could also consider the squeezed rubber tube idea mentioned above with digital oil actuation from an Artemis machine. For laboratory tests we will have to collect spray in a plastic bag made from lay-flat polythene and recirculate it. The power rating will be about 20 kW, possible for three-phase laboratory supplies.

It would be sensible to design for possible outdoor spraying from a dock-side when winds are blowing offshore. This could be done with a flat-bed trailer and electrical power from a dock building or our own generator. We will need a Grundfoss submersible pump to raise water to dockside level. This will test quite a large part of the system at an intermediate scale with the right materials and components. However we do not want to mix engine exhaust with salt spray so any generator will need its exhaust to be discharged under water. Getting planning permission for any outdoor test will be a non-trivial problem but also a useful training exercise in spray politics.

Multi-wafer tests on land.

With no final decision made on the logistics or test site it is not possible to estimate even remotely accurate costs for field trials and they are not included in this proposal. But several options are possible. The present full-scale sea-going plant has been designed with an emphasis on sealing in a marine environment. One module would contain eight Pentair ultra-filters with blister valves for back-flushing feeding water to a spray head on the mast. A second module will contain a 350 bar to 85 bar free-piston pressure transformer and two oil-to-water converters. A third will contain a digital hydraulic multibank pump, hydraulic rams and some pressure accumulator smoothing. The flow from 6 wafers will be 10 litres per second and the power rating a bit under 100kW. It might be possible to fit filtering and pumping into a single module which could be attached to a ship hull and be driven by electrical power from the ship engines. There is nothing sacred about the 48 inch pipe. We can calculate the largest spray rate that could fit all the functions in to a standard ISO sea container which can be easily moved anywhere in the world. The spray head would have to be identical to the spray vessels one but could be raised to the height of the container length on a mast.

Although we need a long fetch of sea both upwind and downwind we can release spray from a dust-free land site on a small, suitably soggy, island. Many possible sites will be far from a grid connection. If pollution from the exhaust can be avoided we can use Diesel power. For clean and windy conditions such as the Faeroes or Aleutians we can get power from a mobile wind turbine like the Uprise mobile wind turbine described at http://upriseenergy.com/50kw-portable-power-center/ This is not yet in full production but will be in 5 months. The cost is expected to be $320,000 and we would need three units. My contact is jonathan@upriseenergy.com . Leaving a turbine behind at the end of the test would be a great way to reduce local opposition!

With computer addition of a few hundred satellite images of downwind clouds which have been rotated about the release point to suit changes of wind direction, a group of three turbines could produce detectable results.

Sea trials.

Doing tests from a mobile spray source at sea will allow collection of information from a wide range of climate conditions. It would be easy to put containers on container ships but observations of ship tracks in satellite images show much higher increases in cloud contrast than will be needed for full-scale reversal of climate change. The container ships are already emitting a great many condensation nuclei and will be travelling along great circle routes with many other equally dirty ships. Doing research on them will be like testing hearing aids in the middle of an artillery barrage. The requirement for clean air would seem to rule this out.

Research vessels use cleaner fuel and go to cleaner places but usually have very little spare room on deck. It turns out to be quite easy to make magnetic attachments which could hold a module on the outside of an uneven hull. It is a lot harder, but possible, to get it off. This looks a feasible option provided that we can take electrical power from the ship system. If we are confident that final equipment will fit in a 48 inch envelope, work on the hull attachment and practicing its connections and reconnections to the hull for a 10 kg/second spray could begin soon.