# Ice Shield Strategies

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Greenland Ice as a pictorial representation of an artificial ice shield. Source: [www.mnn.com](http://www.mnn.com)

## Introduction

Climate change in the polar regions has the potential to cause a mass extinction event that is probably worse than that which ended the dinosaurs. Humanity itself is gravely threatened. The early symptoms of impending environmental catastrophe are already in stark evidence. These include: the retreat of polar summer sea ice and mountain glaciers; starvation of species dependent upon sea ice, such as polar bears, seals and penguins; the destabilisation of polar ice caps, ice tongues and glaciers; destabilisation of the jet stream and polar vortices; the increase in frequency and severity of extreme weather events; the increasing reach and warmth of the North Atlantic Current/ Conveyor and Gulf Stream; the melting of the Arctic permafrost and consequent release of its contained or metabolised greenhouse gases; and the bubbling of vast amounts of methane up through Arctic lakes, vents and seas.

All these events are related. Indeed, they all started from three unintentional climate engineering experiments that humanity commenced when we decided to burn fossil fuels, clear the bulk of global forests and swamps and impoverish the oceans of marine life. What the first two of these did was to send into the atmosphere and oceans such masses of greenhouse gases that could not be sequestered safely and at a rate that the world could not safely accommodate. The early results were some global warming, ocean acidification, species loss, and weather extremes. The ongoing impoverishment of the oceans is degrading the largest and most effective carbon sink that the world possesses, thereby making almost all the other environmental problems much worse. Each of our three unintentional experiments produced a chain of deeply undesirable knock-on effects. The first two sent vast amounts of greenhouse gases into the air and sea. These initiated the early stages of runaway global warming and ocean acidification. In turn, that global warming is beginning to release potentially even larger deposits of methane into the atmosphere, where it will cause even faster global warming in positive feedback loops that exacerbate the many looming environmental catastrophes, and at the same time allow us less time and fewer resources to fix them.

This paper describes several ways by which the adaptation and deployment of a single, relatively simple technology can be made to mitigate runaway global warming. The adaptation required is to use floating, buoy-mounted wind turbines to pump seawater onto sea ice, thereby creating deepening ice fields or lens/shield-shaped ice mountains around them. In seas shallower than a kilometre or so, these ice shields can be securely grounded on the seabed. They may also freeze together in rows, arrays, or onto land. Their annual accumulation of ice on top can be made to match, or exceed, that of any melting happening beneath. They can thus be made to cause selective glaciation in most polar regions that we choose, provided that the polar winter remains cold enough to generate sea ice. Careful siting and timing of these ice shields and arrays may deliver several beneficial outcomes. These include:

* Reversing the loss of polar sea ice and its beneficial albedo (reflectiveness) effect that helps cool the world.
* Preventing, slowing, or facilitating the capture of emissions of methane from clathrates in the polar oceans and some surrounding lakes and land masses.
* Slowing or stopping the loss of polar and sub-polar glaciers.
* Placing ice range barriers, dams, or deep, floating booms in the way of the warm North Atlantic Current (NAC), ‘warm’ riverine, and Southern Ocean water that are catastrophically warming polar regions.
* Preventing the loss of polar species that depend on sea ice, such as krill, seals, penguins, cetaceans and polar bears.
* Making use of the heat island effect of the growing ice shields to convect the heat derived from freezing seawater high into the atmosphere, from whence it radiates out into space, avoiding most of the insulating effect of atmospheric greenhouse gases.
* Stabilising the jet stream, polar vortices and ocean currents.
* Producing increased polar biomass by virtue of the nutrients that are brought to the sea surface from the depths by the pumps powered by the wind turbines operating during the warmer polar seasons. Some of this biomass moves up the food chain to become our marine catch, whilst another part sinks to become more or less sequestered carbon.
* Generating ice weirs across polar rivers, thereby backing up their waters until the ice formed from them insulates part of the melting Arctic tundra. Such weirs may also cause the riverine water that spills over them to freeze in extensive sheets on the sea ice, being uninsulated by any ice above, and thereby able to thicken considerably the sea and riverbank ice thereabouts.
* Economical construction of ice dams on remote Arctic rivers, from which renewable hydroelectric power might be generated or their waters made to turn south (possibly via tunnels or pumped in pipes) to irrigate crops.
* Construction of secure, accessible and economical bases for polar research and stable, long-lived drilling platforms.
* Create open, polar sea channels and polynyas for shipping and wildlife.
* Renewable electric power from offshore, ice shield-based wind farms that is transported to land via HVDC lines over flat ice ranges or undersea. The power could also be used locally to liquefy harvested methane and pump it into vessels or along pipelines to markets, or to pump fresh water South.

## Concept Technology Overview

If seawater is pumped onto sea-ice during cold times, it spreads out and freezes, see Zhou & Flynn (2005) paper *Geoengineering Downwelling Ocean Currents: a cost assessment* https://www.see.ed.ac.uk/~shs/Hurricanes/Flynn%20downwelling.pdf. The process also serves to radiate more heat off-planet, because more heat is given off as more ice freezes quickly without the insulating effect of other ice above it. Should the discharge continue, then an iceberg or ice shield forms in a way similar to which volcanoes form mountains, except that ninety percent of the growth in height-depth of each lens-shaped ice shield is underwater, as the base of the ice shield sinks under the increase in ice mass above it. Unlike our vanishing sea ice, these ice shields would not disappear in the warmer months, as they would have become too thick. Furthermore, with additional pumping they would tend to grow even larger, or at least regain any summertime lost mass, each cold season. Multiplied, they could thus be used to keep our polar regions safely frozen in regions where we decided it were best, leaving other parts ice-free, at least in summer.

Existing technology can be adapted to make and operate such a ‘glaciating’ system. Wind turbines mounted on moored buoys, then bound in sea-ice, then grounded as they grew taller, could be made to power, with renewable energy, the seawater pumps, water stream distributers, de-icing equipment, sensors, communications and other power requirements of each forming ice shield installation.

Possibly a better alternative to the above is to send the power from commercial, offshore, floating wind turbine designs to sealed motors and pumps inside vertically-oriented cylindrical tubes that conduct seawater onto the forming sea-ice above. These satellite installations would be arrayed in hexagonally-close-packed, concentric rings around each moored wind turbine. The turbine would thus remain in the polynya amongst the three, adjacent installations. Buoyed powerlines would connect each turbine to its satellite installations until they were safely encased in ice. The tubes could be constructed out of non-polluting and eventually biodegradable material, such as spiral-wound plywood bonded with hot-melt lignin. Each tube would mount perhaps three pumps (for redundancy and power incrementation purposes) mounted near its sealed base in order to provide stability, with each pump accessing the ocean through its own horizontal valve. A hollow, toroidal buoy made from ferro-concrete, and secured around the middle of the tube, would provide any additional buoyancy necessary. As an ice lens formed around the tube and buoy they would gradually subside until the tube and surrounding ice jacket reached the sediments beneath and grounded. Above the toroid, helically-located penetrations in each tube, increasing in diameter with altitude, would direct the freezing seawater so that it formed a roughly circular ice lens around the tube. Each projecting tube would need to be tall enough or extendable in order to remain some metres above the final ice level after the ice lens had grounded. As the ice lens grew, more power would be directed to the first pump activated. Eventually other pumps would be cut in, so that at all stages the film of seawater flowing over the conical ice surface remained at near-optimal depth for both flowing and freezing. Unfrozen brine at the perimeter would tend to flow into cracks in the surrounding sea-ice generated by the increasing weight and subsidence of the ice lens. Each successive circumferential crack would eventually be frozen shut. For deeper waters, a perforated extension sleeve could be added to the top of each tube before ice formation reached the top of the existing satellite tube.

In relatively shallow water, one mid-sized floating wind turbine might progressively power the generation of many satellite lenses in a linked ice array. Thereafter, apart from maintenance pumping to replace lost ice, most of its power might be sold to a mainland grid via HVDC lines laid earlier on the ice array and protected with subsequent ice.

Where wide expanses of flat ice array were required without the intrusion of polynyas, the centre of each polynya could be given a vertical ‘sump’ tube, made of similar, spiral-wound, perforated plywood and warmed electrically to keep it open so that brine from the ice forming around the tube could be given passage to the sea, thereby allowing the ice surface to build up and become level. Pumping would thus need to continue longer over the cold season until the surface was level.

## Capability Prospects

Such ice shield arrays have several prospective capabilities. These include their use as: solar reflectors, barriers to warm water intrusion, methane emission suppressors, methane harvesting arrays, thermal bridges, weirs, power plants, dams, shipping channel walls, research, maintenance and production bases, and for polar habitat development and protection. Details of these capabilities appear in Part Two of this document.

*This paper seeks support for the further development of the concept and participation to allow the funding of scientific modeling and validation, followed by pilot and sea trials. The intellectual property is offered free.*

## Proof of Concept

Preliminary tests on the viability of the ice shield concept may be performed at modest cost. A protective capsule and platform, mounted on a triangular assembly of three floating buoys, or fuel tanks on a pallet, might house a diesel-powered pump, pipework, controls and fuel tanks designed to pump seawater through a slowly-rotating nozzle (or the helical arrangement of holes or radial tubes in the central tube previously discussed) to distribute seawater so that it froze over a wide disc of sea ice, once that had formed. Sensors would monitor and relay the build-up of ice into a low iceberg, together with its overall shape and slope. Given planned variations in the design and operation of each pilot pumping facility, results will record for each the angle of inclination of the resulting conical iceberg, its changing volume, its evolving undersea profile, the energy required to produce the berg, and where improvements might be made to the design. The results would also identify some of the problems to be encountered by future wind-turbine powered designs that are designed to generate large ice shields. Such experiments should incur only modest risk, as sea ice has already been thickened many times by means of such pumping, in order to provide sufficiently firm bases for Arctic drilling platforms, see http://pubs.aina.ucalgary.ca/arctic/Arctic33-1-168.pdf. In some such cases, thickening has made the ice platform ~12m thicker. Much greater thickening can be achieved.

## Arctic Strategy

Once the pilot experiments have been analyzed and computer models of its working established, the initial detailed design of the ice shield installation can be developed and its theoretical performance characteristics and effects determined. Thereafter, each of its collective prospective capabilities may in turn be tested, refined, and be provided with an individual cost-benefit analysis. Those designs with good prospects would then become subject to international vetting, staged approval, trialing and implementation.

Although most of the benefits would be public ones, there would be some with profit potential from the sale of power and perhaps other services. However, it seems likely that a respected international body, such as the Arctic Council or UNFCCC, would co-ordinate the program, with corporations and scientific institutes being contracted to do most of the work.

Once the ice shields were grounded and had reached effective height, utility companies might wish to purchase the resulting offshore ice shield wind farms to access the substantial power residual from ice shield maintenance requirements. These power plants would be more reliable than are those from most wind farms because of the reliability and strength of Arctic winds and the stability and economy of their platforms. Pumping to benefit phytoplankton might be used mainly to remove excess power from the grid. Pumps inside especially long tubes that were buoyed vertically in some of the polynyas of each ice array might be used for this purpose, their inlet bases reaching down into the deeper and better-nutriated waters, yet not so close to the sediments that they would shortly become clogged with sediment or crushed. Such pumps might also be of use actively to harvest dissolved methane from the depths at the same time as nutriating the surface waters. Gas companies might then wish to purchase these ‘gas wells’, using cheap local wind power to process, compress and transport by pipeline the gases.

Ice shield arrays might be so designed as to allow for high-voltage direct current (HVDC) transmission lines to be laid economically along completed, nearly level, ice shield highways to landfall. These lines would become encased in protective ice and might each last for several decades. Intentional gaps in the highways could employ undersea HVDC power lines. Where all-season ocean passage was required through an ice shield array, it might be possible to buoy HVDC lines just off their ice walls, so that the unavoidable heat loss from the lines would help prevent sea-ice formation during the ensuing cold seasons.

## Initial Phasing

As a subset of two of the capabilities, emission suppression of methane in the Arctic Ocean, may well be regarded as being both the most urgent and important of capabilities to be developed and deployed. These are the ones that probably should strategically be addressed first. Beneficially, their deployment should inform the feasibility, cost, effects, and effectiveness of several of the other potential capabilities.

There is one location that requires only a modest number of ice shields, set in a very shallow sea, in order to have a substantially beneficial effect upon reducing Arctic methane emissions. This is the Bering Strait which is an average of ~40m deep and is ~110km wide, less the two, small Diomede Islands and gap between them which are located near the centre of the strait. This strait separates Siberia from Alaska and is the only eastern outlet of the Arctic Ocean. Should Earth Systems modeling suggest it to be environmentally desirable, short ice shield ranges in the form of a causeway might be constructed partially to block off the Strait, leaving open only the narrow shipping and wildlife passage between the two Diomede islands at the centre of the Strait.

There are three northerly currents in this strait, the shallower two of which bring relatively warm Alaskan Coastal and Bering Shelf water into the Arctic Ocean. Blocking off these, whilst allowing the deeper, colder Anadyr water in, would cool the Arctic. Ice shield barriers are ideally suited for this task, as they are porous at the bottom yet impervious at shallower depths. Such a barrier would also hinder the high albedo and methane-suppressing ice floes in the Arctic Ocean from flowing out south into the Bering Sea under the influence of strong winds. Hence, this could be a fast and economical way to limit the damage being done by Arctic warming until surer methods can, together with it, prevent this from evolving into global warming catastrophe. The project forms a good test of the ice shield technology, and one from which further improvements might be derived. Some three rows of lenticular ice shields, grounded and frozen together, but with gaps for island and passages, containing a total of 130 ice shields or lenses (for the triple layer) with a conical surface slope of 3-50, and each ~2.3km in diameter, might do the job. Ice shields might be securely grounded in a single cold season in any near-polar water that is less than 85m deep. Each Bering installation could require power from a 2.5MW wind turbine operating at a yearly average of 40% capacity, each with an estimated cost of $1.7m/MW, giving a total cost of around $5m/floating wind turbine. Larger turbines would generate multiple ice shields each.

Assuming a 50 surface slope and a radius of 1.14km for each completed ice shield, this would require some 700 turbines (assuming the satellite option were not chosen that would reduce this number substantially). In 2008, Vestas’ pricing rule of thumb was ~$1.4m/MW for their wind turbines. Thus, for a bulk order of 700 2.5MW installed ice shield turbine installations in 2017, it might be reasonable to suggest a June 2014 US dollar cost of $5m/commissioned installation, or a total capital cost of ~$4.5b after the inclusion of linkages. Operational, financing and overhead costs up to 2020, when all the ice shields might have been completed, plus subsequent HVDC cabling and other works, might bring the cumulative investment to ~$6b before it might conditionally be sold to utility companies. These companies might be interested in both the electricity generation capacity and in the methane that might be captured from the submarine deposits there. As well as by special pumps to liberate deep dissolved methane, this might be done using flexible polymeric covers to capture the fugitive methane rising, or what could be induced to rise perhaps by pressure reduction methods, between ice shields in open spaces called polynyas. Furthermore, collector gas pipelines, laid along the ice shield range, might be advantageous both to Russia and the USA, particularly as this might be key to harvesting and marketing otherwise fugitive methane emissions, and hence to rendering them less destructive. Power from the wind farms could be used to pump the methane to its markets, or to condense it as liquefied natural gas (LNG) for ocean transportation.

The capital cost might be substantially reduced assuming that larger wind turbines would power three satellite installations. As each satellite would generate a grounded ice lens over a single cold season, this porous Bering Barrier might be constructed for as little as $3b, most of which might be recouped from the subsequent conditional sale of the wind farms. And if more than three satellite ice shield installations could be grounded in a single cold season in the particularly shallow waters of the Bering Strait by these larger and probably more efficient wind turbines, then the cost might be reduced still further. In such shallow waters, the floating turbines might even be replaced by possibly cheaper ones mounted on piles hammered into the sediments.

As an additional economic incentive, with the addition of a bridge spanning the narrow shipping passage to be left in the Bering Strait, it should be possible to use the ice shield range, or causeway, as the base for an East-West ice road-rail highway linking the two continents. The first industrial ice shields constructed might be the ones that connect each of the two Diomede islands to its respective continent. The bridge would link the two islands.

With success in the Strait, more ambitious ice shield projects might then follow. Now, the linked Laptev, East Siberian and Chukchi Seas contain some of the ocean seabed and vents that are most at risk of spewing out catastrophic methane emissions. These areas could partially be protected from warming by the North Atlantic Current (NAC) by a double line of ice shields, grounded in the shallow ocean (average depth ~80m), located at the edge of the continental shelf and running from Barrow Point in Alaska to the Taymir Peninsula in Russia, a sinuous distance of some 2,400km. This barrier would protect some 1.8m km2 of shallow, methane-rich sediments and vents. Into this barrier, one might wish to have some narrow shipping and wildlife channels left open. Depending on the depth and softness of the underlying sediments, there would possibly also be undersea gaps between ice shield bases. The depth of these sediments is typically measured in kilometres.

Should this Siberian Barrier to the intrusion of warm water into shallow, methane-clathrate-rich waters prove efficacious, then two other similar Arctic projects should be worthwhile considering. The first of these would be to erect a similar barrier to protect the sediments and sea ice in the Kara and Barents Seas from being warmed too much by the North Atlantic Current. This might be called the Barentsz Barrier. It is a more difficult area in which to form a barrier with ice shields because of its several deep, undersea canyons and because the south of the Barents Sea is typically ice free due to the NAC, or North Atlantic drift of relatively warm salty water, and to warm coastal water. However, modeling should be able to determine whether constructing ice shield ranges to connect (but possibly with gaps over canyons and for shipping and wildlife) the Taymir Peninsula to Novaya Zemlya, to Franz Joseph Land, to Svalbard (plus a short westward arm), to the North coast of Norway would be both feasible and worthwhile. Along this line, waters average approximately 200m deep, with some short stretches up to nearly 500m deep. Ice shields can probably even create an ice barrier at these depths, though the possible requirement for multi-year mooring could make it more difficult. Creating ice shield arrays should itself make neighboring waters more easily glaciated with ice shields.

It may even prove feasible to construct tethered, floating ice shield ranges over the canyons, provided that they could be sufficiently constrained by perhaps giant, looping cables. These ranges over canyons would only need to be made and maintained deep enough to fend off the warmer surface water currents, winds, waves and floes, whilst possibly leaving any deeper, colder currents unimpeded. However, should the growth of each ice shield be enabled to continue for years, there appears to be little reason why most could not eventually become securely grounded. Constructing the section of ice shield barrier to insulate the Kara Sea from the NAC would be the easiest part of the task. Following this, ice shield barrier construction might best proceed from the northeast to the southwest, as each new construction would then tend to make the construction of the next one easier as more warm NAC water is repelled, making ice shield construction thereafter the easier. Moreover, done this way, the ice-free passage from Murmansk to the Atlantic might be preserved.

Similar modeling and calculations might be made regarding the erection of an ice shield range at the edge of the continental shelf between Mackenzie Bay and Prince Patrick Island in Canada. This is typically less than 400m deep. Alternatively, other ice shield ranges might be made linking the islands (whilst missing out on protecting some of the methane-rich sediments) and thereby reducing the number of required ice shield installations. This would hinder the westward flow of water amongst those islands by acting as a partial plug, rather than being the initial barrier itself to NAC water. Such barriers and constrictions may well be sufficient to turn the bulk of warm North Atlantic Current water back into the North Sea, thereby helping to save the Arctic ice, stabilizing the polar vortex, and helping to prevent catastrophic emissions of Arctic methane. Ice shield extensions might even be considered to Ellesmere Island or Greenland.

Development of ice shield arrays behind these barriers, whilst providing channels in the arrays for shipping and wildlife, may then also be considered. The pattern of such arrays might best be one that left some spaces or channels in each array, as this would provide shipping and wildlife access, whilst encouraging sea ice formation and allowing additional ice shield growth, should that be so desired. Unusually deep areas might be avoided, unless it were decided that floating ice shields which moved under wind, wave and current, but were constrained by corralling ice shield ranges, shoals and land, would be desirable additions thereto. Anchoring is probably not a viable option here. Corralled areas might eventually be entirely covered in a single ice shield array that would prevent normal wave action from breaking it up.

Once the remaining open and seasonally frozen parts of the Arctic Ocean had been porously corralled, consideration could be given to whether floating ice shields in open water there might also benefit global climate, wildlife, scientific endeavour, and industry.

One region where it could be advantageous to generate ice shields that might float free during the warm season is in the higher latitudes of the Southern Ocean. This is so for three reasons. First, the strong circumpolar winds that blow there, together with the Southern Antarctic Circumpolar Current (SACC), would both tend to keep the new ice shields/icebergs productively in the Antarctic and from forming navigational hazards elsewhere. Second, there is relatively little seaborne traffic or marine installations there that would be adversely affected. Third, as the area covered by winter Antarctic sea ice is presently expanding, if only for an uncertain number of years, there is a window of opportunity to thicken part of the sea ice there such that it may last for some useful decades before requiring refurbishment. In turn, this would tend to stabilize the ice tongues there, to help cool the world as a result of the increased oceanic albedo, and to delay sea-level rise that would otherwise be caused by the on-going disintegration and melting of the unstable West Antarctic ice cap. However, research should be undertaken to try and have such an increase in sea ice provide net benefit, rather than net harm, to marine species breeding and foraging. Modeling would also need to establish the regions and latitudes where the increase in thickness of ungrounded ice shield ice through pumping seawater onto the ice during the colder seasons would offset or exceed that of its thinning by melting and abrasion during the warmer seasons. Given the protective and nucleating effects of an array of ice shields, it might even be that such a cryogenic area could, for a while at least, increase its extent and/or its seasonal duration by as much as 30% more than was reached in the Antarctic winter of 2010. Furthermore, should deep, pumped Southern Ocean seawater be close to its freezing point, it may be convenient to continue pumping it over or around each roughly circular ice shield, rather than installing separate piping, as this would tend to disperse its nutrients more effectively to surface waters whilst not melting too much of the ice shield. This variant would tend to produce unusually well-nutriated icebergs, to the probable benefit of marine life.

## Cost Benefit Analysis

Taking the Laptev to Alaska barrier as being a representative investment, the principal benefit would be that the methane-clathrates in the shallow sediments behind the barrier would no longer be warmed by the NAC (though they still might be warmed and stratified somewhat by riverine flows and the atmosphere in the warmer seasons ), so that this NAC factor neither caused nor exacerbated catastrophic methane emissions.

Secondary, but possibly substantial, benefits might well result from: increased Arctic albedo leading to global cooling; convective heat removal; some beneficial effect on stabilising the jet stream and polar vortices; excess renewable power generation carried by undersea HVDC lines from ice shield installations to land; stabilisation of some Arctic glaciers; stable and permanent drilling and production platforms; secure access for controlled, submarine methane extraction and piping; additional fish stocks; air strips; research station bases; and reclaimed wildlife habitat.

Modelling would need to determine what effects there might be to or from: partially constraining Arctic riverine water to the corralled area; sea conditions; wind conditions; ice floes and their movement; snow cover; global climatic changes; Arctic and sub-Arctic life, including that of migratory species and vegetation changes; shipping; the NAC and Great Conveyor Belt, particularly assessing where the redirected NAC heat and cold briny currents would thence end up and their effects in those places. Here it should be noted that, whilst warm surface currents would be constrained by the ice shield range barriers, cold or particularly salty deeper water might tend to find its way through the undersea gaps between the ice shields. Thus, the global ocean current driver of dense, Arctic, cold and briny water would tend to be maintained.

# Part Two – Individual Capabilities and Installation Design

### Capability One: Thermal Bridge

What ice shield pumping does, is to create a thermal bridge between the ocean water under the ice and the below- freezing atmosphere. A thermal air convection effect extends the bridge to the upper atmosphere. This is so, because the heat liberated by the freezing of the seawater on each ice shield surface is convected upwards in localised, rising air columns or thermals. These carry the released heat into the upper atmosphere where it is above most insulating greenhouse gases. With therefore little interference, the heat radiates directly into outer space via long wave radiation. In Bonnelle’s phrase, a *thermal shortcut* is formed linking the seawater under the otherwise insulating ice and insulating atmosphere, to the lower stratosphere. The process is akin to the action of a heat pipe, where differential heating and cooling is applied between two zones, either actively by pumping, as in this case, or passively as in the millions of heat pipes, or thermosiphons that de Richter notes are used to keep frozen the permafrost under some Arctic pipelines, roads, railways and other infrastructure.

Each growing ice shield would act as a conical heat island, where the heat released by the freezing water would flow centripetally (centre-seeking) as a ‘warm’ air current up the gently inclined, conical ice shield to produce a cylindrical updraft, or thermal, of relatively warm air from its pinnacle. This might be lofted as high as the tropopause (the boundary between the troposphere and stratosphere), even when strong winds are present. From high in the troposphere there is little insulating greenhouse gas or cloud above the top of the thermal to prevent its contained heat from radiating directly into space, thereby efficiently cooling the world. The heat would tend not to be radiated back to the Earth’s surface because of the reflecting clouds and insulating greenhouse gases below.

### Capability Two: Solar Reflector

Ice shield installations would increase the albedo (solar reflectivity) of the Arctic in three ways. Their brilliant white would reflect much more sunlight than does the dark blue ocean. The light green concentrations of phytoplankton produced in surface waters as a result of the ice shield pumps bringing deep, highly-nutriated water to the surface in summer would have a similar effect. And finally, the extra DMS compound indirectly produced by the extra phytoplankton would serve to increase and brighten marine clouds. Furthermore, because of maintenance pumping, the ice surface would tend to remain a brilliant white, being undulled by black carbon deposits.

### Capability Three: Physical Barrier

In waters up to perhaps 900m deep, though typically much less, the creation of grounded ice shield ranges can act as a physical barrier to the lateral movement of water. As much of the Arctic Ocean is shallow, this means that areas in danger of being heated by warm currents might be virtually sealed off from them. This is particularly the case with warm, less-dense water currents, as these tend to travel near the surface, whilst colder, saltier currents tend to travel at depth. Moreover, because of the way they are constructed and tend to melt more from below, ice shield barriers, both before and after they are grounded, provide greater resistance to surface water lateral movement than they offer to deeper water movement.

The creation of such grounded ice shield ranges might even be able to prevent the collapse of ice shelves and glaciers, such as the Thwaites in Antarctica, thereby stabilizing the Western Antarctic ice sheet and thus preventing the sea level rise of ~4 metres to be caused by such a collapse. A ‘warm’ ocean current is currently undermining and melting the Thwaites ice tongue and shelf, and its intruding water, together with meltwater from the upper surface, is helping to lubricate the base of the glacier itself. However, the water just ‘offshore’ there is only ~600m deep and has transverse ridges to help grounded ice shield ranges provide strong resistance to further glacial collapse. Unmoored, floating and still-growing ice shield arrays might be expected to run aground offshore of the Thwaites and other glaciers, thereby providing the required barriers.

As wave action and swells over 3m high can penetrate up to hundreds of kilometres into an ice pack or sea ice of normal thickness, cracking it up along the wave direction, the barrier to these waves caused by massive ice shield ranges would itself tend to retain sea ice integrity for longer duration each year. It would also prevent the ice breaking up so readily into smaller pieces that melt faster due to their increased surface area and frictional heating.

### Capability Four: Emission Control and Capture

Ice shield range barriers and arrays could be constructed to protect the shallow, methane-rich sediments of the Arctic Ocean from submarine warming and the consequential emission of their methane. In particular, they might be used to suppress Subsea Methane Eruption Centres (torches) where the NAC (Gulf Stream) is causing them to appear in the Laptev and East Siberian Seas.

The ice shield arrays could also be used as cold caps or plugs to regulate and direct the outflows of methane to zones within the arrays where they might be aggregated, or selectively released by reducing the local pressure on methane clathrates by pumping, or released by warming them with pumped-down warmer surface water, then captured, compressed and piped south. There is enough methane in Arctic and other sediments to replace the energy from all high-carbon, coal-fired power plants and high-polluting unconventional oil and gas resources until sustainable sources can, in turn, replace them. In short, the Arctic methane can be used as a low-carbon transition fuel, as well as a temporary source feedstock for food/fodder, chemicals and polymers.

When hexagonally close-packed, and with the direction of their growth controlled once they reached their intended dimensions, there would form open areas at the juncture of any three shields. In polar regions, such openings in the ice cover of the ocean are termed polynyas. In our case, each polynya would typically be in the shape of an equilateral triangle with its sides bowed inwards. Polynyas are vital to much air-breathing polar marine life, including seals, walruses, cetaceans, polar bears and migratory birds. Without special provision, polynyas serving as aggregation points for bubbles of methane ascending vertically from the seabed, or following the sloping underside of a lenticular ice shield, might become death traps. Such can be avoided by the designs by which we harvest the methane. One such set of designs follows.

To collect the methane being emitted from the sediments and vents directly below the polynya, all that might be required is a thin membrane fixed to the ocean floor in the form of a shallow, inverted funnel. For strength and simplicity of construction, the membrane might be made of transparent PET film of circular form, possibly with a weighted, springy rim of brine-filled PET piping and a tube leading to an off-take gas pipe at the surface. Such funneling at depth would tend to restrict metabolisation of the methane on its way up. Furthermore, prior to the three intersecting ice shields reaching their full extent, a triangular boom with hanging skirt would be placed where the polynya was to form. The boom might be made from PET piping, to which was fixed a semi-flexible skirt of the same material. The ice growing from each ice shield would eventually enclose the boom, allowing the methane to collect just outside the skirt. Drillholes made in the ice should allow this gas and that from the funnel to be tapped, compressed, and pumped away by pipeline, leaving the polynya largely methane-free and accessible to drones, divers, birds and marine life. Where methane was only emitted very slowly from the sediments immediately below the polynya, either the funnel alone or the boom and skirt as well might be omitted. Presumably, seals would soon learn not to breathe the collected under-ice methane, just as they now avoid breathing the methane/CO2 bubbles collected under the ice.

Where the provision of polynyas for wildlife is not required, but methane capture is, the simpler strategy of ensuring that each three adjacent ice shields overlaps may be sufficient to create an ice cavern, void or vent from which the gas may be harvested. The covers for these should probably be black or opaque so as not to attract wildlife from underneath. New seawater-forming ice from one or more of each of the three adjacent pumping stations may eventually meet where the shrinking polynya finally disappears, unless care is taken to avoid this. Once sufficient ice forms over a polynya, an inverted tetragonal, subglacial cavern is formed, into which methane bubbling up from clathrates and ocean sediments below can accumulate. Provided there are no cracks in the ice above the cavern (or a membrane is in place), and the ice is thick enough to form a strong barrier, the methane will become pressurized, forcing the ocean surface beneath it to become lower, thereby pressurizing the gas even more. Taps can be made into this cavern to extract the gas, or better, buoyed vertical pipes with elevated valves and gas pressure & flow-rate sensors could be placed in the polynya before it freezes over. Once a strong cavern has been formed, the valve may be closed and harvesting can commence. The caverns so formed may become quite large, thereby performing a useful storage system function between extractions, or when market demand or off-take capacity is low. A single such irregular tetragonal cavern, with horizontal sides each 500m long and a height of 30m, would hold just over a million cubic metres of modestly pressurized gas. However, because of the chance of cracks or holes developing in its icy container, it might be wise to keep such interim storage containers relatively small and at pressures below three atmospheres. The gas-holding capacity per cubic metre of cavern and its underlying water would increase with both pressure increase and reduced temperature. It would suddenly increase much more, once the hydrate-gas phase boundary had been passed in freezing conditions at approximately 17atm pressure (or below ~170m depth) due to the formation of clathrate. Methane clathrate is lighter than water at 0.95gm/cm3.

The renewable power generated by the ice shield wind turbines could be used to capture, compress, process and transport Arctic methane. Should the Arctic winds temporarily fail, then it should be possible to send power from other sources back along the same, or parallel, HVDC lines in order to maintain the flow of gas.

In the early stages of ice shield deployment, some preference might be given to plugging hot spots, rift zones and vents that were then releasing methane, provided that they were in relatively shallow water. However, care would need to be taken that the wind turbine itself, or nearby vessels, did not spark a conflagration. Moreover, fire (probably from lightning or internal sources) is the single greatest risk to wind turbines.

### Capability Five: Weir

An ice shield installation on either side of the mouth of a north-flowing Arctic river, or a string of such structures across the wider estuaries of such rivers, might well be able to freeze together to form a weir designed to hold back some or all of the issuing riverine water. Once the weir had formed, the river flow (even under some of its own ice) could back up and rise in level sufficiently for a portion of its water to cascade over the weir onto the still-frozen sea ice beyond. As fresh water freezes at a higher temperature than does seawater, provided that the flow was not sufficiently strong initially to melt the underlying sea ice, the freezing fresh water would tend to increase the area of thickened ice many times over. Furthermore, the surface of the area-increased fresh water behind the weir might also tend to freeze. This would have the effect of encasing the newly-submerged, low-lying land in a coat of ice, thereby possibly increasing its albedo and tending to lock in most of the otherwise outgassing methane, NOx and CO2 beneath it. Thus, both shallow ocean, littoral, and nearby tundra could be frozen over by such applications. The area frozen over by such river mouth, inter-island (particularly Canadian), or shallow ocean installations might come to cover many thousands of square kilometres.

### Capability Six: Hydroelectric and Diversionary Dams

Tall ice shields might be created in river valleys, thereby providing economical and non-polluting dams in Arctic and sub-Arctic regions from which hydroelectricity might be generated. However, unless the ice dams were thick and frozen onto the permafrost, they might not be as stable as traditional dams. Hence, care would need to be taken regarding the safety of inhabited areas, infrastructure and wildlife in the lower levels downstream. Ensuring that each ice shield froze solidly onto the local permafrost might be as easy as installing passive heat siphons similar to those used to keep Arctic infrastructure frozen. It may be necessary to hold back the flow until sufficient water could flow downstream not to be quickly frozen, thereby shutting off continuous flow. Such dams might be useful in providing power to the grid when Arctic winds failed to deliver enough power to it.

Similar dams might be constructed to help divert a portion of some north-running rivers south, to where their water could be used for irrigation and industry. This would also serve to diminish their undesirable warming and stratification effects on the Arctic seas.

### Capability Seven: Wind Farm Power Plant

As has already been noted, ice shield installations can become major producers of renewable energy, once their shields have become sufficiently well-grounded. Their construction and operation allow them to operate as grounded, off-shore power plants in waters less than about 900m in depth, though they are more readily constructed in shallower waters where a single cold season is enough to ground them. Their ability to be linked together in shield ranges linked to land, and the flatness of their topography, makes laying HVDC power lines on them relatively easy. The lines are then readily protected by pumping seawater over them to encase them in protective ice. Should the power lines generate heat, it may be necessary to support them by transverse strips of tape or polymeric meshes frozen into unmelted ice nearby. Thermosiphons may also be useful here. Access to the power lines and supporting infrastructure by maintenance crews becomes relatively easy by air, land or sea.

Once established, their marketability as icy wind farms, onto which HVDC powerlines and gas pipelines can be laid, should make them an attractive funding option.

### Capability Eight: Shipping Channels

Under current global warming, the Arctic Ocean will develop valuable shipping routes. Even with the increased Arctic glaciation that hopefully results from these ice shield techniques, selected routes may still be able to be maintained ice free for much or all of the year. This should be possible by the careful placement of shipping and wildlife channels between and through ice shield ranges and arrays, possibly aided by residual flows of warm water, emitted HVDC cable heat, periodic ice-breaking, or the pumping of brine from the depths using ice shield wind turbine power.

### Capability Nine: Wildlife Habitat

We are progressively losing polar wildlife habitat because of the retreat of sea ice, on which so many species depend. These species include phytoplankton, krill, penguins, pinnipeds (seals), cetaceans (whales) and polar bears. Reversing global warming by means of increasing global albedo and keeping warm water away from polar regions will help. However, possibly the best way to use ice shields to provide additional habitat for these species is to construct open or closed arrays of grounded ice shields. These might populate the areas enclosed by ice shield ranges constructed for power generation. The open spaces amongst the arrays would provide access for air-breathing marine species. Sea ice and snow would tend to cover the narrower spaces; and the ice shields might provide algae and krill habitat, undersea, sea surface and land transit routes, and convenient rest and feeding areas called polynyas.

### Capability Ten: Access, Research, Maintenance & Production Bases

The grounded and nearly level ice shields would provide stable, long-term platforms for drilling operations, though drilling for fossil fuels should be discouraged. With some grading, the elevated flat surfaces would be useful as ice roads, causeways or aircraft runways. The nearly level plateaus of linked ice shields that reached to the land would provide near-all-weather ‘land’ access for vehicles. Should it be desirable, the ice roads, or even railway lines, might be transformed into covered bridges or ice tunnels whose passages were safe from weather extremes, wind, ocean waves, snowfall and wildlife. This might be done economically by encasing parallel, seawater-filled PET tubes in ice. Inflated transverse PET arches, linking the tubes, would support bulging, inflated and externally-textured PET membranes onto which seawater was sprayed to freeze, thereby forming thick tunnel walls and roof.

Pipelines and power lines could be buried in ice running along the plateaus. Such pipelines might be constructed economically by unrolling flat, PET+glass fibre tubes from tractor-borne reels along the ice roads, inflating them, then spraying them with seawater that freezes, forming a lined ice pipe of almost any wall thickness required, thereby to conduct pressurized and well-insulated LNG over long distances.

Some of the ice shield installations could also be designed to include laboratories, storage facilities, utilities, pumps, power, communications and accommodation.

The ability of the larger wind turbine installations to act as self-powered, all-weather bases and observatories should also prove advantageous. Indeed, the larger ice shield installations having accommodation, that are to be spaced amongst the regular arrays of unstaffed ones, might prove to be ideal platforms for the East Siberian Arctic Shelf (ESAS) observatory network, as well as for other Arctic research studies.

## Proof-of-Concept Experimentation

The small-scale pilot pumping experiments to be conducted would be designed to increase the 8-12m ice-thickenings previously achieved by substantial factors. Each experiment might be performed using a diesel-powered pump, housed and protected on a rigid triangle of hollow, cylindrical or spherical, steel, wood or polymer buoys. After the experiment, each installation would desirably be retrieved, so it might be best if the experiment were to be conducted in a sand-banked inlet or in waters that could otherwise be closed off until each ice hill had melted, thereby freeing the equipment. This could take long. Regrettably, such corralled experiments might do little to test the effects on ice shields of ocean currents and waves. Each experiment would be intended to run until its fuel tank on the buoy assembly was exhausted, thereby reducing the likelihood of pollution. With refueling, each experiment might continue for some years, provided that its inlet and outlet pipes were not blocked.

Parallel experiments at the same general site and time should be able to provide data regarding the optimization of: pump type; pumping rate; pumping velocity; nozzle height above ice, inclination and speed of nozzle rotation; nozzle shape and flow cross-section; development of ice cone inclination; radial and mass growth rate; wind effects; tilt and remediation methods; insulation and de-icing effects; radial ice salinity gradient; submarine, radial and surface profile development; brine and temperature effects; wildlife effects (if any); stressing and cracking phenomena; encrustation and fouling; mooring stresses; equipment performance; and warm current/warm season melting effects, amongst others.

Should greater control be required over the seawater issuing from the tube, then an adjustable lozenge might be located at the exit to produce an umbrella shaped sheet of water flowing down onto the forming ice cone. Both direction and flow rate could be adjusted by moving the lozenge. Alternatively, and assuming that such ice shields would not become unbalanced, helically-arranged apertures in satellite vertical pumping pipes might distribute the seawater radially as is required, but without the expense of active directional control. Pipe subsidence under increasing ice shield mass might then be accommodated with simple upward pipe and power line extensions, the pumps and sealed motors remaining inside, near the inlet base of the slowly submerging pipe. Such satellite pipes might be of biodegradable plywood, spiral wound and adhesively bonded with hot-melt lignin. Each satellite pumping installation would be connected to its wind turbine power source by buoyed or floating power lines. Those installations in outer concentric circles surrounding a wind turbine would be connected by possibly split and extension power lines laid on the ice shields and possibly protected with further ice accumulation. It may be advisable to have the insulating material of each power line linking a wind turbine to its satellite pumping installations strengthened with a high-tensile strength, braided polymer fibre, such as Zylon. Such cable-cum-power lines could be looped and buried in later ice in order to anchor new-forming but still ‘loose’ ice shields and to improve ice array integrity.

Whilst the fierce Arctic winds could be a problem for the even distribution of seawater that freezes over each growing cone, there are mitigating effects. First, as the water is not to be sprayed high, but instead will gush out of the orifices in each tube that are very close to the ice surface, there will be little chance for momentum to be transferred from the wind to the seawater stream. Second, any surface water that were pushed downwind would tend to begin freezing there, thereby decreasing the inclination of the forming ice cone and possibly causing later water to be pushed uphill, thereby offsetting the tendency for it to be pushed preferentially downwind. Third, although strong wind would cause an otherwise nearly perfectly even cone (or lens) of ice to form a distorted cone, similar distortions would tend to occur in all such cones resulting from similar winds. Hence, roughly hexagonal close-packing would still occur to make an integral ice array incorporating polynyas, some of which would have a non-submerging wind turbine floating in them, but that each circular lens would become elongated and its peak would be offset from the centroid. Fourth, should prevailing winds cause each ice shield to tilt because of excess ice accumulation on the downwind side before it froze onto its downwind neighbor (thereby arresting any further tilt), the extension tubes added periodically to compensate for ice shield subsidence could be made curved to offset further tilting by preferentially directing the gushing seawater upwind.

## Mobility

To prevent evolving ice shields from becoming moving navigational hazards, they should perhaps be initially moored or anchored in shallow enough water that just one cold season of nine months would allow enough ice to be accumulated so that the growing ice shield became grounded, or else that it became frozen onto some immovable structure. Should the ice shield be allowed to melt, the facility might become free floating or anchored again, provided that its buoy were still intact.

# Ice Shield Design



Fig. 2 A horizontally-compressed view of an eight month build-up of an ice shield, now grounded on the seabed.

The concept is to use the power generated by a wind turbine mounted upon a special buoy to pump seawater onto sea ice, possibly from satellite installations. As it flows away from the pumping tube, ice forms leaving the remaining flowing water saltier. Gradually, a gently sloping cone of ice forms around the tube and a lens of ice grows below it. The increasing weight of the ice lens presses it deeper into the water. Some of the remaining brine from the flow runs through developing cracks in the sea ice, back into the depths of the sea where it helps drive critically useful ocean currents. The rest will tend to freeze, as it is no longer insulated from the freezing temperatures above the ice. The leading edges of the growing ice shield will tend to melt somewhat faster than the rest, being exposed to warmer and shallower water. These factors result in the generation of a thick ice shield that wraps around the pumping tube. Melting will cause the toroidal buoy on each tube support to be fully exposed at some distance beneath the shield. Each ice shield may grow to be as thick as a kilometre, only ten percent of which is above sea level. Ice shields become securely grounded once their lower portions are pressed firmly against the sea floor by the weight of ice above sea level.

Once completed, and except for maintenance pumping, most of the generated power from ice shield installations can be applied to other purposes. Frozen together to form nearly-level expanses, ice shield arrays or ranges can become sustainable, semi-permanent polar highways for vehicles, powerlines, pipelines and wildlife. Ice formation from maintenance pumping in colder seasons, when the sea ice has reformed, replaces any ice lost through melting, calving and abrasion.

Arctic conditions are particularly harsh, but are not that different from those experienced by existing North Sea wind turbines in winter. However, unmanned ice-shield wind-turbine installations in the Arctic are individually possibly less mission-critical than are those in the North Sea and they may not have the complication of marine power line maintenance to the shore. Hence, most of the maintenance and repair of installations used to generate ice shields, albedo, thermals and biomass can probably be left to the summertime. However, given the corrosiveness of brine, together with the effects of extreme cold, marine organisms and ice, pumping elements in contact with the brine may need to be made of highly resistant materials, such as titanium, ceramics, polymers and/or carbon fibre. Inlet pipes might not need to be so resistantly structured, as these would be able to be replaced periodically. Both remote and artificial intelligence (AI) control of the ice shield infrastructure should be possible.

Wind turbines come in many capabilities, sizes and heights. The largest current ones deliver 8MW of power and have blades that, at their lowest sweep, are still 45m off the ground. It is surmised that only relatively modest capacity wind turbines of approximately 2.5MW power output will be required for most ice shield purposes, provided that their initial supporting column could be perhaps 160m or more above the ~30m diameter, supporting toroidal buoy. Alternatively, a shorter column could be designed to be extendable by the insertion of additional segments (each operation being only performed in a warm season) or by telescoping using internal jacks. In either case, for extra column strength, cable guys would secure the upper part of the turbine support column to projections extending from the outer rim of the hollow, reinforced concrete (ferro-concrete) toroidal buoy, in a way similar to some tall radio masts. With a supporting column this tall, and with each turbine blade being perhaps 50m long, allowing 10m clearance leaves 100m of column that can be allowed to become ice-encased before any extension is required, if it is at all. Without extension, such a configuration could ground itself securely in water up to 100m deep. With extensions, it might be grounded in water up to 900m deep, particularly if it did not require anchoring or mooring whilst it grew. Whilst not impossible, the creation of ice shields much taller than a kilometre are marginally less feasible due to the pump having to lift water over 100m above sea level. Note, for floating turbines that use satellite pumping tubes, no provision for semi-submersibility is required, as each of these would remain floating on the seawater surface of its generated polynya, secured from wave and unlimited lateral movement by the surrounding ice shield array. Spring-loaded mooring lines secured to the three neighboring ice shields could be used to keep each floating wind turbine in the centre of its polynya before the securing sea ice melts in summer.

The maximum rate at which water freezes whilst flowing over an ice shield surface at an optimal depth and velocity during a single, nine month cold season may help determine the maximum depth in which ice shields can use integral sea ice as their temporary securing medium. Thus, the colder the location, the deeper is the grounding possible in one cold season. However, thicker and larger ice shields could be constructed where other anchoring, mooring, attaching, directing or corralling means can be used. Should twenty centimetres depth per day (or less than a centimetre per hour if the water is properly distributed over its cone) over nine months be the effective maximum freezing rate at a given location, then (ignoring undersea melting) 54m is the height of the ice shield generated, and ~50m the water depth in which grounding will occur that year. Forty centimetres per day, or else two years growth, would allow ~104m deep grounding. Ready ways to increase this depth might include: spraying the water high into the cold air so that it cooled faster (undesirable as it makes weaker ice and takes more energy); using fresher water from the sea surface that freezes at a higher temperature; using a strong undersea support column; using floating piles frozen into the sea ice or driven into the sediments to increase the effective grounding thickness of the ice shield; or tethering a floating ice shield to one that had already grounded, or having it freeze onto land.

For reasons of economy, perhaps only two standard sizes of pumping facility might be considered, the larger version being designed to permit location in deeper water, or for use as storage, workshops, laboratories and accommodation. Both sizes could be used for stable drilling platforms, gas collection, and as landing strips, habitat and highways. Note, building bases in the satellite facilities would avoid the discomfort of turbine noise and vibration, though pumping would still generate some, if much less.

Now, a 2.5MW wind turbine is capable of producing enough power for a 60% efficient pump, to pump seawater some ten metres above sea level at the rate of six cubic metres per second, when at full capacity. However, as winds are inconstant and there will be power losses elsewhere, an average 1MW pumping delivery is used here in the calculations. In nine months this 1MW would generate an ice shield of volume of 0.14km3, less any undersea and subsequent warm season loss. Call it 0.12km3 per year to allow for residual brine loss, snow & ice accumulation and melting. Provided the water could be frozen fast enough, such a rate might enable a single ice shield to ground itself in water that was less than ~85m deep before the encasing sea ice melted, thereby threatening the mooring system. This might translate to three satellite ice shields being grounded in water that is <65m deep. Subsequent years of ice accumulation would tend to secure the ice shield even more firmly. However, as the ice shield grew above the size it would reach in the first year, its volumetric growth rate would decline progressively because the seawater might need to be lifted progressively higher than seven metres. Note, for satellite operations the average height above sea level to which the seawater would need to be lifted might be as low as ~5m to create a 70m thick ice shield, though early pumping would require much less than this height. If warm season pumping for algal nutriation purposes was not required, the system might be shut down or else used to generate power for other purposes.

Installations located in greater depths of water might take several years before they grew thick enough to become grounded. They would thus tend to require interim mooring or corralling by other means. This might be by freezing them onto nearby land or previously grounded ice shields, or else situating them such that the prevailing currents and winds would force them against restraining obstacles. They might also be corralled in deeper waters by ice shield construction in surrounding shallower waters. Should each ice shield installation be roughly circular, the open spaces within an array of them could be useful to wildlife, navigation, and possibly to methane capture.

Purpose-designed vessels may be needed to fit the components of the installation together on-site at sea. This is because installations are likely to be too unwieldy and unstable to tow there in assembled form. Whilst one such vessel might tow a string of ferro-concrete buoys to the general area, the other installation components will be more easily transported as deck cargo or in-hold. The stern of the vessel would have a dock into which a single buoy could be secured, with one or more cranes alongside to manipulate the components for assembly. The order of attachment to the buoy would be: anchors; lower support column (lower part of which could be a cable) and wings; pump and piping; upper support column and guy lines; nozzle assembly; nacelle, generator, gearing and equipment; sensors, controls and communications; and lastly, turbine blades. Excepting possibly the anchor laying and mooring of each toroidal buoy, these functions would not be easily performed in either rough seas or high winds.

The superstructure of each installation is to be supported on a hollow, reinforced concrete buoy, shaped something like a doughnut, lifebuoy or toroid. This toroid is designed to encase the top of a downward and stabilizing extension to the turbine’s supporting column. Weights and projecting wings at the base of this extension help stabilize the buoy before it is thoroughly encased in thick enough ice. Each buoy is designed to resist being crushed by ordinary sea ice. Each might be constructed economically on a submersible mold that is floating in a dock. The dock or harbourside facility may house many such molds, so that mass production, or even fully automated techniques, can be used. Note, for satellite installations, turbine construction would be much simpler, possibly using existing floating designs except for replacing the floats with the toroidal buoys for both turbine and satellite pumping tubes structures.

The mold for each buoy is shaped like the lower third of a toroid, but with an even-diameter inner neck to accommodate and secure the lower and upper support columns. Above the mold is suspended an inflated, afterwards spirally-wound reinforcement, polymeric, toroidal-shaped bladder that is held in place by straps and wires attached to a surrounding, toroidal mesh of steel reinforcing bars, each of which may typically be pre-formed into circle. The bladder acts as an integrated mold and is not removed. Its outer layer may be textured on the outside to increase wet concrete adhesion. Fibres in the concrete help it resist cracking. The steel mesh skeleton and bladder of the forming buoy is then lowered onto a bed of fresh, liquid concrete lying in the mold. This is vibrated to remove air pockets. In a process called shotcreting, concrete is then sprayed onto the pressurized bladder and steel skeleton until the buoy shape and the desired wall thicknesses in each part are complete. The pressurized in-situ bladder helps prevent subsequent water intrusion. When the setting concrete of the buoy is steam cured from inside out and the resulting condensed water is removed if found necessary, the semi-submersible mold is detached from the buoy by sinking or raising it by crane. This may be done in order to allow painting or other forms of surface treatment, should they be thought necessary.

On-location, four pre-laid, spring-loaded, drag-embedded anchors laid at right angles would initially anchor each buoy. Any such anchoring system could only be expected to restrain a buoy that was not encased in massive free-floating ice. This is so because once even a modest ice hill had formed, the tension placed on the anchoring system due to wind, wave and current would tend to break it loose, unless the ice structure itself were already grounded or otherwise attached. An ungrounded ice shield not encased in sea ice, and that was itself not attached to the land or immovable ice, would tend to be a hazard like unto an iceberg and to move until beached or breached.

A stabilizing weight with locking wings is then attached at the end of the lower supporting column and the whole is then lowered through the toroid’s hole. The top of the now mainly-submerged column is then attached to the buoy, possibly with the use of padding or bushes. Holes near the top of this column admit one or more, wide-diameter, flexible, corrugated or otherwise-strengthened PET pipes, that are coated internally with copper or other encrustation inhibitor, of different lengths, that are each designed to conduct seawater from a selected depth to the submersible pump inside the column. The holes or slots for these pipes are designed to allow the pipes to be drawn smoothly through them when the pump is raised, thereby keeping their inlets at roughly the same depth. Each pipe was earlier sealed and is now filled with sterilizing agent and seawater to keep it submerged until it is required, in order to prevent internal marine encrustation from clogging it. The longer, lower part of this submerged column is designed to snap off below the slots when its base encounters the seabed. A self-priming, submersible pump is then installed to sit on a float inside the support column. Cables attached to it, allow it to be raised and reconnected to the outlet and variable nozzle whenever the progressive submersion of the installation, or other reason, requires it. The turbine support column, nacelle, turbine system and gearing, and turbine blades may then be progressively attached. Note, many of the elements here are not required for the simpler satellite systems. These require little more than mooring, pumping tube, buoy, pumps, motors, sensors, AI and connections.

In case all these lower pipes are destroyed or clogged, inflatable tunnel conduits for replacement piping might be run from higher hatches in the support column when the ice reaches near to the base of each hatch. These would be run along the then top surface of the ice shield to the sea. In case of early puncture, the tunnels would also have inflatable ring reinforcements along their length. Such tunnels would soon become encased in insulating and strengthening ice. They may have external protrusions to anchor their thin, flexible walls deeply into the ice. For the sake of economy, these backup systems are in the form of inflatable tunnels that could be unrolled by hand from a reel on the upper surface of the growing ice shield. These tunnels might also find use as access routes from the sea. Ladders would be needed for the vertical section as each tunnel would lead via a J-bend to the sea. If it were decided to make use of a given tunnel, lightweight, possibly insulated, polymeric pipe sections might be assembled inside it, possibly on pads. When required, the far end of the tunnel would be punctured by a sharp end on the piping being emplaced. The existing submersible pump (perhaps an eccentric disc type of pump that is both efficient and provides its own air suction for priming purposes) located in the column would then be connected to the piping, possibly by flexible or jointed fittings. Similar changes might also be made, should a pipe become sufficiently blocked by marine encrustation, biomass, sediment or crushing. If the backup hatches and tunnels were located at 1200 angles around and up the support column, one or more would remain unblocked as the ice shield finally grounded and possibly tilted. If the later pipe fittings were flexible, or flexibly-jointed, it would not matter much if the pumped water were warm enough eventually to melt some of the ice surrounding each tunnel. Upward pipe extensions would also need to be made whenever telescoping or section extension was performed. Telescoping might reasonably safely and economically be put into effect by internal jacking. Note, for non-submersing turbine assemblies and submerging satellite installations, most of the foregoing in this paragraph can be omitted.

### Base Construction

Some of the satellite ice shield installations might be increased in size and customised to include year round accommodation and facilities. If so, the pumping tube might be annular in cross-section surrounding a lift. Shelter, workshop and storage space might be provided by means of inflating a flexible, toroidal-shaped dome over an insulated annular platform placed on the ice that encases the supporting column of the wind turbine. Later on, a solid dome of ice might be formed over this inflated dome by spraying seawater over it. Such an installation could become like Norway’s Svalbard facility for seed preservation or Sweden’s IceHotel. The space inside the dome would then be accessed via short corridors leading to hatches or doors in the column. Successively higher, linked habitats could be constructed as the ice shield grew upwards from its top surface. When the planned full height was reached, a final habitat level might be constructed with direct access to the nearly-flat surface of the ice cone and triple-glazed windows to the outside. This topmost habitat could easily be over 30m in diameter just by using inflated and triple-insulated roofing material. Linked and similar radiating domes at the end of short corridors might be used for diverse purposes. Utility services for them would be provided via the support column. Spare power from the wind turbines might even permit hydroponic horticulture and waste recycling to occur there. Each completed ice shield would be able to include landing strips in different directions. Power storage systems would ensure that air-conditioning, communications and other vital services did not fail when the winds did.

##  Ice Shield Creation and Characteristics

The main constraints on the eventual mass of the ice shield are two: the height above sea level to which the seawater can economically be pumped; and the depth of water in which it is to be located. Also of relevance is the distance and gradient down which the pump’s flow of seawater would flow as less salty water from it froze out, leaving the increasingly cold and briny residuum to flow somewhat further. Regarding this, once the forming ice shield has reached its maximum extent, during maintenance pumping, it may be desirable to allow some brine to run off the edge of the ice shield into the sea, in order to allow faster and longer lasting freezing atop and to provide modest help to maintain global thermohaline circulation (THC) which keeps Western Europe unusually and desirably warm for its latitude.

The mass of each ice shield would be typically composed mainly of nutriated seawater, depleted of some of its salts by the freezing process, salt accretions, snow, and marine organisms drawn from the middle depths. As this mass partly melted (probably mainly from below) in warm times or by non-freezing waters, nutrients from it should help generate Arctic biomass, possibly far more than did the original, nutrient-depleted brackish pack ice and freshwater snow. Furthermore, in warm times and when the power was not required for other purposes, pumping energy might be used to bring nutriated water to the sea surface for fine dissemination and consequent uptake of its nutrients by phytoplankton, thereby increasing both Arctic biomass and ocean albedo.

The shape of each ice shield would tend to be that of a lens, convex on both sides. A thick ice shield, with much of its mass above sea level, might be expected to last several decades, perhaps even longer, after decommissioning – unless it were refurbished or replaced, whereupon its life could be indefinitely prolonged. Of course, in summertime the outer edges of each ice shield array could be expected to melt and break off under the influence of storms, abrasion and warm currents. However, under maintenance pumping, these edges would be reformed and possibly extended outwards the following winter, or else frozen onto neighboring arrays or land.

It is surmised that, with good management, the angle of slope on the surface of the cone might be able to be kept to as low as 3-50 or perhaps even lower. Directing the flow of pumped seawater outwards should be able to prevent ice build-up that is too much above the rest of the nearby ice shield surface. Furthermore, by varying the transverse cross-sectional shape and size of the nozzle opening (or umbrella-like flow), more or less surface area of water might be exposed to cold air, thereby making the water flow either further or less far down the slope before it froze, as was desired. Similarly, might the nozzle be so directed as to keep the ice cone level in the water by preferentially building up the ice in one direction or at a selected radial distance. Either artificial intelligence or remote control may be required to perform these tasks cost-effectively. Note, helically-placed outlet holes of increasing diameter upwards in the pumping tube might simply replace any need for active shaping and directing of the water outflows.

After being towed into place and anchored, operators would wait for a sufficiently thick sheet of sea ice to form around the buoy. When this was thick enough, possibly re-directable nozzles (helical holes or umbrella flow) would send streams of pumped seawater radially outwards in one or more directions, typically as single streams or as jets flattened to increase their exposure to the freezing atmosphere. Each jet would be so variably shaped, sped and directed as to form an increasingly high, but low-angled lens of frozen seawater, with a central conical top, that progressively encased more of the reinforced supporting column of the wind turbine. As this lens-shaped ice shield grew, its base would slowly submerge as its mass increased, keeping only around ten percent of the forming ice shield above water. As the weight and perimeter of the ice shield increased, the sea ice around it would both bend and crack. The cracks would tend to let any brine that had reached the perimeter flow through them. Soon however, these cracks would tend to freeze shut again, letting the seawater/brine flow ever further outwards. Eventually, the base of the ice shield would tend to ground upon the ocean bed, making its own, possibly deep, impression in the possibly very deep sediments. Any rock strata in the vicinity would tend to anchor it even more firmly than did its weight in its sedimentary depression. Care would need to be taken that such new stresses did not set off submarine ‘landslides’ and tsunami.

Although the column supporting the turbine above the toroidal buoy may initially be built tall (perhaps 160m), should this not be tall enough for its particular locational purpose, then it might be extended upwards almost indefinitely, either by the insertion of sections, or by telescoping the column upwards by means of internal jacks, as has been previously explained. Once the ice shield had grounded, if its pinnacle were then built-up 100m above sea level, then the ice shield could be 2-3km or more in diameter, the diameter depending in part upon how far seawater could flow down the sloping conical ice surface of the ice shield before it froze. The closer in temperature the air is to the freezing point of the seawater, the further the water would tend to flow over the ice shield surface. Hence, in the Arctic spring and autumn the diameter might well be extended to more than 3km. Note, satellite operations would not require vertical extension of the turbine support, only possibly those of the pumping tubes. However, the lower sweep of the blades should be made high enough not to be sheltered from wind by the formation of surrounding ice shields.

## Ice Shield Placement

The placement of such installations would not necessarily be restricted to the extensive shallow waters inside and just outside the Arctic Ocean. Provided that a new installation had its forming ice shield frozen solid onto that of an existing one or land, thereby mooring it before the warmer season began, there seems to be no reason why arrays of such installations might not extend progressively further offshore and into sub-polar regions. They might even be linked by a series of massive cables with loops frozen into the ice of each to provide solid anchor points. Where grounding is impractical, one wind turbine might be made to form and maintain concentric rings of ice shields. These freeze-linked satellite ice shields would not require the expensive support structures of wind turbines, but could be little more than insulated vertical pipes frozen into the ice. Many such installations might be made to freeze together, and onto grounded ice or land, when nestled together by wind or current.

Thus, there seems to be no physical reason why these human-made ice sheets, shields and arrays might not cover most of the Arctic Ocean, leaving only selected passages and open areas clear for wildlife, shipping and other activities. The total area north of the Arctic Circle that appears to be suitable for such ‘glaciation’ is well in excess of 4M km2. Antarctica, Greenland, Russia, Norway, Chile, Argentina and Alaska and some other polar and sub-polar regions also have some suitable sites for ice shield construction. Colder areas enclosed in chains of islands, such as the Bering Sea (Aleutian Islands), the Sea of Okhotsk (Kuril Islands) and Hudson Bay might also be so ‘glaciated’ with an acceptably low chance of iceberg escape, given our need for global cooling.

## Conclusion

Should constructively-critical expert review, followed by preliminary Earth Systems and engineering modelling, confirm that some of the capabilities of ice shields claimed here may be valuable tools in the fight to save the polar regions and the planet, or may otherwise be wise investments, then responsible agencies will not hesitate to provide early and sufficient funding to develop and deploy them.