Solar ponds on Mars: ideal habitats for Earth life

Colin Bruce Jack ColinBJ@gmail.com

Abstract

There is a cheap, simple way to create habitable zones on Mars: the solar pond. At a few metres depth in such a pond, the pressure and temperature are benign for Earth-evolved life, with ample sunlight but negligible hard radiation. To create and sustain the pond, lightweight mirrors of silvered plastic film similar to solar sail fabric are mounted on inclining masts, positioned by day to divert additional sunlight into the pond, by night horizontal above its surface to minimize thermal energy escape. A submersible at the pond's warmest depth emits jets of water to melt any opaque surface ice that forms. A surface film of oil suppresses evaporation and absorbs UV. Tents of transparent bubble-wrap-style plastic, filled with breathable air like diving bells and anchored to the pond floor, provide pleasant sunlit living space. Crops can be grown both inside and outside the tents. Only the mirrors are exposed to the harsh conditions of the Martian surface: everything else is in a protected, quasi-terrestrial environment.

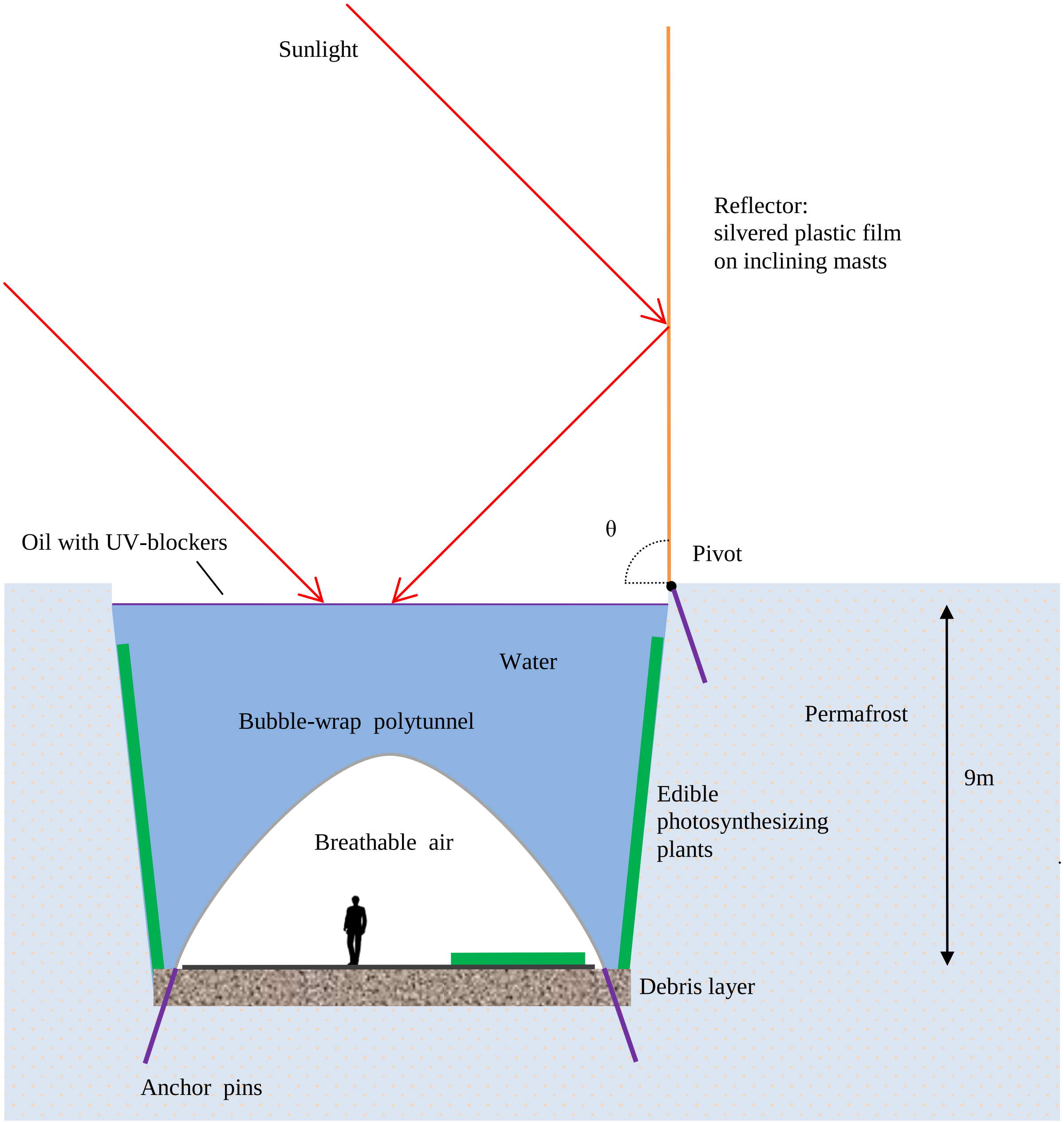

Figure 1 **Minimum size habitat-containing canal in cross-section**

A Martian solar pond is superficially similar to a terrestrial one. However the usual purpose of a terrestrial solar pond is to provide high temperature in its depths, with convection suppressed by a salinity gradient. The purpose of a Martian pond is to provide pressure, radiation shielding and thermal inertia, with a relatively small temperature gradient. A pond containing freshwater with temperature increasing from 0°C at the surface to 4°C at the base is stable against convection. Forced circulation melts any opaque surface ice which forms.

This paper describes ways to create and sustain such ponds using minimal material brought from Earth: a few tens of grams per square metre, reflecting foil mounted on inclining masts, which can be deployed by unmanned vehicles. Low-lying areas of Mars where the atmospheric pressure is high enough for such ponds to be easily created extend over millions of square kilometres, including Hellas Planitia in the southern hemisphere and shallower planitias of collectively much larger area in the northern.

If plastics, oils and UV-absorbing organic chemicals are made on site from the carbon, hydrogen, oxygen and nitrogen available from the Martian atmosphere and pondwater, habitats within the ponds ready for human occupation, as shown in Figure 1, can be created without additional resources, possibly by robots before the first humans arrive.

The useful services provided by the pond to the habitat are:

- No part of the habitat is exposed to the harsh conditions of the Martian surface: even the outer-facing surfaces of the habitat walls are in a quasi-terrestrial environment.
- External pressure which cannot suddenly reduce. Even in the event of a major structural failure, the weight of the pondwater is still present, and the habitat will take time to flood due to the high viscosity of water, permitting escape using small aqualung-type respirators. No equivalent of vacuum blowout is possible.

- Excellent shielding against hard radiation: minimum 380 g/cm^2 of water of which 42 g/cm^2 is hydrogen, yet permitting sunlight to enter from all directions and unobstructed lines of sight to sky and external vegetation.

- Thermal inertia: water temperature varies <<1°C over the diurnal cycle.

- External but readily accessible gardens of edible photosynthesizing plants.

Martian surface atmospheric pressure averages close to the triple point of water, 6.1 millibars. However there is considerable variation with topography and season. A large deep basin where the pressure is double this value, amply sufficient for liquid water, is Hellas Planitia in the southern hemisphere. Data from the Mars Reconnaissance Orbiter's SHARAD radar indicate Hellas Planitia may contain up to 28,000 km^3 water ice in its eastern lobate debris areas, including occurrences of nearly pure ice beneath a thin layer of surface debris***(1)***.

To create a pond of liquid water, the temperature must be raised from its natural value. Solar flux averages 587 W/m^2 at Mars orbital distance: allowing for the ratio of a sphere's surface area to its cross-section $4\pi r^2/\pi r^2$, this equates to 147 W/m^2 Mars top-of-atmosphere (TOA), essentially all of which energy reaches the surface, although only about half does so directly even in low-dust conditions: the remainder is scattered, or absorbed than reradiated in the far IR, by atmospheric dust***(2)***. This corresponds to black body radiation from a surface at - 47^0C. Water at 0^0C emits as a fair approximation to a black body***(3)*** so radiates about double the mean insolation, ~300 W/m^2.

A mirror of lightweight reflecting material similar to solar sail fabric, mounted on inclining masts, can raise the surface temperature in two ways. By day it reflects additional sunlight into the pond. By night, inclined to a horizontal position just above the pond's surface as a cover, it returns almost all IR emitted back into the pond. Surface ice can thus be melted, and liquid water sustained, using a structure massing only a few tens of grams per square metre of pond surface. Note that wind force on Mars is negligible, as wind speeds are comparable to Earth's, while atmospheric density is ~2% of Earth's even at the lowest elevations.

A preferred shape for the pond is a trench running in the east-west direction: it is irresistible to call this a Martian canal. A habitat-containing canal is sketched in cross-section in Figure 1. The canal and the polytunnel habitat within it can extend for any length desired in the east-west direction. The polytunnel containing breathable air is made from transparent bubble-wrap plastic reinforced with load-bearing webbing which also acts as rip-stop. The shape adopted by the bubble-wrap is neither a parabola nor a catenary, but has curvature at a given point proportional to the height above the floor. The floor of the habitat, at which point the internal air pressure is equal to the external water pressure as in a diving bell, is at depth 9m. Mars surface gravity is 3.7 m/s^2 and Martian atmospheric pressure at the Hellas floor is 0.01 bar, so if the pond contains freshwater the air pressure inside the habitat will be 0.34 bar. Air at this pressure with 70–75% oxygen content has been successfully used for long duration spaceflights including Skylab in the 1970s***(4)***: an effect of the low pressure is that sound including the human voice attenuates more rapidly, potentially beneficial when people are living in a confined space.

The initial surface debris layer, plus any debris frozen within the ice, ends up at the base of the pond as shown. Provided the layer thickness is small compared to the canal depth, its presence has little effect on the melting process. Note that it is much easier to allow debris to settle naturally in this way as soil and ice are heated than to attempt to remove surface debris or drill through debris-containing permafrost.

The illustration shows a canal of width 14m containing a habitat of floor width 10.5m and central height 5.2m, at local noon with solar elevation 45°. For example this could be a point within Hellas, Arcadia or Utopia Planitiae around the spring or autumn equinox. The optimal mirror inclination is then 90°, and if all TOA radiation penetrated direct to the surface a perfect mirror would double the energy striking the pond surface. In practice the fraction of insolation which reaches the surface directly, the only part which can be directionally reflected by the mirror, varies considerably with the dustiness of the atmosphere. Optical opacity of the atmosphere τ ranges from 0.3 in clear to 1.0 in moderately dusty local conditions***(2,5)***. Direct sunlight as a fraction of TOA varies correspondingly, from 0.68 x 0.91 = 0.62 x TOA with τ = 0.3 to 0.76*0.32 = 0.24 x TOA with τ = 1 ***(2, see esp. p9 bottom left)***. The aluminized fabric reflects ~90% of this, so a flat mirror of height equal to the canal width as in Figure 1 multiplies the energy striking the pond surface by ~1.56 when τ = 0.3.

The mirror inclination does not need to vary during the day: as the sun makes its east-west transit both direct and mirror-reflected insolation increase until noon, then decrease until sunset. The noontime solar elevation angle α varies with the seasons: when it is above or below 45° by an amount $\Delta\alpha$, the mirror inclination is altered by $\Delta\theta = (2/3)\Delta\alpha$ on that day. The geometry tends to increase the ratio of reflected to direct insolation at the pond surface for α below 45°, and decrease it for α above 45°, with atmospheric dust effects countering this variation.

A slightly concave cylindrical mirror of greater height can give a greater solar concentration factor if required: the concavity can be adjusted by reeling in guy wires attached to the top of slightly flexible masts, for example to compensate for atmospheric dust conditions. For example if the height of this mirror is 2.5x greater than the width of the pond then the energy multiplication factor of 1.56 can be maintained down to $\tau = 1$.

At night the inclination is reduced to 0° and the aluminized fabric hangs horizontal just above the pond surface, returning 95% of radiated heat, so reducing radiative escape to 16 W/m^2. In fact it will be optimal to keep the mirror in this ‘horizontal cover’ position for about 2/3 of total hours in the year: near dawn and sunset, areal insolation reduces, moreover at shallow incidence angle an increased proportion of light is reflected from the pond’s surface without entering it, and in summer the sun rises and sets from positions actually behind the mirror.

Over all hours in the year, radiant energy escape from the pond’s surface averages ~120 W/m^2, radiant energy capture ~200 W/m^2. Energy loss by conduction and convection is negligible from the pond surface, due the small volumetric heat capacity of the Martian atmosphere. The thermal conductivity of ice is ~2 W/m.K, so a gradient of 10°C/m produces a loss of 20 W/m^2 through the pond floor and sides, equivalent to 50 W/m^2 surface area. There is a comfortable energy surplus margin of 30 W/m^2 surface area with the pond surface at 0°C.

Smaller effects omitted from the above calculation include that when $\theta < 90°$, the mirror reflects some emitted thermal energy back onto the pond surface while also capturing sunlight during the day. A small percentage of direct and mirror-reflected sunlight which strikes the pond’s surface is reflected rather than entering the pond; however the pond also radiates less effectively than a true black body.

Energy capture decreases in extreme dusty-atmosphere conditions, when $\tau > 1$. However even a major dust storm, which reduces unscattered insolation to virtually zero for a period of a month or longer, is survivable. The mirror is lowered to its horizontal position to reduce surface heat escape to 16 W/m^2, total heat loss including conduction through the surrounding ice to ~66

W/m^2 pond surface area. The enthalpy of the water-ice transition is 333 J/g, so this generates ice cover at initial rate ~2 cm/sol, decreasing as the thickening ice layer provides insulation: even after an intense month-long storm, ice thickness will be ~50 cm. In their lowered position, the top ends of the masts can be clamped at the far side of the pond, improving the structure's ability to survive high winds. Resuming operation at the end of the storm, a scattering of sunlight-absorbing dust will have been deposited atop the surface ice, so normal mirror operation can melt the ice in a time roughly equal to the duration of the storm.

Evaporation is minimized, and UV wavelengths potentially damaging to humans, plants and plastics prevented from entering the pond, by a surface film of transparent oil containing UV-absorbing chemicals. As an indication of the areal mass needed, the Sun Protection Factor (SPF) of lotion for use on human skin is defined as the inverse of the fraction of damaging UV which passes through a $20g/m^2$ layer of lotion, e.g. 2% for SPF 50***(6)***.

Whereas the usual function of a terrestrial solar pond is to provide elevated temperature at depth, the water around the habitat should be cool so that despite the good insulating properties of bubble-wrap and plentiful insolation, it does not overheat. Indeed it may be necessary to provide heat exchangers within the habitat through which cold water from the exterior can be circulated. Freshwater has a density maximum at 4°C, so a temperature gradient from 0°C at the surface to 4°C at the bottom of a pond is nominally stable against convection. In fact the density of water varies only 0.03% over the range 0-10°C, so natural convection is minimal in this range. To prevent surface freezing during the day, and melt any opaque ice which has formed overnight, warmer water is forcibly circulated from the depths of the pond: a few watts of pumping work can provide megawatts of heat to the surface. This can be done using a small solar-powered submersible stationed in the depths of the pond, which emits a directed jet of the relatively warm water surrounding it both to melt surface ice when needed and to tailor the shape of the pond.

To melt out a canal from the initial permafrost requires 100 J/g to raise the ice temperature from -50° to 0°C and a further 333 J/g to melt it, 50 GJ/m canal length. At net energy capture 30 W/m^2 canal surface, 420 W/m canal length, this would take two Mars years in the setup of Figure 1. However as soon as a significant length of mirrors have been deployed and a shallow surface layer of meltwater produced, warm water can be pumped along the canal length, initially to quickly create a full depth pond in the central portion, later to extend the canal ends at a rapid rate, doubling its length every Mars year as new mirrors are added.

Surface debris and debris embedded within the ice will add little to the heat energy needed, especially for the first ponds which can be placed in optimal locations with the purest ice and thinnest debris cover. As the canal grows, a directed jet of water from the submersible tailors its exact shape. The submersible is assisted by a surface vessel equipped with a high pressure pump, which removes contaminants including unwanted salts by pumping water through osmotic membranes, squirting the unwanted portion beyond the pond edge to freeze to the ground.

(As an alternative to lowering the mirror to minimize thermal energy escape from the pond surface at night, a possible alternative is to create a layer of artificial snow by injecting water droplets or steam into the cold Martian air. Due to the low pressure, as compared to a terrestrial atmosphere this requires ~1% of the work and the mean free path of gas molecules present is ~100x longer: if the gaps between the snow grains are smaller than this, a significantly better thermal insulator than terrestrial snow will result. A fixed mirror could then be used.)

Anchorage points are created at the base of the pond by inserting perforated tubes a few tens of centimetres into the ice. This can be done with almost no physical force by pumping warm water through the tubes to melt out the immediately surrounding ice as they are sunk. After emplacement, their roughened sides grip the ice and can withstand substantial vertical pull: the tensile and shear strength of natural ice increases to several MPa at low temperature***(7)***. Strong anchorage points are necessary as the habitat will have substantial buoyancy, producing tension 60 kN per metre of wall.

The bubble-wrap is emplaced and Martian air is pumped to partially fill the habitat. Edible photosynthesizing plants are placed on the sidewalls of the canal, their roots either embedded in processed Mars soil with added fertilizer, or fed hydroponically. Canal water is circulated through osmotic filters to extract oxygen: enough to make the atmosphere in the habitat breathable will be produced in a few months.

Pond creation, and even the main stages of habitat construction, can be performed before the arrival of humans. If all materials are brought from Earth, the silvered film mirrors will mass a few tens of g/m^2 pond area including their support masts. To prevent UV entering the pond, a surface film of oil with UV-absorbers, a further few tens of g/m^2 pond area, is required before the habitat is emplaced. The habitat itself is more massive: if the bubble-wrap tent is made from PEEK of tensile strength 100 MPa, for safety factor 4 the bubble-wrap will mass 3 kg/m^2, dominated by the tensile webbing which also acts as rip-stop: the transparent film of the bubble walls themselves should be as thin as possible, a few microns. Aircraft-style floor panels mass ~3 kg/m^2***(8)*** so total habitat mass will be ~8 kg/m^2 floor area.

While it is entirely feasible to bring all material for the first habitats from Earth, a wide range of plastics, oils and UV-absorbing organic chemicals can be made using only carbon, hydrogen, oxygen and nitrogen available from the Martian atmosphere and pondwater. A plausible first step is to make benzophenone: benzophenone derivatives are used as UV absorbers in sunscreen lotions and to protect plastics, and are soluble in oil but insoluble in water. Another derivative, benzophenone difluoride, is the main precursor for the high-performance plastic polyether ether ketone (PEEK). This material has strength up to 100 MPa, is UV-resistant, and is compatible with both 3D printing and CNC milling. In addition to thin transparent sheets and stronger webbing for the bubble-wrap, it can be used to make almost all rigid parts required: anchorage pegs, Lego-like interlocking blocks for walls and floors, plumbing pipes, basic furnishings; even Mars surface structures. PEEK contains only C, H and O, so fluorine and other elements in precursors used can in principle be recycled indefinitely.

A bubble-wrap tent within a pond provides accommodation far more pleasant than other extraterrestrial habitats proposed to date. During the day there is sunlight from above. The pondwater is pumped through filters so that it is almost as clear as air, invisible to the eye, as is the transparent bubble-wrap plastic of the habitat wall. A person looking out from within the habitat sees green vegetation in the foreground. Due to refraction of light as it enters the pond, providing the surrounding terrain is not absolutely flat, Martian landscape is visible just beyond. Above that sun and sky are visible: selective light absorption by the water will even give the sky a blue tinge. The view is much like that from a terrestrial valley. At night the combination of lowered mirror and a thin layer of ice on the pond surface acting as a diffuser reflects artificial light from the habitat to give an impression of night sky with low cloud, as often encountered in Earth’s tropics.

The tent-within-a-pond format is the safe and practicable form of the crystal-domed cities of fantasy literature. Advantages compared to other Mars habitats proposed to date include –

- Pleasantly sunlit throughout: insolation level, boosted by the mirrors, is equivalent to Earth mid-latitude, optimal for both crop growing and human comfort, yet there is excellent protection against both hard radiation and UV
- Almost all material needed can be made from Mars air and water, so locally sourced even before humans arrive: as little as a few tens of g/m^2 pond area plus a few tens of kg per colonist need be transported from Earth
- No claustrophobia: transparent surfaces in all directions
- No claustrophobia: generous living space can be provided
- No danger of sudden depressurisation: external pressure is maintained by the weight of water even in the event of structural failure
- The system requires no airlocks or space suits. With unmanned vehicles to perform surface tasks, it will rarely if ever be necessary for colonists to exit the ponds. To deliver the colonists, a capsule splashes down in a wider section of canal, then is towed adjacent to a habitat and winched vertically downward. When the external water pressure at the capsule base matches the internal air pressure, a hatch is opened and the capsule effectively becomes a diving bell. Colonists can swim a short distance to a similar hatch in the base of a nearby habitat with no protective clothing or equipment required, touching Mars soil en route: a rite of passage with obvious baptismal overtones.

If access to the Martian surface is required, space suits are obviously necessary, but not airlocks. A suited colonist dons a weighted belt so that they will have slight negative buoyancy immersed in water. They can then descend through the hatch in the habitat base and climb to the surface using a ladder attached to the canal sidewall.

Earth return capability can be provided cheaply by manufacturing fuel to refill rockets by electrolysing pondwater, starting in advance of the first humans arriving. Electricity for the purpose can be provided by carpets of solar cells unrolled on the surface by rovers; liquid hydrogen and oxygen can be stored in tanks well away from the ponds, which can also provide emergency supplies of oxygen and power to the colony if needed. However a completely self-sufficient colony, with redundancy, safety margin and the capacity for growth can be achieved remarkably quickly. Ponds which are separated by even a short distance are isolated physically, chemically and biologically: an individual pond which suffers a disaster can be completely and permanently evacuated if necessary. Unlimited C, H O and N are available from the start. Small quantities of other elements will eventually be needed: these can either be collected from the surface by rovers, or accessed by extending a canal to intersect a deposit of the required ore. The ability to make new high-tech equipment such as solid state electronics will not be essential: a Martian civilisation can continue indefinitely on a low-tech basis.

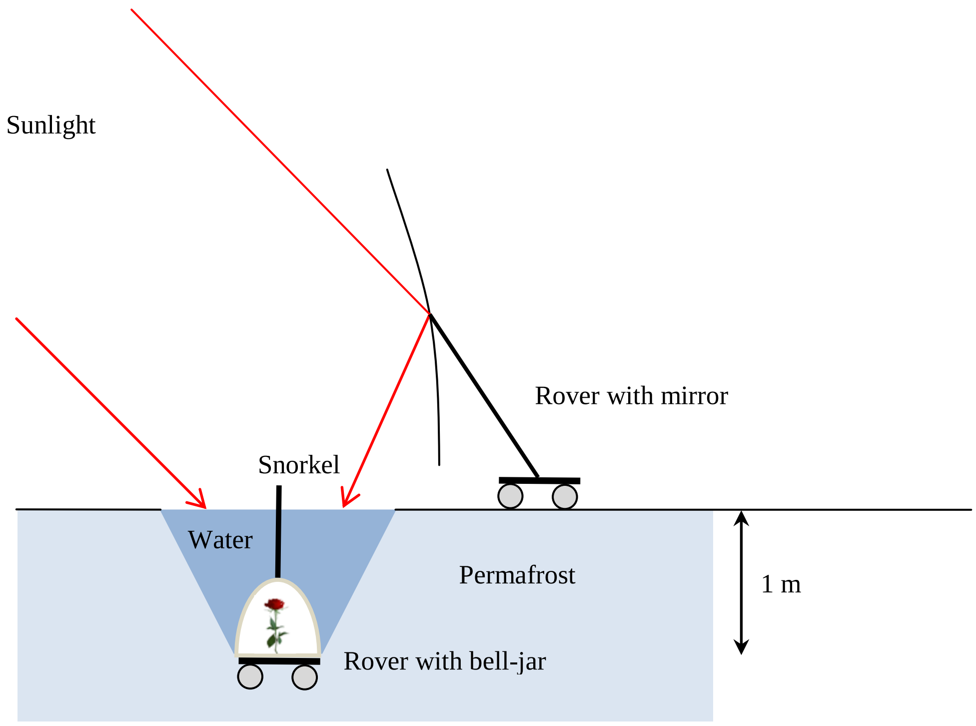

Figure 2 **Rapid pond demonstration using two small rovers**

A small demonstration pond can be made rapidly using two rovers as shown in Figure 2. One carries a parabolic reflector which unfolds umbrella-style, the other a bell-jar made of any type of glass which blocks UV, atop which is a tube which acts as a snorkel.

The first rover moves and angles its mirror so as to melt out a pond to the bottom of which the second rover sinks, reflecting sunlight into the pond by day and covering it at night to minimize heat escape. The process takes only a few days. A small pump within the snorkel pushes Mars air down into the bell. It has been demonstrated that land plants can develop in pressures as low as 30 millibars***(4)***, so pond depth of 1 m or less is sufficient.

Spores and seeds are released into the bell, which may be subdivided into several independent chambers: photosynthesis produces oxygen. Invertebrate eggs, fish eggs and even hardy animals such as tardigrades are then released. Small cameras transmit magnified pictures of the developing ecosystem for scientific and public relations purposes. The interior surface of the bell may be partially silvered, and/or partially covered with solar cells, so that the relatively intense sunlight focused into the pond to maintain its temperature does not expose plants within the bell to excess light.

For a permanently self-supporting colony with a healthy variety of locally grown food, a crop-growing area larger than the walls of the habitable canals is desirable. Modern Earth agriculture routinely obtains annual yield ~35,000 kcal/hectare as 10 tonnes of wheat***(9)***, 40 tonnes of potatoes***(10)*** or 10 tonnes of rice***(11)***, so 250 m^2 per colonist would be the minimum: 500 m^2 can provide a varied diet, including items such as eggs and meat from grain-fed poultry. It has been demonstrated that rye can germinate at 30 millibars, and wheat actually grows better at 200 millibars in an air mix with plentiful CO_2 and O_2 but little N_2 than in an Earth-standard atmosphere***(4)***, so agricultural canals of depth ~5m can be used, possibly much less with selective breeding and/or genetic modification. The shallower water permits a larger proportion of red light, significant for photosynthesis, to pass. The crops are tended by robots: higher radiation levels and lower safety factors compared to human-habitable canals are acceptable.

The minimum separation between canals is set by the need for each canal's mirror not to overshadow the nearest parallel canal. If the width of each canal is $\mathbf{W}$, the ratio of mirror height to canal width $\mathbf{n}$, and the noontime solar elevation angle on the shortest day of the year $\boldsymbol{\alpha}$, adjacent canals should be set at intervals $\geq \mathbf{W}(1 + \mathbf{n} / \tan \boldsymbol{\alpha})$. Mars' axial tilt is 25°, so at latitude 45° N or S, $\boldsymbol{\alpha} = 20°$. By the time a planitia is densely covered, the mirrors act as windbreaks, greatly reducing wind speed hence dust levitation, and active weather control by adjusting them will also be possible, so $\tau < 0.3$ can be assumed. Then $\mathbf{H} \sim \mathbf{W}$ and canal interval ~3.75$\mathbf{W}$, so ponds can cover 27% of a mid-latitude planitia floor: 300,000 km^2 in the case of Hellas, able to support a human population of at least 600 million. A 10m thick ice layer is needed to create a habitat-containing pond in situ, 5m or less for an agricultural pond, so ~2,000 km^3 of ice is required, a fraction of the quantity present in Hellas***(1)***. In the northern hemisphere, the slightly shallower planitias Utopia and Arcadia are also known to contain plentiful near-surface ice***(12,13)***: similar ponds can be created here, for total pond area 1 million km^2 supporting a population of 2 billion.

This is by no means an upper limit. There is sufficient water ice on and just below the surface of Mars to cover the entire planet in a layer 35m deep***(14)*** and sufficient CO_2 ice in the south polar cap to increase the present atmospheric mass by 80%***(15)***, permitting liquid water to exist almost anywhere on the surface. Orbital mirrors, e.g. a swarm of small solar sails capable of self-orientation without moving parts***(16)***, can provide optimal levels of sunlight and seasonality for crop growing to the entire Martian surface. A pond area approaching Mars’ total surface area could ultimately be created: 140 million km^2, capable of supporting a human population up to two orders of magnitude larger than Earth’s current 7 billion.

Endnote

The pond concept is described in similar text to this paper in UK patent filings 1616538.3 dated 29 September 2016 and 1700409.4 dated 10 January 2017; an earlier version was described in UK patent filing 1019917.2 dated 24 November 2010.

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