Solar ponds on Mars: ideal habitats for Earthly life

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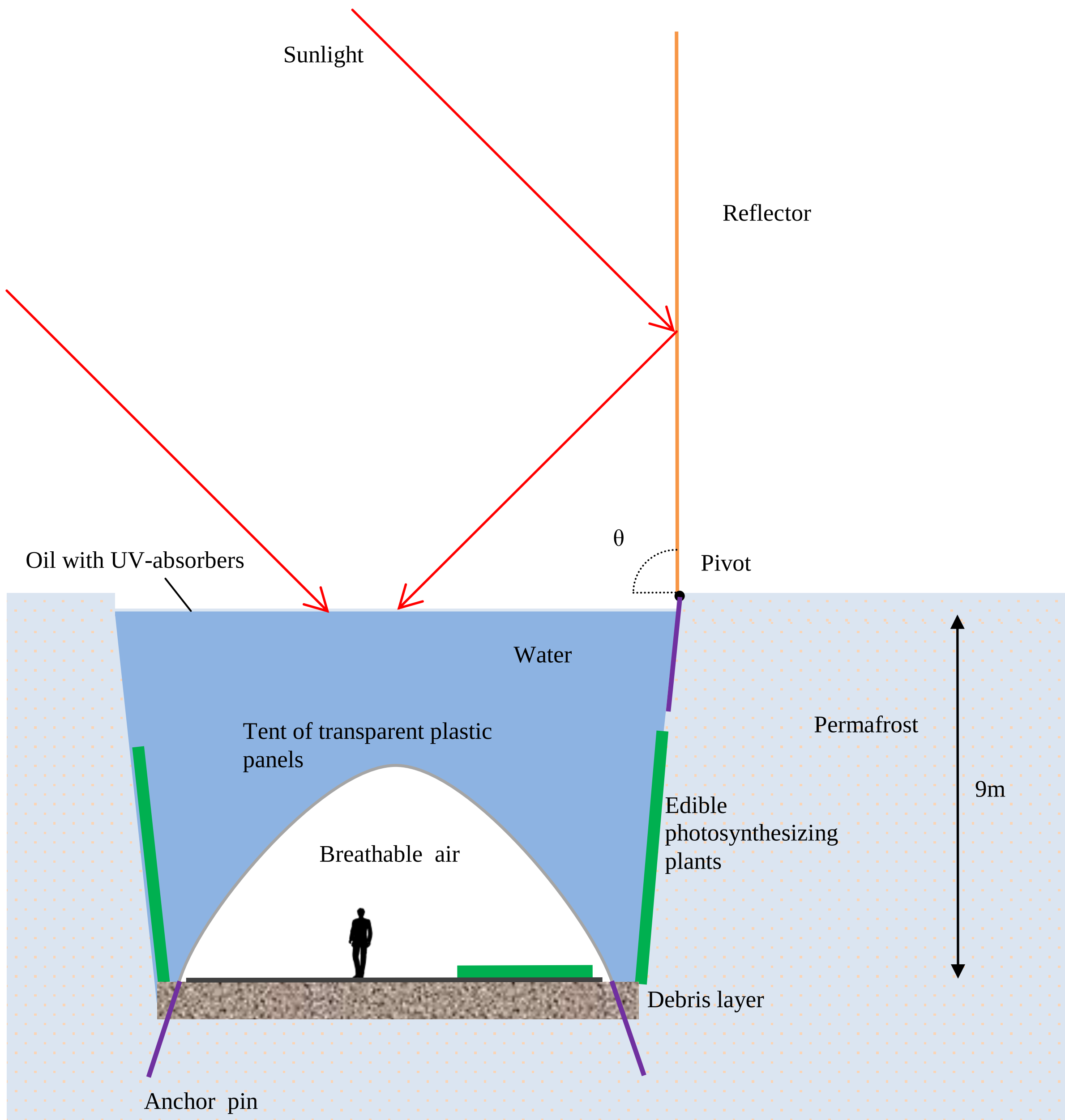
Abstract

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 melt out the pond and sustain terrestrial life within, inclining mirrors initially mounted on unmanned rovers are positioned by day to divert additional sunlight into the pond, by night horizontal above its surface to minimize thermal energy escape. Any location with near-surface ice at sufficiently low elevation that the atmospheric pressure remains above the triple point of water is suitable: the SHARAD radar and HIRISE camera aboard the Mars Reconnaissance Orbiter have identified many such sites. No digging or drilling is required: the surface merely needs to be warmed.

A solar-powered amphibious vehicle pumps and purifies water from the pond's warmest depth to melt any opaque surface ice that forms overnight, renews a surface film of 'suntan oil' which minimizes evaporation and absorbs UV, and could also manufacture plastics using C, H, O and N from Mars air and water. Manned capsules can land directly into the ponds. No space suits are required: exiting at a depth of a few metres, the pressure is sufficient that humans need wear only aqualungs, and can perform delicate work with their bare hands. A first task will be to erect transparent tents filled with breathable air like diving bells, anchored to the pond floor to 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; they can be serviced or replaced by withdrawing them into the pond, which can be extended into an ever-growing canal network, if necessary without assistance from Earth.

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. Low-lying areas of Mars where the year-round atmospheric pressure is high enough for such ponds to be easily created and sustained extend over millions of square kilometres, including Hellas Planitia where the pressure is double the triple point and water boils at 10°C. 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 water, habitats within the ponds for human occupation, as shown in Figure 1, can be created with minimal resources from Earth. The first and lengthiest step, melting the debris-covered permafrost to depth ~10 metres, can be performed by unmanned rovers with no drilling or digging, warming the surface using lightweight mirror panels unfolded from the rovers. Later more permanent mirrors are deployed from within the ponds (they can be retracted for servicing or replacement as required) and the rovers are redeployed to melt additional areas.

The benign environment provided by the pond ensures:

- No part of the habitat is exposed to the harsh conditions of the Martian surface. Even the outer-facing surfaces of the walls are in a quasi-terrestrial environment, the habitat can be made from interlocking tiles of transparent plastic.

- 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.
- Capture of gas escaping from microleaks in the habitat: the pondwater is circulated to extract dissolved gas, including oxygen made by underwater photosynthesizing plants.
- Thermal inertia: water temperature varies $\ll 1°C$ over the diurnal cycle.
- External but readily accessible gardens of edible photosynthesizing plants or algae.
- 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.

Evaporation and gas escape are 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 a first estimate 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. The absorbing chemicals must be continuously reprocessed in situ as they have only short stable life in sunlight. Fortunately a wide range of UV-absorbing organic chemicals can be made using only carbon, hydrogen, oxygen and nitrogen available from the Martian atmosphere and pondwater. They include avobenzone, a broad-spectrum UV absorber used in suntan lotions, and benzophenones, widely used as UV stabilizers in plastics.

Likewise a wide range of plastics can be made from C, H, O and N, including the high-performance polyether ether ketone (PEEK) which has strength up to 100 MPa, is UV-resistant, is compatible with both 3D printing and CNC milling, and could be used to make almost all rigid parts required.

A key piece of equipment not shown in Figure 1 is a small solar powered amphibious vehicle which is present from the pond's inception and performs the following functions:

- Circulates warmer water from the pond's depths to melt any opaque surface ice which forms overnight, and during the day if required. Due to the tiny vertical density gradient, a few watts of pumping work can provide megawatts of heat to the surface. The warm water is emitted in a directed jet which can also be used to tailor the pond's shape.
- Removes corrosive salts likely to be present when the pond is first melted out, either by osmotic filtering or partial distillation, to produce pure water which is returned to the pond. The unwanted highly saline residue is squirted from a nozzle to fall on the Martian surface some distance from the pond, where it immediately refreezes.
- Uses C, H, O and N from the Martian air and pondwater to make some or all of:
    - Transparent oil for the surface layer, of sufficiently high molecular weight to inhibit escape of dissolved gases and evaporation.
    - UV-absorbing chemicals dissolved in the oil, continuously replenished and reprocessed as required.
    - Interlocking flexible plastic tiles to make the tent, most of whose area is transparent, but whose edges are made from a strong structural plastic such as PEEK.
    - More Lego-like rigid bricks for the habitat floor and walls.

- Rigid tubes to serve as anchorage pins, from which miscellaneous plumbing can also be constructed.

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 layer of surface debris sufficiently thin to be invisible to SHARAD, thickness at most 10m and likely less***(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^{0}C. Water at 0^{0}C 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 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 surface structure massing only a few 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 habitat within it can in principle extend for any length desired in the east-west direction, but in practice may be split into sections of ~100m length to limit biological contagion, the propagation of engineering failures, and the possibility of significant ripples or waves being created on the surface by wind. The shape adopted by the tent containing breathable air 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 permafrost is heated than to attempt to remove surface debris or to drill through debris-containing ice.

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 or Utopia 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. 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 $\tau = 0.3$ to 0.76 x 0.32 = 0.24 x TOA with $\tau = 1$ ***(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 $\tau = 0.3$.

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 to compensate for changing atmospheric dust conditions. For example if the height of the 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 mirror extends horizontally just above the pond surface, returning 95% of radiated heat, so reducing radiative escape to 15 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. Because the total solar energy falling on the canal surface plus the adjacent area shadowed by the mirror is unchanged from its original value, permafrost a few metres below and to the sides of the canal remains close to its original temperature ~-50°C. Any porosity or cracks through which canal water might escape are immediately sealed by freezing water. 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 fraction of both 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 15 W/m^2, total heat loss including conduction through the surrounding ice to ~65

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 the lowered position, the top edge of the mirror 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 layer 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.

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 plentiful insolation the habitat does not overheat. 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 practice the density of water varies only 0.03% over the range 0-10°C, so natural convection is minimal in this range. To prevent opaque surface ice forming during the day, and melt the layer which forms overnight at dawn, warmer water is circulated from the depths of the pond as described above.

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 if the mirrors initially deployed from the rovers are taller than the canal width, and the hinges connecting the panels can be adjusted to form a slightly concave shape, this period can be shortened. 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 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 ~100 x longer than at Earth's surface: if the gaps between the snow grains are smaller than this, a significantly better thermal insulator than terrestrial snow will result. Fixed mirrors 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***(6)***. Strong anchorage points are necessary as the habitat will have substantial buoyancy, producing tension 60 kN per metre of wall.

Pond creation and manufacture of plastic tiles for the habitat can be performed by robots before the arrival of humans. The mirrors, silvered plastic film stretched on supporting frames which are linked by hinges driven by small electric motors for deployment, must be brought from Earth, but can mass <1 kg/m^2 pond area. The habitat itself is more massive: if the tent tile edges are made from PEEK of strength 100 MPa, for safety factor 4 the tensile structure will mass 3 kg/m^2 base area, plus the mass of the transparent windows which form the tile interiors, plus at least a comparable mass for a floor comprising more Lego-like bricks.

The tent habitat, plus its floor and anchorage system, can be emplaced by humans who do not need to wear pressurized space suits but only lightweight aqualungs, using their bare hands for delicate manipulations when necessary. Pondwater is then electrolyzed to provide oxygen to fill the habitat, with nitrogen and CO_2 added from the Martian atmosphere.

A 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 sterilized and filtered on a frequent cycle so that it remains almost as clear as air, invisible to the eye. 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 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 g/m^2 pond area plus a few 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 depressurization: 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. On arrival colonists could swim the short distance from the exit hatch of their capsule to a 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 they will have slight negative buoyancy immersed in water. They can then descend through an opening 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, e.g. by electrolyzing pondwater or by the Sabatier process, 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; cryogenic liquids can be stored in tanks well away from the ponds. The fuel can also provide emergency power if needed, for example during a prolonged dust storm, by being reacted in fuel cells.

A completely self-sufficient colony, with redundancy, safety margin and the capacity for growth can be achieved remarkably quickly. Photosynthesizing crops sufficient to feed the colony will also generate sufficient oxygen for breathing in an approximately closed system. Unlimited C, H O and N are available from the start. Small quantities of other elements will be needed for full self-sufficiency: 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. 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.

For a permanent 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***(7)***, 40 tonnes of potatoes***(8)*** or 10 tonnes of rice***(9)***, 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 mainly by robots: higher radiation levels and lower safety factors compared to human-habitable canals are acceptable.

Algae grown in the water, either on the banks of habitat-containing canals or in separate canals, can very efficiently provide oil as a feedstock for many chemical processes, as well as food ingredients.

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 **H** ~ **W** and canal interval ~3.75**W**, so with modest pumping to raise water to canals at different levels, they can cover 27% of a mid-latitude planitia floor: ~0.75 million km^2 in the case of Hellas, able to support a human population of 1.5 billion. A 10m thick ice layer is needed to create a habitat-containing pond in situ, 5m or less for an agricultural pond, so ~4,500 km^3 of ice is required, a fraction of the quantity present in Hellas***(1)***. In the northern hemisphere, the shallower planitias Utopia and Arcadia are also known to contain plentiful near-surface ice***(10,11)***: similar ponds can be created here, for total pond area ~2 million km^2 supporting a population of 4 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***(12)*** and sufficient CO_2 ice in the south polar cap to increase the present atmospheric mass by 80%***(13)***, providing sufficient pressure for liquid water to exist almost anywhere on the surface. Mirrors orbiting the Sun-Mars L_2 point, e.g. swarms of small solar sails capable of self-orientation without moving parts***(14)***, can evaporate all CO_2 ice and most water ice and 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 many times greater than Earth's current 7 billion. Electrolyzing about one-fifth of the water, allowing the hydrogen to escape into space, would give Mars a breathable atmosphere, and would take only decades using the solar energy available.

The proposed pond system could be started on a small scale immediately. The HIRISE camera aboard the Mars Reconnaissance Orbiter has directly imaged fairly pure ice >100m thick exposed on poleward-facing scarps beneath only 1-2m of ice-cemented surface debris, in multiple locations at latitude ~55-58° in both Martian hemispheres***(15)***. One set of scarps, in Milankovic crater, is at similar latitude and almost identical elevation to the Viking 2 lander site, and should experience very similar atmospheric pressure, comfortably above the triple point of water throughout the Martian seasonal cycle. We could send unmanned rovers there immediately with high confidence to prepare one or more ponds for human occupation.

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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