Will we colonize other planets, why, and how?

Several hundred people or so have said publicly and credibly that they would like to colonize Mars. Elon Musk has said he wants to die on Mars… just not on first impact. That's a good part of the "Who" in the classic newspaper reporting mandate of "Who, what when, where, and why?" There are others who may come forward, and many more who offer encouragement or even propose help with technologies.

The "What" question has multiple dimensions. First, there is no one with credibility proposing the colonization, much less visitation, by any humans of other bodies in our Solar System. Anything beyond Mars is terminally cold and bereft of support for ecosystems (well, Mars is really close to that, too). Much more extreme ideas propose colonizing another stellar system. I readily dismiss this out of hand for the duration of the trip, exceeding by far even the 75,000 years I cited earlier for travel to the nearest stars, Proxima Centauri. To say that the goal is to colonize Mars is not a full specification. Is the duration limited or is it for as long as possible? Is it proposed to shift over time to supporting itself only on Martian physical resources (water, metals, etc.)? Will the human population be replenished periodically from Earth (avoiding a solar system analogy of the Jamestown settlement), given not only risks of death but also the risk of inbreeding in a small population? Re the last point, consider that we each carry, on average, about six conditionally lethal mutations. I mentioned this earlier. Trading genes within a small population, hundreds or thousands, gives high odds that many bad genetic combinations will arise to cause a significant death rate.

Let's admit as a first estimate that colonization is irreversible for the colonizers: no one is coming back from Mars. A special psychology is a must. IMAGE The bases of this assertion are, first, the famous rocket equation of Tsiolkovsky and, second, the size of the gravitational bindings to overcome on the way to Mars that dwarf those for going to the Moon. First, the rocket equation. I have a derivation, rather a standard one, and a discussion in an Appendix that you may find interesting. Here's a simple case for a rocket in free space, not fighting gravity. The rocket burns propellant that exits its body at an exhaust velocity, v_{ex}. The force has a magnitude equal to the mass rate of burning multiplied by v_{ex}. It gives better and better acceleration as the rocket lightens with the using up of propellant….but then less of the rocket is left. In a single stage, the final velocity is related to its initial velocity, v_0, and the *ratio* of the initial to final mass, m_0/m_f:

$$v_f = v_0 + v_{ex} \ln\left(\frac{m_0}{m_f}\right)$$

Here, *ln* is the natural logarithm. Now, the highest exhaust velocity with chemical propellants is 4400 meters per second (assuming no one wants to be around a rocket using intensely poisonous beryllium with hydrogen!). That's with liquid oxygen and liquid hydrogen, a bit dicey to use practically. Current rockets use liquid oxygen and kerosene, with its v_{ex} of 2,941 meters per second. We need to reach much higher velocities, over 11,200 (to get to the Moon) or even 4 times larger, if not all at once (to get to Mars). Take the case of the Moon. Take v_0 as zero and ignore the extra push needed against the initial atmospheric drag (and a delay-to-escape-velocity time that wastes fuel, in a sense). We need v = (11200/2941)v_{ex}. That is, we need the natural logarithm of m_0/m_f to be 3.81. That occurs when the initial mass is 45 times the final mass, or the empty rocket weighs just 2.2% of the initial mass! That is not possible; the shell of the rocket and its fuel tanks alone weigh more that that. OK, jettisonable boosters help, but not enough. The way around this is to use multiple stages – get rid of the heavy shell and tanks and propel a smaller fraction of the take-off mass. Really, use 3 stages. That's what the Apollo missions did. Of course, that means that the final mass is still a tiny fraction of the take-off mass. We could calculate it from assumptions about the staging, but suffice it to say that the final masses of the Apollo spacecraft that made it to the Moon had a mass (119 tonnes) that was just 4% that of the enormous rocket at lift-off (2950 tonnes).

That all worked with these advantages over flights to Mars and back:

- No fighting to move to higher energy in the Sun's gravitational field (calculations are in a sidebar), thus, only ¼ as much total energy to gain;
- A much easier return from the Moon with its gravity 1/6 as strong as that on Earth; the escape velocity is only 2,380 meters per second, about 1/5 that for escaping Earth – so, only a light engine needed to be carried to get back home. From Mars the escape velocity is 5,030 meters per second, 45% as much as from Earth.

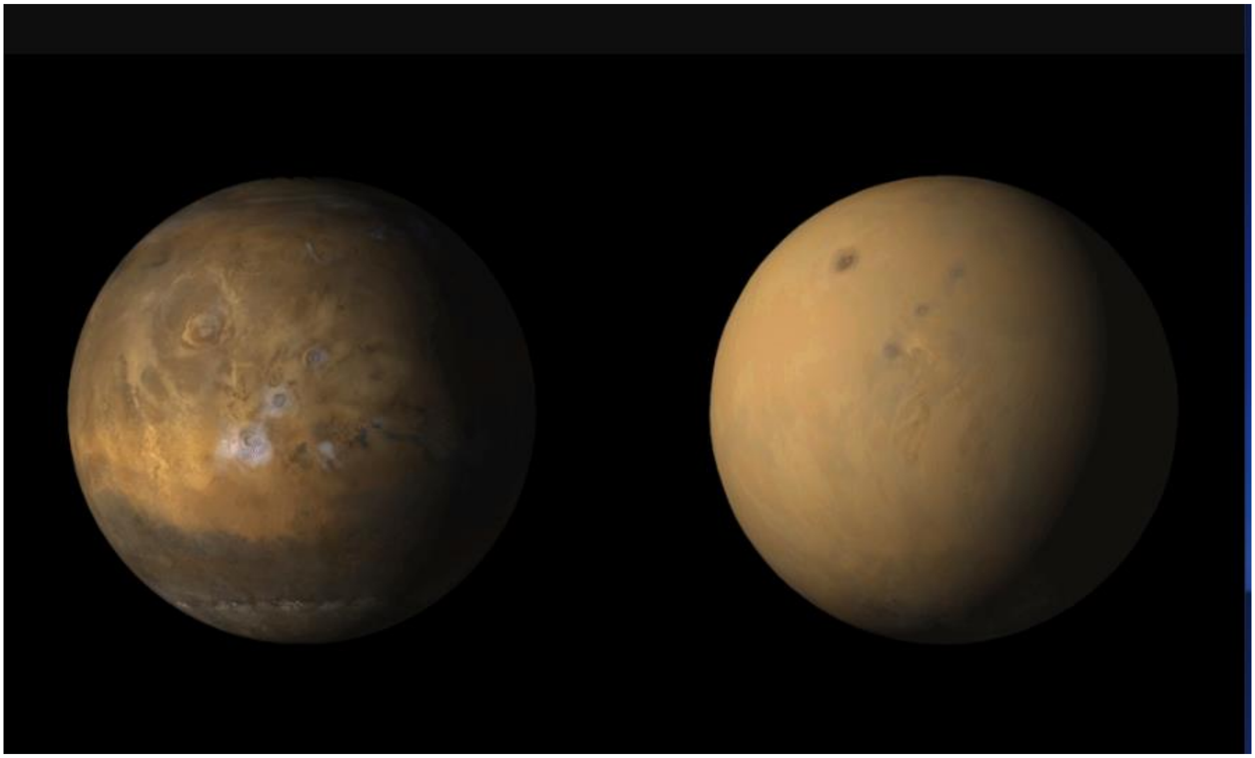
Admittedly, there's less need for retrorocket braking for landing on Mars if the drag of its atmosphere is used, just as there's no retrorocket need for landing on Earth. It's tricky to use the thin atmosphere on Mars for braking. Remember the seven minutes of terror when the Curiosity Rover landed on Mars with a supersonic parachute. It's even tricky using Earth's dense atmosphere – hit it at the wrong angle and the craft bounces off, not to return!

What about ion propulsion and other modes that have very high v_{ex}? The problem is that the rate of firing is so low that the thrust is very small; the time to reach the needed velocity is extremely long. Chemical propellants will always be needed for fast trips and absolutely for lift-off and landing.

More "what:" What would a Mars colony look like?
A lot of technology would have to be brought on multiple supply runs, mostly uncrewed. Needed as infrastructure: habitations, electric power, water supply, storage facilities, transportation, food production… All have great challenges. It's up to the adventurers to design the logistics (compare preparations for a lunar colony: https://www.lpi.usra.edu/lunar_resources/documents/13_0IntegratedISRUPresenta.pdf) – what parts arrive first, who assembles them, etc. Rather, we may focus on a few points.

Keeping warm is difficult on Mars. At its aphelion it is at 1.67 astronomical units, that is, 1.67 times as far from the Sun as is the Earth at the Earth's mean distance. By the energy balance equations presented earlier, the radiative temperature at the top of the Martian atmosphere is $1/\sqrt{1.67} = 0.774$ times that of the Earth. That's 0.774*255K = 197K, or -76°C. The temperature is higher at low latitudes but still very low.
https://www.space.com/16907-what-is-the-temperature-of-mars.html
Mars's atmosphere is about 100 times thinner than Earth's. Without a "thermal blanket," Mars can't retain any heat energy. On average, the temperature on Mars is about minus 80 degrees Fahrenheit (minus 60 degrees Celsius). In winter, near the poles temperatures can get down to minus 195 degrees F (minus 125 degrees C). A summer day on Mars may get up to 70 degrees F (20 degrees C) near the equator, but at night the temperature can plummet to about minus 100 degrees F (minus 73 C).

The thin atmosphere offers a negligible greenhouse effect. It's up to the colony to provide habitation with a huge greenhouse effect, or harvesting solar energy on additional area for electrical heating, or both. Both methods are shut off by dust storms. That makes battery storage imperative. That then adds notably to the mass of technology that would have to be carried.



Mars, viewed before the dust storm (left) and during the dust storm (right) by the Mars Reconnaissance Orbiter (NASA/JPL)

The storm that peaked on 2 July 2018 reached an optical depth of 10.7. That represents a decrease of sunlight by a factor of e^{-10}, leaving only 45 millionths of the clear sky value. Battery storage of high capacity will be needed; dust storms have lasted for months. They killed the Opportunity Rover.

Energy sources: Well, the Sun in any term over a few months, given optimistic estimates of what could be carried on arrival by the spacecraft and at the expenses of reducing the size of the human crew. Recall the rocket equation and sequelae for the tiny fraction of liftoff mass that is the payload.

The colony would need energy for: ● Heating of habitations, battery storage area…and the greenhouses for growing food crops ● Water recovery from soil (see below) ● Water electrolysis for some oxygen production (see below, but this becomes theoretically unnecessary or minimal once plants start growing well in, say, a year) ● Transport… to where? ● Industrial processes, including production of medicinals (presumably minor, with only latent diseases carried in genomes; care of ageing colonists comes a lot later) ● Several other processes, but especially, ● Lighting! On Earth lighting is about 10% of the total energy budget in industrial or post-industrial economies, but on Mars it's critical to support crop plant growth during dust storms and seasonal lows.

The details of crop growth are fascinating to many, including me, as I've made a long career of it from the physiology to the biophysics to the global system.
● Sunlight intensity on the surface of Mars is low. On average at the top of the atmosphere or TOA it's 43% of that reaching the Earth, as noted earlier from simple geometry of light propagation over different distances from the Sun. On Earth clouds reduce mean sunlight at the surface to 0.69 that at the TOA. On Mars persistent dust reduces intensity at the surface by a factor of about e^{-1} = 0.37 and

much more during month-long dust storms. Make it about 0.34 (there are studies from landers and rovers to consult for higher accuracy). The annual average solar radiation per ground area is then about 0.43*(0.34/0.69) = 0.21 or 21% that of sunlight on Earth.

● Essential fact: crop plants can grow at significantly lower light levels than Earthly sunshine. In fact, leaves at the top of the canopy of field crops are supersaturated with light. In an Appendix I reproduce a model of total-crop photosynthesis that compares ordinary plants with plants bred or naturally occurring to have half the normal content of chlorophyll in leaves. The top leaves are less supersaturated in strong light while passing more light to share with lower leaves. My model predicted an 8% seasonal gain in yield. It was verified by D. B. Peters and colleagues at the University of Illinois with pea mutants. No one followed up on it commercially because (1) yield is actually subsidiary in breeding programs to many other crop traits, especially pest and disease resistance, harvestability, etc., and (2) farmers don't want light green crops! Still, with realistic densities of leaves termed as leaf area index (leaf area per ground area), photosynthetic rates per ground area respond close to linearly with light level. So, the choice is slower growth with more area or supplemental lighting, and that is very energy-costly.

● Essential fact: photosynthesis is absolutely limited to 6% efficiency as the energy content in biomass produced divided by total energy in sunlight intercepted. That's at high CO_2 enrichment of the atmosphere, which is easy on Mars. A more realistic figure is 3%. For all vegetation on Earth it's 0.3%, given losses to herbivory, damage from weather, costs of maintaining organs and tissues, and the like. For the crops, the 3% figure applies only substantially complete crop cover. Early in growth of a crop it starts near 0%. The canopy might be kept nearly complete at all times by clever intercropping. It's a lot of work, but what else do the colonists have to do?

● Put these together. Mars' surface has 0.21 times the mean solar energy flux density of the Earth's surface. That's 50 watts per square meter. It's higher near Mars' equator but the colony may opt for middle latitudes (see below), so we'll take that figure. A crop operating at 3% energy efficiency captures 1.5 watts per square meter.

● How much food energy does that supply? Most crops have less than 25% of their total growth as edible portion. A big part of the Green Revolution was breeding short grains that had less stem and root and more seed mass. We might assume that in the mix of all crops to be grown that the harvest index is somewhat lower, perhaps 15%. Colonists will want and need a diverse diet. Now we're at an edible crop mass production of 1.5*0.15 = 0.225 watts per square meter.

● There will be processing costs. The processing needs and methods are hard to project but may cut consumable food yield to 0.8 times the above, about 0.18 watts per square meter. Oops, we have to increase that cost quite a bit. Assume that the colonists will want, and need, food that is both more attractive and nutritious. Some plant protein will need digestion to amino acids and synthesis of a balance of essential amino acids. My rough estimate is a final consumable yield of no more than 0.6 times the cost above, or 0.135 watts per square meter.

● How much food does a human need in terms of energy? The classic figure is 2500 kilocalories per day or 10,500,000 joules per day. Spread over 86,400 seconds in a day that's 120 watts. If Martian sunlight provides this each colonist would need a greenhouse area of 120/0.135 or close to 900 square meters.

● There must be intermittent artificial lighting, certainly during lengthy dust storms.

- Solar panels would intercept sunlight, on average, at 50 watts per square meter. I assume that the panel arrays are not steerable to constantly face normal to the Sun but that they are optimized for the latitude.   That increases the average by about 20%, as one can calculate.
- Standard solar panels have a 25% energy efficiency. I'll omit the possibility that the colonists have multilayer panels that have attained 50% efficiency. These are very expensive. So, the panels provide 15 watts per square meter on average.

- Their output would be stored in batteries and recovered for the adverse times. Storage has a fair energy efficiency. Batteries store and then release energy with about 80% efficiency. Put the delivered power density at 12 watts per square meter.
- LED lights would be used, with an efficiency of 25% in converting electrical energy to radiant energy in the photosynthetically active part of the spectrum. A square meter of solar panels then gives 3 watts on average.
- The average natural sunlight intensity on the crop would be 50 watts per square meter, reduced by a light transmission factor of the greenhouse covering. That might still be 90%, giving 45 watts per square meter.
- Replacing that full time would require 15 square meters of panels per square meter of greenhouse space.
- Assume that 1/10 of the time lighting is needed. That comes to 1.5 square meters of solar panels per square meter of greenhouse footprint.
- Per capita that's 1.5*900 = 1350 square meters of solar panels. Compare that to a terrestrial home that might have perhaps 750 peak watts of panel output per resident from about 4 square meters of panels. Growing plants is costly with the low energy efficiency of plant photosynthesis, the small fraction of the crop that's edible, and so on. The expense of energy sources is staggering. So is the mass of panel material to be delivered. The energy demands other than for the crops – heating (hey, no cooling need!), habitation lighting, transport, etc. are quite modest. Still, the colonists must eat!
- To ameliorate these costs, the crop might be harvested when a dust storm starts… but there's no good predictor of storms to time the crop planting months earlier. Having a range of sowing dates and thus of harvest dates could help, but some major fraction of all crops would have to be kept going during a dust storm to avoid a bare-ground (bare hydroponic system) start, with its low light capture efficacy.

When

Is the technology ripe? SpaceX has proven the launch capability of its heavy rockets. One suited for lifting significant payloads to Mars is its Starship, which may test-launch in summer, 2020. The company's reusable rockets have proven their function, and the Starship is designed for orbital refueling: get it into low Earth orbit (up to about 25% of the battle of getting to Mars), refuel it there, and continue. There are other competitors as I write this, particularly Blue Origin.

Rockets are only part of the effort. Designing the colony habitations and support, selecting crews, and timing the orbit for the lowest-energy approach to Mars are all difficult tasks. The next good window for launch that the crewed missions could make is in 2022.

How? … as in, How would colonizers get there and how would they survive?

Getting there: For travel between two places (e.g., planets), each in elliptical orbits around a star, the most efficient route in energy use is almost always the Hohmann trajectory, using two engine burns (https://en.wikipedia.org/wiki/Hohmann_transfer_orbit). Surprisingly it was invented in 1925 by Walter Hohmann, well before space travel was remotely feasible. Use of the trajectory requires a specific alignment of the planets. Such a launch window recurs every 26 months for Earth to Mars travel.

The journey takes 9 months, which brings a number of hazards:

● **Exposure to particulate radiation** (energetic atomic nuclei) as cosmic rays and solar flares. Travel will be outside Earth's magnetic field that deflects particles and outside Earth's atmosphere that kills most of the kinetic energy of the particles. Remember, ten tonnes of air are above you on every square meter if you're at sea level – a nice blanket. We who live at higher elevations have less protection, but still a lot. For the Moon missions, exposure for 8+ days is not critical. For Mars "missions" the more than 30 times greater duration is problematic. Shielding of sufficient thickness x density can reduce the exposure to what we may call space-health limits. However, it makes the spacecraft so heavy as to drastically reduce the crew size and total payload. An option suggested by our friend physicist David Anderson, is no shielding. Cosmic rays generate a shower – the primary rays hits a nucleus that sends two or more fragments off, and these each set off more fragments, until there's a whole tree of many particles. Most of the energy deposition is later in the branching. Letting the first or a few of the first collision occur in the crew results in less energy deposition with its physiological and genetic damage. David said he wouldn't suggest it to NASA because he thinks that crewed Mars missions are irresponsible and of low scientific value. For colonizers, what can one say?

● **Adverse physiological changes.** These are well documented in astronauts and cosmonauts who made long flights on the International Space Station. Wanted: human beings evolved to withstand extended space flight. Or, that's what I infer from the analyses of physical and mental conditions of astronauts who spend long times at the International Space Station. One US resident there, Scott Kelly, is the identical twin of Mark, who stayed Earthbound. When Scott returned to Earth, more ways that we evolved for Earth's gravity showed up. Earlier studies with other astronauts showed loss of bone mass and muscle function. By comparison with Mark, Scott also had a different gut microbiome (now seen as quite important for health). His chromosomes showed inversions from space radiation, though these returned to near normal. More of the end caps of his chromosomes were critically shortened or lengthened. His carotid artery was distended. His cognitive capacity declined, largely recoverably. The same would happen on a flight to Mars, but with more genetic damage from radiation in space. Still, some people are promoting colonization of distant star systems. The crew members suffer loss of bone and muscle mass, even needing help walking when they land. Exercise regimes don't prevent much of the losses. Brains swell when gravity no longer keeps more blood at the extremities. The crew suffer cognitive deficits.

● **Psychological challenges – during the trip and then "forever.**" For the ultra-long no-return stay, toss in the hazards of extreme cabin fever; our psychology isn't made for this. Let's suppose that the colonists have been rigorously selected for personalities that tolerate long, close, highly dependent associations with others. They must also lack mood and cognitive disorders such as manic depression and schizophrenia, as well as lesser disorders that get amplified on long trips in close quarters. Astronaut and cosmonaut programs have done well at such selection. There will still be challenges during the trip. Space station crew members have shown shrinking of communication with others, greater egocentricity, and formation of cliques. Less well-selected exploratory teams have shown catastrophic breakdowns in group organization. Post-flight, some space station crew members have shown anxiety, depression, and substance abuse. Of course, for the colonists there is no post-flight; the stressors stay in place. On the plus side for the space crews who have been surveyed they reported greater appreciation of beauty, especially of the Earth. That's going to swing to the other side as colonists view an Earth never to be experienced again. There will be no long walks, no wild lands with fauna and flora, a black sky or a dusty one, and small living quarters. Actually, tawny from persistent dust – see sections_to_put_in…docx,"Mars lost its magnetosphere…

To alleviate some of these challenges, some people argue for genetic selection of colonists. They've overlooked the negative effects of inbreeding in a small population, including the founder effect. Let's have a time out for a few millenia to evolve humans who can take all this.

More "how:" Keeping hale and hearty on the ground on Mars

- ***Making and retaining oxygen… and water***

We metabolize our food. We inhale oxygen and exhale carbon dioxide. The loss of one and gain of the other clearly can't be sustained in a closed environment without releasing new O_2 into the air and disposing of or reprocessing CO_2. Let's consider CO_2 first. While we exhale CO_2 at about 5% molar fraction, inhaling air at about 10% CO_2 or higher is fairly quickly lethal. It's not a simple asphyxiant like nitrogen. As it dissolves in blood it reversibly creates carbonic acid - $CO_2 + H_2O \leftrightarrow H_2CO_3$. Higher acidity in our blood puts many biochemical reactions askew. In 199x, Lake Nyos in Cameroon literally fizzed over. Its waters over a volcanic vent had supersaturating amounts of CO_2. Some small disturbance made some water release bubble of CO_2. That made the water column less dense, so it rose, also pulling other water up. At the lower pressures higher in the water column, even more gas came out. It overtopped the crater rim and flowed down the mountain slope, killing thousands of sleeping people and their livestock. So, on a spacecraft we must get rid of CO_2. On the International Space Station (ISS) that was easy. Cabin air was compressed into a container with zeolites, porous ceramics that adsorb CO_2. The CO_2-laden zeolite was then connected to space, where the CO_2 quickly desorbed.

The result is the two gases that the ISS vented

The other problem is restoring the oxygen level. On the Apollo missions to the Moon, the spacecraft simply carried compressed O_2. That works for the 8+ day missions but not for a long mission on the ISS. There's not enough space on the craft to store enough O_2. That was, and still is, solved by electrolyzing water: $2H_2O \rightarrow 2H_2 + O_2$. The hydrogen gas was also vented to space. The mix sent off was really the loss of the elements in carbohydrate. We may look at the full stoichiometry (balance of the chemical constituents):

FIGURE

The net reaction of our human metabolism is pretty closely like the biochemical oxidation of glucose, which is $C_6H_{12}O_6$. Take 1/6 of a glucose, CH_2O. Metabolize that with oxygen:

$$CH_2O + O_2 \rightarrow CO_2 + H_2O$$

Add the electrolysis of water done at the same time:

$$2H_2O \rightarrow 2H_2 + O_2$$

Strike out the same things that appear on both sides and add these:

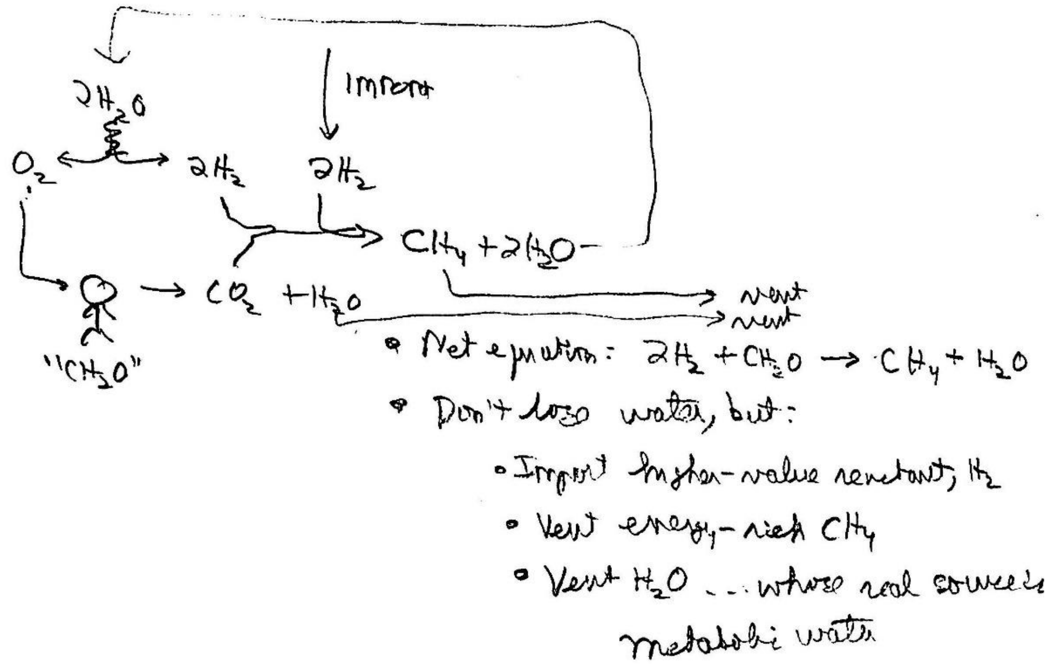
$$CH_2O + H_2O \rightarrow CO_2 + 2H_2$$

The result is the two gases that the ISS vented.

The unwanted effect was using up water that had to be resupplied. On a long mission out of reach of resupply – as a crewed Mars mission would be – that's a problem: carry a lot of water and fewer humans. NASA used the ISS as a testbed for an alternative chemistry. It uses the Sabatier reaction:

$$CO_2 + 2H_2 \rightarrow CH_4 + O_2$$

The hydrogen from the reaction is supplied again by electrolyzing water but the water can be fully recycled. Here's a figure with the whole scheme.

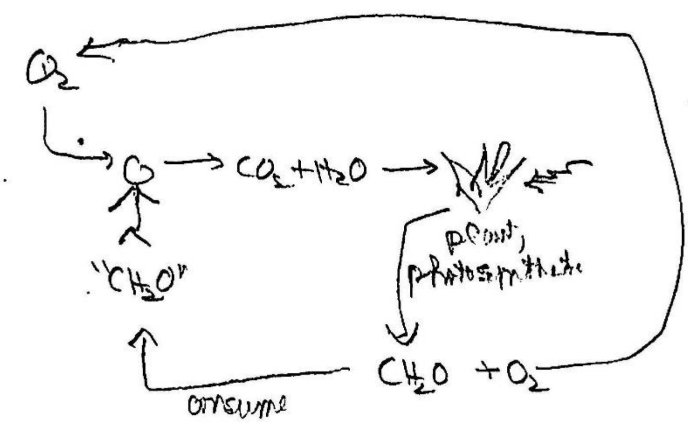


So, the net result per use of an O_2 is the venting of ½ CO_2 + ½ CH_4. Note that this is just a remake of CH_2O when you add up all the atoms. Cute. Of course, one of the vented gases, methane, is valued on Earth as a fuel for combining with oxygen. It could be kept and stored in case more oxygen is obtained, as upon landing on Mars and (very optimistically) getting water from the soil to electrolyze with solar power.

Of course, as much precious O_2 and water must be kept contained in the habitat, using careful airlocks whose air gets pumped back into the habitat after an astronaut (colonizer) is ready to open the outer door and take a walk (not to admire the flowers).

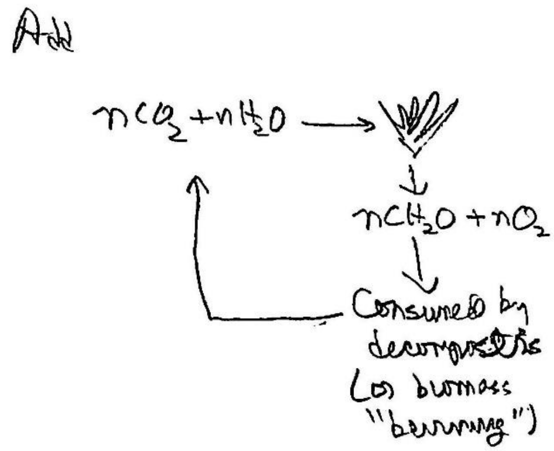
The loss of carbon compounds is equivalent to the loss of food. That's the next problem after keeping the atmosphere breathable in the colony habitation, once the spacecraft lands.

- **Naturally, growing plants to do photosynthesis is a good way to replenish oxygen**, as well as food. The nominal ideal cycling is this:



This is oversimplified: the crew can't eat and digest all the plant productivity

So, add another closed cycle. Plant photosynthesize CH_2O (and other stuff) in excess, most of which is human-inedible waste consumed by decomposers (or potentially combusted as fuel, which includes biomass digestion)



- The combined cycles are closed… in the long term
- In the short term there are lags and advances in the availability of food and O_2; excesses must be stored and then consumed later.
- The balance is tricky in another way. If plants are grown in soil, the soil organic carbon has a high latent demand for oxygen. In the original Biosphere experiment, a substantial amount of SOC got metabolized by soil organisms, depleting the O_2. A way around this is to grow plants hydroponically.

More about growing food

- Crops are always at risk of latent diseases in soil (OK, go hydroponic) or in their genomes (latent viruses). They can also fail from errors in managing the abiotic environment (insufficient aeration of the hydroponic solution). The special hazard of hydroponics is the easy spread of disease. Loss of a crop means death up there. Can everything being sent to Mars be fully sterilized? What about viruses in the lytic state in a crop? In terrestrial cropped ecosystems the backup is genetic diversity. Wild relatives of crop plants can be found with genes for tolerance of pests and diseases. Breeders introgress those genes into the crop varieties by traditional cross breeding (with minor help from genetic engineering). Who knows enough about what genes and what wild relatives that carry them may be necessary? Sending such genetic stocks in an emergency doesn't work: there's a 26-month wait of the next Hohmann trajectory, or a little less with an inefficient but faster trajectory for a small payload of plants.
- Any simplified ecosystem is at risk of collapse from continuing over- or underexpression of ecosystem functions. All natural systems have several levels of decomposers for plant residues – small invertebrate animals such as *Collembola*, a variety of fungi, a similar variety of bacteria. Who knows what to take along in case of problems?
- Hydroponics is more technically demanding for circulation, monitoring, and provision of exacting amounts of chemicals.
- There has to be disposal of even the plant exudates into the hydroponic solutions. A sophisticated separation and decomposition system is needed.

- Sorry, no meat. It takes 3 to 8 times the mass of crops as food for animals as the mass of meat harvestable. Vegans! This is not to mention the complications of animal husbandry, acclimation (or not!) of the animals to colony conditions (no free-range chickens!). Soy burgers, anyone?

Recycling wastes

- In any system at all, there are wastes other than CO_2 and water, particularly nitrogenous wastes from humans and as crop residues. Recycling these has its challenges:
    - One can let microorganisms break down the amino compounds – to ammonia (recoverable), but some will continue to be nitrified (with partial loss as N_2O) and then denitrified (in anaerobic parts of the environment, to N_2 and N_2O). The N_2 and N_2O have to be converted back to reactive N, as in ammonia equivalents. That means either biological nitrogen fixation (tricky to balance) or an energy-intensive technology (Haber-Bosch – but no one wants to run a high-temperature high-pressure reactor on a spacecraft or in a foundling Mars or lunar colony).
    - Other elements have to be recycled – P, Fe, etc. This is much more easily done in soils with a complex ecosystem of organisms…. but these ecosystems can hold plant diseases, as noted, or can crash with management mistakes (poor temperature control, or even latent diseases of the organisms themselves!).
- Human wastes. Let's consider how these are handled on near-Earth space missions.
    - Urine can be and is recycled, involving as it does simple soluble chemicals. The recovery of water is important.
    - Fecal matter, hair trimming, skin sloughing... much less agreeable stuff. What do the ISS crew do with this? They pack it in a capsule, jettisoning it back to Earth, to burn up in the atmosphere like a meteor. A poop meteor. This is not an option on Mars – no good landfills, certainty of contamination of Mars with human gut microbes (sterilization is hard to do 100.000%), and loss of valuable carbon, nitrogen, and various minerals.
    - Chemical and physical recycling of these organic wastes (organic in the true chemical sense) is clunky (fair-sized machinery) and power-hungry. Consider how it happens on Earth. Let small soil animals, fungi, and bacteria do it, with careful selection of all these critters.
    - Other gases. We humans create in our intestines gases with odors and with other problems. Thiols and skatole (fart smells), methane, hydrogen sulfide need all be removed. Soil organisms can handle some of this. On Earth, hydroxyl radical helps, it being generated in the atmosphere thanks to solar radiation and some organics – a bit of smog, as it were. Ask some Los Angelenos to create air pollution? Not really, but the concern is there. On the Space Station, the gases are filtered out (and then what?)
- ***Other components of air are necessary for comfort or more.*** As on the Space Station, the colonizers will want nitrogen, as on Earth. That's for their air and also for plant growth. Some loss of nitrogen from the soil as N_2 or N_2O is inevitable from denitrifying bacteria, and some will be vented from habitations and greenhouses, as when airlocks are opened. The colonists will definitely want water vapor (normal relative humidity levels). Close control is mandated to avoid drying out (causing respiratory distress) or excess humidity (condensation, discomfort, damage to electronics). Powered humidifiers/dehumidifiers can/must handle this.
- **Getting water – no simple matter.** Mars orbiters and rovers have explored the planet extensively. Ice is found seasonally at the poles, far from habitable latitudes. Liquid water is not to be found on Mars except at rare times in rare places. The problem lies in the phase diagram of water – that is, which of the phases of ice, liquid water, and water vapor are present at a given temperature and pressure. On the surface of the Earth, ice and vapor coexist below the freezing point, commonly near 0°C with a tiny variation with atmospheric pressure. Above the freezing point, liquid and vapor coexist. Vapor pressure increases markedly with temperature, 6% to 7% per 0°C near "room temperature." On Mars, temperatures above 0°C occur rarely in time and place – only near the equator. Even then, the atmospheric pressure is so low that only vapor is stable; essentially, liquid water cannot remain, evaporating instantly if it were to be introduced. As a result, water for a colony would have to be retrieved from polar regions (out of the question for costs in energy and travel time) or from subsoils. The surface soils are dry. Water would have to be obtained by drilling to "wet" soils where water is

adsorbed (lightly bonded to mineral soil). Colonists would not expect to find ice at any practical depth in the soil because its vapor can traverse soils to the atmosphere readily over the millions of years since the atmosphere had significant water content; water ice has left. Water would be extracted by heating the soil (an energy-intensive process) and condensing the vapor. A precious resource for the first stage of colonization would be the water carried from Earth, with an equally precious resource being equipment for solar energy capture and storage. There will be no long, steamy showers for the colonists.

Shielding from cosmic radiation and solar flares. Mars lost its magnetosphere 4 billion years ago, https://planetary-science.org/mars-research/martian-atmosphere/

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- **Lesser problem: ultraviolet radiation.** About 8% of the Sun's total electromagnetic radiation is UV. Of course, shielding for the more energetic radiation should take care of this, though for Mars walks the colonists' faceplates will need hefty UV screening.
- **System safety.** Any complex technological system needs proactive care for safety against simple interruptions of critical services, fire, electrical hazards, internal radiation hazards (e.g., as from a nuclear power reactor), chemical contamination among system parts, etc. There's no calling in an outside fired department, cleanup crew, etc.

Where

I have relatively little to offer here. The flux of solar energy for power and for growing crops n special greenhouses is highest at the equator. It falls off on an annual scale closely as the cosine of the latitude. Weather events strongly modify the seasonal pattern – that is, dust storms. These are more likely at perihelion, the closest approach to the Sun. They also have been analyzed and modeled as having a role in the loss of water from Mars, a loss that is nearly complete. Because dust storms readily envelop the entire planet, there is no place to escape them for purposes of keeping a supply of solar energy. For solar energy capture the lowest latitudes are the most favorable. Much energy storage would be needed to survive the long time at aphelion with 40% lower energy flux density and even lower temperatures. Surviving long dust storms adds to the storage requirements.

The second major problem is acquiring water, noted above. It would be acquired from water adsorbed on soils. The likelihood of finding sufficient adsorbed water decreases markedly with mean temperature. The low latitudes with higher temperatures would be the most problematic for recovering water. A compromise would be middle latitudes.

Why?

Elon Musk takes an extreme position, that our future on Earth is limited in duration. Even omitting the prospect that we may do ourselves in with pollution, wars, lethal climate change, or the like, there is the Sun's role in our future. He points out, rightly, that in around half a billion years the Sun will have become so much brighter that the mean temperature on Earth will be lethal. At 1% gain in luminosity or expressed alternatively as radiant flux density per 100 million years, the projected gain is 5%. The calculations done earlier here would tie that to an increase of about 1.2% in absolute temperature. That's 0.012*288K, at least another 3.5K, which is another 3.5°C. Sure, in 500 million years the Sun will brighten and expand, toasting the Earth to lethal temperatures beyond what any sentient life could tolerate, and, yes, that would warm Mars "nicely."

Let's face the facts. On Earth, large vertebrate species such as ours have a lifetime of about 2 million years. For mammals in the "modern" or Cenozoic era, that lifetime has been about 1 million years on average. We big vertebrates go extinct for a variety of reasons.- competitors (e.g., we modern humans vs. archaic *Homo* species), predation (esp. by humans now– the dodo by European hunters, and probably the North American megafauna by Paleo-Indians), habitat shrinkage from climate change (a good part of the cause of five mass extinction events), exotic species invasion (bird malaria in Hawaii introduced by humans; extinction of South American marsupial species by North American mammals after Isthmus of Panama emerged close to 3 million years ago), overspecialization on food sources (watch out, koalas and pandas), natural emergence of novel diseases (transmissible facial cancer threatening the Tasmanian Devil), and, surely a mix of several causes. Larger species are more likely to go extinct fast; they are, among other things, slower-breeding. Once a population shrinks very much in what's termed a population bottleneck, the remaining individuals represent low genetic diversity for adaptive responses to new threats (climate ,and other species). Extinction probability rises – a worry of ours for cheetahs. There have been studies, mostly genetic analyses that show we humans also have low genetic diversity for a species with such an enormous population. These studies have been interpreted as evidence that humans went through a population bottleneck – say, 70,000 years ago during the eruption of the Toba supervolcano in Indonesia. More recent analyses say that our genetic diversity has an explicable pattern and, moreover, that this pattern is not what derives from a population bottleneck. Most of the causative agents of extinction are other biological species, and some are climatic. In an isolated Mars colony one expects very few other species and fewer active agents of extinction, but the very simplicity of the ecosystem gives little recovery potential from crop failures or emerging diseases. Lethal failure of life-support technologies is a more likely cause. In any event, it is supremely unlikely that humans could survive more than a handful of millions of years. I dismiss the idea as specious that humans can become a near-eternal multi-planetary species. Besides, who wants to live forever on one more planet. Recall how bored was the character Bowerick Wowbagger in the hilarious social commentary trilogy, *the Hitchhiker's Guide to the Galaxy*. Having become immortal by an industrial accident, he spent his time traveling to insult every other being. The Dyson Sphere of a long-lived civilization (look it up) sounds just as terminally boring.