Alan Mole
1441 Mariposa Ave.,
Boulder CO 80302
ramole@aol.com

Baseline Design for a Mars Colony

Let us imagine a working Mars colony of one thousand people. How can it be economically viable? It cannot export ores to Earth – the shipping costs are too great – and it cannot export food or anything else heavy. Yet it must earn money from Earth. It will probably do so in the form of tourism and research – nothing else seems practical. As a result the city should be perched on the rim of a canyon or other spectacular view, and near interesting research areas.

Ultimately, the city wants to import from Earth the minimum mass of materials possible. Conceptually it wants to produce its own food, air and building materials, and import computer chips (which weigh almost nothing and require stupendous factories to produce.) It wants to roboticize farming and mining and manufacturing, because humans require expensive food and lodging, while robots need only energy and maintenance. Thus materials will be produced by self-driving loaders, trucks and smelters; manufacturing will be by 3-D printers, lasers and milling machines; assembly by robots; and repair by robots and the occasional human. Farming will be by specialized weeding, planting and harvesting robots. Humans, assisted by powerful AI, will plan and organize these activities, and perform research.

The rest of this paper deals with the required area of greenhouses and their design, and by extension structures for housing and factories, and the required nuclear generator, but it does not address smelting or manufacturing.

Elon Musk intends to put humans on Mars in 2024 and launch a colony a few years later, so it is timely to determine the basic parameters of such an enterprise. What size of greenhouses is needed, what weight of fertilizer, how much structural material per greenhouse, what mass of insulation and radiation protection etc.? This paper is a first cut at such calculations but others must fill in the details.

It is assumed that irrigation water and fertilizer (phosphates etc.) have been found on Mars, and that buried structures will provide sufficient shielding against radiation. A nuclear generator design of 2kW per capita is included, courtesy of Frank Williams.

To a first approximation total mission mass is proportional to human mass, so very small people should make up the crew. That is, hundred pound gymnasts will eat less food, require smaller vehicles and quarters, and think just as well as three hundred pound football lineman. Small, fit, smart people will therefore be chosen. They need only about 1600 calories a day.(1) (This has not been used in the calculations below, but holds promise for cutting the size of the greenhouses.)

Size of the Colony

F.B. Salisbury discussed experiments done by his lab and one in the Soviet Union using dwarf wheat.(2) He concluded "... only about 15 m² plant growth area would be required to provide adequate nutrition to a single crew member if that crew member were willing to eat nothing but wheat! With addition of other crops plus a safety factor, 50 m² should be sufficient." For 1000 colonists some 50,000 m² or 500,000 ft² would be needed. This seems low so a further factor of four is applied, bringing the figure to 2,000,000 ft². Living quarters, labs and walkways are estimated to require 1,000 ft² per capita, or 1,000,000 ft² for a thousand. Thus the total covered area comes to 3,000,000 ft².

The crops produce enough oxygen for the colonists to breathe. Salisbury reports on the Soviet Bios 3 experiment (2 p152) that there were three crew members and three compartments totaling 63 m² and planted with vegetables, "...which provides ample air regeneration capability".

It may be that the Martian soil is less fertile than Earth's soil so these numbers must be increased, but this paper will use 3,000,000 ft² for preliminary sizing. This is a square 1700 ft on a side, about six city blocks of 300 ft, a reasonable distance for colonists to walk. A colony of a million will be ten miles square so the colonists will need bicycles.

Basic Design of A Martian Greenhouse

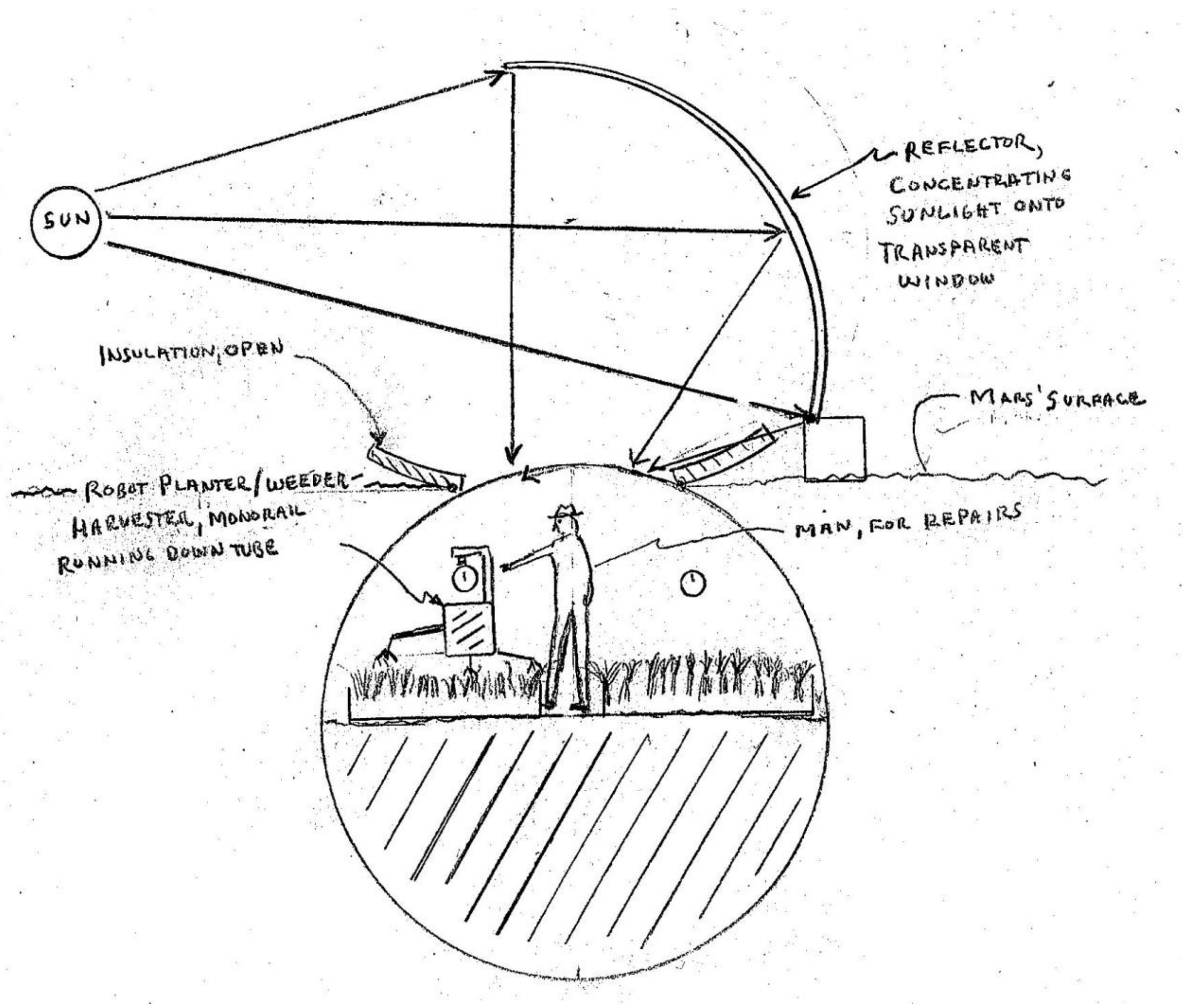

Figure 1. Overall Design

Mars is cold so the plants will freeze in a plastic greenhouse on the surface. One way to prevent this is to cover the houses with opaque insulation and use nuclear power to run lights, but a better way is to bury the house except for a transparent strip along the top, and use aluminized mylar mirrors to reflect concentrated sunlight in along the strip. Low mass mylar reflectors can disperse light evenly to the plants.

Air must be held in by the plastic membranes and thickness is minimized by making the diameter of the tubular houses as small as possible, say 16 feet as shown below. This minimizes the mass that must be brought from Earth.

Structural Design

The important point is that the weight of material in the greenhouse membrane for coverage of the same area is proportional to the radius of the tube. That is, though they will cover the same area, one tube 32 ft in diameter will weigh twice as much two tubes 16 ft in diameter. This weight must be hefted about on Mars by the astronauts, and the material must be transported to Mars at vast expense, so it is desirable to minimize it. Therefore, the tube diameters should be the minimum possible, subject to the constraint of being big enough for astronauts to walk through (plus perhaps a few feet for psychological effects).

Here is the proof that material volume and mass increase with tube diameter. Consider two structures covering the same span, and each extending one unit into the paper. One has a single tube, diameter D; the other has n tubes, diameter D/n each.

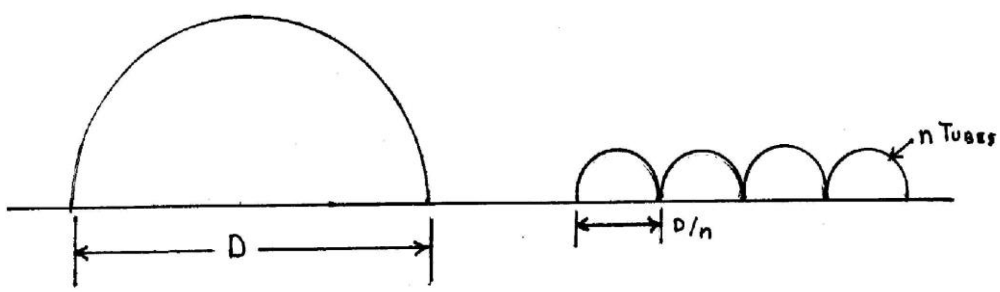

Figure 2.

The area of both systems is the same. The single span area is 1 (unit into the paper) x $\pi D/2 = \pi D/2$ Units^2. The multi-span area is (per span) 1 unit into paper x $\pi D/2n = \pi D/2$ x 1/n. But there are n units so the total area is $\pi D/2$ x 1/n x n = $\pi D/2$ -- identically the same area as the single span. Thus the area of plastic required to cover the same area of ground is the same, regardless of the number of spans. But the thickness is different. For a cylinder $S=Pr/t$ (where S is Stress, P is pressure, r is radius, t is thickness and $S_{allowable}$ is the working stress for the material in question.) Then $t_{required}=Pr/S_{allowable}$-- that is, t is proportional to r. So the thickness, and hence the volume and mass of the membrane, are proportional to the radius. Therefore the radius should be kept as small as feasible. (The same is true of domes. The thousand foot domes beloved of illustrators will cost a huge weight penalty if they are built at all.)

The tube should be a full tube, not the half tube above. Anchoring and leakage problems would be severe for a half tube.

Suppose the interior pressure is 8 PSI, about equal to 15,000 ft on Earth (possibly with more than 21% oxygen, the Earth-normal level, to make up for the "high altitude") The wall membrane consists of a bladder to hold the air, t= 0.003 inches (a guess based on three-mil mylar seeming strong enough) plus a web of Kevlar fibers. NASA used a similar design for the inflatable Mars Transhab design, with a safety factor of 4.0. This sf seems high but people will be sleeping in the Transhab and there are many micrometeorites in space; here 3.0 will be used because people will not normally sleep in the greenhouse and so can get out faster in the event of a leak. (The Transhab design cannot be copied directly because it is meant for use in space and has heavy anti-micrometeorite shielding.)

Kevlar fiber has an ultimate tensile strength of 435,000 psi (3); dividing by the sf gives an allowable stress of 145Ksi. Trequired = Pr/Sallowable = 8psi x 96in/145,000=.0053in thickness, or the equivalent in tangential-direction fibers. However, the axial stress in a pressurized cylinder is exactly half the tangential stress, so axial fibers equivalent to a 0.0027 thickness will be needed, for a total of .008. Allowing for interaction effects in the composite material, say 0.009 inch total thickness. Plus the .003 inch bladder gives a grand total of .012 inch thickness. Kevlar weighs 0.052 pci (assume the bladder weighs the same; most plastics do.)

The one foot by 16 foot section above covers 16 sf and weighs: .012 in x 12” x 16ft x 12in/ft x π x .05 pci = 4.4 lbs, or 0.27 lb per covered ft^2 . For the greenhouse plus facilities some three millionft^2 are required for 1000 people, so the whole colony weighs 800,000 lbs. Adding to this the 176,000 lbs for the nuclear generators gives 976,000 lbs. Adding construction machinery, smelters, fiberglass machines etc. may double the mass to two million lbs. At $225/lb (below) delivered to Mars, this costs $450 million. For a million people the cost is $450 billion. SpaceX assumes the colonists will pay for their own one-way tickets at $200,000 each, or $200 million for a thousand people.

Estimated cost per pound of payload delivered to Mars' surface

SpaceX engineer and presenter Paul Wooster says they are trying for less than $500 per kg, or $225 per lb.(5)

Will the hydrostatic pressure crush the tube?

Dry sand weighs 100 pounds per cubic foot, so at 8 feet depth on Earth its hydrostatic pressure is 800 psf or 5.5 psi. Mars' gravity is only 3/8 that of Earth's, so at 8 feet on Mars the pressure is only 2.0 psi. The tube will be pressurized to 8 psi so there is a safety factor of four against crushing.

Shadowing Problem

Figure 3 shows a shadowing problem with the mirrors. If the greenhouses are touching as in Figure 3A the mirrors will shadow one another. Thus the mirrors must be spread out as in 3B, or placed on a slope as in 3C. An exact design must await selection of a site for the colony. If the spacing is three times the tube diameter then the tubes with the living quarters can be put between the greenhouse tubes and the colony will be the same size as before. (Without the factor of four applied to the greenhouse area. Again, an exact design is to be determined.)

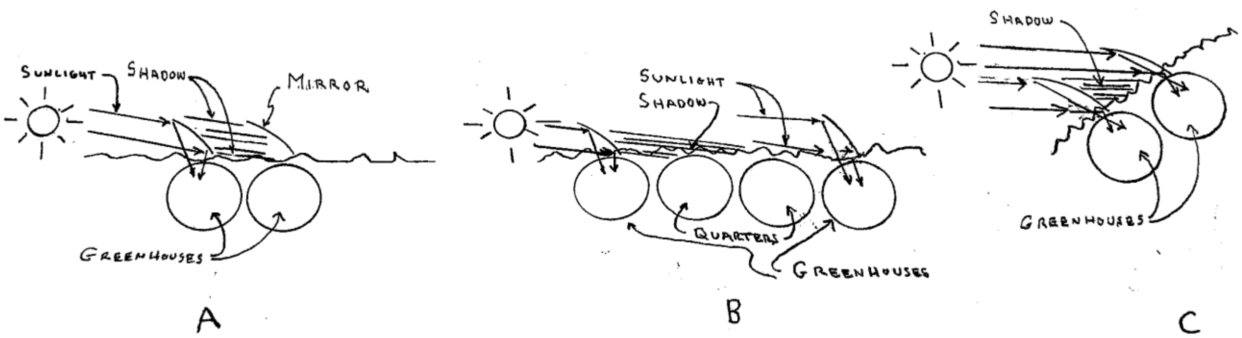

Figure 3.
Shadowing Problem

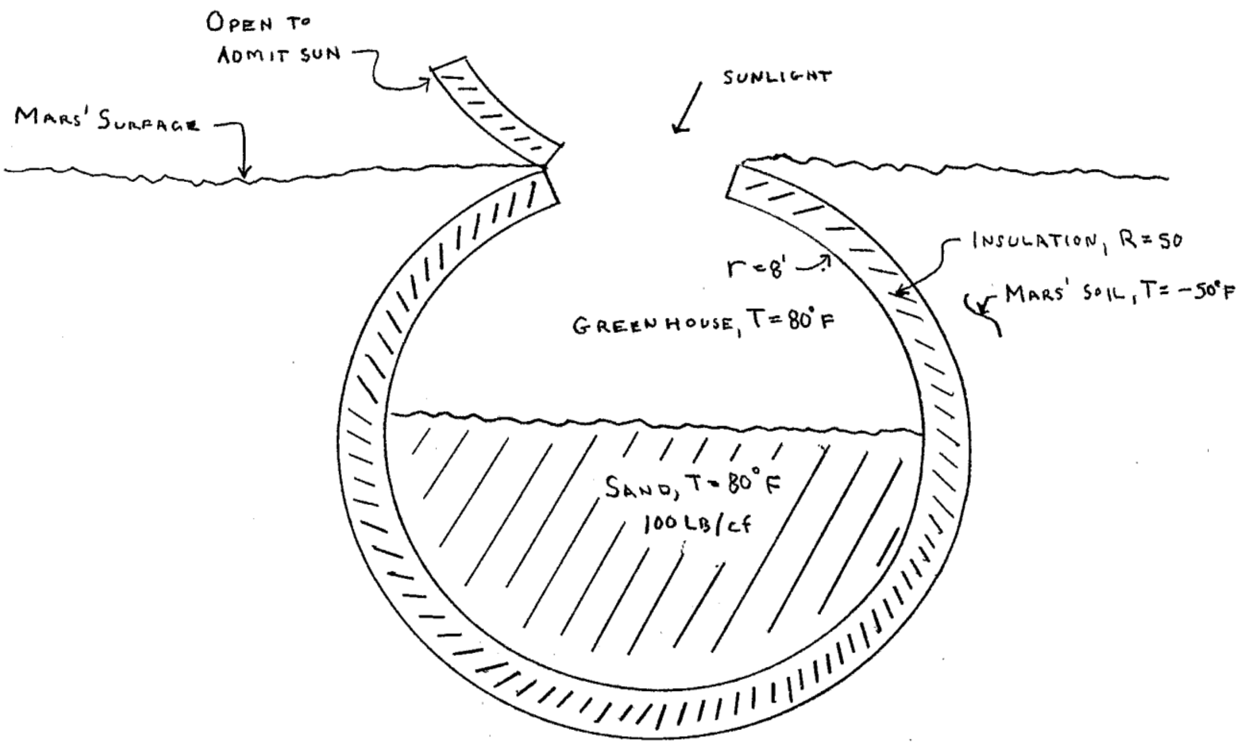

Figure 4. Thermal Design

Thermal Analysis

Figure 4 shows a typical section. The insulation is not specified but most insulations (aerogel, lumberyard foam board etc., are R10 per inch, so R50 would require about 5 inches of insulation, which seems reasonable.(4) The half of the tube filled with sand provides thermal mass (stabilizing the temperature from day to night.) Mars' average temperature is -50°F and the greenhouse runs 80°F so the ΔT is 130 F.

Consider a section one foot into the paper. The area of insulation is 2π x 8 ft x 1ft = 50 sf. Heat loss per day is 50 x 130°ΔT x 1/50 x 24 = 3100 btu. Input is 16 sf x 317 btu/hour sf x 10 hr of daylight = 51,000 btu/day. This is more than the loss, so heat must be vented through radiators (not shown). (The input level is determined by the photosynthesis requirement of the plants, assumed to produce maximum growth at Earth-normal level of insolation.)

The mass of the insulation is not calculated because it will almost certainly be produced on Mars. Insulation is light but voluminous so it cannot be brought from Earth. There would not be room in landing capsules for it. For the first greenhouses plastic will be brought and foamed in place, and for the colony the first colonists will manufacture fiberglass or aerogel from Martian sands. Identifying the best method would certainly be of interest.

The greenhouses provide oxygen and food for a thousand colonists. If there is a three-month dust storm and the greenhouses freeze, then the colonists all die, which is unacceptable. The greenhouses must stay warm during the worst case dust storm of several months.

How will the system stay warm in a sandstorm?

Mars' soil is -50°F. Then ΔT at the start of cooling = 80 - (-50°) = 130°F. At the end it is only 32 - (-50) = 82°F, and on average it is 106°F. Average loss per day is 50 $ft.^2$ x 1/50 x106°F x 24 = 2,500 btu per day.

On a normal day the temperature will vary only a degree from day to night. The sand in the semicircular bottom of the house has a volume of 1 ft x ½ x π x 8^2 = 100 ft^3. At 100 lb/ft^3 it weighs 10,000lb with a thermal mass of 0.2 btu/lb = 2000 btu/F°. This comes to 130 btu/hr loss x 12 hr/ 2000 btu/F°= 0.8 F°.

Martian dust storms can last a few weeks but it is necessary to find the worst case, which may be much longer.

There will be a nuclear power plant. A nuclear generator is needed because solar cells do not function without light, as during a storm. Can its output be used to run heaters? A nuclear plant for 1000 people producing 2kWe per capita produces 2MWe, which is 6,820,000 btu per hour. (8MW thermal output and 2MWe electrical output at 25% efficiency. The thermal output of the generators is 27 million btu/hr.) There are 187,000 ft of greenhouses, losing an average of 2,500 btu per day per ft, or 104 btu per hour-ft. Then 187,000 ft loses 19.4 million btu per hour, compared to 27 million btu per hour from the generators. The generators can indeed warm the greenhouses.

Next there is the problem of oxygen production. In a dust storm the plants will not perform much photosynthesis. Their output must be made up by oxygen production from the generator. In good times food and oxygen should be stored too.

The lives of the colonists are at risk if the dust storm analysis is wrong. Great care should be exercised with these calculations.

Nuclear Generator

Courtesy of Frank Williams

Electric power generation and distribution will be a combination of uranium based nuclear reactors and a minimum system of batteries and super capacitors for energy storage and load leveling. Appropriate nuclear reactors implementations will be independent of environmental conditions thereby providing consistent power for even severe conditions, e.g., dust storms that can last for several weeks and the ensuing period of digging out from resulting dunes.

We propose a scaled approach rather than a single monolithic 2 megawatt electric (MWe) reactor (average of 2 kWe per member of the colony). There are many reasons for this.

- Implementation over time: reactors can be launched as initial site build up equipment is launched.
  - Prior to human arrival robotic missions can set up initial equipment
  - Reactors can be launched with waves of humans as the colony grows
- Eliminates a single point failure mode
  - While full failure of a large reactor is unlikely, taking a single, large reactor off-line for repair will have significant negative impacts on the colony
  - Large reactors are inherently more difficult to repair for major issues simply due to their larger sizes and component masses
- Robotic start up is easier for smaller reactors prior to human arrival.
  - Smaller reactors can be designed to be self starting
- Smaller reactors are easier to design and operate as primarily self moderating systems.
  - Self moderating reactors become less thermally (and subsequently electrically) efficient as their size and power increase
- Several smaller reactors can be operated as sets to cover variations in daily, weekly, or monthly power requirements
  - Power requirements shall vary over time.
  - Reactors need to be designed for peak power requirements or a significant energy storage and disbursement system needs to be implemented.
  - Using multiple reactors that can be brought on-line as needed and/or actively moderated as needed will minimize the need for any electrical load leveling and energy storage system
- Smaller reactors can be placed near power needs
  - Small reactors with moderate amounts of shielding can be placed much closer to equipment and power needs than a single large reactor

The baseline reactor is currently envisioned to be an evolution of NASA's Kilopower Reactor shown in Figure 5. The evolution will result in a 100 kWe reactor from the maximum of the currently envisioned design of 10 KWe. (NASA believes the current Kilopower Reactor design can evolve to 10 kWe.) The evolved design will replace the single, cylindrical highly enriched uranium (HEU) core with a single central core encircled by concentric rings of HEU. Interspersed between the central core and the next ring of HEU will be several elements: boron neutron absorber moderators, Beryllium Oxide neutron moderators, sodium metal heat pipes, and spacers that have a high coefficient of thermal expansion (CTE). The boron central cylinder at the center of the central HEU cylinder (as in the Kilopower Reactor) and the boron elements between the central core of HEU and the concentric layer of HEU will be removed at reactor start up and reinserted at reactor shut down. The high CTE spacers between provide self moderation of the reactor allowing it to run at near maximum without constant human monitoring.

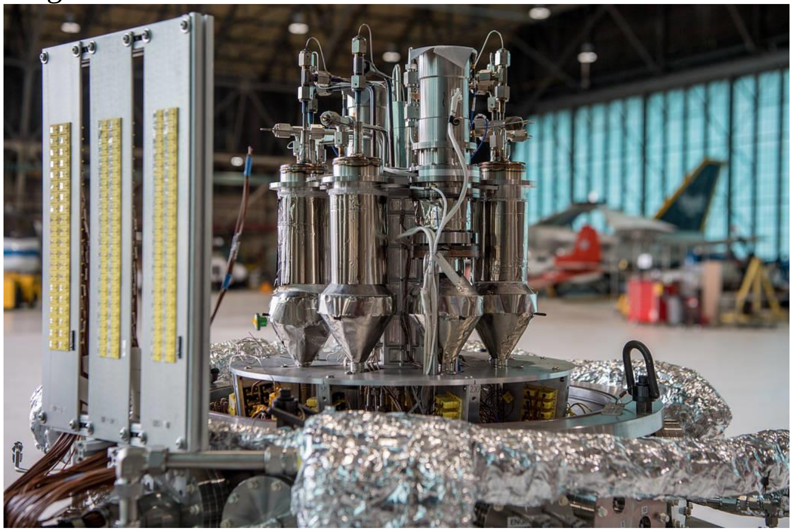

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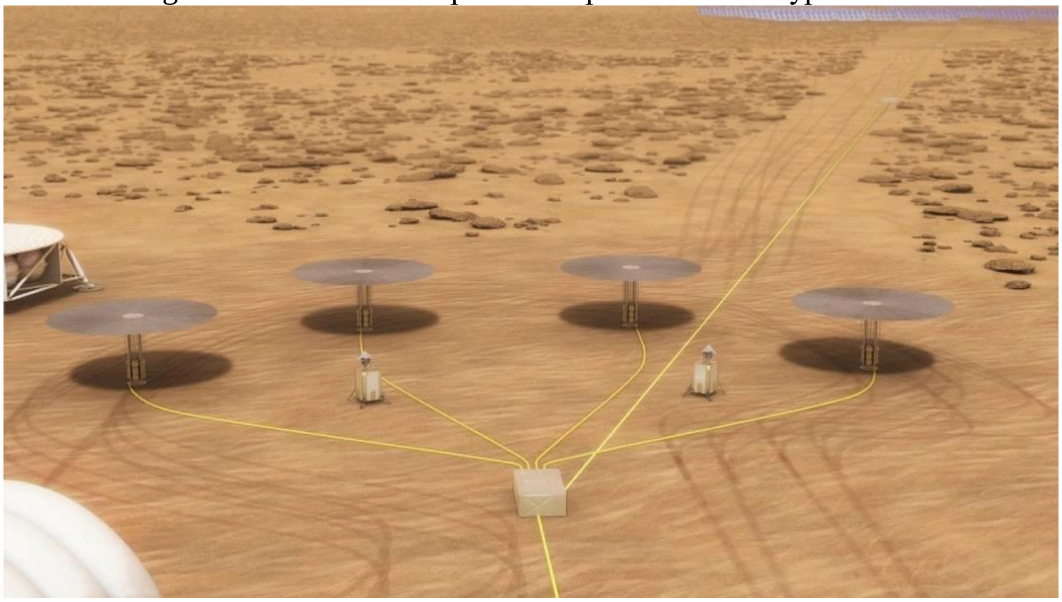
Figure 5. NASA's Kilopower Space Nuclear Reactor showing the Sterling energy conversion systems.

Early placement of the first few reactors will use atmospheric heat rejection systems as currently envision by NASA's concept for use of Kilopower Reactor as shown in Figure 6. After human inhabitants arrive and can install the reactors, they will utilize a more robust system of cooling by placing the heat rejection heat pipes into the Martian surface, which will allow for a consistent heat sink during all environmental conditions.

Image courtesy NASA GRC. Use of this image does not constitute an endorsement of this paper by NASA.

Figure 6. NASA's concept for Kilopower Reactor type installations on Mars.



Individual reactor and heat conversion system's mass is expected to be on the order of 4,000 kg each. This will allow these reactors to be launched from Earth as part of larger, more compressive missions rather than as stand alone missions for a single 2 MWe reactor which could easily have a mass of greater than 18,000 kg. This gives further mission flexibility as the colony evolves.

Mass of Generators (Alan Mole)

Some twenty 100kWe generators are needed for 2MWe for a colony of 1,000 people. They mass 4,000 kg each, for a total mass of 80,000 kg or 176,000 lbs.

Alternative per rule-of-thumb (Alan Mole)

A 100 kWe generator masses about 4000 kg and the mass increases as the square root of the output.(6) Thus bigger generators provide the same output for less mass. Two one MWe generators would allow one to be repaired or refueled. Each would mass $10^{.5}$ x 4000 kg = 13,000 kg so the total would be 26,000 kg or 57,000 lbs., one third of the 176,000 lbs above. Clearly the best number of generators is a imporetant subject as it has the potential to lower the cost of the colony significantly.

Discussion (Alan Mole)

Most of the mass imported from Earth is nuclear generators and building material for the greenhouses. Meanwhile most colonists are farmers, explorers or researchers. The farmers are replaced by robots and the explorers may be replaced too, with robots bringing material for researchers to study. This leaves most colonists unemployed. The solution is to put these people to work building infrastructure for the million inhabitants ultimately expected, and to make materials for the greenhouses from Martian material. The bladders are plastic derived from petroleum and so must be imported from Earth, but the Kevlar fibers can be replaced by fiberglass fibers made from Martian sand. Sand can also be used to make fiberglass or aerogel insulation. Importing machines to make these materials will be less expensive than importing the materials themselves. Much of the mass from Earth is the nuclear generators so improvements to these are very important too. Perhaps many of the parts can be made on Mars.

Thus the colonists go from farming and exploring to building and manufacturing, and as more arrive they are employed the same way. Ultimately the colony is completed and the colonists will have nothing to do, so they may work at terraforming. Terraforming Mars is hard because there is no known source of nitrogen or carbon dioxide to stabilize the atmosphere, and a pure oxygen atmosphere is dangerous in case of fire, but if a source of non-reactive gases is found then the colonists can become terraformers.

It is suggested that a good subject for investigation would be the manufacture of insulation and structural material for the greenhouses and other structures, and the heavy parts of the generators. Detailed thermal analysis of greenhouse thermal performance in dust storms is also relevant, as is the maximum duration of the storms.

Mars' atmosphere is CO_2. Many plants on Earth grow faster in higher densities of CO_2. If the plants grow faster then fewer greenhouses would be needed, saving money on imports from Earth. Sunlight can be concentrated to more than Earth normal too. It is assumed that Earth-normal insolation is provided, since Earth plants are evolved for that. But would plants grow faster with more light? What if they were provided with both more CO_2 *and* sunlight? It would be interesting to find out.

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